COMPUTER MODELING AND SIMULATION

Труды международной научно-технической конференции

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Сборник содержит тексты докладов ежегодной международной конференции КОМОД 2014 (Компьютерное моделирование 2014), проводимой Санкт-Петербургским государственным политехническим университетом и Национальным Обществом Имитационного Моделирования (НОИМ), с участием представителей европейской ассоциации EuroSim. Конференция посвящена компьютерному моделированию и исследованию сложных динамических систем: теория и практика создания сред визуального моделирования сложных динамических систем, математическое обеспечение сред визуального моделирования, компьютерные модели сложных динамических систем, компьютерные инструменты в образовании. В сборник также включены лучшие доклады студентов и аспирантов, участвовавших в конференции.

Материалы докладов печатаются в авторской редакции.

Ответственный за выпуск – председатель оргкомитета конференции, доктор технических наук, профессор Ю.Б. Сениченков

International scientific and technical conference "Computer Modeling and Simulation-2014" (COMOD 2014) was organized by Saint Petersburg state Polytechnical University, National Simulation Society, with assistance of Federation of European Simulation Societies – EuroSim.

Complex natural, technical and industrial systems require complex mathematical models and sophisticated technology to develop, research and visualization. Modern visual simulation environments are the basis of these technologies and are used in scientific research, industrial design, education.

Significant attention was paid to the joint operation of complex technical systems, problems of electromagnetic compatibility. Consideration of the problems of mathematical modeling in electric power industry, again becoming more and more popular in Russia was new for the COMOD - 2014.

The Conference Subjects were: mathematical and numerical modeling; development and application of visual modeling environment of complex dynamic systems; modeling in electrical engineering and electric power industry; projects of young scientists; author's presentation of new books; author's presentation of software systems; information about planned and completed theses; author's lectures about software products and subsequent issuance of certificates.

Editor – Chairman of Organizing Committee, Prof. Yuri Senichenkov
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Realisation preserving modelling in Modelica

Borut Zupančič

Laboratory of Modelling, Simulation and Control
University of Ljubljana, Faculty of Electrical Engineering
Ljubljana, Slovenia
borut.zupancic@fe.uni-lj.si

Abstract— Realisation-preserving modelling means in this contest a modelling when a computer aided approach is used with the basic aim to keep the physical structure of a real system or its topology as much as possible in the model. Bond graphs represent a very efficient and traditional approach. However new object-oriented and multi-domain tools based on Modelica language are more appropriate for the people who do not have a deep insight into modelling and simulation. The important advantages of such tools in comparison with traditional block oriented modelling approaches are described. In the paper we also describe several education and industrial application projects in Dymola-Modelica environment and some experiences obtained from these projects but also from more general usage of the Modelica environment.

One of important observations was that some of our models proved to be very complex and difficult to simulate, verify and validate. Namely models in Modelica become very complex which causes also numerical problems which are difficult to diagnose. So, a conclusion was that our models are too complex and should be simplified or reduced. Therefore we propose some model reduction solutions for equation and diagram layer as well.

Keywords— Realisation-preserving modelling, Object oriented modelling, Acausal modelling, Physical modelling, Multi-domain modelling, Model reduction.

I. INTRODUCTION (Heading I)

Good modelling means good understanding of a real system. In order to truly understand how a physical system works, we need to collect knowledge about the system under study and organize that knowledge in a meaningful way. If we study traditional literature about modelling of predominantly continuous dynamical systems, the usual term used is mathematical modelling and the approaches are usually divided into theoretical, experimental and combined modelling. It is well known that theoretical modelling is based on basic physical laws or better on mass and energy balance equations. Experimental modelling is based on measurements and the whole system is regarded as a black box with inputs and outputs and therefore only input-output relations are modelled or better identified. Finally the combined modelling is a combination of both approaches. But what is then realisation preserving modelling? In our case we are talking about a computer support modelling, when models are not described at least at the model top level with differential equations, transfer functions or state space, but with more practical and less mathematical building blocks or library components. So models become more similar to technological schemes and therefore a good media for understanding and discussions in interdisciplinary working groups.

Which are then approaches that can be characteristic for realisation preserving modelling? Among several approaches we would mention two – Bond graphs and object oriented modelling approaches originated in Dymola and later Modelica developments. Both methodologies have many common features. Both approaches allow us to capture and organize knowledge about physical systems in a systematic way. Both approaches enable so called acausal modelling. Both approaches enable multi-domain modelling. And both approaches connect the components on more complex way – not on the way of traditional CSSL or Simulink models when one variable is present in each connection point but there are several variables with different features, more precisely two types of variables. These two types of model junction variables are not dislocated from each other as in traditional block or signal flow diagrams. This special way of connections actually enables appropriate working of such models with the basic feature that they preserve the topological structure of real systems.

In the paper we shall describe basic concepts of realisation preserving modelling in Modelica. The approach will be illustrated with some education and more industrial applications. In the last part some guidelines of our last research activities – reduction of Modelica model complexity will be briefly described.

II. MULTI-DOMAIN AND OO MODELLING WITH MODELICA

The disadvantage of traditional general-purpose simulation tools is a lack of object-orientation, which does not enable to develop reusable components. Therefore some special-purpose tools were developed (for electrical, mechanical, chemical systems, …). However such systems do not support multi-domain modelling – modelling of systems from different areas, which is frequently needed particularly within automotive, aerospace and robotics applications.

When analysing the advantages and disadvantages of traditional and more advanced modelling and simulation tools the basic distinction appears from the term- causality. This term can explain the evolution which was in the past declared
as the evolution from block oriented tools into object oriented tools.

A. Acausal modelling

When using general-purpose simulation software for predominantly continuous systems (e.g., Simulink) we assume that a system can be decomposed into block diagram structures with causal interactions. Often a significant effort in terms of analysis and analytical transformations is needed to obtain a problem in this form. This procedure requires a lot of engineering skills and manpower and it is error-prone. However in order to allow the reuse of component models, the equations should be stated in a neutral form without consideration of computational order. This is so called acausal modelling approach. In nature namely systems are acausal. We never know whether a flow causes pressure difference in a tube or vice versa. Causality is artificially made because physical laws have to be transformed into a convenient computational description. It is much easier, more convenient and more natural then to use acausal modelling tools such as Dymola with Modelica [7][8][9][10]. We write balance and other equations in their natural form as a system of differential-algebraic equations. Computer algebra is then utilized to achieve an efficient simulation code.

There are some important processing tasks and features in acausal oriented modelling tools which will be briefly described in the sequel.

B. Object orientation

As in each object oriented programming principles encapsulation, information hiding and inheritance are very important. Inheritance is a way to form new classes (instances of which are called objects) using classes that have already been defined. These new classes take over (or inherit) attributes and behaviour of the pre-existing classes, which are referred to as base (ancestor) classes. So an existing code can be used with little or no modification.

However we do not intend to discuss about well-known general concepts of OO programming. From a modeller point of view, object orientation means that one can build a model similar to a real system, using libraries’ components and putting them together.

C. Component coupling

Connections between submodels are based on variables, which define proper relations and influences between movements, flows, temperatures, etc. Fig. 1 shows how three thermal subsystems are connected. Three physical variables are presented in connectors: \( q_i \) – thermal flow, \( j_i \) – radiant flow and \( T_i \) – temperature. Generally there are two types of variables in connectors of subsystems: potential variables that become equal in connection points (potentials, temperatures, pressures, ...) and flow variables which sum equals zero (currents, momentum, forces, ...). Connector is a structure in which all mentioned variables are collected. By joining connectors the sub models are connected. During processing the tool generates appropriate equations from connect statements and connector definitions and this is fundamental concept making acausal modelling to work.

D. Hybrid features

This means that continuous-time, discrete-time and discontinuous modelling are supported. Such approach demands many original solutions in symbolic processing and in run time during simulation. Events can be periodically or relation (state) triggered. The variable structure models which can be studied in such environments are very useful especially in control systems studies.

E. Symbolic processing

Multi-domain OO modelling tools have a modelling pre-processor with some basic functions. Each variable (unknown) must be calculated from a single equation. The equations should be sorted on the way that all variables on the right hand side are calculated before the equation is executed (in each step size). Size and complexity is also reduced in this stage (elimination of trivial equations \( v1=v2 \), symbolic elimination of algebraic loops, reduction of the problem size (number of unknowns) with tearing, index reduction, ...).

III. EDUCATION APPLICATIONS

Some more recent education activities will be presented in this section. A process control system and a laboratory helicopter were modelled in Dymola-Modelica environment.

A. Optimisation of a process control system

Process systems are dynamical systems dealing with physical quantities like level, flow, temperature, pressure, ph. Appropriate control strategies in such systems are very important. As all modern and sophisticated control methods are model based, the appropriate M&S environment is very important. In the past we used more or less Matlab-Simulink environment. It is extremely efficient for the design of control schemes. However due to the lack of object orientation the modelling of processes were usually inefficient.

The process used for demonstration was a three tank laboratory set-up which is shown in Fig. 2.

For modelling the Dymola-Modelica environment was used. The combination of Dymola-Modelica and Matlab-Simulink was also examined. Modelica was used to model the physical part - hydraulic process. The process model was then used in Simulink as the `Dymola` block. So the complete Matlab environment can be used for control system design (e.g. the usage of Control toolbox, Optimisation toolbox, ...).

A new library was developed [12]. The following components were implemented beside others: reservoir, pump, valve, flow element, flow generators, interface components.
between hydraulic and control signals and appropriate
connectors.

To confirm the efficiency of the combination of the Matlab-
Simulink and Dymola-Modelica we modelled the following
control system: with controlled pump the level in the Tank 3
must be controlled to the level 0.1m. At time t=0 the reference
step change 0.1m appeared and at time t=200s there was a
disturbance: the valve V1 was opened for 20%.

A cascade controller with Matlab Optimisation Toolbox
(function fminsearch for multidimensional unconstrained
nonlinear minimization (Nelder-Mead)) was developed. The
objective function was

\[ O_f = \int_{0}^{400} t |e(t)| \, dt \]

where \( e(t) \) is the difference between the desired and actual
level in Tank 3.

Fig. 3 shows the model, which was prepared in Dymola-
Modelica for the use in Matlab-Simulink as a Dymola block. The
connectors (input and outputs) between Dymola-Modelica and
Matlab-Simulink were defined. Fig. 4 depicts the Simulink
model for the cascade control system which includes also the
Dymola block as the physical part.

We optimised the cascade controller with the main (PI) and
auxiliary (P) controller. The optimisation was performed with
the presence of reference and disturbance signals. Fig. 5 shows
the optimal responses – all three levels after reference step
change in Tank 3. There was also a disturbance in the middle
of the observed period; however the control system eliminates
it so it has almost no influence to the controlled variable (level in
Tank 3).

Why did we develop the hydraulic library? In the period
when we started with these activities there were no libraries for
the modelling of process control systems. Later many other
possibilities became available. However from the education
point of view these libraries are usually very complex and too
complicated and therefore cause sometimes numerical
problems. Our library is the implementation of the elementary
equations for tanks, valves, pumps, etc. – just how we teach at
the basic modelling course. And as only the basic equations are
used, it is also very convenient to model hydraulic systems
with the Modelica textual approach. Then students can
compare results obtained from icon and textual models.

B. Modelling and control of laboratory helicopter

Laboratory set-ups, which model real processes and
mathematical models, have a significant role in efficient
control design and education. The CE150 (Fig. 15) is a
laboratory helicopter made by Humusoft [15]. It is used for
studying system dynamics and control engineering principles.
and enables a wide range of practical experiments. The goal of modelling and identification is to prepare a basis for the students’ laboratory assignments, such as designing a multivariable controller that ensures satisfactory control in the wide operating range. In helicopter modelling both approaches – theoretical and experimental were combined. The mathematical model is described in details in [16].

The laboratory helicopter set-up comprises a helicopter body carrying two motors, which drive the main and the tail rotors and a servomechanism, which shifts the centre of gravity by moving a weight along the helicopter’s horizontal axis. The helicopter body is mounted to the stand so that two degrees of freedom are enabled: the rotation around the horizontal axis (pitch angle \( y_1 \)) and the rotation around the vertical axis (rotation angle or azimuth - \( y_2 \)).

Fig. 6 depicts the helicopter as it finally appears during animation in Dymola/Modelica environment. The model can be described as a nonlinear multivariable system with two inputs: the voltage driving the main rotor motor (\( u_1 \)) and the voltage driving the tail rotor motor (\( u_2 \)). The system has two outputs: pitch angle (\( y_1 \)) and rotation angle (\( y_2 \)).

Multi-domain approach is useful because we combine two different areas: mechanical systems and control systems which are usually modelled with block diagrams. We chose Dymola-Modelica as mechanical systems and block diagrams are included in the Standard Modelica library. For animation the body of the helicopter and both rotors were drawn with program SolidEdge and with DxfExport add-in exported into dxf file format. Dymola uses dxf files to create an animation of model components. The helicopter body and the stand were modelled with the standard Modelica libraries Mechanics\MultiBody and Mechanics\Rotational.

The overall scheme of the top level model in Dymola-Modelica is shown in Fig. 7. The scheme is very clear. It consists of the coordinate system definition (World), the stand model, the helicopter body, the tail and main rotor model (rotor means motor and propeller) and the controller with two reference signals – for the pitch and rotation angle.

The control system was designed and optimised using Matlab-Simulink environment. In Simulink the overall mechanical model was presented with the Dymola block. The input \( u_1 \) into the helicopter model is the voltage driving the front rotor and the input \( u_2 \) is the voltage driving the tail rotor. These are control signals. Output \( y_1 \) is the pitch angle and \( y_2 \) is the rotation angle. These are controlled signals.

![Fig. 6. Laboratory helicopter with forces affecting the body and control input/output signals](image)

![Fig. 7. Top level model of the control system](image)

Both control loops are combinations of the feed-forward control and the PID feedback control with windup protection. Feed forward signals are obtained from the reference signals \( r_1 \) and \( r_2 \) which are processed with two nonlinear functions realized with two lookup tables. The feed forward signals bring the controlled signals into the vicinity of the reference signals. Fine corrections and steady state error eliminations are achieved with appropriately tuned PID controllers.

The laboratory helicopter was earlier modelled also in Matlab-Simulink. The effort to produce the Simulink simulation model was much greater as with the Modelica. One needs much more time and much more modelling knowledge for Simulink based approach. But again we noticed that Matlab-Simulink is more suitable for the design and implementation of control schemes as it has more facilities especially in conjunction with some toolboxes. – e.g. Control System Toolbox, Optimisation Toolbox. Modelica is much superior when modelling physical systems when the concept of algebraic manipulation and specially defined connectors bring many advantages.

There is also one comment which can appear from the example: is it better that students work on real (laboratory) systems or on models. For beginners it is difficult to start with working on real systems. Laboratories usually do not have enough set-ups to form small groups. Then the control on real systems brings so many other application problems that real modelling and control problematic is completely fuzzyfied. We noticed it many years ago and that was the reason why we introduced more exercises in modelling and simulation environments. But when we used causal block oriented environments – CSSL or Simulink, it was somehow far from reality, the level was too abstract in comparison with real experiments. However when we started with Dymola-Modelica, this was a completely new story. The connection with physical system was significantly improved and OO model became very transparent especially when using diagram layer modelling, e.g. when using icons from pre-prepared model libraries. And if animation possibilities are used then the relation with real systems is even better. So we can conclude that such physical modelling can replace to some extent the real laboratory set-ups.
IV. INDUSTRIAL APPLICATIONS

In this section some recent applications will be described: modelling and control of thermal and radiation flows in buildings and an application from the mineral wool production: a recuperator.

A. Modelling and control of thermal and radiation flows in buildings

Bioclimatic conditions are extremely important for pleasant and healthy living conditions. As such, they represent a process with inexhaustible possibilities for studying the modelling, simulation and control concepts [17][18][19][20][21][22][23].

There are many aspects when talking about building automation. Our activities were focused on one important aspect of building automation: how to ensure good living conditions, but also energy savings, with the appropriate harmonization of thermal and daylight flows. Our approach was based not only on real experiments, but also on mathematical modelling.

1) Mathematical modelling

The main modelling goal was to efficiently use the model for control systems design. The theoretical modelling of the heat dynamics of a room was based on energy-balance equations that take into account thermal conduction, thermal convection and solar radiation [19][20]. The model was basically developed for a cube-shaped room with several layer walls. Each wall can contain a double-glazed window with a gas between the two panes.

The incoming thermal flow is partly transmitted and partly absorbed in the glass and in the air inside the room. In the isolated wall only the absorption takes place. Artificial heating (or cooling) is included. A part of global solar radiation is reflected at the surface of the glass and a part is absorbed in the glass. The part that comes into the room is absorbed in the isolated wall because of the assumption that the wall is black in the sense of infrared radiation. The effect of the infrared radiation is modelled with flows between walls and the glass and between the glass and walls. Many other phenomena were included, many suppositions were used and many simplifications were considered (see details in [19]). The basic inputs (influence variables) of the simulation model are the outside conditions as well as changeable properties of the envelope: the outdoor air temperature, the temperature of the terrain, global solar radiation, the properties of opaque elements (thermal capacity and resistance), the properties of transparent elements (geometry of openings, optical characteristics of glass and resistance of fill between panes are variable), interior properties (absorption, emission coefficients of walls and thermal capacity of furnishing are changeable), some other characteristics (changeable orientation, additional heating and cooling - the power of heater, cooler and ventilator). The outputs of the simulation model are: different thermal and radiation flows, the indoor temperature, walls, windows and surface temperatures.

2) Implementation of the simulator in Dymola-Modelica

The simulator was originally developed in the Matlab-Simulink environment [19]. However, the main drawback of this conventional approach became very evident – the simulator components could only be used for the developed configuration. Almost every structural change demanded a new development from the scratch. We were not able to establish a library of reusable components for walls, windows etc.

So we decided to implement the model in Modelica within the Dymola environment. The basic idea of the implementation in Modelica was to decompose the described system into components that are as simple as possible and then to start from the bottom up, connecting basic components (classes) into more complicated classes, until the top-level model is achieved.

The components provided by the Modelica Standard Library were sufficient to start with the implementation of the Modelica model in a graphical way – by connecting the appropriate components (icons). The HeatTransfer library contains the components for 1-dimensional heat-transfer modelling with lumped parameters, e.g., ThermalConductor, BodyRadiation, Convection, etc. All these components include a single connector (port) that contains two variables: the temperature $T$ (potential variable in Modelica nomenclature) and the heat-flow rate $Q_{flow}$ (flow variable).

3) Implementation of the wall

The wall is actually the simplest component of the model. It consists of several layers. The resulting Modelica scheme for a one-layer implementation is depicted in Fig. 8.

![Fig. 8. Scheme of a wall-layer in Modelica](image)

The block called the LayerCapacity is a model of a heat capacitor, while the blocks InnerSide and OuterSide are models of the thermal conduction through the layer, and are connected on one side with the LayerCapacity and on the other side with the stand-alone connectors inside and outside. The described structure is defined as a Layer model class. There are three connecting points with three different temperatures: in the middle the average temperature of the layer, and two boundary-layer temperatures on both sides. The model of the wall is obtained by simply connecting several layer instances in series. The structure of the wall is further connected to the other connectors according to the wall’s boundary conditions.

4) Implementation of the window

A similar procedure was used to implement the model class of a window. The scheme is shown in Fig. 19. The heat capacities of the outer and inner panes are modelled with two HeatCapacitor model classes, OuterPane and InnerPane, the connectors of which also contain the panes’ average temperatures. Both panes interact with each other via thermal radiation and thermal conduction through the air in the gap between the panes. Therefore, OuterPane and InnerPane are connected with the model classes AirInside and PanedRadiation. There are also model classes named OPAbsorbedLight and IPAbsorbedLight in Fig. 9. These are conversion blocks which transform the absorbed solar-radiation flows into connections.
of the panes' heat-capacity blocks. They are needed to convert the absorbed radiation flows, calculated as a real variable, into the HeatPort connector type. A more detailed description of the solar radiation flows and the appropriate Modelica implementation can be found in [17][18]. All other blocks, which model other thermal flows coming from the window's surroundings, are connected to the stand-alone connectors Outside and Inside, respectively. It is clear that the connector Outside is not connected directly to the heat-capacity model class OuterPane of the pane in Fig. 9, but through the NightIsolation model class that models the influence of a (partially) shaded window, which influences the thermal conductance through the window (prepared for control through the connector RollerPosition).

Finally, the room model can be built from the prepared model classes. The appropriate model scheme is shown in Fig. 10. The class Interior in the middle is surrounded with the classes of the room envelope. The inner surfaces of the envelope (represented by the connectors facing towards Interior) are connected to the RadiationBox class, which models the thermal radiation exchange between the surfaces (and is beyond the scope of this paper – see [18]), Interior class, which model the air mass and the furniture inside and to the lower-right connector of the Window class, which is an array of solar-radiation heat flows received by each surface. The external surfaces of the envelope are connected to connectors that are visible from the outside of the model of the room, and were used in the top-level model. The blocks that model the convection between the outdoor air and the walls of the building (ceiling, north, south, east and west walls) are therefore connected to those connectors. The Floor connector is connected to a constant ground temperature. The intensity of the solar radiation is routed to the class named Sun in the top-level model, where the direction vector of the solar rays is also calculated from a specified start date and simulation time and packed together with the solar-radiation component intensity into one connector. (Sunlight in Fig. 10).

A small cube-shaped 'test chamber' with the appropriate sensors for temperature, solar radiation and illumination measurements was built with the main goal to validate the developed models and control systems. Simulations were performed with the measured outdoor temperature and the global solar radiation as the input variables, taken from experiments, as well as with the variable signal for the roller-blind moving regime.

6) Control system

The simulator was used for different control systems implementations. The solutions designed with the help of the simulator were then tested on the real object - test chamber. Besides the conventional approaches with control actions on the heater/cooler and the ventilator, the emphasis was put on the envelope's dynamical adaptations. Therefore, the position of the roller blind was controlled in order to achieve the appropriate harmonisation of the thermal and daylight flows that influence the indoor temperature $T_e$ and the illumination $j_e'$. The external temperature $T_{e_{0}}$ and the global solar radiation $j_0$ were treated as external disturbances. The block diagram of the control strategy is depicted in Fig. 11.

As in some other examples we started with Simulink modelling. We developed the models with close cooperation with people from the Faculty of Civil Engineering. However Simulink based approach was definitely not what the mentioned people could accept. This was the first reason why we continued with Modelica based modelling approach. This methodology was fully accepted and our interdisciplinary cooperation became more efficient and easier. The second reason was the clear limitation of block oriented causal simulation: the Simulink components were not reusable. We were not able to expand one room model into more complex structures. With Modelica model it was rather easy to model several rooms building. Nevertheless such expansion introduces another, above all numerical problems which are usually difficult to solve.

Finally, what did we expect from these models? Hopefully better understanding of the influences of thermal and radiation flows on comfortable living conditions, model-based control system design, which will enable the harmonisation of active
and passive energy resources, and so important energy savings. Finally the Modelica model is very suitable for education. We plan to use with several subjects at the Faculty of Electrical Engineering and at the Faculty of Civil Engineering.

B. Recuperator in a stone wool production

There are many thermal processes in a stone wool production cycle. In cupola furnaces the exhaust gasses must be properly cleaned and this cleaning procedure represents an ideal way to integrate the exhaust-air cleaning into a production process. Namely, the exothermic energy from the combustion can be used to preheat the process air, which is used as a blast air in the cupola furnace. This ensures significant energy savings. The central part of this sub-process consists of four cross-flow and shell and tube heat exchangers – see Fig 26.

The modelling aim is twofold: it has to enable a better understanding of thermal processes to technologists and mechanical engineers who are primarily involved into the design of such systems and secondly it has to be efficiently used for the design of control strategies which influence mainly the flaps and ventilators. Our goal was to find components from existing Modelica libraries or to develop new components for pipe, heat-exchanger, flap, ventilator, flow source, etc., with the intention to use them for building transparent and user-friendly models also understandable to the industrial staff.

![Fig. 12. Recuperator process](image)

1) Mathematical model of the heat exchanger

Heat exchanger is a device in which energy in the form of heat is transferred what is usually realized by the confinement of both fluids in some geometry in which they are separated by a conductive material. The properties of heat exchanger are strongly dependent on geometry and material as well as on properties of both fluids. It is known that such devices had usually nonlinear behaviour [24]. The mathematical modelling is described in more details in [25]. The observed recuperator process comprises of shell-and-tube cross-flow heat exchangers.

While the shell’s length is relatively small in comparison to its cross section and the flow through it is highly turbulent (Reynolds number is of the order 105), temperature differences across the shell are negligible and shell can be modelled sufficiently accurate as a lumped model with three different temperatures: input temperature, output temperature and shell average temperature. As Modelica does not support solving partial differential equations implicitly, the tube section was discredited by a finite volume method. Some additional equations were added in order to properly model walls. Heat capacity of the wall is significant and was taken into account. On the other hand we neglected thermal conductivity. Then media changeable properties (density, heat capacity) were considered. The pressure drop was modelled with a quadratic function of velocity. Finally we include nonlinear empirical expressions (with Reynolds and Prandtl numbers) for the convective heat transfer coefficient of the gas.

2) Implementation in Modelica

The model of the heat exchanger, which is the most complicated part of the recuperator, basically consists of two thermally coupled pipes. So it should be built up by two pipe classes and intermediate heat-transfer class. Many public available Modelica libraries for modelling thermo dynamical systems exist. In our case basic components from Modelica_Fluid library are used and adopted. Here a tube bundle is described by distributed parameters. So the component of the pipe with distributed parameters discretised by finite volume method is taken from the library. For the model of shell the pipe component was also used. Thermo-fluid governing equations and properties of the media are realized by a nested component of the Modelica.Media library. Components of the tube bundle and the shell are connected over a wall model, which is a custom made component. The resulting scheme is shown in Fig. 13.

![Fig. 13. Modelica scheme of the heat exchanger](image)

We can notice that the shell and the tube consist of three components – the basic pipe is split into two parts and a pressure drop component is placed in-between. At the outermost edges appropriate connectors are used, namely inlet and outlet. They represent the connecting interface of the heat exchanger component.

The part of the Recuperator in Fig. 14 consists of two connected heat exchangers. The tubes of both exchangers are connected and the temperature at the outlet of the exchanger_1 is controlled by two coupled flaps which define the portion of the flow passing through the heat exchanger_2.

![Fig. 14. Part of the recuperator with two heat exchangers and with some periphery](image)

Up to now we validated only the model of the heat exchanger as the validation of the whole recuperator was not possible due to the lack of data. The available measurements were temperatures of the exhaust gases at the input and output of the shell, input and output temperatures of the tube gases as well as volume flow through the tube.
Modelling and simulation as a modern approach is rarely used in Slovenian industry. People from industry understand that investments are urgent for automation but they usually do not understand that modelling and simulation can be an important part of control system design. As we had one candidate from a company presented at our specialisation courses we succeeded to motivate him for described modelling project. As we had enough experiences with the fact that traditional causal models are more or less un-understandable for industrial staff, technologists, and maintenance engineers but also for many other high educated people who did not have more profound modelling courses in their education, we started from the very beginning with OO Modelica modelling.

In particular we were facing with numerical problems related mainly to the gas features, because strong and nonlinear dependencies among the pressures, temperatures, densities and internal energies exist. So basic equations obtained from mass and momentum balance equations are extended with nonlinear algebraic equations which also increases the DAE (differential algebraic equation) index of the system. Under the ‘surface’ of transparent object-oriented models, very complex structures are generated, which often leads to severe numerical problems.

The aim of the modelling was to obtain a better insight into dynamic behaviour of the plant and to use this knowledge for some improvements in the design of new production lines but also to establish an efficient environment for the appropriate optimisation of processes with advanced model based control strategies. In this project we cooperate with several mechanical engineers. They are rather skilled in dimensioning components for new lines. But their procedures are based only on steady state or static understanding. Although they use very complex and sophisticated computer aided design tools, they never use the possibilities for dynamic simulation. So simulation with Modelica models gave them a new way of understanding and hopefully we can expect from this cooperation many benefits in the future.

V. REALISATION-PRESERVING MODEL REDUCTION OF MODELS IN MODELICA

What did we learn from our examples, especially from the last one? OO and multi-domain modelling approach in Modelica is very efficient especially in model definition phase, but unfortunately not so much in model execution. Namely under the surface of very transparent models very complex structures for execution are obtained. If we use well tested components it does not mean that the model will produce accurate results when many components are put together into a model. A simplification and/or model reduction is therefore very important in each modelling application. It is a well-known guideline that a model should not be more complex as necessary for a given purpose. Models satisfying this requirement, i.e. having proper complexity, are often designated as proper models [26].

However, contemporary component-based modelling approach often yields very detailed models from the beginning and the obtained models can be too complex for many intended tasks. Therefore, automatic model reduction techniques are active research topic and so far numerous automatic model reduction methods have been developed [28], [34], [35]. In some fields, e.g., integrated circuits design, they reached a stage when they became an indispensable part of system analysis and hence provided as a part of designated modelling environments [27].

The most successful methods, for example, those based on projection techniques, are not realisation-preserving [28]—the reduced model retains input-output behaviour of the system, but loses physical interpretability of its structure and parameters. In some cases it may be no longer possible to simulate the reduced model with the simulator of the modelling environment which was used at design of the full model. Although preservation of realisation is a very desirable property, realisation-preserving reduction methods are mostly neglected in the literature, mostly due to their bad efficiency. Furthermore, most of existing methods are limited to a certain type of models, e.g., RC circuits [29]. There are no realisation-preserving model reduction methods known to the author that could adequately handle multi-domain models implemented in contemporary object-oriented modelling languages such as Modelica.

Models in Modelica are usually decomposed into several hierarchical levels. At the bottom of the hierarchy, differential-algebraic equations are used for the component description, while on higher levels, model is described by connecting acausal objects (components). This is often done graphically and resulting schematics are called object diagrams [10]. In order to preserve the organisation of original model a combination of model reduction methods is needed. Furthermore, for some tasks, e.g., model verification [30], only a part of the model might be desired to be reduced.

A. Realisation-preserving reduction at object-diagram level

The simplest procedure for reducing models represented with a scheme (graph) is to remove connections (edges) or components (nodes) estimated to have insignificant effect on salient dynamics of the system. Very intuitive approach to determine these connections or components is to use energy and power related metrics.

Most energy-related metrics were developed to reduce bond graphs [31], [32]. Bond graphs are object-oriented modelling formalism based on energy and energy exchange and hence very appropriate for energy-based model reduction methods. A power associated with each component is easily obtainable by multiplying variables of the associated bond. However, bond graphs are not prevalent modelling methodology anymore.

Energy, which a component exchanges with its environment, is not so explicitly available in Modelica as in bond-graph formalism [30],[34],[35]. However, it can be obtained by inspecting the connections of the components. There are only few different types of physical interactions and therefore types of connections, so if a connector is defined appropriately, a list of rules for calculating power of each connection-type is generated and power associated with a component is calculated as the sum of powers of its connections.

Elimination of low ranked components (or connections) in Modelica is even more difficult, because components usually can’t be classified in generalised inductance, capacitance and
resistance as in case of bond graphs. After ranking of the component is done, it can be whether left to the user to decide how to reduce the model (which is adequate in some cases) or the rules for proper removal of components are derived by automatic manipulation of underlying equations.

B. Realisation-preserving reduction at equation level

There are already commercially tools available [33] for reduction and simplification of a general set of differential-algebraic equations. The method combines various algebraic manipulations and approximation techniques, for example, deletion of a single term in an equation, replacement of a term with a constant, deletion of a variable or its derivative, etc. Simplification/reduction operations are ranked according to estimated discrepancies of reduced- and full-model trajectories. The method gives good results for algebraic set of equations, while efficient extension to differential-equation systems more difficult.

CONCLUSIONS

We have a long modelling and simulation education tradition based at the beginning on analogue computers and later on CSSL languages and Matlab – Simulink environment. But a real big change happened when we introduced Dymola in the mid of 90’s. Students became much more motivated as they had also a strong modelling support and not only a pure simulation tool. The problem was actually that we started in the 3rd year of our university study with Matlab-Simulink approach and later with Dymola. Recently we changed this way starting with Dymola-Modelica already in the 2nd year. We start with basic modelling exercises in which students do not need almost any additional modelling knowledge as they use standard Modelica libraries. So we can start with interesting exercises from the very beginning. Later we continue with other modelling techniques and introduce also Matlab-Simulink, which can be treated as a much lower level approach but important to understand how modelling and simulation really works. So I would like to emphasise that for me it is not a question whether to use causal block oriented Matlab-Simulink approach or OO multi-domain Dymola-Modelica approach but simply both. I also do not see the necessity to introduce other approaches for the analysis of models in Dymola Modelica e.g. linearization, steady state solver, optimisation, identification etc. For these Matlab is simply better. I would propose to use Dymola-Modelica for the tasks for which it was designed, i.e. for the physical modelling. And this physical model can be efficiently used in Matlab.

The intention of the paper is to briefly present the acausal advanced modelling with some other terms which were invented in order to emphasise the modelling and simulation as a part of modern research activities: OO approach, physical modelling, multi-domain modelling, realisation preserving modelling. We described some projects and some experiences obtained during many years of Matlab-Simulink and Dymola-Modelica usage. Modelica is declared as a language for modelling of complex dynamical systems. As explained the complexity of Modelica models becomes often really huge so the question is how complex models can really be handled. In my experiences – not too much, so we propose simplifications and model reduction techniques wherever possible. Unfortunately there is no single model reduction method that would be applicable for all problems. Therefore a combination of methods needs to be available to the user. The advantage of our approach in comparison with external model reduction tools is a close integration with the modelling environment which prevents uncontrolled loses when exporting the information between tools and also enables more interactive work with a model.

REFERENCES


Modeling of Combustion Engines Vibroactivity Using the Methods of Similarity Theory and Analysis of Dimensions

Bezyukov O. K.
Professor, Head of the Department of theory and design of marine internal combustion engines
Admiral Makarov State University of Maritime and Inland Shipping
Dvinskaya st. 5/7, St. Petersburg, 198035, Russia
e-mail: okb-nayka@yandex.ru

Afanaseva O. V.
Ph. D, Associate Professor, Department of Systems Analysis and Management
National Mineral Resources University (University of Mines)
V. O., 21st line 2, St. Petersburg, 199106, Russia
e-mail: OVAf@rambler.ru

Abstract— This article discusses the problem of modeling the vibrations emitted by marine engines. The authors introduce the method of assessment developed by them marine engine vibroactivity, generated by the gas dynamics and mechanical factors. This method of marine engines vibro-diagnosis can be used effectively to address the negative impact of ship machinery per person.

Keywords— modeling, vibration, criteria, similarity theory, dimensional analysis, vibro-diagnosis.

I. INTRODUCTION

It is well known fact that method of mathematical modeling is widely used for many research facilities, and mathematical model of an object or process adopted by the set of equations. They describe state, movement and interaction of objects based on the laws of physics and received within the selected physical models.

Now due to the growth of loading and speed engine is significantly increased regulatory requirements to limit vibration levels engines.

Vibration and noise levels associated with the dynamic intensity and reliability of engines, this effect on the performance, well-being and health, work of the equipment and machinery etc. [3]. Vibration effect on the human body depends on its spectral composition [11], direction, the point of application, duration of exposure, as well as on the individual [3, 7]. Besides the above, the vibration plays a big role in erosive and corrosive destruction of transportation system elements. To prevent them is necessary to use fluids which do not contain toxic components [4].

The main objectives of engine vibrating condition study are vibration reduction at the source of their origin, identifying opportunities to reduce transmission of vibro-energy through supporting contacts, learning the basic laws of the energy transmission, reduction the sound vibrations intensity through damping coatings and install silencers on the inlet and outlet [5,7,8,9].

Defect detection by vibration parameters is one of the most knowledgeable sections of reciprocating machines diagnosing, which include marine engines. Not all the problems are fully resolved; both have scientific and practical importance [13].

It is known that we need physical object model and its mathematical description for mathematical modeling that adequately reflects the studied vibration processes [7, 13].

Any mechanical system consists of a number of elements connected by a certain law. The complex functional relationships between elements of the engine and a large number of structural parameters make difficult to describe formally the behavior of mechanism. Nevertheless, there are methods and techniques that facilitate the process of complex systems diagnosing. First, a physical model is constructed, that is, in a real system physical bodies are allocated and “idealized”, traffic conditions, interaction, as well as physical laws are formulated to describe the interactions [13], and then a mathematical model is created.

Research presented is associated with internal combustion engines vibro-activity modeling using methods of similarity theory and dimensional analysis.

II. METHODOLOGY

One of the most important indicators of diesels technical state are level and nature of changes in vibration parameters, the most sensitive to various deviations from the normal technical condition.
Magnitude and nature of the engine vibration depend on the number, size, nature, place and method of perturbing forces application and reciprocating machine properties as vibration system [13].

It is known [13] that the main sources of diesel engines vibration are: cylinder piston group; combustion of fuel; joints and contacts of moving parts; fuel injection equipment; valve gear; gearing; air supply system; gas outlet system; unbalanced moving parts; torsional oscillations.

To investigate the vibration of diesel engines can be effectively used theory of similarity and dimensions methods [1, 10]. Empirical regularities they established, allow to abstract from detailed unnecessarily information and, nevertheless, reproduced experimentally with very good accuracy [6, 12].

On the basis of differential equations and boundary conditions system analysis, describing the phenomenon under investigation, there are links between variables of individual groups, and then they are connected in a certain kind of complexes. These complexes, as combinations of variables that are relevant for the investigated processes are generalized variables (simplex and similarity criteria).

Compilation of specific expressions of similarity criteria based on the following rules [13]:

1. Convert all variables to dimensionless form by selecting the appropriate scale (conversion factors) or divide each variable by its characteristic value, pondering any characteristic value variable.

2. Divide all the equations on value of the one coefficients of equation, to make each of its members a dimensionless (secondary reduction).

Dimensional theory is used in the event that we cannot derive equations reflecting quite thoroughly researched phenomenon [10, 13]. In this case study has to be based on less specific ratios, using the results of experimental studies. On the basis of studies essential for the process values are determined.

The method of dimensional analysis (the theory of dimensions) - mathematical method of determining the type of formulas expressing the relationship between the physical quantities in the phenomenon, based on dimensions of these variables consideration [13].

The study prepared by the similarity criteria, reflecting the engine vibration characteristics, that can afford to analyze vibro-activity performance given the gaps in the kinematic pairs, stiffness of structural elements, workflow settings, the visco-elastic properties of oils in the gaps, and to determine the extent of wear parts [2]:

- Criteria for assessing the impact on the level of vibration bushings and engine blocks, gas dynamic processes in combustion [2]:

\[ \pi_1 = C_2 \cdot \frac{S_n \cdot D_h^2 \cdot p_z}{D_{czvt} + k \cdot D_{czb}}. \]

This criteria includes the characteristics such as the hardness of block \( D_{czb} \) and sleeve \( D_{czvt} \) of cylinders, maximum cycle pressure \( p_z \) stroke \( S_n \), cylinder diameter \( D_h \). Here \( k \) - empirical coefficient depending on the design features of the engine and its damping properties of materials.

- Similarity criteria for assessing the impact on the level of vibration bushings and engine blocks from rudder of piston in thermal gap [2]:

\[ \pi_2 = \frac{N_{max} \cdot \delta}{D_{czvt} + c \cdot D_{czb}}. \]

This criteria includes characteristics such as stiffness cylinder \( D_{czb} \), stiffness sleeve \( D_{czvt} \), the maximum lateral force \( N_{max} \) and the distance between the piston and the trunk of a mirror cylinder liners \( \delta \), \( c \) - empirical coefficient depending on the design of the engine and damping properties of its materials.

- Criteria allowing to account vibration velocity dependence on the density of the material and to make measurements of vibration velocity on the surface of the cylinder:

\[ \pi_3 = \frac{\rho \cdot h \cdot w \cdot n^2}{P_z}, \]

where \( P_z \) - the maximum pressure cycle, \( w \) - vibro-displacement; \( h \) - thickness of the sleeve; \( \rho \) - density of the material; \( n \) - engine speed.

Note that the first and third criteria were based on a theoretical analysis of the equations describing forced vibrations of shells, and the use of methods of similarity theory. A second similarity criterion was obtained on the basis of dimensional analysis.

To analyze the relationship between vibration level and characteristics listed above equation was built vibration velocity, which depends on the intensity of both mechanical and gas dynamic effects on parts of the core:
\[
\bar{V} = C_4 \cdot \omega \cdot S_n \cdot \left[ \frac{P_z}{\rho \cdot h \cdot n^2} \right]^r \cdot \left[ \frac{N_{\text{max}} \cdot \delta}{D_{czvt} + c \cdot D_{czb}} \right]^m \cdot \left[ \frac{S_n \cdot D_y^2 \cdot p_z}{D_{czvt} + k \cdot D_{czb}} \right]^n,
\]

where \( \omega = 2\pi f \) - angular frequency, \( f \) - cyclic frequency, \( C_4, r, m, c \) and \( k \) - unknown coefficients depending on the design of the engine and its damping properties of materials. Note to determine six unknowns is advisable to use the method of least squares.

### III. CONCLUSIONS

On the basis of dimensional analysis to obtain a criteria for evaluating the impact on the level of vibration bushings and cylinder blocks of processes occurring during the transposition of the piston in the thermal gap and evaluate vibration velocity dependence on the density of material.

Based on the theoretical analysis of the equations describing the forced vibrations of shells and the use of similarity theory methods obtained a criteria to evaluate the impact on the level of vibration bushings and engine blocks, gas dynamic processes during combustion.

Proposed criteria equation obtained previously described combination of similarity criteria that can be used as the basis of methodology to determine the amount of diametrical clearance between the sleeve and trunk piston cylinder, calculate the current wear rate of piston assemblies and more reasonably choose the frequency of maintenance and repair of diesel engines.

Direct measurement of vibration on the outer surface of sleeve will simplify the criterion equation and improve the prediction accuracy of the wear process piston assemblies.

From the above it follows that the methods of similarity theory and dimensional analysis – are a powerful tool that can be used to diagnose marine diesel engines, primarily for the study of vibrations generated by strikes in friction units.

The author considers it appropriate to undertake further research to develop methods for determining the gaps between parts piston and crankshaft bearings based on vibration measurements diesel considering elastohydrodynamic friction units in these processes.

### REFERENCES

Abstract — the paper presents a generalized mathematical model of multifunctional power supply control system of high veracity for management and control of power facilities. The model is aimed for synthesis of integral quality criterion based on the usage of the following parameters with unified functionality: message delivery time within connection channel, time to failure, the probability of message distortion detecting in connection channel. The analysis of mathematical model allows of concluding about the need for a dynamic performance testing of all system elements, i.e. detecting faults that are equivalent to short circuits and bonds breaking. The proposed approach will synthesize fail-safe code, diagnosing track performance from the receiver to the transmitter and lower probability of undetectable remote signaling distortions in power control systems by 2-3 orders of magnitude. The results of the experiments have confirmed the effectiveness of the principles of noise combating coding proposed by the authors.

Keywords — power supply control system, mathematical model, integral veracity, dipulse coding, remote signaling, management.

I. INTRODUCTION

For the last few years there appeared a trend to spatial dispersal and complexification of technical power systems, increasing the capability of power network grids and flow of information, which necessitated the creation of efficient systems for increasing the output result of equipment being operated in power industry [1, 2]. These factors determine the significant toughening of the requirements for the reliability of management and control, veracity and accuracy of measurements, combined with parameter versatility [3-5].

Nowadays more and more shows the trend of building energy management systems based on programmable logic controllers (PLCs) [2, 6-9]. At the same time there are some drawbacks of base PLCs that hinder the creation of high quality power management systems based on it:

- The impossibility of combining information input with bounding “events” to the timestamps, the impossibility of precise ordering of “events”, recorded by different modules and different PLCs. As a consequence, real “events” order is distorted very likely and generated and transmitted timestamps are futile;
- Limited capacity of the diagnostic procedures and the formation of diagnostic messages;
- Non-compliance with standards for remote control systems GOST 26.205 and IEC 870-4 belonging to the most important functions - remote control and remote signaling results in a risk of abnormal (emergency) situation [10].

II. MATHEMATICAL MODELLING OF POWER SUPPLY CONTROL SYSTEM STATES

To identify a theoretical approach to development of power supply control system (PSCS) of high veracity we should make its mathematic model, defining the possible states of the system.

State of the system is limited to five possible options for \( X = \{ x_1, x_2, x_3, x_4, x_5 \} \) with corresponding probabilities of \( P = \{ p_1, p_2, p_3, p_4, p_5 \} \), as shown in Figure 1.

Nowadays more and more shows the trend of building energy management systems based on programmable logic controllers (PLCs) [2, 6-9]. At the same time there are some drawbacks of base PLCs that hinder the creation of high quality power management systems based on it:

Model agreed designations: \( x_1 \) state characterize intactness of equipment, no requirement to enable system; \( x_2 \) is characterize the intactness of the system, but it is busy servicing received requirement; \( x_3 \) is characterize system malfunction, detected by control and diagnostics tools, repair is carried out, no requirement to enable system; \( x_4 \) is characterize malfunction, undetected by control and diagnostics tools, system repair is not carried out, no requirement to enable system; \( x_5 \) is characterize...
system; \( x_5 \) is characterize malfunction during the receipt of the request of system enabling, possible information distortion.

We assume the requirement flows as the simplest and display them respectively to intensities: \( \lambda_{m} \) – the intensity of the requirement flow on the information usage of system; \( \theta_{m} \) – rate of requirement service flow; \( \lambda \) – the intensity of the total flow of faults and: \( \lambda = \lambda_{m} + \lambda_{n} \) where \( \lambda_{n} \) – flow rate of detected faults and \( \lambda_{m} \) – flow rate of undetectable faults; \( \theta_{m} \) – flow rate of recovery.

Using the properties of the elementary streams we can write the system of equations for the states of “conventional” system and the possible state transitions \( x_i, i=0,5 \) for the time interval from \( t \) to \( t+\Delta t \) [11].

\[
\begin{align*}
\lambda t_{x_0}(t+\Delta t) &= \lambda t_{x_0}(t)(1-\lambda_{m}\Delta t) + \lambda_{n}(t) + \theta_{m}(t)\theta_{m}\Delta t \\
\lambda t_{x_1}(t+\Delta t) &= \lambda t_{x_1}(t)(1-\lambda_{m}\Delta t) + \theta_{m}(t)\theta_{m}\Delta t \\
\lambda t_{x_2}(t+\Delta t) &= \lambda t_{x_2}(t)(1-\lambda_{m}\Delta t) + \lambda t_{x_1}(t)\theta_{m}\Delta t \\
\lambda t_{x_3}(t+\Delta t) &= \lambda t_{x_3}(t)(1-\lambda_{m}\Delta t) + \lambda t_{x_1}(t)\theta_{m}\Delta t + \lambda t_{x_2}(t)\theta_{m}\Delta t \\
\lambda t_{x_4}(t+\Delta t) &= \lambda t_{x_4}(t)(1-\lambda_{m}\Delta t) + \lambda t_{x_1}(t)\theta_{m}\Delta t + \lambda t_{x_2}(t)\theta_{m}\Delta t + \lambda t_{x_3}(t)\theta_{m}\Delta t \\
\lambda t_{x_5}(t+\Delta t) &= \lambda t_{x_5}(t)(1-\lambda_{m}\Delta t) + \lambda t_{x_1}(t)\theta_{m}\Delta t + \lambda t_{x_2}(t)\theta_{m}\Delta t + \lambda t_{x_3}(t)\theta_{m}\Delta t + \lambda t_{x_4}(t)\theta_{m}\Delta t
\end{align*}
\]

(1)

To solve the system equations (1) we will use Laplace transforms for functions and their derivatives:

\[
a_{0}(x) = \sum_{i=0}^{5}p_{x_1}(t)e^{-\alpha x}\,dt \tag{2}
\]

where \( a_{0}(x) \) – image of the function that will be further used with no indication of parameter (operator); \( x \) – Laplace operator.

The average time \( T_{wp} \) of system presence in \( x_5 \) state with \( p_{x_5} \) probability can be found as

\[
T_{wp} = \int_{0}^{\infty}p_{x_5}(t)\,dt \tag{3}
\]

Using the properties of the Laplace transform, we can write:

\[
-\int_{0}^{\infty}p_{x_5}(t)e^{-\alpha x}\,dt = x_{a_{0}}(x) \tag{4}
\]

After transformations (1) considering (2)-(4) we get:

\[
T_{wp} = \frac{\lambda_{n}\theta_{m}^{2} + \lambda_{m}\theta_{m}^{2} + \lambda_{m}\theta_{m}^{2}[(\theta_{m}\lambda_{m}) - \lambda_{m}^{2}]}{\lambda_{m}^{2} (\lambda_{m} + \lambda_{m}^{2})} + \frac{\lambda_{n}^{2}[(\theta_{m}\lambda_{m}) - \lambda_{m}^{2}]}{\lambda_{m}^{2} (\lambda_{m} + \lambda_{m}^{2})} - \frac{\lambda_{n}^{2}[(\theta_{m}\lambda_{m}) - \lambda_{m}^{2}]}{\lambda_{m}^{2} (\lambda_{m} + \lambda_{m}^{2})} \tag{5}
\]

The probability of getting conditional system into a state \( x_5 \) is defined by the ratio of intensity of detected failure flows to the intensity of the total failure flow and the probability of exiting the \( x_5 \) state by the ratio of service quality, characterized by the \( \theta_{m} \) value, to the intensity of complex enabling (\( \lambda_{m} \)). It is interesting to study the function \( T_{wp} = f(\lambda_{m}/\lambda) \) for different values (\( \theta_{m}/\lambda_{m} \)) at a constant value \( \lambda \).

It is possible to increase system failure-resistance, i.e. time intervals between getting into a “denial” state by reaching \( (\lambda_{m}/\lambda) \geq 0.9 \), i.e. when it detects almost all emerging devices failures and \( XX \), i.e. decreasing the probability of system getting into a requirements servicing state.

### III. Noiseproof Coding Foundations to Improve the Reliability of the Power Supply Control System

Without going into the theoretical foundation, we present the findings from the above mathematical modeling:

- To improve the reliability of the information it is necessary to introduce virtually permanently functioning diagnostic nodes that can detect distortions throughout the track of delivering information to the staff that will solve the problem should be minimal;
- Diagnostic nodes should provide dynamic control of performance of all elements of the modules, i.e. detect failures that are the equivalent to both short circuit (“superfluous” signals “1”) and disconnect (“superfluous” signals “0”).
- While developing common approach to solving the problem of increasing the veracity of the management, the following principles of coding information have been developed [12]:
  - It is enough to submit to the element’s input test signals, in which it sequentially goes to opposite state, and compare compliance between the actual and required state to detect a failure of some element of control object.
  - Elements installed in the information input and processing circuits shall be exposed to the dynamic control;
  - Telecontrol command must be submitted by dipulse signals and their form should not be changed throughout the track to output devices.

Code indicating the state of all sensors in the form of bit pair is called “dipulse correlation code” [13] as in encoded message the state of each sensor is displayed in two mutually correlated pulses “01” or “10” (Fig. 2).

![Fig. 2. Scheme of dipulse conventional correlated coding](image)
It is important that in the developed method of coding inversion of the second bit of the pair is “conventional” and is depending on the outcome of diagnostic of communication circuits with sensors. It is inverted when the dynamic control has no detected distortions. Only in this case dipulse code takes the form of “10” or “01”. Upon distortion detection a pair of code signals turns into a combination of “11” (short circuit) or “00” (breaking communication circuits with a sensor), enabling to determine the location and type of distortion due to two “unresolved” combinations [12, 13].

Fig. 2A shows the signals of the timing pulses generator which specifies the coding order. The state of a single sensor discrete signal (DS) is converted to the code in two sequential ticks, so it takes “2n” ticks to encode the state of all “n” sensors. The traditional method of coding is illustrated on the figure 2B. At each odd tick the first signal of dipulse code is being formed, e.g. when the sensor state is closed – signal “1”, and when open – signal “0”. On each even tick a second code signal is being formed, inverting the signals of odd times. Dipulse codes and the message information is not modified, as shown in figure 2C, if, for example, communication circuit of a coder will lock with the first sensor or it will break connection with the third sensor. As a result, the transmitted information message will be unreliable. In the figure 2D we can see that the dipulse conventionally correlation code in the case of distortion detection turns into “11” (short circuit) or “00” (breaking communication circuits with a sensor). Thus, the proposed coding method lets detect not only the distortion but also to locate the sensor number and type of the distortion.

Let’s analyze the veracity of the processing x state signals from controlled power facilities. To clarify and illustrate the average statistical numerical values for parameters of power facilities and power supply control systems are used with the following formulas.

The probability of receiving a false discrete signal for developed devices and methods of control power facilities state – $P_{ds}$ can be defined by:

$$P_{ds} = P_{sen} + P_{com} + P_{enc} + P_{dec} \quad (6)$$

where $P_{sen}$ – probability of receiving a false DS when get information from the sensors, $P_{com}$ – the probability of receiving false DS due to noise in the communication channel, $P_{enc}$ ($P_{dec}$) – probability of receiving a false DS in the encoder (decoder).

$$P_{sen} = P_{ns} \cdot P_{enc}^{2} \cdot (1 - P_{ds})^{n_{sen} - 2} \cdot C_{n_{sen}}^{1} \quad (7)$$

where $P_{ns}$ – the conventional probability of the noise effect during the second distortion of input discrete signal, which is opposite to the effects of the distortion in the first one; $n_{sen}$ – number of DS sensors, $P_{ds}$ – the probability of signal distortion by the sensor gating, which is equal to

$$P_{ds} = P_{t} \frac{t_{d}}{t_{c}} \quad (8)$$

where $t_{d}$ – duration of gating signal, $t_{c}$ – period between two sequential sensor status polling cycles, $P_{t}$ – probability of a single code signal distortion. Taking into account that $(1 - P_{ds})^{n_{sen} - 2} \to 1$ $C_{n_{sen}}^{1} \to n_{sen}$ and formula (8) we have the following:

$$P_{sen} = n_{sen} P_{ns}^{2} P_{enc} \left( \frac{t_{d}}{t_{c}} \right)^{2} \quad (9)$$

Distortion of the information message on the part of the track from the discrete signal input device to the communication channel is not detected at the double fault on the encoder to the opposite feedback on any of the $2n_{sen}$ code elements (direct and inverse). Then the probability of receiving a false DS in the encoder ($P_{enc}$) will be

$$P_{enc} = 2 n_{sen} P_{enc}^{2} P_{ns} \quad (10)$$

where $P_{enc}$ – probability of failure of the encoder (decoder). Consider the identity of the structure the encoder and the decoder obtain $P_{enc} = P_{dec}$.

Formed by each discrete signal input device correlation code is integrated in the communication channel with a cyclic code, encoder of which is common for all functional devices. This encoding method allows to form code, diagnosing operability of the functional devices and boosts noise immunity of informational messages in the communication channel [14, 15].

In view of the foregoing, the probability of reception false DS in communications channel ($P_{com}$) can be expressed as follows:

$$P_{com} = P_{1}^{2} \cdot P_{ma} \cdot P_{c} \cdot C_{a_{1} + a_{2} + a_{3}}^{2} \quad (11)$$

$P_{c}$ – the conventional probability that the interference occurred while transferring the main part of the message will remain in the time $\tau$ – transmission of the main part of code; $C_{a_{1} + a_{2} + a_{3}}^{2}$ – the number of possible combinations of pairs of characters in the transmitted correlation code; $a_{1} -$ digit capacity of the code number of the DS sensor, $a_{2}$ – the bit of code for the first timestamp event – binary signal, $a_{3}$ – the bit of code – sensor state. Tightening real conditions, we can assume that $P_{ma} = P_{c} = P_{t}$. Then

$$P_{com} = P_{1}^{4} \cdot C_{a_{1} + a_{2} + a_{3}}^{2} \quad (12)$$

Supplement messages with a cyclic code provides a reduction of the probability of receiving a false DS to the value of

$$P_{com1} = P_{1}^{4} \cdot C_{a_{1} + a_{2} + a_{3}}^{2} \cdot P_{1}^{4} \cdot C_{a_{0} + a_{2} + a_{3} + a_{4}}^{6} \quad (13)$$

where $C_{a_{0} + a_{2} + a_{3} + a_{4}}^{6}$ – the number of combinations of the code containing $(a_{1} + a_{2} + a_{3})$ – character code correlation and $a_{4}$ – symbols of a cyclic code.

Considering (6), (9), (10), (13) and taking $P_{ma} = P_{c}$, we can define the probability of receiving a false discrete signals
\[ P_{ds} = P_{sen} + P_{conc} + P_{enc} + P_{del} = n_{sen} \left( \frac{t_d}{t_c} \right)^3 + 4 \, n_{sen} \, P_{enc}^2 \, P_{1} + P_{8}^{c} - C_{a+1} + a_{3} + a_{4} \]

Substituting in (14) the PSCS average statistical values, for instance \( P_{1} = 10^{3}, P_{enc} = 10^{6}; t_{d} = 10^{-6}; t_{c} = 10^{-3}; n_{sen} = 32, a_{i} = 5; a_{2} = 10; a_{d} = 1; a_{d} = 16, \) we get \( P_{ds} = 10^{-11} \), which greatly exceeds the most stringent regulatory technical requirements established by standard [16].

IV. USING THE TEMPLATE

After the text edit has been completed, the paper is ready for the template. Duplicate the template file by using the Save As command, and use the naming convention prescribed by your conference for the name of your paper. In this newly created file, highlight all of the contents and import your prepared text file. You are now ready to style your paper; use the scroll down window on the left of the MS Word Formatting toolbar.

In order to test the effectiveness of coding principles there was developed an experimental device that should provide an opportunity to test the system under normal operating conditions, as well as to create the conditions to simulate the main factors affecting the testing parameters - veracity, measurement accuracy and bandwidth of the system:

- attenuation of operating signals in communication channels;
- disturbing interference in the communication channels between central control and controlled points;
- the disturbance noise in communication circuit modules with sensors and actuators;
- delays in the formation and transmission of information across the track from the sensor to the actuator;
- probabilistic characteristics of real objects, characterizing the intensity of appearance of requests for data transmission and reception;
- probabilistic characteristics of the system, characterizing the intensity of serving requests, possibility of forming the queue for the service;
- structural features of modules, system and algorithms for processing and transmitting information, providing diagnosis, detection of distortions and minimizing confounding factor losses.

On the basis of this device there was an experimental testing of veracity of discrete signal channel, in which there were received the following tabulated values.

Thus, the experimental results proved the effectiveness of the proposed solutions, enhancing the integral veracity of the channel of equipment state (discrete signals) of power supply control systems.

### TABLE 1. RESULTS OF EXPERIMENTAL TESTS OF VERACITY OF DISCRETE SIGNAL CHANNEL

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal operating conditions (signal/noise ratio 8/1)</td>
<td></td>
</tr>
<tr>
<td>Probability of receiving a false DS</td>
<td>8.7·10^{-11}</td>
</tr>
<tr>
<td>Probability of refusing the DS</td>
<td>1.52·10^{-12}</td>
</tr>
<tr>
<td>Distortions in the communication circuits with sensors (signal/noise ratio 3/1...7/1)</td>
<td></td>
</tr>
<tr>
<td>Probability of receiving a false DS</td>
<td>3.47·10^{-10}</td>
</tr>
<tr>
<td>Probability of refusing the DS</td>
<td>5.1·10^{-14}</td>
</tr>
<tr>
<td>Distortions in the communication channel (signal/noise ratio 3/1...7/1)</td>
<td></td>
</tr>
<tr>
<td>Probability of receiving a false DS</td>
<td>3.09·10^{-10}</td>
</tr>
<tr>
<td>Probability of refusing the DS</td>
<td>5.06·10^{-10}</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS

Summarizing the experimental data, it is possible to state that the low probability of remote signaling receiving both under normal conditions and under the influence of noise heavily exceeding the levels specified in standard [16] (the probability of receiving false RS 10^{-10}-10^{-9} where the ratio of signal/noise is at least 8/1) proves the high quality of developed remote signaling noise combating coding principles. Relatively small percentage of the refusal to accept the RS under conditions corresponded to the maximum permissible proves the high quality of noise cancellation and allocation of operating signals distorted by noise devices.

### REFERENCES


Simulation of Fuzzy Statements in the Problem of the Machine Technological Adjustment

L.V. Borisova  
Department of economics and management in engineering  
Don State Technical University (DSTU)  
Rostov-on-Don, Russia  
kaf_qm@donstu.ru

N.M. Serbulova  
Department of economics and management in engineering  
Don State Technical University (DSTU)  
Rostov-on-Don, Russia  
kaf_qm@donstu.ru

V.P. Dimitrov  
Department of Quality Control  
Don State Technical University (DSTU)  
Rostov-on-Don, Russia  
kaf_qm@donstu.ru

Abstract—Some aspects of presenting fuzzy expert knowledge of such object domain as technological adjustment and hunting for a harvester failures are being considered. The suggested model for the object domain serves as a basis for the knowledge base of the expert system on harvesters’ technological maintenance.

Keywords—fuzzy sets, fuzzy expert knowledge, expert system.

I. INTRODUCTION

It is expedient to consider a grain harvester as a mechatronic system functioning in uncertain and changeable conditions of the environment. The given system (interrelations between its inlets and outlets) is characterized by the complete state space including environment factors, adjusting parameters and quality coefficients of the technological process. The characteristic feature of the object domain is that it is rather difficult to determine with the given accuracy both values of harvesting factors and regulating parameters and operating quality coefficients. Furthermore, practically used recommendations on executing technological adjustment of a harvester, that is description of relations between the features under consideration, possess a distinct fuzzyness [1, 2].

Expert information of a grain harvester operation may be presented in the form of a system of conditional fuzzy statements, interrelating between the values of inlet and outlet parameters of the decision-making process.

II. PROBLEM DEFINITION

Let us consider the problem when, depending on possible values of outlet situation \( B_j \), an expert makes assumptions of possible inlet situation \( A_j \) (about possible values of inlet parameters).

We designate through \( X, Y, Z, \ldots \) inlet parameter set that is value part of adjusting parameters of the machine working mechanisms that considerably influence the value of the outlet parameter \( V \). Then we introduce linguistic variables for the inlet parameters: \( \langle \beta_X, T_X, X, G_X, M_X \rangle, \langle \beta_Y, T_Y, Y, G_Y, M_Y \rangle, \langle \beta_Z, T_Z, Z, G_Z, M_Z \rangle \) and for the outlet parameter \( \langle \beta_V, T_V, V, G_V, M_V \rangle \), determined on the sets \( X, Y, Z, \ldots \) and \( V \). Here \( \beta \) is the linguistic variable denomination; \( T \) is a set of its values or terms being denominations of fuzzy variables characterized by an applicable domain; \( G \) is a syntactical procedure describing the process of forming (from the set \( T \)) new, conceivable for the given problem of decision-making (DM), values for the linguistic variable; \( M \) is a semantic procedure allowing to assign to each new value, formed by the procedure \( G \), some semantics by the way of forming the corresponding fuzzy set, that is to map a new value on the fuzzy variable [3 - 4].

The system of logical statements reflecting the expert’s experience while correcting the harvester adjustments, when external evidence of breakdown in process can be seen, may be presented in the form of [4]:

...
\[
L_i : \begin{cases}
\text{IF } \beta_i \text{ is } \alpha_{ij}, \\
\text{THEN } E_{i1}, \text{ OR } E_{i2}, \text{ OR } \ldots \text{ OR } E_{in},
\end{cases}
\]

\[
L_j : \begin{cases}
\text{IF } \beta_i \text{ is } \alpha_{ij}, \\
\text{THEN } E_{j1}, \text{ OR } E_{j2}, \text{ OR } \ldots \text{ OR } E_{jnn},
\end{cases}
\]

Here \( m \) is the number of basic values for the linguistic variable \( \beta_i \);

\[ E_{ij} : \beta_i = \alpha_{ij} \]

Statement \( E_{ij} \) represents the \( i \)-th inlet fuzzy situation that can take place if the linguistic variable \( \beta_i \) takes on a value \( \alpha_{ij} \). The values \( \alpha_{x_1, i}, \alpha_{y_1, i}, \alpha_{z_1, i}, \ldots, \alpha_{v_1, i} \) are fuzzy variables with membership functions accordingly

\[ \mu_{x_1, i}(x), \mu_{y_1, i}(y), \mu_{z_1, i}(z), \ldots, \mu_{v_1, i}(v), \]

where \( \mu_{x_1, i} \) is a generalized linguistic variable determined on the set of \( W = X \times Y \times Z \) and taking basic values \( \alpha_{x_1, i} \) with a membership function

\[ \mu_{x_1, i}(w) = \text{min} \{ \mu_{x_1, i}(x), \mu_{y_1, i}(y), \mu_{z_1, i}(z), \ldots \} \]

and the totality of the adjusting parameters and quality coefficients of the harvester operating mechanisms.

Applying the rule of conversing linguistic statements, we present the system (1) in a more compact view. In this case the statement \( E_{ij} \) may be written as

\[ E_{ij} : \beta_i = \alpha_{ij} \]

III. PROBLEM SOLUTION

So as to show the problems solution, we consider the situation when an external evidence of the technological process breakdown appears – increased shattering of grain. In this case it is necessary to consider the following adjusting parameters: rotational speed of the drum; “drum-concave” clearance; condition of rasp bars and a concave; an evenness of the clearance along the width of the threshing-separating device (TSD).

In accordance with the approach under consideration [3] we assume linguistic variables \( x_1, y_1, z_1, x_2, y_2, z_2, \ldots, x_n, y_n, z_n \) and \( \beta_1 \): \( \beta_1 < \text{drum rotational speed, min}^1 \), \(<\text{DRS}> \)

\( \beta_2 < \text{rasp bars and concave condition, } %\text{, } <\text{RBCC}> \)

\( \beta_3 < \text{clearance evenness along the width of TSD, } %\text{, } <\text{CEWTSD}> \)

\( \beta_4 < \text{“drum-concave” clearance, mm, } <\text{DCC}> \)

\( \beta_5 < \text{grain shattering, } %\text{, } <\text{GS}> \)

The term-sets conforms to the studied linguistic variables:

\( TX = \{ x_1, x_2, x_3 \} = \{ \text{reduced; rated; increased} \} \)

\( TV = \{ y_1, y_2, y_3 \} = \{ \text{small; average; large} \} \)

\( TO = \{ z_1, z_2 \} = \{ \text{even; uneven} \} \)

\( TV = \{ v_1, v_2, v_3 \} = \{ \text{small; average; increased} \} \)

Values for the membership functions’ parameters \( \mu_{x_1, i}, \mu_{x_2, i}, \mu_{x_3, i}, \mu_{y_1, i}, \mu_{y_2, i}, \mu_{y_3, i}, \mu_{z_1, i}, \mu_{z_2, i}, \mu_{z_3, i}, \mu_{v_1, i}, \mu_{v_2, i}, \mu_{v_3, i} \), determining the semantics of the corresponding basic values for the variables \( \beta_1 \), \( \beta_2 \), \( \beta_3 \) and \( \beta_4 \), are given in [4].

The generalized linguistic variable \( \beta_5 \) has been determined on the set of \( W = X \times Y \times Z \times Q \) with the basic values

\[ T_W = \{ x_1, x_2, x_3, \ldots, x_{36} \} \]

where \( \alpha_{q_0} \) are possible values of the generalized linguistic variable \( \beta_5 \).

In the example under consideration we use 36 values of the generalized linguistic variable \( \beta_5 \): \( \alpha_{q_1} = \alpha_{q_2}, \ldots, \alpha_{q_{36}} = \alpha_{q_{36}} \)

Empirical rules making interrelationship between one of the quality coefficients of harvesting technological process and the totality of the adjusting parameters of the harvester operating mechanisms can be presented in accordance with (1) in the form of the system of fuzzy linguistic statements [5].

Expert statements reflecting fuzzy situations, that characterize possible conditions of one of the deviation indices of quality of the harvester technological process, for example, “Grain shattering” in linguistic and symbolic expression, have the form (a fragment from the set of 36 statements):

\[ E_{i1} : \beta_1 = \alpha_{x_1}, \beta_2 = \alpha_{q_2} \]

\[ E_{i2} : \text{The drum rotational speed – reduced AND “drum-concave” clearance – large AND Rasp bars and concave condition – normal AND Clearance evenness along the width of TSD – even} \]

As a result of the research fuzzy expert knowledge of the object domain “Technological adjustment of a harvester” has been shaped.

According to the accepted approach we have developed the models of the criteria \( X, Y, V \) (environment factors, adjusting parameters and quality coefficients of the harvester operation) in the form of semantic spaces and the corresponding them membership functions:

\( X_i = T(X_i), U, G, M; \)

\( Y_i = T(Y_i), U, G, M; \)

\( V_i = T(V_i), U, G, M; \)

As a result of the analysis the generalized model of the object domain “technological adjustment of a harvester” in the form of composition of fuzzy relations of the studied semantic spaces has been obtained.

\[ R_1 \cup R_2 \text{ for } X \in X_i; \ Y \in Y_i; \ V \in V_i \]

where \( R_1 \) – fuzzy relation between the environment factors and the adjustable parameters. \( R_1 = \{ X_i, T(X_i), U, G, M \} \times \{ Y_j, T(Y_j), U, G, M \} \times \{ V_k, T(V_k), U, G, M \} \times \{ V_y, T(V_y), U, G, M \} \times \{ V_x, T(V_x), U, G, M \} \times \{ V_w, T(V_w), U, G, M \} \)

IV. CONCLUSIONS

The key advantage of the expert system development on the basis of logical-linguistic presentation of fuzzy expert
knowledge consists in compact and adequate presentation of real situations of harvesting machines operation. On the basis of the unified formalism there is a possibility of taking into account quantitative and linguistic factors of environment, parameters of technical condition, adjustable parameters of the machine and quality coefficients of operation.

Domains model on the basis of fuzzy expert knowledge has made it possible to develop the algorithm of solving the studied problems. Being developed on the basis of the model the knowledge base and the mechanism for deriving solution for the tasks of preliminary setting and updating technological adjustments make up the basis of the intelligent information system (expert system); application of this system in practice allows to decrease time for technical stoppage and to reduce yield losses.

Taking into account distinctive features of applying the expert system in the fields it has been recognized rational to use portable digital assistant (PDA) as a platform for expert systems (fig. 1). Fig. 1a presents a process of inlets inserting, and Fig 1b presents setting of values of the adjustable parameters in accordance with expert system’s outlets.

Practical implementation of the studied algorithms is the development of software for automated solution of the problem. The authors have obtained the certificates of state registration of computer programs and data bases for this software (№ 2005612734, № 2005620290, № 2006610834, № 2005612778, № 2006610870, № 2007611656, № 2009620520, № 2009614549).

Application of the expert system in practical conditions while performing technical adjustment with the help of the expert systems has made it possible to reduce time to 2 – 5 times in comparison with traditional methods and, as a consequence, to increase the harvester output by 10 – 12%.

REFERENCES

Fig. 1 Practical application of PDA in field conditions
Abstract - The concept of active diagnostics for detection and registration of failures in digital equipment (computing, sensors, actuators, communication networks). Offered a set of informative features for detection and fault logging for passive components (connectors, contact LSI and VLSI devices, contact conductors of printed circuit boards, including multilayer, interface tires, power and ground, unshielded single and multicore wires, terminal blocks, places Lunches) and active elements (transistors, integrated circuits). In theory failures prompted to enter a new concept: a differential failure, integral failure, combined or integrondifferential failure. Proposed contact or contactless methods and devices to detect and record faults, operating, for example, using the informative tag "electromagnetic radiation" in a range of up to 4 GHz. For detection, differentiation and registering of internal and external electromagnetic interference is considered a majority of signal processing method failures, allowing divide external interference from internal and internal interference classified according to their place of manifestation.

Keywords - differential failure, integral failure, combined (integro - differential) glitch -fail, shoestoychivost sensors failures, active diagnostics, the majority of signal processing method failure.

I. INTRODUCTION

Among the list of hardware failures most problematic for monitoring and diagnosis should recognize intermittent failures, also called short-term, hidden, floating, dismissive or flicker failures. Such failures lead to the malfunction of all equipment and can lead not only to significant financial losses, but also to human victims. Under failure is dismissive disruption of the equipment due to the short-term effects on an element (or set of elements) of the external and internal factors. After a long time equipment failure may work fine, but it can be distorted when information transfer operations, storage or processing.

When designing equipment, being composed of a large (up to several tens of thousands), the number of potential sources of failure (multipin connectors, contact LSI and VLSI devices, printed conductors, communication line - interface tires, power and grounding, etc.), the key radically improve the reliability problem is the diagnosis of failures directly related to the detection and registration of sources to a hardware failure.

Currently, all methods developed to eliminate possible failures in digital equipment (transistors, integrated circuits) are grouped into three groups: structural, functional and design and technology. Structural methods aim at obtaining the desired properties of the device at a constant algorithm for its operation. Functional methods associated with changes in the algorithm works, in particular the change in the coding of the input states. Design and technological methods focused on generating desired restrictions on the level of use of mathematical models. Structural methods can be directed at changing the internal structure, i.e. reconfiguration scheme, in case of failure of a circuit element. Functional methods of failure must be capable of reprogramming scheme.

These methods provide for the elimination of potential hardware failure are, in our view, a number of disadvantages, the main ones are as follows.

First. Failures occurring suggests their probabilistic rather than deterministic. As a result - passive methods fault diagnosis and control.

Second. Consider only failures in the active elements (transistors, integrated circuits) and entirely the left to the detection and registration of failures in passive elements (contact track PCBs, contact LSI and VLSI devices, power bus shielding conductors, connectors).

Third. Also in the left side of the impact and influence of external electromagnetic interference and at prices pyam supply.

II. THE MATHETMATICAL FORMULATION

Reasons for failures in passive elements (PE) can be modern equipment as various external influences (vibrations, force, electric field, temperature and chemical exposure), and latent defects numerous apparatus, leading to its accelerated degradation. The most difficult is to describe such an important element of the apparatus, the connector (contact). The modern theory of electrical contact is in an oscillatory circuit with elements of Rn, Ln and Cn - respectively ohmic, inductive and capacitive reactance of the transition zone contacts (contact resistance) [1-2].

parameters defining the resonant vibrations at high frequencies depend on many factors, difficult to control the operation and, therefore, urgent to make integrated and operational evaluation.

Diagnosing passive components as the process of determining their offending state includes three tasks: study of passive elements as an object of diagnosing failures; construction of algorithms diagnosing failures, develop means of diagnosing faults.

Theoretical generalization process of diagnosing failures of passive components with limited information on their technical condition determines the use of formal description of PE, ie their mathematical model of diagnosis. This model should provide diagnosing malfunctions and be suitable for further synthesis and implementation of algorithms for diagnosis.

In developing a mathematical model of diagnosing failures REA PE must take into account that in PE, as the object of diagnosis, are closely interrelated mechanical, chemical, physical, electrical and electromagnetic properties of the elements. When describing their technical condition necessary to use appropriate methods of formalizing processes
(differential, difference, and logical equations, block diagrams, directed graphs and finite automata).

Synthesis of heterogeneous mathematical models of PE provides a general description of the object as diagnosing faults (hidden defects). Is therefore the most appropriate use of abstract dynamical system operating process which is to change the state of the system under the influence of internal and external reasons. A mathematical model of such a system is defined as the number of functional variables

\[ y = F(T, X, Z, S, S0, C, C, C, L, L), \]

where \( T \) - set of time \( t \); \( X, Z \) - set of input \( x \) and output signals of the system \( z \); \( S \) - set of states of the system; \( S0 \) - closed domain states of the system, which limits the possible movement during the operation;

\[ C^*(T, X, S) = P^* \text{ and } C(T, X, S) = P \] - the transition operators, reflecting the system state changes under the influence of external and internal disturbances; \( L^*(T, X, S) = Y^* \text{ and } L(T, X, S) = Y - O \) operators describing an output signal under the influence of internal and external perturbations.

To recognize the object as a malfunction diagnosis of PE will use a set of classes technical states \( E_i \) (where \( i = 0, 1, 2, ..., k; k + 1, k + 2, ..., m; m + 1, m + 2, ..., N)\).

\( E_i \) - this is a lot of technical states of the object, describing the set of its possible states \( s_i \). Belongs to a set of class \( E_{ik} (i = k + 1, k + 2, ..., m) \) - malfunction (bad) state, and the class \( E_{in} (i = m + 1, N) \) - malfunction (Exemption) state.

To construct a mathematical model of diagnosing faults in PE as a base block diagrams used codon biphasic impulse control asynchronous motors, as they allow you to specify not only the maximum depth diagnostics, allowing a failure to register, but also reflect the real PE designs, allow us to resolve issues of practical implementation diagnostic systems [3-5].

III. RESEARCH METHODS

The principal feature of the new concept of a sharp increase in the reliability of equipment by eliminating the impact of failures on it is that, in contrast to all previously used approaches to solving this problem is not detected and registered places of failures and sources of failures. Depending on the principles of formation and produce informative features, which is estimated to aggregate the failed state of the elements as sources of equipment failures, proposed various methods for the detection and registration of sources of failures [6].

Therefore, the existing degree of reliability and resiliency to ensure equipment is invited to supplement and shbeustoychivostyu -fail. Especially issues of building demand - fail equipment in outer instrument with the increasing life cycle spacecraft from 2 to 15 years [7].

Lifecycle Management when it should be based on information about the precursors refuse the call, as that may be faltering.

Another important area of application - fail equipment is military equipment. To this end - time work GOST devoted to different methods of estimating the frequency of single failures of integrated circuits [8]. Questions build -fail based on recording equipment failures on various sources of informative signs and documented in the literature [9].

Novelty detection solutions and fault logging for technical means using the methods of the active patented diagnostics and has considerable domestic priority, particularly in comparison with the United States on the order of 10 years: see RF [10-14], USA - [15-18]. Patenting decisions on failures in the United States noted in such firms as "General Electric " [15] "Katerpiler " [17], as well as one of the world leaders in the field of supercomputers - "IBM " [18].

All of the above sources on the failed category characterized by random or for Statistics estimates, despite the variety of definitions of "failure". However, in some cases, is important not only the fact of failure detection and reporting, but also required to know and characteristics of this failure, for example, the lifetime of failure, his borderline (properly, failure) or an intermediate state, external or internal manifestation of it (for example, a manifestation of failure as external, internal, or low-frequency electromagnetic interference) time or frequency nature of its manifestations, etc.

In connection with the foregoing, it is proposed the theory of failure, especially in the theory of reliability and security, enter the following concepts: "differential failure", "integral failure ", "integrodifferential failure."

Earlier in the existing methods of detecting and recording sources of failures was first proposed by the differential method [19]. The method allows to fix the source of failure in the passive elements - communication lines, interface -tion tires, tire power and grounding connectors, tire management. All of the above elements with the existing latent defects and acquired during the operation in the form of micro-cracks, micro-annulus, partial breaks, low-quality contacts in connectors, supplemented in electrical circuits of substitution mikroemkostyami [20].

Subsequent high input resistance ohmic load (eg, tens of megohms in CMOS circuits) together with an educated mikroemkostyu defect created the preconditions for the differentiation of data passing through the chain -ing useful signals, and hence registering a latent defect in the form of failure. This, in turn, allows lo - fix initial stage (beginning) of the offending state (failure) of the element.

On the other hand, in the further destruction of the element in fixed source of failure of its electrical resistance increased in tens and hundreds of times. Including additional parallel mikroemkost same CMOS load, as a result, we have been integrating circuit. This circuit can be used as a precursor - nickname element failure [9] in the intermediate state of the offending element, that is, after the failure of the differential lock and until after the integral failure to diagnose the state of a latent defect is possible, using, for example, kodoimpulsnuyu modulation of signals [21].

Thus, introducing the concept of "differential failure" and "integral failure", have the opportunity to a more detailed description (early failure, late failure) of the same failure. Combining these concepts into one, ie in integrodifferential failure, we can talk about the stock already survivability item in the failed state, or the lifetime of failure [22]. In turn, knowledge of the parameter "lifetime of failure " can uniquely identify such an important parameter of the system as a "residual life " [23].

With respect to the logical element of digital equipment should be noted that the change of state of a serviceable condition to the state precursor failure occurs exponentially with a certain exponent or exponential constant [24]. Naturally, the transition to the element of "0" to "1" will be not immediately,
but within a finite time, i.e., front time is finite \( (\tau_{\text{fr}} \neq 0) \). Using the well-known formula, the parameter can be "front time" to reconcile with the upper cut-off frequency of failure \( f_{\text{gr}} \approx 0.35 / \tau_{\text{fr}} \) [25]. Received by the upper limit frequency of this failure can be fixed differential contactless using information option "electromagnetic radiation" [26]. There also described a principle of proximity sensor failure, and its original implementation proposed in [27].

Integral state failure occurring after the state differential failure will fit over a low frequency, given the increase in the pulse rise time. Range duration of fronts to integral differential failure can be determined either experimentally (to use), or by simulating error conditions, taking into account effect of different data delay time of the test element. Ideology of the integro-differential sensor fault condition is configured, for example, at two frequencies (top and bottom) corresponding to the differential and integral element of error conditions, set out in [13] and has been implemented, in particular, in [28].

It should be noted that the detection and registration of failures on differential and integral recognition as well as more intermediate fixation between symptoms associated with intellectual processing of bad signals detected due to intellectual property in the passive elements [29].

In particular, in the failed state of elements was recorded a number of informative features, different from other states of the elements ("regularly", "failure"). Unable to identify these conditions and due to the original processing kodoimpulsnych signals, particularly when they are processed simultaneously in time and frequency regions [3], [30]. The experimental results have confirmed this assumption expressed a priori, which allowed all of the results registered as opening with the issuance of the relevant documents of the Russian Academy of Natural Sciences. [31]

Detection and registration of differential failure, showed appearance or presence of a latent defect, were first proposed for implementation in the automotive sensors [32].

Detection and registration failure integral fixing forthcoming transition element of the failed states in refusal, were first obtained by sensors - flowmeters [33]. Detection and registration integro-differential failure determining the duration (lifetime) of failure, have been proposed in the diagnosis of one - and multilayer printed circuit boards [34], [35]. To the detection and registration of differential and integral failures, as well as the majority of signal processing of internal and external interference, resolved in parking systems of high reliability [36].

IV. PRACTICAL RESULTS

Existing classification methods for the detection and registration of sources of failures, previously proposed by of the author [9], proposed to add the integral-differential method and the majority of bad signal processing (Fig. 1).

Fig. 2 schematically shows a portion of the test printed circuit board comprising a transmitter, a receiver and a communication line connector with the mode "failure". Transmitted electromagnetic power connector (printed conductor) 1 enters the connector (printed conductor) 2, as well (for example, artificial) located in the "failure", and then goes into a high- recorder (e.g., oscilloscope). Example registration mode "failure" type connector 27 RPPM used in domestic supercomputer series "Elbrus", when testing is illustrated in Fig. 3. Curve 1 in Fig. 3 - is the test compound (as a receiver selected one channel oscilloscope), curve 2 - recorded (on the second channel of the oscilloscope) sensor - connector (conductor) in the "failure" (see Fig. 2) frequency of the radiating element 1 in the "failure". From Fig. 3 shows that the failure of the connector has several resonance peaks at the frequencies of 4, 15 and 55 MHz. Tendency to form "bad" resonance frequencies observed with increasing the operating frequency range (100 MHz to 4 GHz).
Fig. 3. Connector emitter (curve 1) and the connector receiver (curve 2) in the mode of "failure".

V. CONCLUSIONS

1. Offered a set of informative features for detection and fault logging for both passive and active elements.

2. In theory failures prompted to enter a new concept: a differential failure, integral failure, combined or integrodifferential failure.

3. Proposed contact and contactless methods and devices to detect and record failures.


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General Ray Method for Identification of Source Distribution in Plane Region

Grebennikov A.

Facultad de ciencias Físico Matemáticas
Benemérita Universidad Autónoma de Puebla
Puebla, Mexico
agrebe50@yahoo.com.mx

Abstract—A new fast method for identification of source distribution is proposed. Its mathematical model is constructed on the basis of General Ray Principle, proposed by the author for distribution of different, in particular, electrostatic and thermostatic fields. Proposed model leads to the classic Radon transformation that appears as specific element in new General Ray Method, constructed using explicit formulas.

Keywords—source distribution; General Ray Method; fast numerical algorithm.

I. INTRODUCTION

In some applied problems it appears the necessity of recognition of source distribution of different, in particular, electrostatic and thermostatic fields [1]. In a plane case it can be mathematically described as an inverse problem for recuperation of the right hand side of the Poisson equation

$$\Delta u(x, y) = f(x, y),$$

where \((x, y) \in \Omega\) - some limited open region on a plane, \(u(x, y)\) is an unknown characteristic that describe distribution of investigated field (electric potential, temperature, etc.) the function \(f = f(x, y)\) characterizes desired source distribution of the field.

In traditional statement [1] it is supposed also that functions \(J_n(x, y)\), \(u^0(x, y)\) are known on the boundary curve \(\Gamma\) and the next boundary conditions are satisfied:

$$\varepsilon(x, y) \frac{\partial u(x, y)}{\partial n} = J_n(x, y), \quad (x, y) \in \Gamma,$$

$$u(x, y) = u^0(x, y), \quad (x, y) \in \Gamma,$$

where \(\frac{\partial}{\partial n}\) is the normal derivative in the points of the curve \(\Gamma\).

Equations (1) – (3) serve as the mathematical model for solution of described problem, when there are known a family of potential and boundary conditions that corresponds to different parameters of measurement scheme.

We will name this problem as Identification of Source Distribution (ISD). Traditional approach for solving ISD leads to ill-posed problem. A lot of investigations are dedicated to existence, uniqueness and construction of numerical solution of this problem [1], but up to now there are not sufficiently general theoretical and constructive results. Known numerical schemes are difficult in computing realization.

Here we propose a new approach for construction of the mathematical model of ISD based on the General Ray Principle [2] that require some different input data, but give possibility to construct fast algorithms for numerical solution of ISD.
II. GENERAL RAY PRINCIPLE AND NEW MATHEMATICAL MODEL FOR ISD

General Ray Principle [2] consists in considering some physical field as a stream flow of “general rays”. Each one of these rays corresponds to some straight line \( l \). The mathematical part of the General Ray Principle consists in reduction a Partial Differential Equation (PDE), to which satisfies the characteristic \( u(x,y) \), to a family of Ordinary Differential Equations (ODE). Such basic ODE describes the distribution of the characteristic of the field on the segment of the straight line. In our case the equation (1) for variable \( t \) in one dimensional domain (segment \([a, b]\) of a straight line \( l \)) can be written in the next form

\[
\tilde{u}^r(t) = \tilde{f}(t), \quad t \in [a, b]. \tag{4}
\]

To construct the mentioned family of ODE we will use the family of all straight lines \( l \) that intersect the domain \( \Omega \).

Let the line \( l \) has the parametric presentation:

\[
x = p \cos \varphi - t \sin \varphi, \quad y = p \sin \varphi + t \cos \varphi,
\]

where \( |p| \) is a length of the perpendicular, passed from the centre of coordinates to the line \( l \), \( \varphi \) is the angle between the axis \( X \) and this perpendicular [3]. Then, using the Radon idea, we shall consider for each line \( l \) equation (4) that describes the characteristic \( u(x,y) \) of the field with corresponding function \( f(x,y) \) for \((x, y) \in l\) using one dimensional functions (traces) \( \tilde{u}(t) \) and \( \tilde{f}(t) \) of variable \( t \).

For simplicity of the next explication let suppose that domain the circle of radius \( r \). Hence, we have for every fixed angle \( \varphi \) and given \( p \) the next formulas for limits of the segment \([a, b]\) at each line: \( a = -b = -\sqrt{r^2 - p^2} \).

We suppose that functions \( v(p, \varphi) \) and \( J(p, \varphi) \) are given for \( \varphi \in [0, \pi], -r < p < r \) and we can write boundary conditions

\[
\tilde{u}(a) = J(p, \varphi), \tag{5}
\]

\[
\tilde{u}(b) - \tilde{u}(a) = v(p, \varphi). \tag{6}
\]

Equations (4) – (6) are considered as the basic mathematical model for new type of ISD.

III. GENERAL RAY METHOD AND FAST ALGORITHMS FOR SOLUTION OF ISD

Integrating twice the equation (4) we obtain relation

\[
\tilde{u}(b) - \tilde{u}(a) - (b-a)\tilde{u}'(a) = \frac{1}{b-a} \int_a^b \tilde{f}(\xi)d\xi dt \tag{7}
\]

Let us define function

\[
\tilde{f}_1(t) = \int_a^t \tilde{f}(\xi)d\xi.
\]

Clear that there exists one function \( f_1(x,y), (x,y) \in \Omega \), for which it is fulfilled:

\[
\tilde{f}_1(t) = f_1(x,y), (x,y) \in l.
\]

We shall consider further extensions of functions \( f(x,y) \) and \( f_1(x,y) \) out of the domain \( \Omega \) as zeros. So, we can use the traditional Radon transform \( R \) and write the right hand side of equation (7) as

\[
\int_a^b \int_a^t \tilde{f}(\xi)d\xi dt = R[f_1(x,y)](p, \varphi) \tag{9}
\]

Using relations (5), (6) we can write the left hand side of (7) in the next form

\[
v(p, \varphi) - (b-a)J(p, \varphi), \tag{10}
\]

and for variable \( p \not\in [-r, r] \) we use extension of this function as zero. So, substituting formulas (8) – (10) to (7), we obtain equation

\[
R[f_1(x,y)](p, \varphi) = v(p, \varphi) - (b-a)J(p, \varphi),
\]

from which we have formula for the function \( f_1(x,y) \):

\[
f_1(x,y) = R^{-1}[v(p, \varphi) - (b-a)J(p, \varphi)], \tag{11}
\]

where \( R^{-1} \) is the inverse Radon transform operator [3]. Hence, we can calculate values of function \( \tilde{f}_1(b) \) for every angle \( \varphi \) and variable \( p \). From formula (8) it follows that \( \tilde{f}_1(b) \) coincides with the direct Radon transform of the
desired function \( f(x, y) \). So, the final formula of constructed General Ray (GR) method for solution of ISD is:

\[
f(x, y) = R^{-1}[\tilde{f}_1(b)],
\]

(11)

GR-method gives the explicit solution of the ISD problem for considering case. It can be generalized and applied also for any convex domain. The numerical realization of formulas \((10)–(11)\) can be constructed as fast algorithm, because it does not require solving any equation and the Radon transform can be inversed by fast manner using discrete Fast Fourier Transform algorithm.

At the same time, formulas \((10)–(11)\) are unstable with respect of the data perturbation. This instability is initiated by application of two inverse Radon transform and is equivalent to double differentiation [4]. So, in numerical realization of constructed variant of GR-method it is necessary to use some regularization [5]. Most simple and fast in its realization is Recursive Spline Smoothing method, based on cubic local basic splines, which guarantees regularization effect for considering case [6].

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Modeling the Effect of Tilt Angle on Natural Convection from a Ground-Mounted PV Panel

Klimenta D. & Jevtić M.
Faculty of Technical Sciences
University of Priština in Kosovska Mitrovica
Kosovska Mitrovica, Serbia
dardan.klimenta@pr.ac.rs & miroljub.jevtic@pr.ac.rs

Tasić D.
Faculty of Electronic Engineering
University of Niš
Niš, Serbia
dragan.tasic@elfak.ni.ac.rs

Klimenta J.
Independent consultant
in the field of urban and spatial planning
Niš, Serbia
klimenta.jelena@gmail.com

Abstract—This paper presents an approach for modeling the average heat transfer by natural convection for both laminar and turbulent flows from a ground-mounted photovoltaic (PV) panel at tilt angles of 0-90°. Using experimental results obtained by other researchers, the heat transfer correlations based on the fundamental dimensionless number for natural convection from tilted plates were derived. The proposed correlations cover the whole range of Prandtl numbers, and were applied to estimate the heat transfer coefficients for natural convection from a real PV panel. Effects of the solar radiation and radiation heat losses from both surfaces of the PV panel are taken into consideration as well. The finite element method (FEM) together with the appropriate experimental results has been used for validation of the approach. All FEM-based computations were carried out using the COMSOL.

Keywords—COMSOL, heat transfer, modeling, natural convection, PV panel, tilt angle.

I. INTRODUCTION

The efficiency of a PV cell or a PV panel decreases with an increase in the operating temperature and cooling is beneficial [1]. Hence, natural or forced convection heat transfer from a tilted flat plate is of considerable interest to engineers because of its application to solar PV electricity systems. On days with little or no wind, the natural convection heat transfer from the upward-facing (UF) and downward-facing (DF) surfaces becomes more significant [2]. This is especially true in cold climates where the temperature differences between the surfaces of a PV panel and the ambient air may be relatively large [2,3]. Therefore, the tilt of a PV panel is very important to its effective operation [4,5]. In order to produce the maximum amount of electrical energy, a PV panel must receive the highest possible radiation from the Sun. This occurs when the PV panel is normal to the sunrays [5].

Many prior and recent studies have been devoted to natural convection heat transfer from vertical, tilted and horizontal flat plates, as well as from UF and DF isothermal surfaces [6-12]. Some of these studies are experimental [6-9], while others are numerical [10-12]. Raithby and Hollands [13] correlated a number of experiments on the natural convection heat transfer from a flat plate in both vertical and horizontal positions. They proposed a set of natural convection correlations for laminar and turbulent flows from vertical, horizontal UF and horizontal DF isothermal plates, and suggested the use of the correlations for different tilt angles. According to [14], the natural convection from a vertical plate may be correlated with the fundamental dimensionless number, while the only correlations available for natural convection from horizontal plates are in the form of Nu=C(Ra)α. Furthermore, to the best knowledge of the authors, there do not appear to be any correlations in the literature, based on fundamental dimensionless number, for modeling the natural convection from a flat plate or PV panel at tilt angles between vertical and horizontal limits. Application of such correlations is the objective of this paper.

Neglecting orientation, typical parameters of a tilted PV panel are its height L and tilt angle from the vertical ψ [2,4]. If the flow is laminar, the natural convection heat transfer from the UF or DF surface of a PV panel falls as it stands from the vertical (ψ=0°) to the horizontal (ψ=90°). For turbulent flow, however, the natural convection heat transfer from the UF surface of a PV panel rises as it stands from ψ=0° to ψ=90°. According to [14], for a vertical PV panel, the characteristic length is the height L of the panel in the direction of gravity; while, for a horizontal PV panel, the characteristic length is one side of a square panel and the mean of the two sides of a rectangular panel. Therefore, Arpaci et al. [14] used the different characteristic lengths for vertical and horizontal plates, and proposed the correlation in the form of Nu=C(Πn)α only for vertical plates; where Πn is the corresponding fundamental dimensionless number for natural convection. However, other researchers used the same characteristic length L for different tilt angles between 0 and 90°.

In this paper, the authors aim to propose an approach for modeling the effect of tilt angle on the natural convection heat...
transfer from a ground-mounted PV panel. Moreover, they used the height \( L \) and tilt angle \( \psi \), and introduced the empirical correlations in the form of \( \text{Nu}(\psi) = C(\psi)(L_0)^{\alpha} \) for which the characteristic length is the height \( L \), and where \( C \) vary depending on the tilt angle \( \psi \). Natural convection correlations were derived based on the experimental results presented in [12] and [15], and based on analytical solutions obtained in accordance with [14]. Validation of the approach has been performed numerically and experimentally.

II. HEAT TRANSFER MODEL

The following section presents the theoretical analysis of the heat transfer along the surfaces of the PV panel as shown in Fig. 1. In order to estimate the values of natural convection heat transfer coefficients, the model is derived on the basis of conservation of energy and appropriate empirical correlations (which are presented in Table I). The parameters displayed in Fig. 1 have the following meanings: \( n \) is a normal to the UF surface of the PV panel; \( g \) is the angle between the vertical and the normal \( n \); \( \psi = 90^\circ - g \) is the angle of tilt from the vertical; \( g \) is the gravitational constant; \( W_{PV} = 0.45 \) m is the width of the PV panel; \( L_{PV} = 0.52 \) m is the length of the PV panel; \( \Delta_{PV} = 0.05 \) m is the thickness of the PV panel; \( T_{UF}, T_{DF}, T_{sky}, T_{g} \) are the temperatures of the UF surface of the PV panel, the DF surface of the PV panel, the ambient air, the sky, and the ground, respectively; \( T_{PV} \) is the average temperature of the PV panel; \( \alpha_{UF} = 0.91 \) is the absorption coefficient of the UF surface of the PV panel; \( Q_{E_{S,S}} = 920 \) W\( \cdot \)m\(^{-2} \) is the solar irradiance component which is perpendicular to the UF surface of the PV panel [17]; \( Q_{h_{th,UF-sa}} \) and \( Q_{h_{th,DF-sa}} \) are the amounts of heat exchanged by natural convection between the UF and DF surfaces and the ambient air at a tilt angle \( \psi \) per second, respectively; \( Q_{h_{th,s,UF}} \) and \( Q_{h_{th,s,DF}} \) are the amounts of heat exchanged by natural convection between the UF and DF surfaces and the ambient air at a tilt angle \( \psi \) per second, respectively; and \( Q_{el} \) is the electric power generated by the PV panel. Fig. 1 shows the sky and the ground are modeled with the two infinite parallel flat plates. Moreover, the sides of the PV panel are assumed to be adiabatic, the UF and DF surfaces are assumed to be isothermal surfaces having the same temperature \( T_{PV} \) and it is taken that \( T_{sky} \) and \( T_{g} \) are equal.

The heat transfer coefficients corresponding to the heat transfer processes \( Q_{h_{th,UF-sa}}(\psi) \), \( Q_{h_{th,DF-sa}}(\psi) \), \( Q_{h_{th,s,UF}} \) and \( Q_{h_{th,s,DF}} \) are \( h_{UF}(\psi), h_{DF}(\psi), h_{UF} \) and \( h_{DF} \), respectively. When a number of the parameters given in Fig. 1 are known, the temperature of the PV panel as well as the amounts of heat exchanged by natural convection and radiation need to be estimated for different tilt angles \( \psi \).

The iterative procedure for computing \( T_{PV} \) requires knowledge of \( h_{UF}, h_{DF}, h_{UF} \) and \( h_{DF} \), which are initially unknown. To obtain an initial estimate of \( T_{PV} \), the same numerical value (e.g. 12 W\( \cdot \)m\(^{-2} \)\( \cdot \)K\(^{-1} \)) can be taken for all unknown heat transfer coefficients. Therefore, an initial estimate of \( T_{PV} \) can be made from

\[
\alpha_{UF} \cdot Q_{E_{S,S}} = \left( \frac{Q_{h_{th,UF-sa}} + Q_{h_{th,s,UF}} + Q_{h_{th,DF-sa}} + Q_{h_{th,s,DF}}}{S_{PV}} \right) \]

where [2.16-18]

\[
T_{PV} = \frac{\alpha_{UF} \cdot Q_{E_{S,S}} - Q_{el}/S_{PV}}{h_{UF} + h_{DF} + h_{DF} + T_{s}} + T_{s} \]

Fig. 1. Heat transfer along the UF and DF surfaces of the PV panel.

as follows

\[
T_{PV} = \frac{\alpha_{UF} \cdot Q_{E_{S,S}} - Q_{el}/S_{PV}}{h_{UF} + h_{DF} + h_{DF} + T_{s}} + T_{s} \]

where [2.16-18]
an open rack PV panel with a glass/PV cell/polymer sheet composition [2,18].

Four temperature dependent parameters for air at film temperature $T_{f}(T_{PV} + T_{a})/2$ are used: kinematic viscosity $\nu$, thermal diffusivity $\alpha_t$, thermal conductivity $k_t$, and Prandtl number $Pr$. These parameters have been read from corresponding input data files and interpolated using a cubic spline. The thermal expansion coefficient of air is taken as $\beta = 1/T_c$. Thus, the Rayleigh number based on the length of the PV panel can be expressed as

$$Ra = \frac{\beta L^3}{\nu \alpha_t} \cdot (T_{PV} - T_{a}) \cdot L^3$$

(13)

where $L = L_{PV}$ is an appropriate characteristic length.

A Nusselt number for natural convection along a flat plate tilted at an angle $0 \leq \varphi \leq 90^\circ$ can be correlated with

$$Nu = C(\varphi) \cdot (\Pi_{cr})^{3/4} = C(\varphi) \cdot [Ra / (1 + 0.492 / Pr)]^{3/4}$$

(14)

where $C(\varphi)$ and $n$ are the coefficients which should be selected according to the conditions from Table I. In Table I, $Gr$ is the Grashof number; $Gr_{cr1}$ and $Gr_{cr2}$ are the critical Grashof numbers at which the flow along the UF and DF surfaces starts deviating from laminar behavior, respectively. In accordance with Corcione et al. [11] and Warneford [19], the following equations were constructed for the calculation of the critical Grashof numbers $Gr_{cr1}$ and $Gr_{cr2}$ as functions of the tilt angle $\varphi$ and the Prandtl number $Pr$:

$$Gr_{cr1} = (1/Pr) \cdot 10^{(9 \cos \varphi + 1.65)}$$

(15)

$$Gr_{cr2} = (6.31 \cdot 10^9 / Pr) \cdot e^{0.017 \varphi}$$

(16)

for $0 \leq \varphi \leq 90^\circ$ and $0 \leq Pr \leq \infty$. In case of a laminar flow ($Gr \leq 10^9$, $Gr \geq Gr_{cr1}$ and $Gr \geq Gr_{cr2}$), the coefficients $C(\varphi)$ and $n$ are determined based on empirical correlations, numerical studies and experimental results from [6,11,12,20]. In case of a turbulent flow ($Gr \geq 10^9$, $Gr \geq Gr_{cr1}$ and $Gr \geq Gr_{cr2}$), the coefficients $C(\varphi)$ and $n$ are determined based on empirical correlations and experimental results from [8,12,15]. This implies the heat transfer coefficients $h_{UF}$ and $h_{DF}$ equal

$$h_{UF} = Nu(\varphi) \cdot k_t / L$$

and

$$h_{DF} = Nu(\varphi) \cdot k_t / L.$$  

(17)

Moreover, the value $T_{PV}$ should be recomputed by averaging the assumed and found values of $h_{UF}$, $h_{DF}$, $h_{UF}$ and $h_{DF}$ in each iteration. This approach must be iterated until the difference between the assumed and found $T_{PV}$ values becomes negligibly small. Ultimately, this iterative procedure utilizes the final value of $T_{PV}$ to evaluate the final values of $h_{UF}$, $h_{DF}$, $h_{UF}$ and $h_{DF}$, as well as $T_{UF}$ and $T_{DF}$ using (11) and (12).

A 2-D FEM-based model was built in the COMSOL Heat Transfer Module. Where

$$k_{eff} = \frac{(Q_{h,UF,DF,\varphi} + Q_{h,DF,DF,\varphi}) \cdot \Delta \rho_{PV}}{T_{UF} - T_{DF}}$$

(18)

is used as the effective thermal conductivity of the materials placed between the UF and DF surfaces.

| TABLE I. NATURAL CONVECTION CORRELATIONS FOR ISOTHERMAL TILTED PLATE |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Geometry        | Surface         | Flow regime     | Plate temperature is constant | Correlation |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Vertical        | (\varphi=0^\circ) | Sideward-facing | Laminar          | Turbulent       | Gr>10^9         | 0.67            | 1/4             |
| Tilted          | (0^\circ<\varphi<90^\circ) | Upward-facing  | Laminar          | Turbulent       | Gr>0.67         | 0.098-0.057     | (\sin \varphi)^3 | 1/3             |
| Horizontal      | (\varphi=90^\circ) | Downward-facing | Laminar          | Turbulent       | Gr>0.67         | 0.67-0.037      | (\sin \varphi)^3 | 1/4             |

III. SIMULATION RESULTS AND DISCUSSION

Table II summarizes the analytical results obtained for various tilt angles. For each tilt angle $\varphi$ a set of 16 or 17 iterations was needed. The heat transfer coefficients $h_{UF}$, $h_{DF}$, $h_{UF}$ and $h_{DF}$ were computed using a program developed especially for the purposes of this paper.

It can be noticed from Table II that the natural convection heat losses on the UF and DF surfaces of the PV panel change between 31.9-35.5% and 33.4-19.2% then tilt angle $\varphi$ increases from 0 to 90°, respectively. Moreover, the heat transfer coefficients $h_{UF}$ and $h_{DF}$ have the same type of trend as the ones that were obtained by Lim et al. [12] for a tilted flat plate.

The differences between analytically and numerically obtained temperatures $T_{UF}$ and $T_{DF}$ have been negligible. The temperature field distribution over the solution domain (i.e. the cross-section of the PV panel) for $\varphi=0^\circ$ is presented in Fig. 2. Experimental validation of the model has been performed according to [17]. They measured the temperatures on a PV panel placed at 37° facing north, i.e. at $\varphi=53^\circ$. The PV panel was tested in Australia, where the solar irradiance is 920 W m⁻² [17]. Fig. 3 shows the measured and computed temperatures.

<p>| TABLE II. HEAT TRANSFER COEFFICIENTS FOR THE PV PANEL AT DIFFERENT TILT ANGLES |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>$\psi$</th>
<th>$h_{UF}$</th>
<th>$h_{DF}$</th>
<th>$h_{UF}$</th>
<th>$h_{DF}$</th>
<th>$T_{UF}$</th>
<th>$T_{DF}$</th>
<th>$T_{DF}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>deg</td>
<td>W⁻²K/°C</td>
<td>W⁻²K/°C</td>
<td>W⁻²K/°C</td>
<td>W⁻²K/°C</td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>0</td>
<td>4.098</td>
<td>4.098</td>
<td>8.743</td>
<td>8.166</td>
<td>6.065</td>
<td>52.052</td>
<td>49.292</td>
</tr>
<tr>
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<tr>
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<td>4.036</td>
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<td>8.164</td>
<td>6.041</td>
<td>52.083</td>
<td>49.323</td>
</tr>
<tr>
<td>30</td>
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<td>3.952</td>
<td>8.746</td>
<td>8.170</td>
<td>5.980</td>
<td>51.988</td>
<td>49.228</td>
</tr>
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<td>3.832</td>
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<td>8.170</td>
<td>5.922</td>
<td>51.989</td>
<td>49.229</td>
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<td>3.671</td>
<td>8.741</td>
<td>8.165</td>
<td>5.859</td>
<td>52.079</td>
<td>49.319</td>
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<tr>
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<td>3.612</td>
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<td>8.162</td>
<td>5.838</td>
<td>52.125</td>
<td>49.365</td>
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<tr>
<td>70</td>
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<td>3.453</td>
<td>8.729</td>
<td>8.154</td>
<td>5.786</td>
<td>52.270</td>
<td>49.510</td>
</tr>
<tr>
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<td>4.641</td>
<td>3.148</td>
<td>8.710</td>
<td>8.136</td>
<td>5.692</td>
<td>52.599</td>
<td>49.839</td>
</tr>
<tr>
<td>90</td>
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<td>2.670</td>
<td>8.678</td>
<td>8.106</td>
<td>5.551</td>
<td>55.187</td>
<td>50.427</td>
</tr>
</tbody>
</table>
The main conclusions arising from the present paper are:

- Introducing the correlations based on the fundamental dimensionless number for natural convection into the model, it is provided a simple procedure for the estimation of average heat transfer coefficients due to natural convection which correspond to different tilt angles.

- Introducing the effective thermal conductivity $k_{eff}$ into the COMSOL model, it is provided that the heat conduction can be used to visualize the complex nature of the heat transfer occurring between the UF and DF surfaces of the PV panel.

- The heat transfer coefficients $h_{UF}$ and $h_{DF}$ have trends which were expected for a tilted PV panel.

- The natural convection heat losses on the UF and DF surfaces of the PV panel are between 31.9-35.5% and 33.4-19.2% of corresponding total heat losses then tilt angle $\psi$ increases from 0 to 90$^\circ$, respectively.

- The accuracy of the proposed model has been successfully verified numerically and experimentally.

IV. CONCLUSIONS

The main conclusions arising from the present paper are:

- The temperature distribution over the solution domain for $\psi=0^\circ$. 

- Measured and computed temperatures on a ground-mounted PV panel for $\psi=53^\circ$ and $Q_{inc}=920$ W/m$^2$. 

REFERENCES


Abstract— The main purpose of this paper is to propose procedures for analytical and numerical modeling of the heat transfer processes for both laminar and turbulent flows around an evacuated tube collector (ETC) at tilt angles of 0-90°. A new set of heat transfer correlations based on the fundamental dimensionless number for natural convection was derived. A modified Nusselt number, which represents the mean of the heat transfer correlations based on the collector diameter and based on the collector length, was introduced and applied to estimate the heat transfer coefficients for natural convection on the outer surface of the ETC surrounded by air. Effects of the solar radiation and radiation heat loss from the outer surface of the ETC were taken into consideration as well. The finite element method (FEM) has been used for the linear/non-linear steady-state thermal analysis, i.e. for validation of the analytical procedure. All FEM-based computations were carried out using the COMSOL Heat Transfer Module.

Keywords— analytical model, ETC, FEM-based model, heat transfer, natural convection, tilt angle.

I. INTRODUCTION

It is well known that the tilt angle affects the operation of an ETC. When an ETC is horizontal its efficiency is near zero. The efficiency of the ETC grows when the tilt angle increases up to a certain value and then decreases. Tilt angle influences especially the heat transfer by natural convection around an ETC, i.e. the corresponding heat loss. Furthermore, the installation manuals explain in details the effects of tilt angle on the performances for these collectors. In order to ensure reliable operation, according to the installation manuals, a minimum tilt angle must be between about 20° [1] and 30° [2,3] from horizontal.

Among other researchers Tang et al. [4] have analyzed optimal tilt angles of ETCs, while Wu et al. [5] investigated the influence of aperture position on natural convection heat loss of a solar heat-pipe receiver. Zambolin and Del Col [6] as well as Pluta [7] have studied the thermal performances of ETCs. All these studies were performed to determine the efficiency, optimal tilt angles and other ETC performances eliminating the natural convection heat transfer on the outer surface of ETCs, as well as the conduction heat transfer through the inner and outer tube walls. According to [8], the natural convection on the outer surface of an ETC affects its efficiency and cannot be neglected, while the influence of the conduction through the tube walls is negligible. Following the guidelines for computation of the heat transfer on the outer surface of an ETC proposed by Incropera et al. [8], it can be revealed that the natural convection heat loss amounts of up to 35% of the overall heat loss for the horizontal orientation. Moreover, ETCs are sensitive to the influence of tilt angle [8].

Typical parameters of an tilted ETC are its length L, outer diameter D and tilt angle from the horizontal \( \psi \). The natural convection heat transfer outside the ETC falls as it stands from the horizontal (\( \psi=0^\circ \)) to the vertical (\( \psi=90^\circ \)). In accordance with [9], horizontal cylinders should be treated as infinitely long in the axial direction, so the remaining characteristic length is the outer diameter of the collector D. Vertical cylinders with a large diameter are treated as vertical planes, and the characteristic length is the collector length L [10]. Arpaci et al. [11] used the same characteristic lengths and proposed the correlations \( \text{Nu}_D = C (\Pi_{ND})^n \) and \( \text{Nu}_L = C (\Pi_{NL})^n \) for horizontal and vertical cylinders, respectively; where \( \Pi_{ND} \) and \( \Pi_{NL} \) are the corresponding fundamental dimensionless numbers for natural convection. However, the characteristic lengths for tilted ETCs and cylinders are both diameter and length due to the fact that the natural convection is three-dimensional phenomena around them [12].

In this paper, the authors used the diameter D, length L and tilt angle \( \psi \) and introduced the modified Nusselt number \( \text{Nu}_D^* \) for which the characteristic length is the diameter D. The correlations for the turbulent natural convection around horizontal and vertical cylinders proposed by Arpaci et al. [11] at \( \psi=0^\circ \) and \( \psi=90^\circ \) do not agree with the correlation for a
The length of this ETC is \( L = 1 \) m. The glass tube is transparent to solar radiation and the absorption coefficient of the copper tube with respect to solar radiation is \( \alpha_{tr,o} = 1 \). The surface of the copper tube has a thermal emission coefficient of \( \epsilon_{tr,o} = 0.13 \) with respect to its radiative interaction with the inner surface of the glass tube. The borosilicate glass may be assumed to be opaque to thermal radiation from the copper tube with a thermal emission coefficient of 1 on both its inner and outer surfaces, i.e. \( \epsilon_{tr,o} = 0.13 \).

### III. ANALYTICAL AND FEM-BASED MODELS

The iterative procedure for computing \( h_{tr,o} \) requires knowledge of \( T_2, h_{tr,o} \), and \( h_{2,o} \), which are initially unknown. To obtain an initial estimate of \( T_2 \), the same numerical value that corresponds to the turbulent natural convection in (e.g. 12 \( W \cdot m^{-2} \cdot K^{-1} \)) can be taken for all unknown heat transfer coefficients. Therefore, an initial estimate of \( T_2 \) can be made from

\[
S_{1,o} \cdot Q_{tr.o.1-2} = S_{2,o} \cdot Q_{th.o.2-a_o} + S_{2.o} \cdot Q_{tr.o.2-a_o} \tag{1}
\]

as follows

\[
T_2 = \frac{h_{tr.o} \cdot S_{1.o} \cdot (T_2 - T_f)}{h_{tr.o} \cdot S_{1.o} + (h_{2.o} + h_{r.o}) \cdot S_{2.o}} \tag{2}
\]

where

\[
Q_{tr.o.1-2} = h_{i,o} \cdot (T_1 - T_2) \tag{3}
\]

\[
h_{i,o} = \varepsilon_{tr.o} \cdot \sigma_{SB} \cdot F_{i.o} \cdot (T_1^4 + T_f^4) \tag{4}
\]

\[
Q_{th.o.2-a_o} = h_{2.o} \cdot (T_2 - T_f) \tag{5}
\]

\[
Q_{tr.o.2-a_o} = h_{r.o} \cdot (T_2 - T_f) \tag{6}
\]

\[
h_{r.o} = \varepsilon_{r.o} \cdot \sigma_{SB} \cdot F_{r-a} \cdot (T_2 + T_a) \cdot (T_f^3 + T_a^3) \tag{7}
\]

\( S_{1,o} \) is the outer surface area of the copper tube; \( S_{2,o} \) is the outer surface area of the glass tube; \( F_{i.o} = 1 \) and \( F_{r.o} = 1 \) are the appropriate radiation shape factors; and \( \sigma_{SB} \) is the Stefan-Boltzmann constant.

Four temperature dependent parameters for air at film temperature \( T_f = (T_2 + T_o)/2 \) are used: kinematic viscosity \( \nu \), thermal diffusivity \( \alpha \), thermal conductivity \( k \), and Prandtl number \( Pr \). These parameters have been read from corresponding input data files and interpolated using a cubic spline. The thermal expansion coefficient of air is taken as \( \beta = 1/T_f \). Thus, the Rayleigh number based on outer diameter of the ETC \( Ra_D \) and the Rayleigh number based on length of the ETC \( Ra_L \) can be expressed as

\[
Ra_D = \frac{g \cdot \beta}{\nu \cdot \alpha} \cdot (T_2 - T_f) \cdot D^3 \tag{8}
\]

and

\[
Ra_L = \frac{g \cdot \beta}{\nu \cdot \alpha} \cdot (T_2 - T_f) \cdot L^3 \tag{9}
\]
where D and L are appropriate characteristic lengths, and g is the gravitational constant.

The fundamental dimensionless numbers for natural convection \( \Pi_{3D} \) and \( \Pi_{2D} \) as well as the average Nusselt numbers \( Nu_{D}(\psi) \) and \( Nu_{L}(\psi) \), should be computed using numerical values and equations for \( C_{0}, n \) and \( C(\psi) \) from Table I. Therefore, if the modified Nusselt number is defined as

\[
Nu_{D} = \frac{Nu_{D}(\psi) \cdot L + Nu_{L}(\psi) \cdot D}{2 \cdot L},
\]

the diameter D represents the characteristic length and coefficient \( h_{2,o} \) becomes

\[
h_{2,o} = \frac{Nu_{D} \cdot k}{D}.
\]

Moreover, the heat transfer coefficients \( h_{1,0} \) and \( h_{2,0} \) should be computed using equations (4) and (7); the value of \( T_{2} \) should be recomputed by averaging the assumed and found values of \( h_{1,0}, h_{2,0} \) and \( h_{2,o} \) in each iteration; and, the problem must be iterated until the difference between the assumed and found \( T_{2} \) values becomes negligibly small. Ultimately, this iterative procedure utilizes the final value of \( T_{2} \) to evaluate the final values of the heat transfer coefficients \( h_{1,0}, h_{2,0} \) and \( h_{2,o} \).

It can be noticed from Table II that the heat transfer coefficient \( h_{2,o} \) has the same type of trend as the one that was obtained by Wu et al. [5] for a solar heat-pipe receiver. According to [7], the heat loss due to natural convection is negligible. However, Table II shows the coefficient \( h_{2,o} \) is in the range of or slightly greater than the overall heat loss coefficients for ETCs amounting to 1.5-2.5 \( \text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1} \) [7]. Moreover, the natural convection heat loss on the outer surface of the ETC changes between 34.3 and 23% then tilt angle increases from 0 to 90°.

**TABLE II. HEAT TRANSFER COEFFICIENTS AND TEMPERATURE \( T_{2} \) FOR THE ETC AT DIFFERENT TILT ANGLES**

<table>
<thead>
<tr>
<th>( \psi ) in degrees</th>
<th>Analytical model</th>
<th>FEM-based model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( h_{2,o} ) in ( \text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1} )</td>
<td>( h_{2,o} ) in ( \text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1} )</td>
</tr>
<tr>
<td>0</td>
<td>1.141</td>
<td>1.141</td>
</tr>
<tr>
<td>10</td>
<td>1.141</td>
<td>1.141</td>
</tr>
<tr>
<td>20</td>
<td>1.141</td>
<td>1.141</td>
</tr>
<tr>
<td>30</td>
<td>1.141</td>
<td>1.141</td>
</tr>
<tr>
<td>40</td>
<td>1.141</td>
<td>1.141</td>
</tr>
<tr>
<td>50</td>
<td>1.141</td>
<td>1.141</td>
</tr>
<tr>
<td>60</td>
<td>1.142</td>
<td>1.142</td>
</tr>
<tr>
<td>70</td>
<td>1.142</td>
<td>1.142</td>
</tr>
<tr>
<td>80</td>
<td>1.142</td>
<td>1.142</td>
</tr>
<tr>
<td>90</td>
<td>1.143</td>
<td>1.143</td>
</tr>
</tbody>
</table>

In both the analytical analysis and the FEM-based analysis the influence of the glass tube wall thickness on temperature distribution was neglected. The differences between analytically and numerically obtained temperatures are negligible as well. The temperature field distribution over the solution domain (i.e. the cross-section of the ETC) for a tilt angle \( \psi=0° \) is presented in Fig. 2.

**IV. SIMULATION RESULTS AND DISCUSSION**

Table II summarizes the results obtained for various tilt angles. For each tilt angle \( \psi \) a set of 14 iterations was needed. The heat transfer coefficients were computed using a program developed especially for the purposes of this paper.

**V. CONCLUSIONS**

The conclusions arising from this paper are:

- Introducing the modified Nusselt number \( Nu_{D} \) into the analytical model, it is provided that only one average
heat transfer coefficient due to natural convection corresponds to each tilt angle $\psi$.

- Introducing the effective thermal conductivity $k_{\text{eff}}$ into the numerical model, it is provided that the heat conduction can be used to visualize the radiation heat exchange occurring between the two tubes of the ETC.

- The heat transfer coefficient $h_{2,o}$ has a trend that was expected for a tilted ETC.

- The natural convection heat loss is between 34.3 and 23% of the total heat loss then tilt angle $\psi$ increases from 0 to 90°.

- The accuracy of the analytical model has been successfully validated by the FEM-based modeling.

REFERENCES


The Combinative Algorithm of Identification and State Estimation Based on Combined Maximum Principle for Solving Inverse Problem in Structural-Parametric Uncertainty

Andrey A. Kostoglotov¹, Aleksandr I. Kostoglotov¹, Sergey V. Lazarenko², Boris M. Tsennih³, Igor V. Deryabkin³
¹ Rostov State Transport University, Rostov-on-Don, Russia
² Don State Technical University, Rostov-on-Don, Russia
³ Moscow State University of Technologies and Management named after K.G. Razumovsky, Rostov-on-Don, Russia
e-mail: science@xjcrm.org, kostoglotov@me.com

Abstract—The paper proposed new approach based on combined maximum principle. The minimum of residual functional by nonsmooth analysis with state space representation obtain new method to solving inverse problem. This method reduces the computational costs confirmed by mathematical simulation of temperature sensor in parametric uncertainty.

Keywords—inverse problem, state space representation, structure parametric identification, nonsmooth analysis.

I. INTRODUCTION

Correction of machining errors problem occurs from fast-dynamic detection of response sensor. In addition, this problem occurs when the sensors have a long response time with fast-dynamic processing. The accuracy of input signal ensures by identification parameters of transducer. This aspect impact on solving of Ill-Posed Problems. The solving this problem actually, when the solution is instability. The low identification error provide high output signal error. Generally this problem solving by different of state space representation as different modification of Kalman filter. This method provide high computational cost and this method need the struct of model of dynamic system and noise information.

We propose the new approach based on combined maximum principle.

II. PROBLEM FORMULATION

Let us consider inverse problem of temperature sensor. The mathematics model of sensor defined Lagrange’s equation [1]. The formal model of sensor considers energy dissipation when the model influenced eclectic and magnet fields. The model described by an equation

\[
E = \dot{q}^2 + a_s \dot{q}^2 + a_\alpha \dot{q}^2; D = q \dot{q}; \quad \Pi = q_s q, \quad a_s \text{ are iteration coefficients}; \quad q_s = \lambda_1 \left( \frac{S_1}{c_s} + \frac{S_0}{c_o} \right) + \alpha_s \frac{S_0}{c_o}
\]

are unknown parameters; \( \lambda_1 \) is a heat conductivity of space between sensing element and shell; \( S_1, S_0 \) are a surface areas of sensing element and shell; \( c_s, c_o \) are total heat capacity of sensing element and shell; \( \alpha_s \) is a convective coefficient shell exchange with the environment [1].

The system described by an equation

\[
\ddot{q}_s(t) = -q_s \dot{q}_s(t) - q_s q(t) + Q(t); \quad \dot{q}_s = Q_s/a_s; \quad \dot{q}_i = Q_i/a_i.
\]

The observation function by equation:

\[
y(t) = q_s(Q)
\]

Requires a value of state estimate \( \hat{Q}_s \) and parameter \( \hat{q}_s, \hat{q}_i \), by minimizing residual functional

\[
J = \frac{1}{2} \int [y(t) - \hat{q}(Q)]^2 dt \to \min
\]

III. ALGORITHM OF STRUCTURE PARAMETRIC IDENTIFICATION

The equation of algorithm of structure parametric identification

\[
E = \dot{q}^2 + a_s \dot{q}^2 + a_\alpha \dot{q}^2; D = q \dot{q}; \quad \Pi = q_s q, \quad a_s \text{ are iteration coefficients}; \quad q_s = \lambda_1 \left( \frac{S_1}{c_s} + \frac{S_0}{c_o} \right) + \alpha_s \frac{S_0}{c_o}
\]

are unknown parameters; \( \lambda_1 \) is a heat conductivity of space between sensing element and shell; \( S_1, S_0 \) are a surface areas of sensing element and shell; \( c_s, c_o \) are total heat capacity of sensing element and shell; \( \alpha_s \) is a convective coefficient shell exchange with the environment [1].

We propose the new approach based on combined maximum principle.

The system described by an equation

\[
\ddot{q}_s(t) = -q_s \dot{q}_s(t) - q_s q(t) + Q(t); \quad \dot{q}_s = Q_s/a_s; \quad \dot{q}_i = Q_i/a_i.
\]

The observation function by equation:

\[
y(t) = q_s(Q)
\]

Requires a value of state estimate \( \hat{Q}_s \) and parameter \( \hat{q}_s, \hat{q}_i \), by minimizing residual functional

\[
J = \frac{1}{2} \int [y(t) - \hat{q}(Q)]^2 dt \to \min
\]
\[ \ddot{q}_i(t) = \frac{1}{\lambda} \left[ - \frac{\phi_i}{\lambda} \right] \hat{q}_i - (y - \hat{q}_i) \]
\[ \hat{q}_i(0) = \hat{q}_{i0}, \dot{\hat{q}}_i(0) = \dot{\hat{q}}_{i0}, \]
\[ \hat{q}_i(t) = \frac{1}{a_i \lambda} \left[ - \frac{\phi_i}{L_i} \right] \hat{q}_i - (y - \hat{q}_i)G_i, \]
\[ \hat{q}_i(0) = \hat{q}_{i0}, \dot{\hat{q}}_i(0) = \dot{\hat{q}}_{i0}, \]
\[ s = 2,3, \]
\[ G_i = \hat{q}_iG_i + \hat{q}_iG_i + \hat{q}_iG_i, \]
\[ \dot{\hat{q}}_i = \hat{q}_iG_i + \hat{q}_iG_i + \hat{q}_iG_i; \]
\[ G(0) = [G_i \ G_i], \quad G(0) = [G_i \ G_i], \]
\[ \text{where} \quad G_i = \frac{c\hat{q}_i}{\hat{q}_i} \text{ is a response matrix of system.} \]

Assessment of algorithm (4) provided by mathematical simulation. The real value of parameters are \( q_i = 6, q_i = 0,3 \).

The input signal is a step-function by an equation
\[ Q(t) = \begin{cases} 0, & t < 0, \\ 1, & t \geq 0 \end{cases} \]

The initial conditions are \( \hat{q}_i(0) = 0, \hat{q}_i(0) = 0, \hat{q}_i(0) = 0.5, \)
\[ \hat{q}_i(0) = 0, \quad \hat{q}_i(0) = 7.5, \quad \hat{q}_i(0) = 0, \quad \lambda^{-1} = 2 \cdot 10^{-5}, \]
\[ \alpha_i = \alpha_i = 50, \quad L_i = 12000, \quad L_i = 12000, \quad L_i = 12000, \quad L_i = 8.4, \quad \lambda_i = -250, \]
\[ \varepsilon_i = 3.2, \quad \varepsilon_i = 11.5, \quad G(0) = [0 \ 0], \quad G(0) = [0 \ 0]. \]

Results of mathematics simulation in figure 1 and 2, where full lines are identification processes and state estimate and dotted lines are real values. The error identification parameters amounted \( \delta\hat{q}_i = 1.1 \%, \delta\hat{q}_i = 0.05 \% \).

This algorithm needed for calculate 10 difference equations. The Kalman Filter needed for calculate 14 difference equations. The proposed algorithm reduces the computational costs.

**IV. CONCLUSIONS**

The proposed algorithm provide the solution of inverse problem in parametric uncertainty. This algorithm characterizes many applications problems of processing the measurement signals. This approach can be apply to wide class of research objects.

**REFERENCES**


Servoanalysers Synthesis with Adaptive Discrete Extrapolator Based on Combined Maximum Principle

Andrey A. Kostoglotov, Sergey V. Lazarenko, Boris M. Tsennih, Igor V. Deryabkin, Anton A. Kuznetsov

1 Rostov State Transport University, Rostov-on-Don, Russia
2 Don State Technical University, Rostov-on-Don, Russia
3 Moscow State University of Technologies and Management
4 Air Force Academy named after Professor N.E. Zhukovsky and Y.A. Gagarin (Voronezh), Voronezh, Russia
e-mail: science@xjcrm.org, kostoglotov@me.com

Abstract— A combined maximum principle allows find the constructive solution of navigation and servoanalysers problem for a wide class of objects (rail, road, air and other transport). The main difference new algorithm is that synthesized algorithm based on other different models for extrapolated values of coordinate versus traditional algorithms based on statistical theory of synthesis. Results of mathematics simulation showed that method based on CMP have lower error and computing costs versus classical approach.

Keywords— combined maximum principle, navigation processing, Hamilton’s principle, servoanalysers.

I. INTRODUCTION

Approach of synthesis problem based on combined maximum principle (CMP) [1] provide solution of objects data processing from navigation system for wide range of objects (train, automobile, aviation and other). The main difference with proposed algorithm is that new extrapolator based on hypotheses about the nature of dynamic [2]. Adaptation of observation results to Hamilton’s principle by stationary point. Results of mathematic simulation now suggests that proposed algorithm can outperform generally algorithms [1, 3] for accuracy and computational cost.

II. PROBLEM FORMULATION

Let the model of dynamic object by Lagrange equations [1]

\[ \sum_{k=1}^{n} \sum_{m=1}^{n} \sum_{s=1}^{n} \left[ k, m, s \right] q_{s} \dot{q}_{s} q_{s} + U_{s} - \frac{\partial \Phi}{\partial q_{s}} - \frac{\partial \Pi}{\partial \dot{q}_{s}} = 0, \]

where \( \dot{q}_{s} \) are generalized coordinate; \( [k, m, s] \) are Christoffel symbols; \( a_{s} \) are fields of kinetic energy quadric matrix; \( \frac{\partial \Pi}{\partial q_{s}} \) are generalized forces of potential energy; \( U_{s} \) are generalized forces of motion; \( \frac{\partial \Phi}{\partial q_{s}} \) are dissipative generalized forces. \( n \) is a number of degrees of freedom. Same generalized forces right value (1) are unknown in practice. The problem of tracking amounts to inversive problem.

The observation function by equation:

\[ y_{s}(t) = H_{s}(q_{s}, t) + \xi_{s}(t), \]

where \( H_{s} \) is a known function; \( \xi_{s} \) is a communication noise with determinate random characteristics.

The residual functional in observation aria is

\[ J_{1} = \frac{1}{2} \int_{0}^{T} \sum_{s=1}^{n} R_{ss} \left[ y_{s}(t) - H_{s}(q_{s}, t) \right]^{2} dt, \]

where \( R_{ss} \) are fields of weighting matrix. The matrix characterizes communication noise intensity.

III. SYNTHESIS OF SERVOANALYSER

The solution of this problem by combined maximum principle theorem [1]. The theorem allow determinate set of forces accurate to same constant sign function by minimization residual functional (3)

\[ Q_{1} = \lambda^{-1} \left| Q_{1} \right| \text{sign} \left[ \mu(q, \dot{q}) \dot{q}_{s} - R_{s}(t) \right] \left[ y_{s}(t) - H_{s}(q_{s}, t) \right] \left[ \frac{\partial H_{s}}{\partial q_{s}} \right], \]

Whence general equations of adaptive extrapolator by:

\[ \dot{q}_{s}(t) = q_{s}(t), \quad s = \lambda, n. \]

Comparison result of method based on CMP and Kalman filter in figure 1 and 2, where illustrate the root-mean-square to time. In figure 1 and 2 full lines for method based CMP and dotted lines for Kalman Filter.
Analysis of computing costs showed that Filter Kalman needed calculate 145 basic arithmetic operations and method based on CMP needed 88 basic arithmetic operations by Euler's method.

IV. CONCLUSIONS

Results of mathematics simulation showed that method based on CMP have lower error and computing costs versus classical approach in path manoeuvre.

REFERENCES


Abstract—this paper is devoted to the modeling of cognitive training system, which supported interaction of student and teacher, resulting in the development of distributed computing system basics on technical diagnostics.

Keywords—modeling, cognitive training system, complexes, technical diagnostics, fault, distributed computing, model knowledge.

I. INTRODUCTION

The technologies and methods that underlie current approaches to cognitive learning, e-learning, expert systems, performance support systems, world-wide-web browsers, and just-in-time training systems are rapidly converging. The current pace of technological development and technology upgrades in various spheres of human activity require continuing education and professional development. Heads of organizations in our worlds, they are wishing to improve staff skills to face the problem of separation of employees from their duties at the time of learning. Solution to this problem is to design and create cognitive training system (CTS), which aimed at improve the efficiency and quality of the learning process using by modeling [1].

At present, a number of high-tech industries, research and educational processes use many kinds of instrumentations and computer complexes that greatly improve the efficiency of information processing. Despite the undoubtedly positive effect of the use of instruments, complex ongoing devices, we have to state their lack of effectiveness, due to a number of technical and economic circumstances. In particular, rather acute problem of improving the resiliency and reliability of elements of instrumentations, the life of which often exceeds the standard. In connection with the above, one of the most important requirements for instrument complexes is their high availability and the ability to effectively identify failures [8, 9].

The analysis showed that the modern industrial technologies used in various fields, require new approaches to ensure their reliability and effective methods of technical diagnostics. In this regard, there is a steady increase in the number of faults and failures, worsening the number of products increase the probability of accidents and crashes. Such a negative situation related to the unreliability of the devices can be neutralized by increased personnel skills, able to justify decisions taken in the event of a negative situation.

However, the analysis of the existing training system showed that among the many software products did not exists any system that would carry out full training trainee technical diagnostics of computer complexes (distributed computing), while providing adaptive learning process.

Thus, current paper of our research aimed to create modeling for efficient information processing during times of technical diagnostics and processing of cognitive training system (CTS).

II. COGNITIVE TRAINING SYSTEM

Due to the emergence of new trends in science up-to-date conceptual framework was born. Thus, the term "cognitive" (from the Latin word "cognition" – knowledge, perception), meaning "informative", "pertaining to knowledge," appeared in the sixties of the last century as a result of existence of a new paradigm in psychological research (cognitive psychology, cognitive science). In this paradigm special attention is paid to traditional cognitive training processes (CTP): perception, attention, memory, imagination and thinking etc.

However, the cognitive approach is fundamentally different in a way that all of these processes are considered as components of the overall process of information exchange between the individuals during the learning.

Under the new conditions new learning technologies must be created – cognitive, i.e. ways, techniques, methods to ensure effective understanding by the individuals of information on the bases of unique indicators and characteristics of their CTP. The task of great importance is to develop the modern methodologies of organizing individuals’ learning and continuous monitoring and assessing of individuals’ CTP indicators, as well as of forming individual productive paths in the cognitive processes by means of introducing effective feedback systems via using the computer testing controlling methodology.

Recent scholarly research in the field of creating computer learning technologies can be divided into several categories: Intelligent Tutoring Systems: information-reference systems;
consultative type systems; intellectual training (expert-type tutoring) systems; accompanying type systems (e.g., ELM-ART-II, AST, ADI, ART-Web, ACE, KBS-Hyperbook, ILESA, DCG, SIETTE) [1].

E-Learning Management Systems elaborated the following SCORM standards, the specifications of the IMS Global Learning Consortium, and the Aviation Industry Computer-Based Training Committee (AICC) that regulate certain aspects of their development and use: the system’s architecture and the system’s interaction with outside systems; the ways of the learning system’s interaction with learning resources; the presentation of courses’ contents; the models of learning control; the testing algorithms and ways of presenting testing results (e.g., Bauman Training, e-Learning 3000, Web Tutor) [2,3].

Diagnostic and Planning Expert Teaching Systems based on using the methodological tools of computer testing [4-6]. Despite the wide range of scholarly achievements and market offers in the field of computer learning technologies, all of them have a number of similar specifications:

a) The use of testing technology mostly for measuring students’ learning individual achievements and the lack of methods for obtaining the specific characters of their individual intellectual activity and features of CTP.

b) The necessity of development of the methods of intellectual diagnostics of test materials for increasing the quality of CTP assessment.

c) The inflexible demands in most Ukrainian higher schools (HS) to the software required for their functioning and to the technical characteristics (in particular, the capacity characteristics) of computers, as well as to the speed and time of Internet resources use.

The purpose of this paper is brief description of the author’s results of development of CTP computer modeling concept on the basis of innovative approaches to improving the methodology and expanding the area of using the computer-based testing systems (CBTS) technology. The paper is also aimed at the presenting the key aspects of developing the use of author’s modeling propositions as an instrument for receiving and adequate interpretation of the set of quantitative and qualitative identifiers of individual intellectual characteristics of individuals. Scheme of the organizational and technical structure of CTS is presented in (Fig. 1). The central part of the system is a server - the information center of the university, containing all kinds of supporting information which is existing educational systems as the distance form.

III. FORMALIZATION OF COGNITIVE TRAINING PROCESS FOR COMPUTER MODELING CONCEPT

The CTP for computer modeling concept suggested by the author is based on implementing the following functional components: the database, the expert system of integrated diagnostics and cognitive process control (the latter comprising the logical conclusion mechanism, the working memory, the knowledge base, as well as the explanation subsystem and the dialogue subsystem), control systems, and CBTS.

A. The Database Structure
The database of the computer model is designed for storing:

- the structured learning content (LC), presented in the following systemically coordinated forms: brief textual notes of lectures for individuals’ self-studying before the actual in class teaching/learning starts Teach1, (contain the basic notions, definitions, laws, examples, and algorithms of situational knowledge use from the course); slide-notes of the lecture materials for demonstrating and discussing directly in the in-class teaching/learning process – Teach2;
- laboratory assignments – Teach3;
- testing materials for assessing the degree of individuals’ CTP – Teach4.

- reference and factual information about the syllabus, the number of individuals, the distribution of academic hours and learning units between in-class and out-of-class (independent) individuals’ work;

B. Knowledge Base Structure

The core of the expert system of integrated diagnostics and cognitive process control is the knowledge base designed for storing: expert knowledge and the acquired analytically knowledge.

The foundations of expert knowledge are the author’s research results in the area of computer testing methodology improvement and the development of intellectual instruments for supporting decision-making in what concerns the CTP analysis. There are the following heuristics:
a) Reference time $T_{ni}$ is the objective tool of complex quantitative formalization (scaling) of the degree of difficulty: the statement and visual representation of TT; the TT itself causes the timetable for task processing; the technology of entering the results of CTP.

b) The degree of mismatching in factual and reference time for solving the TT - dynamic coefficient $D^i_f = \frac{t^i_f}{T_{ni}}$, demonstrates the objectivity of determined indicator of degree of difficulty of the TT - $R_i$.

c) The complex indicator of the degree of confidence of CTP and the probability of guessing the correct solution is the correlation coefficient $K^i_j$ between series of factual $T_{pj}$ and reference time $T_{ni}$ spent on correct result of cognitive processing of TT. The value of $T_{ni}$ is determined after checking the testing of a group of experts [5].

d) The interpretation of the normalized $K^i_j$ ranges may be the following: an individual with high level of the confidence solves the TT at steady pace $(K(t^*, t^i_f) \geq 0,5)$; in the behavior of an individual, who has middle level of CTP confidence, there are “gaps” in the problem domain's assimilation and uncoordinated pace of solving the tasks $(0,3 \leq K(t^*, t^i_f) < 0,5)$; the individual, whose CTP level is low, may try to guess the correct decision $(K(t^*, t^i_f) < 0,3)$.

e) The concept of modes of stability of CTP is a consequence of entering the concept of interpretation of the CBTS and individuals as a dynamic system. In this regard, the interpretation of equilibrium (EM) and periodic (PM) modes of the individual's CTP may be the following [6]: EM corresponds to the situation, which is characterized by in time constancy CTP during the testing session; the PM is characterized by fluctuations in the CTP individual's entropy as a result of changes in the level of complexity of TT.

f) In the author's interpretation the EM of CTP is quantitatively identified by $(K(t^*, t^i_f) \geq 0,5)$ and PM - by $(K(t^*, t^i_f) < 0,5)$.

g) The concept of the CTP phases is defined as a set of functional states of an individual during the testing session: the primary reaction - short-term of reduction of the actual level of confidence and precision of CTP; overcompensation and compensation - gradual improvement and stabilization of indicators of confidence and precision of CTP; sub compensation and decomposition - reduction of actual level of confidence and accuracy of CTP.

h) The concept of the in formativeness level is considered on the basis of quantification of the effectiveness of test performance.

i) The concept of the target level $TL_T = f(U_j, P_h, Z_i)$ is considered on the basis of scaling the TT by: TT forms $U_j$ (from lowest to highest: with only one correct answer; closed form of TT with multiple choice; matching TT; open form of TT with sequence-setting); boundary probability ($P_j$) of guessing the correct solution of TT; cognitive process difficulty levels $iZ$ (from lowest to highest: recognition and presentation; reproductive replay; productive replay).

j) The efficiency of CP testing is increased due to determining the consecutive order of giving TT in accordance with the decrease of their target level [10]. The Expert Block of the Knowledge Base includes the knowledge about subject area and the control knowledge:

a) The Algorithms of TT Quality Analysis:

Heuristic Algorithm of the TT Quality $Qi$ Express Analysis. Presupposes the methodology of stage-by-stage guaranteed acquisition of a complete testing results’ matrix from two incomplete matrices - the results of preliminary and final testing in the framework of one class period [10];

Heuristic Algorithm of Expanded Analysis and of Improving the TT Quality $Qi$. Includes possibility of establishing the fact (1) and assuming the ways of eliminating the “problematic” character of TT. This algorithm is based on entering the indicator of dynamic coefficient $D^i_f$, in accordance with the following rule [6]:

$$\text{if } \text{Low}_{fi} \leq \text{Low}_{R} \text{ and } \text{High}_{fi} \geq \text{High}_{R} \text{ then } PROBLEM_i = -1,$$

$$\text{if } \text{High}_{fi} \leq \text{Low}_{R} \text{ and } \text{Low}_{fi} \geq \text{High}_{R} \text{ then } PROBLEM_i = +1,$$

else $PROBLEM_i = 0$ (1)

where $D^i_f = \{\text{Low}_{R}, \text{High}_{R}\}$ is the boundary percentage of individuals, whose factual time of TT completion does not meet the reference one $(D^i_f \neq 1)$.

b) The Algorithms of Adaptive Sequence of Distributing TT in order of decreasing the target level $TL_T$. This algorithm determines the necessity of transition $\lambda$ to the next TL $(2)$ in the conditions of surpassing the value of the boundary percentage $G_{ni}$ of correct answers to TT as compared to the factual $G_{ni}$ percentage. In the opposite case, this algorithm determines the necessity of terminating the testing procedure[12]:

$$x = \begin{cases} 
0, & \text{if } G^i_f < G^n_i \Rightarrow R_i = R_i - 1 \\
1, & \text{if } G^i_f \geq G^n_i \Rightarrow \text{Stop}
\end{cases}$$

(2)

c) The Algorithm of Cognitive Individual's Profile (CP_PROFILE) obtaining:

- in the author's interpretation CP_PROFILE is a set of specific specifications describing: modes (MODES) and phase (PHAZES) stability of CP; in formativeness level (IL) of problem-oriented knowledge of individuals; CP_PROFILE= <MODES> & <PHAZES> & <IL>

- via using a statistical series of reference and actual time
of CP of TT: processing transfer function charts for groups of individuals with a stable EM and PM of cognitive processes and individual "pictures" - structure of the time distribution (TD) during the test session and the intensity (high, middle or low frequency of correct answers) within the phase. It helps to identify differences between individual’s behaviors concerning the specificity of CTP.

IV. COMPLETE TESTING ALGORITHM FOR TECHNICAL DIAGNOSTICS OF DISTRIBUTED COMPUTING

This paper proposes a model of the system's knowledge of the cognitive area of learning the basics of technical diagnostics. Generalized model of the field of knowledge and relationship training modules presented in Figure 1. In general scientific sense knowledge area appears limited natural language formed grammar G:G → {T, M, P, H} where T - terminal alphabet, M - full glossary, P - the rule of substitution, N - the start symbol. Language can be broken down into several thematic language groups (sublanguage) in accordance with that of the disciplines. To the terminal symbols (terms) in particular include: element; bond; input; output; message; state of the object; fault; search; detection, etc.

Full language of the theory of diagnosing complex systems is divided into sections: the fault; failure; performance; fault tolerance; testing; "AND-OR" graphs; diagnostics; reliability; probability. Building a theoretical model based on unit area of expertise and learning technology provides three disciplines. As sections of the domain, the corresponding standard deviation units, the following: 1. Probability, 2. Queuing Theory, 3. Reliability Theory, 4. Models area of expertise: 4.1. logical models, 4.2. are the production, 4.3. frame-based, 4.4. ontology model, 4.5. object-oriented, 4.6. special, 4.7. complex, 5. Methods distributed computing processing information, 5.1. multiprocessor systems, 5.2. multi-computer systems, 5.3. cluster systems, 6. Fundamentals of technical diagnostics, 6.1 Mathematical models and methods in the theory of technical diagnostics, 6.2 Methods troubleshooting, 6.2.1 Methodology troubleshooting PB based on the "AND-OR" graphs, 6.3. Patterns of failure detection, 6.3.1. Methodology for determining the expected number of failures, 6.3.2. Method for the detection of single failures, 6.3.3. Complete testing algorithm elements PB, 7. Methods of testing complex systems, 8. Graph Theory In order to represent the structure of the model formalizing the field of knowledge with regard to technical diagnostics in the following form.

Optimize the process of diagnosing for distributed computing system (DCS) using overlapping tests with complete coverage of elements. The theoretical aspects of the problem are the following.

Let the beginning of a M-th step of the verification process carried out by a sequence of tests $H^{(M-1)} = \{h_1, ..., h_{(M-1)}\}$ and the problem reduces to finding a subset of the failed component of $\Omega^{(M-1)}$. (Before the start of the system checked $\Omega^{(0)} = \Omega$. $\Omega^{(0)}$, including all elements of the system, but $H^{(0)}$ does not include any tests ). The search algorithm of failed components are follow [4].

1. Defined values $\tilde{q}_j^{(0)}$ - conditional probability of failure is the j-th element, if the tested set exactly one element failed:

$$\tilde{q}_j^{(0)} = q_j \left( \sum_{i \in \Omega^{(0)}} q_i \right)^{-1}$$

2. For each significant test to calculate the probability of unsuccessful outcome of the tested subset:

$$Q_i^{(0)} = \sum_{j \in \Omega^{(0)} \setminus \Omega^{(1)}} \tilde{q}_j^{(0)}$$

3. For each material test $h_i$ are associated costs $Z_i^{(0)}$ in view of the fact that a test sequence is performed $\sigma^{(0)}$. In general, the costs of conducting the test as $h_i$ can decrease or increase, subject to other tests. (For example can be connected by previous inspections necessary for the test devices, or vice versa, holding previous audits may hinder access to the right parts of the system).

For each test $i$, determined values

$$g_i^{(0)} = Z_i^{(0)} / Q_i^{(0)}$$

4. Selected this test $h_i$, for which a minimum:

5. Applicable test $h_i$:

- If the test succeeds $h_k$, the problem reduces to finding a subset of the failed component $\Omega^{(0)}$; $\Omega^{(0)}$;
- If the test $h_k$ fails, the problem is reduced to finding a subset of the failed component $\Omega^{(0)}$.

In these cases, if the subset consists of a single element, the search failed element ends here.

6. New fixed sequence of tests applied $H^{(1)}$, which contains the previous sequence $H^{(0)}$ and the last applied test $h_i$:

$$H^{(1)} = \{H^{(0)}, h_i\}$$

7. To Subset, starting with test 1, the procedure checks with the corresponding change in the superscript (0) in the index (1). The verification procedure continues as long as claimed in 6, at some step k is formed subset $\Omega^{(1)}$, which consists of a single element.

Procedure described in the application to multi-computer complexity will implement consistent with the development of the verification process. For current calculations and selection of another tests used computer with the necessary software and advance the memorized array of source data (probability of failure, duration of inspections, test specifications).

The same procedure can be done in advance and make usage of the instruction sequence of tests depending on
the results of previous, for example: "if the test \( h_i \) is successful, then continue to test \( h_i \), if the same test \( h_i \) unsuccessful, then to test \( h_j \) » (Figure 2).

![Diagram](image)

Fig. 2 Fragment algorithm of complete testing for DCS

Concretizing the task, when testing DCS chooses to 8 devices (main modules). №1 — LA (line adapter), №2 — controller for internal line devices MCC; №3 — first PC; №4 — second PC; №5 — Linear controller for interfacing of PC; №6 — Analog Input Module; №7 — third PC; №8 — Output of the module of control commands and can be tested within six tests which matrix is shown in Table 1.

Table 1 Matrix of testing

<table>
<thead>
<tr>
<th>Numbers of test</th>
<th>Numbers of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td>2</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td>3</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td>4</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td>5</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td>6</td>
<td>1 1 1 1</td>
</tr>
</tbody>
</table>

Known time costs (in relative terms) to conduct each test:

\( Z_1 = 2.5; \ Z_2 = 2; \ Z_3 = 1.0; \ Z_4 = 1.2; \ Z_5 = 1.5; \ Z_6 = 1.3 \), where in the values \( Z_i \) do not depend on the order of tests.

Empirically established as a priority probability of failure of the above-listed items: \( q_1 = 0.04; q_2 = 0.03; q_3 = 0.01; q_4 = 0.01; q_5 = 0.03; q_6 = 0.02; q_7 = 0.01; q_8 = 0.02. \)

Form the complete test of complex instruction checks the minimum average cost for necessary in this test.

Find the conditional probability of failure for each element:

\[
\tilde{q}_1 = 0.028; \quad \tilde{q}_2 = 0.018; \quad \tilde{q}_3 = 0.005; \quad \tilde{q}_4 = 0.005.
\]

Calculate the magnitude of the probability of unsuccessful outcome \( Q_i^{(0)} \) for each test:

\[
Q_1^{(0)} = \tilde{q}_1; \quad Q_2^{(0)} = \tilde{q}_2 + \tilde{q}_4; \quad Q_3^{(0)} = \tilde{q}_3 + \tilde{q}_5 + \tilde{q}_6 = 0.034; \quad Q_4^{(0)} = \tilde{q}_1 + \tilde{q}_6 + \tilde{q}_8 = 0.049; \quad Q_5^{(0)} = \tilde{q}_1 + \tilde{q}_3 + \tilde{q}_4 + \tilde{q}_5 = 0.055; \quad Q_6^{(0)} = \tilde{q}_5 + \tilde{q}_7 = 0.034.
\]

Next, for each test we find:

\[
g_1^{(0)} = \frac{Z_1}{Q_1^{(0)}} = \frac{2.5}{0.075} = 33.2; \quad g_2^{(0)} = \frac{Z_2}{Q_2^{(0)}} = 72.4; \quad g_3^{(0)} = \frac{Z_3}{Q_3^{(0)}} = 29.8; \quad g_4^{(0)} = \frac{Z_4}{Q_4^{(0)}} = 24; \quad g_5^{(0)} = \frac{Z_5}{Q_5^{(0)}} = 26.8; \quad g_6^{(0)} = \frac{Z_6}{Q_6^{(0)}} = 38.8.
\]

It is seen that the first test should be used \( h_4 \), the value \( g_4^{(0)} \) is the smallest. The test \( h_4 \) can be successful or unsuccessful. Consider first the outcome, i.e. the failed element is among those which were not covered by the test \( h_4 \). In a subset of the \( \Omega^{(2)} = \{2, 3, 4, 5, 7\} \). We calculate for each of the remaining test \( Q_i^{(1)} \):

\[
Q_1^{(1)} = \tilde{q}_3 + \tilde{q}_5 = 0.036; \quad Q_2^{(1)} = \tilde{q}_2 + \tilde{q}_4 + \tilde{q}_7 = 0.028; \quad Q_3^{(1)} = \tilde{q}_3 + \tilde{q}_5 = 0.023; \quad Q_5^{(0)} = \tilde{q}_3 + \tilde{q}_4 = 0.028; \quad Q_6^{(0)} = \tilde{q}_5 + \tilde{q}_7 = 0.023.
\]
And then $g_i^{(1)}$:

$$g_1^{(1)} = 68, 8; \quad g_2^{(1)} = 72, 4; \quad g_3^{(1)} = 43, 7; \quad g_5^{(1)} = 54, 3; \quad g_6^{(1)} = 56, 8. $$

Thus, after a successful test $h_i$ should be carried out test $h_3$. By itself, this test may be, in turn, successful and non-successful. Considering the second possibility, the failed element is in the subset, which is verified test $h_3$ of the elements $\Omega = \{2, 4, 7\}$.

Then:

$$Q_1^{(1)} = \tilde{q}_2 = 0.036; \quad Q_2^{(1)} = \tilde{q}_2 + \tilde{q}_4 + \tilde{q}_7 = 0.028; \quad Q_5^{(0)} = \tilde{q}_4 = 0.028; \quad Q_6^{(0)} = \tilde{q}_7 = 0.023,$$

$$g_1^{(1)} = 68, 8; \quad g_2^{(1)} = 72, 4; \quad g_5^{(1)} = 54, 3; \quad g_6^{(1)} = 56, 8. $$

Value $g_5^{(1)}$ is lower, but successful test $h_5$ will not give useful data, as it does not share many elements into two subsets. We now consider the other branch, i.e. test $h_3$ is unsuccessful, and for a subset of elements $\Omega^{(1)} = \{3, 5\}$ we need to compute $Q_i^{(1)}$, i.e.

The next step - the test $h_4$ is unsuccessful. Repeat the procedure for a subset of $\Omega^{(2)} = \{1, 6, 8\}$.

$$Q_1^{(1)} = \tilde{q}_6 + \tilde{q}_8 = 0.039; \quad Q_3^{(1)} = \tilde{q}_6 = 0.011; \quad Q_5^{(0)} = \tilde{q}_1 = 0.028; \quad Q_6^{(0)} = \tilde{q}_8 = 0.011,$$

And then $g_i^{(1)}$:

$$g_1^{(1)} = 64, 3; \quad g_3^{(1)} = 94, 3; \quad g_5^{(1)} = 53; \quad g_6^{(1)} = 122, 5. $$

Hence, we conclude: if $h_5$ is unsuccessful, then refused the first element. If successful, it will explore $\Omega = \{6, 8\}$.

$$Q_6^{(0)} = \tilde{q}_8 = 0.011,$$

And then $g_i^{(1)}$:

$$g_1^{(1)} = 235, 7; \quad g_3^{(1)} = 94, 3; \quad g_6^{(1)} = 122, 5. $$

Obviously, that has minimal cost test $h_3$, and if it is successful, then the failed element is turn into elements - 8. If not succeed, the element - 6 will be presented. If you want to make a guide with a description of the sequence of inspections, you should fix the resulting sequence only (Figure 3) and return to the stage when the test $h_i$ was performed, but now assume that the test was unsuccessful, i.e. search for the failed element of the subset $\Omega^{(i)} = \{1, 6, 8\}$. The result is a second fragment of test instructions complex, shown in Fig. 4. Such a procedure continues until all the pieces are constructed algorithm complete testing systems to localize the failure to a set of single element. Chart of a complete test for this case is shown in Figure 4.

It should be noted that in the case of testing one element after another, we can get a simple rule for numbering test for finding procedures minimizing search costs failed element. Commutes trick is that from any arbitrary numbering, and the pair permutation tests will only determine to the neighboring finite number of steps to go on with any predetermined sequence of them, including optimal.

![Fig. 3 The first fragment of the algorithm for complete testing of DCS (in the circles - numbers of failed elements)](image-url)
If we could possibly find a useful criterion for comparing two different tests on the effect of their applications on the target function will give us the average search time failed component. Under certain conditions, it is possible to calculate the criterion for each test and then enumerate all the tests in accordance with a monotonic variation of this criterion [7-14].

For an arbitrary numbering objective functional tests

\[ C [\sigma(\Omega)] = z_1 + \tilde{q}_1 C [\sigma(e_1)] + (1 - \tilde{q}_1) C [\sigma(\Omega \setminus e_1)] \quad (3.1) \]

have a specific form:

\[ C [\sigma(\Omega \setminus e_1)] = c_2 + C [\sigma(\Omega \setminus e_1 \cup e_2)] \quad (3.2) \]

where, as e₁-singleton. That is why, which is no longer need to check and

\[ C [\sigma(\Omega \setminus e_1)] = c_2 + C [\sigma(\Omega \setminus e_1 \cup e_2)] \]

Finally we get the formula (3.3).

\[ C = z_1 + \tilde{p}_1 (z_2 + \tilde{p}_2 (z_3 + \tilde{p}_3 (z_4 + ... ))) \quad (3.3) \]

Writing a similar expression for this case when the item numbers k and k + 1 changed the procedure for checking and comparing the values of the total cost for both of these cases. And we find the optimal order, if possible, we need to consider to check the components of responsible numbering elements in accordance with the condition:

\[ \frac{z_1}{q_1} \leq \frac{z_2}{q_2} \leq ... \leq \frac{z_n}{q_n} \]

To be confirmed, the benefits of the proposed method was carried out in the software simulation for different numbers of test - \( N_{h_i} \), providing complete testing of multi-computer complexity. During the simulation of testing DCS, we need to compare the relative time spent on the search for a single failed component to the traditional \( Z_{cyM_i}^{mp} \) and the proposed methodology \( Z_{cyM_i}^{np} \). And it defines the improved performance testing by the formula

\[ \sigma_i = \frac{Z_{cyM_i}^{mp} - Z_{cyM_i}^{np}}{Z_{cyM_i}^{mp}} \]

Simulation results are presented in Table 2 and Figure 6 shows a graphical representation of \( \sigma_i \left( N_{h_i} \right) \).
From the data presented in Table 2 and in Fig. 6, it is clear that depending on the number of tests provide speedup complete testing multi-computer complexity from 12 to 20%. And the result of simulation will show the advantages of the proposed method, which helps to test the full DCS searching by criteria single failure.

V. IMPLEMENTATION OF MODELING FOR CTS

During the development of a cognitive training system, we had been developed to provide forms of screen user interface. Intelligent simulator contains the following types of screen forms are shown in Fig. 7.

The results of application of the developed cognitive training system in the educational process of National Research University of Electronic Technology showed that, depending on the training technology provided by increasing of average achievement in 3-13%, reduction in the average time of a student’s classroom work by 22-33% and the average time spending with the teacher’s monitoring activities at 9-13%, compared with conventional technology.

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Adaptation of CFD Simulation Techniques for Mine Ventilation Problems

Lev Yu. Levin
The Department for Exploration of Mineral Deposits
Perm National Research Polytechnic University
Perm, Russia
aero_lev@mail.ru

Mikhail A. Semin, Yuri A. Klyukin
Aerology and Thermal Physics Department
Mining Institute, Ural Branch of RAS
Perm, Russia
mishkasemin@gmail.com, aero_yuri@mail.ru

Abstract—This paper is about investigation of three-dimensional CFD models acceptability and adaptation for mine ventilation air distribution problems. The main feature of mine ventilation problems is the wall roughness. The wall roughness effects appear on a macro scale and are considered to be predominating in pressure loss and air flow distribution in mine ventilation networks. The classification of wall roughness modeling approaches in existent CFD codes was proposed. A turbulent flow through mine working conduit is considered. A set of numerical computations for arbitrary wall roughness approaches is presented. Solution convergence analysis for different sets of inflow and outflow boundary conditions is considered. Also the comparison with classical formulas for arbitrary mine working pressure loss determination in mine ventilation networks was accomplished.

Keywords—mine ventilation, computational fluid dynamics, wall roughness, standard k-epsilon turbulence model, permissible boundary conditions, pressure loss, air resistance coefficient.

I. INTRODUCTION

In the last years computer simulation became the most powerful tool in theoretical analysis of complex physical systems in a variety of engineering areas. Mine ventilation is not exclusion: many ventilation problems require determination of three-dimensional airflow fields in order to predict correct air flow and pressure distribution in mine workings, to model emergency response ventilation due to fire, to model gaseous and particulate pollutants dilution and removal [1, 2].

Existent mathematical models of three-dimensional airflow in CFD codes are primary developed for flow near sufficiently smooth surfaces (turbine blades, airplanes, airfoils). However, the main feature of mine ventilation problems is the macro scale wall roughness. The wall roughness effects appear on a macro scale and are considered to be predominating in pressure loss and air flow distribution in mine ventilation networks [3, 4].

For the major part of engineering problems inflow and outflow boundary conditions are most conveniently given as a velocity and temperature on inlet areas and free surface with known pressure and zero gradients of velocity and temperature on outlet areas. At the same time boundary conditions formulation in mine ventilation problems is most commonly untypical for CFD methods. For example, investigation of mine ventilation shaft and channel interface requires assignment of velocity on outlet area and pressure on inlet areas. These boundary conditions are not consistent in the context of finite volume methods [5, 6, 7].

Also mine ventilation problems imply computational domain, which is essentially prolonged (mine workings total length \(L\) ratio \(d/L\ll0.1\)). It has negative influence on speed of solution convergence [8].

Above-noted factors provide difficulties for CFD simulation of mine ventilation problems and denote the necessity of improvement and adaptation of CFD-simulation techniques for mine ventilation problems.

II. CLASSIFICATION OF WALL ROUGHNESS MODELING APPROACHES

The problem of wall roughness requires primarily determination of efficient approach for wall roughness modeling. For that purpose the classification of wall roughness modeling approaches was proposed (scheme 1). The variety of methods can be divided into two major groups — explicit wall roughness analysis and implicit wall roughness analysis.

![Scheme 1. Classification of Wall Roughness Modeling Approaches](image)

In case of explicit analysis, wall roughness can be determined using periodic roughness profile of equal height, frequency and form. Another method of this group is generation of random inhomogeneity on wall surface with...
constant integral parameters of roughness height \( h \) and roughness frequency \( \omega \). In this case, the necessary conditions of consistent and stable solution is to accomplish a set of numerical experiments for various generated wall roughness shapes in order to get independent from random factors solution.

Implicit analysis means artificial technique when mathematical equations are modified by adding or substitution of new component representing wall roughness. The computational domain stays fully smooth. In spite of artificiality this approach allows derivation consistent pressure loss and air flow distribution in mine workings system using minimal set of additional parameters [10,11].

The most common approach for implicit wall roughness modeling is modification of law-of-the-wall function for velocity by distortion of curve slope or by its translation, accordingly to [12]. The alternative approach is modification of other wall boundary conditions, for example \( k \) and \( \epsilon \) values. This approach is attached to certain turbulence model and is less suitable.

III. PROBLEM FORMULATION

Next step of presented investigation was consideration of the fully-developed turbulent flow in straight cylindrical channel (mine working). The channel was defined by a set of geometric properties, such as length \( L \), cross section area \( S \), constant wall roughness described in terms of its height \( h \) and frequency \( \omega \). For determination of flow turbulent properties standard \( k-\epsilon \) turbulence model is used [10,11,13,14]. On inlet area uniform normal turbulence model is used [10,15]. A second order schemes for spatial discretization and SIMPLE algorithm for pressure-velocity coupling was used.

The discretization of described mathematical model using finite element method and further numerical solution was achieved using ANSYS Fluent CFD software. The SIMPLE algorithm for pressure-velocity coupling was used [10,15]. A second order schemes for spatial discretization were used.

In order to get mesh-independent solution, a set of numerical calculations for various meshes was accomplished.

IV. NUMERICAL SIMULATION

The correctness of the numerical calculation results largely depends on boundary conditions. For this reason pressure drop was calculated between two cross-sections taken over a distance from inlet and outlet boundary areas. It allows us to exclude influence of uncertain uniform boundary conditions on calculating pressure drop. Distances \( L_1 \) and \( L_2 \) (Fig. 1) were selected according to convergence estimation for pressure drop in the channel.

Implicit analysis of wall roughness requires the law-of-the-wall function for tangential velocity in boundary layer modified for roughness [4].

\[
U^* = \frac{1}{\kappa} \ln \left( E_y^* \right) - \frac{1}{\kappa} \ln \left( 1 + C_{SK}^+ \right),
\]

where

- \( U^* \) — dimensionless tangential velocity,
- \( y^* \) — dimensionless coordinate normal to wall boundary,
- \( E = 9.793 \) — empirical constant,
- \( \kappa \) — von Carman constant,
- \( C_S \) — roughness form coefficient,
- \( K_S^+ = \frac{\rho \cdot u^* \cdot K_S}{\nu} \) — dimensionless roughness height,
- \( K_S \) — model physical roughness height,
- \( \nu \) — kinematic viscosity,
- \( u^* \) — Schlichting dynamic velocity [12].

Results of numerical computations using implicit approach are given on Fig. 2.

For the explicit wall roughness modeling we use several types of roughness profiles with equivalent roughness height and frequency: 1 — sine-shaped profile, 2 — sand grain roughness (sphere packing wall surface), 3 — jogged line profile, 4 — shoulder. Results of numerical computations are given on Fig. 3 — 4.

![Fig. 1. Pressure loss calculation technique](image1)

**Fig. 1. Pressure loss calculation technique**

The correctness of the numerical calculation results largely depends on boundary conditions. For this reason pressure drop was calculated between two cross-sections taken over a distance from inlet and outlet boundary areas. It allows us to exclude influence of uncertain uniform boundary conditions on calculating pressure drop. Distances \( L_1 \) and \( L_2 \) (Fig. 1) were selected according to convergence estimation for pressure drop in the channel.

Implicit analysis of wall roughness requires the law-of-the-wall function for tangential velocity in boundary layer modified for roughness [4].
In addition, total mass flow rate inflow boundary conditions were investigated. In this case speed of solution convergence has small difference from velocity inflow boundary condition.

In all described types of boundary conditions similar solution for pressure loss and mass flow rate was achieved. However, in case of more complex computational domains including mine working interfaces the chosen type of boundary conditions has significant influence on results. For example, consideration of ventilation shaft and channel interface air distribution problem gives different solution for different types on inflow and outflow boundary conditions [2, 10]. Air distribution analysis without thermal processes consideration has shown that the mismatch is less than 15%.

Results of wall roughness for channel on Fig. 1 are presented on Fig. 3 — 5. The analysis of pressure loss dependence due to roughness was accomplished in dimensionless units $\Delta Eu$ and $K_S^{-}\pm$. Here $\Delta Eu$ is Euler number variation ($Eu = p/\rho U^2$), which can be interpreted as dimensionless pressure loss.

![Figure 3](image3.png)

**Figure 3.** Dimensionless Pressure Loss as a Function of Dimensionless Height $K_S^{-}$ in Case of Implicit Roughness Analysis

![Figure 4](image4.png)

**Figure 4.** Dimensionless Pressure Loss as a Function of Roughness Height in Case of Explicit Roughness Analysis

The comparison with classical formulas for arbitrary mine working pressure loss determination in mine ventilation networks was accomplished [3, 4].

For concrete mine workings with obstruction-free flow area air resistance coefficient $\alpha$ can be calculated as [3]

$$\alpha \cdot 10^4 = \frac{150}{1.74 + 2\log \frac{R}{h}}$$

(2)

Here $R$ is mine working radius.

From (2) we can calculate dimensionless pressure loss using formula

$$\Delta Eu = \frac{\Delta p}{\rho V^2} = \frac{\rho L P}{\rho S} = \frac{150}{1.74 + 2\log \frac{D}{2d_0}} \frac{L P}{\rho S},$$

(3)

where $L$, $P$ and $S$ are the length, the perimeter and the square of mine working.

Formula (3) has the same slope as curve $\Delta Eu - K_S^{-}$ in case of implicit approach. Other empirical formulas for air resistance coefficients calculations gives a similar slope as (2).

In addition, the curve $\Delta Eu - K_S^{-}$ has a slope, which sufficiently differs from curves $\Delta Eu - h$ and $\Delta Eu - \omega$ in case of explicit approach. A variety of parameters, which should be determined for explicit model, provides some difficulties for analysis. It means necessity of additional investigations for determination of right proportions between explicit approach parameters in order to get a solution correlated with (3) and Fig. 3. It makes explicit approach less suitable for use.

The relationship between wall function roughness height $K_S^{-}$ and air resistance coefficient $\alpha$ was found.

$$K_S = 4.49 \frac{\nu}{C_H^{1/4}k_0^{1/2}C_S} \left[ 0.342 \exp \left( \frac{3472 \rho_0 \alpha}{\rho} \right) - 1 \right],$$

(4)

where

- $C_H = 0.09$ — k-epsilon turbulence model parameter;
- $k_0$ — inlet turbulent kinetic energy value for k-epsilon turbulence model,
$C_S = 0.5$ — wall roughness shape parameter,

$\rho_0 = 1.225 \text{ kg/m}^3$ — density for normal conditions.

For $\alpha > 0.0017$ we have a physically abnormal values of parameter $K_S$. It is probably caused by micro scale character of expression (3), which leads to physical divergence of roughness height value $K_S$ for large air resistance coefficients $\alpha$. Nevertheless $K_S$ parameter can represent some artificial roughness height with no certain physical meaning and we can obtain some unequivocal $K_S$ value for arbitrary $\alpha > 0.0003$.

V. CONCLUSIONS

The classification of wall roughness modeling approaches in existent CFD methods was proposed. A turbulent flow through mine working conduit is considered. A set of numerical computations for arbitrary wall roughness approaches is presented. Solution convergence analysis for different sets of inflow and outflow boundary conditions is considered. The comparison between achieved “pressure loss — roughness parameters” dependences is carried out. Also the comparison with classical formulas for arbitrary mine working pressure loss determination in mine ventilation networks was accomplished. The approximated analytical formula for roughness height $K_S$ determination using air resistance coefficient $\alpha$ was proposed. This formula establishes the possibility in principle for mine working air flow simulation using wall functions modified for roughness in standard k-epsilon turbulence model.

REFERENCES

Model of Dielectric Polarization in Antiferroelectric and Solid Electrolyte 
$\text{Na}_3\text{Cr}_2(\text{PO}_4)_3$ 

Nogay A.S. 1, Kahlbekova U. M. 1, Nogay A.A. 2

1 Kazakh of Agrotechnical University, Astana, Kazakhstan
2 Euroazian National University, Astana, Kazakhstan
e-mail: nogay06@mail.ru

Abstract— In this article ion-conducting and dielectric properties of a crystal are studied $\text{Na}_3\text{Cr}_2(\text{PO}_4)_3$, from the family NASICON. The parameters of processes of ion conduction, and the relaxation of polarization are determined, as well as the analysis of dielectric properties in this connection. A model explaining the phenomenon of high conductivity, and the relaxation of polarization is proposed in $\alpha'$ – phase $\text{Na}_3\text{Cr}_2(\text{PO}_4)_3$.

Keywords— conductivity; dielectrics; relaxation; polarization; crystal; dielectric losses angle; sodium; phosphate; superionic; conductor; antiferroelectric.

I. INTRODUCTION

One of the interesting and practically important manifestations of poor communication between cationic and anionic subsystems of the crystals is the possibility of occurrence of this super ionic conductivity. Sodium phosphate - chromium has as of dipole-ordered ($\alpha$ - and $\alpha'$ - phases), so sure ionic States ($\beta$, $\gamma$ - phases) depending on the degree of thermal influence from the outside [1-3]. The substance, possessing the polar and ion-conducting properties is interesting from the practical point of view, because they can be used as structural materials in modern electronics. For purposeful search of new structural materials for the elucidation of the nature of the dipole ordering and superionic state samples of the family NASICON.

II. EXPERIMENT

In this context, is an important determination of the regularities of conducting and dielectric properties in sodium phosphate-chromium and in the group of isostructural him analogues.

The purpose of the present work is to study conducting and dielectric properties of sodium phosphate-chromium in antiferroelectric - the superionic conductor $\text{Na}_3\text{Cr}_2(\text{PO}_4)_3$ from a structural type NASICON. For realization of this goal single crystal from the melt of charge by solid-phase synthesis were received. The study of the structure and single phase of the single-crystal samples $\text{Na}_3\text{Cr}_2(\text{PO}_4)_3$ x-ray diffraction methods with the help of diffractometers DRON-3 and DRON-1 have spent. Crystals had the shape of a rectangle the size of $5\times2\times1$ mm the crystal were marked graphite electrodes on both sides. The definition of the ionic conductivity of the samples was carried out by analysis of the frequency dependence of the impedance, obtained with the help of impedance meter BM-507 in the interval of temperatures 293 – 573 K and in the frequency range of 5 Hz -500kHz. It is also the dielectric properties of the investigated crystals determined by. The monocristalline samples caused by the burning palladium paste metal electrodes, which were seen as the ideal blocking. Structural studies of single-crystal $\alpha$-$\text{Na}_3\text{Cr}_2(\text{PO}_4)_3$, carried out by the method of Wiesenberger, show that the period of identity $l_0$ along three axes that is the intersection of the main facets pseudo cubic cut is 12.6 A, that is consistent with the literature data on the pseudo cubic the crystalline structure. Crystals $\alpha$-$\text{Na}_3\text{Cr}_2(\text{PO}_4)_3$ have pseudohombohedral unit cell with the following parameters: $a = 8,65A; b = 14,969 A; c = 8,748 A; \gamma = 124,53^\circ$. On radiographs of oscillation of the crystal were found weak superstructure reflexes, indicating a doubling of the period of identity: $l = 2l_0 = 25,2 A$, that confirms the antiferroelectric nature of the dipole ordering of in $\alpha$-$\text{Na}_3\text{Cr}_2(\text{PO}_4)_3$. According to [3] in $\alpha'$-phase of sodium phosphate-chromium superstructure disappears, that corresponds about disappearance of a dipole ordering of the phase transition $\alpha \rightarrow \alpha'$.

This process meets a small, but a clear anomaly in the temperature dependence of the conductivity of $\lg \sigma (1/T)$ (fig. 1).

Nevertheless, according to the experimental data, one can conclude that the transition from polymorphic status $\alpha$ into $\alpha'$, is not connected with a radical restructuring, and may be caused by only a small increase in the concentration of mobile cations of sodium, as a result of a partial withdrawal of monoclinic distortion of rhombohedral crystalline skeleton $\{\text{Cr}_2(\text{PO}_4)_3\}^\infty$. Temperature phase transitions in figure 1 are marked by dotted lines. As it follows from the experimental results, the phase transition from one state to another is of a diffuse character, since the transition from one line of the site to another depending on the $\ln \sigma (1/T)$ expressed, not "step", and an inclined line. In General, the temperature dependence of electrical conductivity in the range of one phase can be described by the relation of the form:

$$\sigma = A_i \sum_{\gamma} \exp(-\Delta E_i/kT),$$

(1)

where $\Delta E_i$ – activation energy, $k$- Boltzmann constant, T- temperature; $A_i$- constant coefficients characterizing the phase state.
From fig. 2 it is visible that dielectric permeability of a crystal decrease with frequency increase, and it is sharper in superionic phases, than in the dielectric. Thus frequency dependences of a tangent of angle of indicate course of relaxation processes of polarization in dielectric \(\alpha^+\) and superionic \(\beta, \gamma\) phases. Research of dielectric characteristics of a crystal \(\text{Na}_3\text{Cr}_2(\text{PO}_4)_3\) fig. 2, a) and b) specify that the dielectric \(\alpha\)-phase is dipole ordered and all dipoles are in the condensed condition.

### Table 1 Parameters of the ionic conductivity and the temperature of phase transition for the crystal \(\text{Na}_3\text{Cr}_2(\text{PO}_4)_3\).

<table>
<thead>
<tr>
<th>Temperature of transition, K</th>
<th>Ionic conductivity (\sigma, \text{Ohm}^{-1}\cdot\text{cm}^{-1})</th>
<th>Energy of activation (\Delta E, \text{eV})</th>
<th>The temperature dependence of (\varepsilon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha)</td>
<td>(4 \times 10^{-8})</td>
<td>0,62</td>
<td>(T=348)</td>
</tr>
<tr>
<td>(\alpha')</td>
<td>(7,9 \times 10^{-6})</td>
<td>0,92</td>
<td>(T=411)</td>
</tr>
<tr>
<td>(\beta)</td>
<td>(1,9 \times 10^{-4})</td>
<td>0,79</td>
<td>(T=439)</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>(3,63 \times 10^{-3})</td>
<td>0,39</td>
<td></td>
</tr>
</tbody>
</table>

For research of dielectric properties of a crystal \(\text{Na}_3\text{Cr}_2(\text{PO}_4)_3\), frequency dependences of dielectric permeability and a tangent of angle of dielectric losses were measured and constructed at the various fixed temperatures (fig. 2 a, b).

As can be seen from the presented data, low-temperature \(\alpha\)- and \(\alpha'\)-phase connection \(\text{Na}_3\text{Cr}_2(\text{PO}_4)_3\) are dielectric and are characterized by low values of the conductivity and high values of the activation energy. It should be noted that the temperature dependence of the dielectric permittivity is found only phase transition \(\alpha'\rightarrow\beta\) of dielectric \(\alpha'^{\prime}\)-phase into superionic \(\beta\)-phase, presented in the form of step.

Research of dielectric properties of single-crystal samples are shown in figure 2 (a, b) in the form of frequency dependences of dielectric permeability \(\varepsilon(\omega)\) and tangent of the dielectric losses angle \(\text{tg}\delta(\omega)\) accordingly.

It should be noted that the study of the interaction of electromagnetic fields with matter is very useful in the use of the macroscopic theory [3], although this theory gives only a phenomenological description of the phenomena in the dielectric. However, this theory is advisable to use in the analysis of a dielectric state sodium phosphate-chromium. In this case, the material should be viewed as a two-terminal network, consisting of elements of circuits with the concentrated parameters. To determine how well the equivalent circuit corresponds to single crystal sample \(\text{Na}_3\text{Cr}_2(\text{PO}_4)_3\), it is necessary to conduct the calculation of the frequency response of this circuit and compare it with the really measured characteristic, shown in Fig.3 (a). By analyzing the possible combinations of electric RC circuit was installed equivalent circuit shown in Fig.3 (b) the best corresponding to the tested material.

To conduct a comparative analysis frequency response of the equivalent circuit in Open MVL Shell has its own numerical library in which were used accordance with the following expression was built [4]:

\[
\text{tg}\delta = \frac{\omega \tau_2}{1 + \frac{C_1}{C_2} (1 + \omega^2 \tau_2^2)},
\]

where \(C_1\) and \(C_2\) accordingly capacities of the first and second capacitors; \(\tau_2\) - the time of relaxation, numerically equal to the product of the resistance \(R_2\) and capacity \(C_2\); \(\omega\) - frequency of the electromagnetic field.

The equivalent circuit shown in fig. 3 b has paraemtry chain that match a dielectric \(\alpha\)-phase \(\text{Na}_3\text{Cr}_2(\text{PO}_4)_3\): \(C_1 = 1,0 \times 10^{-6}\); \(C_2 = 9,2 \times 10^{-6}\); \(R_3 = 3,0 \times 3\); \(\tau_2 = 2,78 \times 10^{-5}\) (at \(\alpha\neq 0\), \(R_2C_2\) the chain is replaced by a chain depicted bar 2- curve);
\[
\tan \delta = \frac{(\varepsilon_0 - \varepsilon_\infty)}{(\varepsilon_0 - \varepsilon_1 \omega^2 \tau^2)}
\]

where \( \tau \) - the time of relaxation of the dipole in a dielectric medium under the influence of the external field, and the static and optical dielectric permeability, respectively; \( \sigma \) - ion conductivity.

However, the differences between the experimental and the calculated frequency characteristic of the tangent of the dielectric losses angle (pic.1) indicates that the parameters of the relaxation spectrum blurred, and the data obtained for the dispersion does not correspond to the semi-circle in the diagram Cole - Cole. The relationship between the real (\( \varepsilon' \)) and imaginary (\( \varepsilon'' \)) part of the dielectric permittivity for \( \alpha', \beta, \gamma \) - phase sodium phosphate-chromium are shown in Fig. 4. In case of \( \alpha' \) – phase, represented on the 3 fig. 4 Diagram of the Cole - Cole has the form of semi-circle center (0 0) of which is lower the x-axis (curve1) for super ion phases \( \beta \) and \( \gamma \)-Na\textsubscript{3}Cr\textsubscript{2}(PO\textsubscript{4})\textsubscript{3} the experimental points just fall on half of a circle whose center is located on the x-axis (curves 2 and 3). For a description of the dispersion of the complex permittivity (\( \varepsilon' \)) of the dielectric, the spectrum of which is blurred it is advisable to use empirical equation Cole - Cole [5]:

\[
\varepsilon'' = \frac{\varepsilon_\infty + (\varepsilon_0 - \varepsilon_\infty)}{[1 - (\omega \tau)^{\alpha}]},
\]

where \( \alpha \) - distribution coefficient, which characterizes the distribution of relaxation times of the dipoles.
the transition into superionic β and γ - phase distribution coefficients are equal to zero, which testifies to the same relaxation time for all the particles. Taking into account equation (3), which is more versatile for descriptions of the process of dispersion of dielectric permittivity, the equivalent circuit for the dielectric α' phase sodium phosphate - chromium shown in figure 3 (a) corresponds to a more General circuit (pic.3 (b)), in which the resistance is replaced by an impedance. Since in the α'-Na₃Cr₂(PO₄)₃ set the set of relaxation times, the determination of these parameters is difficult. However, the determination of the average value of the relaxation time of the particles is quite possible, because the known high tangent of the dielectric losses angle for the frequency dependence tgd (tgα) α' - phase sodium phosphate - chromium. By constructing the dependence of lgαvill(1/T) you can determine the activation energy (E) and the average relaxation time (τ) at zero temperature for this phase. Because the value is the time constant that characterizes the inertia of the system of dipoles, the establishing of equilibrium state due to thermal motion of dipoles and therefore is of a probabilistic nature, so the relaxation time can be determined according to [5] using the Boltzmann formula:

$$\tau = \frac{1}{2} \tau \exp\left(\frac{-E}{kT}\right),$$

(5)

where ν - is the frequency of oscillation of the dipoles; \(\exp\left(\frac{-E}{kT}\right)\) reflects the likelihood overcome the dipole part of the potential barrier height E, separating the dipoles in their steady state; k - the Boltzmann constant. Since the relaxation polarization is evident single-crystal samples only in α' -phase Na₃Cr₂(PO₄)₃ (Fig.1), and so the parameters of the process were defined in detail the above-mentioned methods only for this phase, and are given in the table.

<table>
<thead>
<tr>
<th>Na₃Cr₂(PO₄)₃</th>
<th>Phases</th>
<th>α</th>
<th>α'</th>
<th>β</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Symmetry</td>
<td>P2₁/n</td>
<td>P2₁/n</td>
<td>R3C</td>
<td>R3C</td>
<td></td>
</tr>
<tr>
<td>distribution coefficient (α₀)</td>
<td>-</td>
<td>0,062</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>ν₀</td>
<td>-</td>
<td>120</td>
<td>280</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>νₐ</td>
<td>-</td>
<td>3200</td>
<td>1880</td>
<td>1600</td>
<td></td>
</tr>
<tr>
<td>Activation energy (E), eV</td>
<td>-</td>
<td>0,393</td>
<td>0,262</td>
<td>0,213</td>
<td></td>
</tr>
<tr>
<td>Relaxation time (τ), c</td>
<td>-</td>
<td>3,5 10⁻⁵</td>
<td>1,3 10⁻⁷</td>
<td>1,7 10⁻⁹</td>
<td></td>
</tr>
<tr>
<td>splitting positions Na₂</td>
<td>2,17</td>
<td>2,21</td>
<td>-</td>
<td>2,26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0,83;</td>
<td>0,84;1,3</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,33</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Parameters of the process of relaxation for β and γ - phases these compounds were determined by analysis of the frequency dependence of tangent of the dielectric losses angle. According to the structural data [3], and experimental characteristics tgd (lgα), shown in figure 2, we can conclude that dipole ordering of cations of sodium in the α - phase Na₃Cr₂(PO₄)₃ is a system of related, slow-moving dipoles in the crystalline skeleton (P₂₁/n). This presentation is consistent with the fact of the doubling of the volume of the elementary cell (established by x-ray diffraction methods), and splitting of sodium positions. At this point the stability of dielectric parameters ε and tgd at low temperatures in the entire frequency range. As it follows from the structural data α' - phase is monoclinic though there is a partial disorder and redistribution of part of the ions in the split sodium positions. With these changes, you can associate observed in figure 1 relaxing polarization of sodium ions and the fact of displacement of the center of a circle below the x-axis in the diagram of the Cole – Cole (Fig. 3). As in the case of close isostructural analogue Na₃Sc₂(PO₄)₃, the specificity of the cations of sodium in the cavities of the crystalline skeleton sodium phosphate-chrome allows to speak about statistical sodiumdipoles. However, given the superstructure reflexes can talk about offsets statistical sodium dipoles. Thus, the process of the relaxation of polarization caused by the movement of sodium ions in the crystal frame, equivalent to turnover voltage offsets statistical sodium dipoles through the potential barrier E = 0,393 eV in the meantime τ = 3,5 10⁻⁵ c. With the consideration of the submission of such interaction of electric dipoles in this phase of the connection is quite acceptable equivalent circuit of the sample, shown in figure 2, sinesishting capacitor C₁ both times, and reflects the interaction of the relaxation of particles.

In this case, for a discussion of the model of the relaxation process it is advisable to make standard equation of the total value of the dipole moment of dielectric, which can be written in the form [6]:

$$\exp(-\Omega_0 t) \frac{d}{dt} \exp(-\Omega t) f(t) = 0,$$

(6)

where t - time, f (t) - normalization the macroscopic function relaxation of some physical quantity Ω₀ - constant speed of relaxation, describing interaction of the macroscopic dipole with thermostat

According to [6], function of relaxation f (t) can be expressed as:

$$f(t) = P(t)P(0),$$

(7)

where P (t) - total dipole moment of a dielectric in an arbitrary moment of time τ; P (0) – the initial total dipole moment of a dielectric. System, for which relaxation at the micro-level can be described by the equation (4) applies the model of deep potential well with the two provisions balance or Flarikh’s relaxation (pic. 4 (a)). Based on this model and the model proposed for dielectric α-phase Na₃Sc₂(PO₄)₃, as well as the data on the study of conductive and dielectric properties and structural parameters of the α - phase Na₃Cr₂(PO₄)₃ can be a model of the potential relief along the channel conductivity for this phase of the (Fig.4. (b)).
In this figure schematically shows the statistical distribution of cations of sodium with the formation of compensated dipole due to the doubling of the volume of the elementary cell in the In B cavity regular crystalline skeleton. The transition in β - phase is accompanied by the partial destruction of statistical sodium dipoles, as evidenced by the high ion conductivity [1], dielectric and structural parameters.

![Diagram](image)

Fig. 4 diagrammatic representation. a) a potential well with the two provisions balance, b) one-dimensional model of the potential relief of the α' - phase Na\textsubscript{2}Cr\textsubscript{2}(PO\textsubscript{4})\textsubscript{3}.

Dark circles in the In B cavity indicate a no equilibrium split sodium positions, which are equivalent to the statistical sodium dipoles. The arrows point to the education statistical sodium dipoles (in this case offsets dipoles). Note that β-phases of this connection has the same structure as β - phase Na\textsubscript{2}Sc\textsubscript{2}(PO\textsubscript{4})\textsubscript{3}, that it clearly follows from the phase diagram of the system Na\textsubscript{2}Sc\textsubscript{2}(PO\textsubscript{4})\textsubscript{3} - Na\textsubscript{2}Cr\textsubscript{2}(PO\textsubscript{4})\textsubscript{3}. All this is perfectly consistent with the fact that relaxations are only «free» sodium ions (distribution coefficient is equal to zero for this phase). High coefficient of dielectric losses for this phase is shifted into the region of high frequencies and outside the frequency range of our research for single-crystal samples. Observed in figure 1 (b) the “tails” of the curves 7 and 8 the coefficient of dielectric losses at frequency dependence tgδ (lgo) and curves 6, 7 on pic.1 (a) characterizes the process of the relaxation of polarization of sodium ions in a crystal frame of the β - phase with lower potential barrier. In addition, the dielectric permittivity for β-Na\textsubscript{2}Cr\textsubscript{2}(PO\textsubscript{4})\textsubscript{3} at zero and infinite frequency, reflecting the relationship ε  и ε through the diagram Cole - Cole are characterized by a smaller circle (curve 2 on the fig.3), than in α ’ - phase of the connection. Peculiarities for β - phase Na\textsubscript{2}Cr\textsubscript{2}(PO\textsubscript{4})\textsubscript{3} are manifested even more during the transition to rhombohedral - phase (3 RC), driven by higher symmetry of crystalline skeleton and full of disordering of offsets statistical sodium dipoles. High mobility and uniform distribution of sodium ions in A- and B - of rhombohedral cavities crystalline skeleton creates all the conditions for the occurrence of rapid polarization processes in the field of high frequencies. The same conclusion is confirmed by the high ionic conductivity in β - and γ - phases.

IV CONCLUSION

Thus, we can conclude that Na\textsubscript{2}Cr\textsubscript{2}(PO\textsubscript{4})\textsubscript{3} from a structural type called NASICON when monoclinic distortions of crystalline skeleton form uncompensated statistical dipoles, due to deformation of cavities and In - cavities crystalline skeleton. And in the case of offsets statistical sodium dipoles more applicable model of the relaxation process of Debye, and the case of uncompensated sodium dipoles model of Flerikh’s, taking into account the availability of a range of times of relaxation of particles.

However, due to the elasticity of the crystalline frame, which manifests itself in a phase transitions, structural distortions completely removed while the destruction of the statistical sodium dipoles. For this phase is characterized by the implementation of rapid polarization processes, well described Debye model.

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An Algorithm of Variable Order and Step, Based on Stages of the Dormand-Prince Method

Eugeny A. Novikov
Institute of Computational Modeling SB RAS
ICM SB RAS
Krasnoyarsk, Russia
novikov@icm.krasn.ru

Anton E. Novikov
Siberian Federal University
SFU
Krasnoyarsk, Russia
aenovikov@bk.ru

Abstract — An inequality for stability control for the Dormand-Prince method of eighth order of accuracy is constructed. A first-order method with an enhanced stability region, based on first seven stages is constructed. Numerical results confirming increase of efficiency due to using an alternating order are given.

Keywords — stiff system; explicit methods; accuracy and stability control; algorithm of variable order and step

I. INTRODUCTION

In solving stiff problems of high dimension necessity of using algorithms, based on explicit numerical schemes arises [1-2]. As a rule, integration algorithms, based on implicit or semi-explicit methods use decomposition of the Jacobi matrix [3]. In this case, it is a separate time consuming task. In this situation, if stiffness of a problem allows to get an approximation of solution in reasonable time, it is preferable to apply algorithms, based on explicit formulas.

Usually, an algorithm for control of an integration step is based on accuracy control of a numerical scheme. It is natural, because the main criterion is accuracy of a solution. However, applying integration algorithms, based on explicit formulas, for solution of stiff problems provides to loss of efficiency and reliability. That's because a contradiction between accuracy and stability on an settling area of a solution leads to a great number of recomputed solutions, and a step is chosen much less than a maximum allowable. One can avoid it by using additional stability control of a numerical scheme [1].

This paper provides several results. An inequality for stability control for the eighth order Dormand-Prince method is constructed. Based on first seven stages, a first order method with an extended area of stability is constructed. An algorithm of an alternating order and step is formulated. Numerical results, confirming increase of efficiency due to using of an alternating order are given.

II. THE DORMAND-PRINCE METHOD

We consider the Cauchy problem for a system of ordinary differential equations

\[ y' = f(t, y), \quad y(t_0) = y_0, \quad t_0 \leq t \leq t_k, \]  

where \( y \) and \( f \) are \( N \)-dimensional real vector-functions, \( t \) is an independent variable. For solution of (1) we use the explicit Runge-Kutta formulas

\[ y_{n+1} = y_n + \sum_{j=1}^{13} p_i k_j, \quad k_j = hf \left( t_n + \alpha_j h, y_n + \sum_{i=1}^7 \beta_{ij} k_i \right), \]

where \( h \) is an integration step. Coefficients \( \alpha_j \) and \( \beta_{ij} \) are known [2] and are not given here because of its cumbersomeness. With coefficients

\[
\begin{align*}
P_{51} &= 14005451, \quad P_{52} = P_{53} = P_{64} = P_{85} = 0, \\
P_{66} &= 59238493, \quad P_{67} = 181606767, \quad P_{77} = 578867731, \\
P_{88} &= 1068277825, \quad P_{89} = 1041891430, \quad P_{99} = 1371345329, \\
P_{h,50} &= 797845732, \quad P_{h,51} = 118820643, \\
P_{h,10} &= 760417239, \quad P_{h,11} = 751138087, \\
P_{h,12} &= 528747749, \\
P_{h,13} &= \frac{1}{4} \frac{1}{4} 2220607170.
\end{align*}
\]

the scheme (2) has an eighth order of accuracy.

III. CONTROL OF ACCURACY AND STABILITY

Numerical formula (2) with coefficients

\[
\begin{align*}
P_{71} &= 13451932, \quad P_{72} = P_{73} = P_{74} = P_{75} = P_{7,13} = 0, \\
P_{76} &= 808719846, \quad P_{79} = 1757004468, \\
P_{78} &= 97600145, \quad P_{76} = 564519321, \\
P_{73} &= 656045339, \quad P_{78} = 3867574721, \\
P_{79} &= 265891186, \quad P_{79} = 1518517206, \\
P_{h,10} &= 465885868, \quad P_{h,11} = \frac{5}{4} 232736535, \\
P_{h,12} &= 6677516719, \quad P_{h,12} = \frac{2}{4} 45.
\end{align*}
\]

has a seventh order. Then for accuracy control of an 8th order scheme can be used an estimation of error

\[ \delta_s = \sum_{j=1}^{13} (p_{ij} - p_{ij}) k_j. \]

Therefore, the inequality \( || \delta || \leq \varepsilon \) is applied for choosing of an integration step, where \( || \cdot || \) is a some norm in \( R^N \) and \( \varepsilon \) is required accuracy of calculations. Taking into account the
relation $\delta_{t}=O(h^{3})$, an accuracy step $h^{ac}$ is chosen by formula $h^{ac}=qh$, where the value $q$ is calculated from an equation $h^{3}|\delta_{t}|=c$. If $q<1$ a solution is recomputed (recovered) with a step $h$ which is equal $qh$. Otherwise, an approximate solution is calculated and a predicted step is set equal to $qh$. The inequality $|\delta_{t}|\leq c$ works well in solving a lot of practical problems and is used below. In the following, we will denote the algorithm of an alternating step, based on the scheme (2) with the inequality for accuracy control $|\delta_{t}|\leq c$ by DP78.

Let’s construct an inequality for stability control of the scheme (2). For this purpose, let’s apply it for solution of a linear problem $y'=Ay$ with a constant matrix $A$. First three stages $k_{1}, k_{2}$ and $k_{3}$ of the scheme (2), applied to this problem are given by

$$k_{1} = Xy_{s}, \; k_{2} = \left( X + \frac{1}{12} X^{2} + \frac{1}{288} X^{3} \right)y_{s},$$

where $X=hA$. It is not too difficult to see that relations

$$8 \cdot (2k_{1} - 3k_{2} + k_{3}) = \frac{1}{18} X^{3} y_{s},\quad k_{2} - k_{1} = \frac{1}{18} X^{2} y_{s},$$

are present. Now an estimation of maximum eigen value of the Jacobi matrix of the system (1) can be calculated with a power method. Let’s denote

$$v_{n} = 8 \max_{i \leq h, n} \left| \frac{2k_{i} - 3k_{2} + k_{3}}{k_{2} - k_{1}} \right|. \quad (3)$$

For stability control of the Dormand-Prince method can be applied an inequality $v_{n}\leq D$, where the constant $D$ limits an interval of stability. An area of stability of the method (2) is shown on a figure one. It is known, that an interval of stability of a numerical of seven order of accuracy is approximately equal to 5 (figure 2) [4]. Therefore, let’s set $D=5$ in the inequation $v_{n}\leq D$. Taking into account the fact, that $v_{n}=O(h)$, a stability step $h^{ac}$ can be chosen using formula $h^{ac}=qh$, where $r$ is calculated from an equation $vr_{n}=D$.

The estimation (3) is raw, because 1) a maximum eigen value is not always very much different from others. 2) In a power method small number of iterations is applied. 3) nonlinearity of the problem (1) makes additional distortions. Therefore, here stability control is used as a limiter for size of an integration step. As a result, a predicted step is calculated with a formula

$$h_{n+1} = \max \left\{ h_{s}, \left[ h^{ac}, h^{n} \right] \right\},$$

where $h_{s}$ is a latest successful step. Notice, that this formula is applied for prediction of size of an integration step $h_{n+1}$ after successful calculation of solution with the step $h_{s}$. If a stability step is less than the latest successful one, it is not reduced, because it may be caused by robustness of an estimation of a maximum eigen value. However, the step will also not be increased, because a numerical scheme might be unstable. If a stability step has to be increased, the latest successful step $h_{n+1}$ is taken as next one. As a result, the formula above is offered for choosing a step. It allows to stabilize a step behavior in a settling area of a solution, where stability has a defining role. In the following, the algorithm of an alternating step with additional stability control of a numerical scheme will be denoted by DP78ST. This algorithm is based on a numerical formula of high (eight) order of accuracy and, consequently, is aimed at solving non-stiff problems with high accuracy of calculations and also for solving moderate stiff problems.

![Fig. 1. An area of stability of the Fehlberg method](image1)

![Fig. 2. An area of stability of the seventh order method](image2)
method (4) are related in equation $B_m P_m = C_m$. Now, when $\beta_{ij}$ and $c_i$ are set, we may define $p_i$ from the linear system of algebraic equations $B_m P_m = C_m$. A condition for first order of the scheme (4) means $\sum n_i p_i^2 = 1$. Therefore, let’s set $c_i = 1$.

Other coefficients $c_i$, $2 \leq i \leq m$ we will use to set size and a form of an area of stability. Both of them can be calculated with a known algorithm [1], so we will assume below, that they are set.

It is known, that if $c_1 = 1$, then for any $m$, coefficients of a stability polynomial can be chosen so, that a correspondent area of stability will be extended up to $2m^2$ along the real axis. However, in this case, in extremum points $x_i$, $1 \leq i \leq m-1$, an equation $|Q_m(x_i)| = 1$ is "almost" manifold. Therefore, in many cases, coefficients $c_i$, $2 \leq i \leq m$ are chosen so, that the relation $|Q_m(x_i)| = |\gamma|$, $|\gamma| < 1$ is true in extremum points. At the expense of choosing appropriate $\gamma$ one might influence on an area size along implicit axis [4].

On $m = 13$ a maximum interval of stability of the scheme (4) equals 338. By substituting corresponding $c_i$, $1 \leq i \leq 13$ in $B_m P_m = C_m$, we will get coefficients $p_i$, $1 \leq i \leq 13$ of the method (4) of first order of accuracy with a maximum interval of stability. Taking into account, that size of an area of stability of the method (2) of eights order of accuracy is equal 5 along the real axis, for those problems, in which a step mostly is limited on stability, efficiency may be increased approximately in 67 times. However, even from numerical calculations of basic problems it follows, that an integration step is significantly less than maximum allowable. It is due to the fact, that areas of stability of inner scheme (4) are small and it, when a step is big, leads to big errors in intermediate calculations.

From results of numerical experiments it follows, that the most efficient is a first order method (4), when $m = 7$.

Coefficients $p_i$, $1 \leq i \leq 7$ of a method with a maximum interval of stability, which is equal 98 are given by

\[
p_1 = -0.4363571319029, \quad p_2 = -0.3975793069175, \\
p_3 = 0.1102728361753 \times 10^1, \quad p_4 = 0.72030701125358, \\
p_5 = 0.1020896360763 \times 10^{-1}, \quad p_6 = 0.5637331643360 \times 10^{-3}, \\
p_7 = 0.12836904213518 \times 10^{-3}.
\]

Let’s give one more set of coefficients $p_i$, $1 \leq i \leq 7$,

\[
p_1 = -0.41342955189830, \quad p_2 = -0.57548324135785, \\
p_3 = 0.1124372564268 \times 10^1, \quad p_4 = 0.8505862373848, \\
p_5 = 0.12991731772814 \times 10^{-1}, \quad p_6 = 0.77368430693719 \times 10^{-3}, \\
p_7 = 0.1885755235957 \times 10^{-3},
\]

with which in extremum points $x_i$, $1 \leq i \leq 6$, of a stability polynomial the condition $|Q_m(x_i)| = 0.9$ is satisfied. In this case, length of an interval of stability is almost maximum and is approximately equal to 90. An area of stability of the constructed method of the constructed method of first order of accuracy is shown on the figure 3.

Along the real axis the area of stability of the method (4) is in approximately 10 times wider than the area of stability of the numerical scheme (2) of eighth order. Furthermore, the first order method in number of computations of a right part of the problem (1) almost in two times cheaper than a given numerical scheme. Therefore, for those problems, in which a step is mostly limited conforming to requirements of stability. Expected theoretical increase of efficiency is equal to 36 times.

![Fig. 3. A stability area of the first order method](image)

Let’s construct an inequality for accuracy and stability control for the method (4). In the inequality for accuracy control we will apply an estimation of a local error $\delta_{n,1}$. Applying expansions of exact and approximate solutions in Taylor’s series, we get, that $\delta_{n,1}$ is given by

\[
\delta_{n,1} = \frac{1}{2} (1 - 2 c_i) \left[ f_i + f_{i+1} \right] + O(h^3).
\]

It is not difficult to see, that the relation

\[
k_{2} - k_{1} = \frac{1}{18} h^2 \left[ f_i + f_{i+1} \right] + O(h^3)
\]

is true. Then for accuracy control can be used an inequality

\[
9 \cdot \left| 1 - 2 c_i \right| \left| f_i - f_{i+1} \right| \leq \varepsilon ,
\]

where $c_i = 0.17242757$, $\varepsilon$ is a some norm in $\mathbb{R}$, $\varepsilon$ is required accuracy of calculations. In this inequality the stage $k_1$ is calculated at the point $t_n$, the stage $k_2$ - at the point $(t_n + h/18)$. As no stages are calculated at the point $t_n$, rapid change of solution can lead to loss of accuracy of calculations. Therefore, in the integration algorithm (5) is used a precheck. Taking into account a relation

\[
h f(y_{n+1}) - k_{1} = \frac{1}{2} h^2 \left[ f_i + f_{i+1} \right] + O(h^3),
\]

a conclusive decision, conforming to requirements of accuracy is made by verification of the following inequality

\[
\left| 1 - 2 c_i \right| \left| h f(y_{n+1}) - k_{1} \right| \leq \varepsilon .
\]

Using of two inequalities for accuracy control of calculations allows to significantly reduce the number of recomputed solutions, because of accuracy degradation.

First order methods with extended stability areas are efficient on regions of settling, where a step is limited, conforming to requirements of stability. Evidently, if a step is limited, conforming to requirements of accuracy, which is peculiarly for transition regions, the explicit Euler method will be in 7 times more efficient, than the constructed method. It is natural, that on calculations with high accuracy on transition regions, the method of eighth order (2) is more efficient. Significant increase of efficiency may be reached by using each method on that region, on which it is the most efficient. The inequality for stability control may be used [1] as a switching criterion. In calculations with the method of eighth order transition to the numerical scheme (4) is carried out on
omission of an inequality $v \leq 5$. In calculations with the first order method, reverse transition is carried out in case of satisfying of $v \leq 5$. Calculations with the first order method are attended with additional control of an inequality $v \leq 90$ and a step is chosen with using a formula $h_{n+1} = \max\{h_n, \min(h^+, h^-)\}$, where $h_n$ is a latest successful step of integration. Notice, that this formula is applied for prediction of size of integration step $h_{n+1}$ after successful calculation of solution with the previous step $h_n$ and consequently doesn't lead to increase of computational cost in practice.

V. NUMERICAL RESULTS

Calculations were carried out on PC Intel(R) Core(TM) i7-3770S CPU@3.10GHz with double precision. Defined accuracy of calculations was set equal to $10^{-6}$. Below by iso, iwo and ifu are denoted accumulated number of integration steps, number of recomputed (recovered), because of violation of required accuracy of calculations, solutions and number of calculations of a right part of the system (1), respectively. For demonstration of operation of constructed algorithms there is given an example

\[ y_1' = 77.27( y_2 - y_1 y_2 + y_1 - 8.375 \cdot 10^{-4} y_1^2) , \]
\[ y_2' = \frac{1}{77.27} ( -y_2 - y_1 y_2 + y_1) , \]
\[ y_3' = 0.161 (y_1 - y_1) , \]
\[ t \in [0, 300], \quad y_1(0) = y_2(0) = 4 , \quad y_3(0) = 1.1, \quad h_0 = 2 \cdot 10^{-1}. \]

It is the simplest model of the Belousov-Zhabotinsky reaction, which is too stiffness for explicit methods and is given here in order to demonstrate a principled possibility of applying explicit methods for solving enough stiff problems. For DP 78 computational costs are $\text{isa}=1434938$, $\text{iwo}=778643$, $\text{ifu}=27997910$ and for DP78ST - $\text{isa}=1437875$, $\text{iwo}=35173$, $\text{ifu}=19114451$. On calculations with an alternating order we have $\text{isa}=132180$, $\text{iwo}=166$, $\text{ifu}=930915$. Same trend continues in integration of ten other stiff test problems [3].

VI. CONCLUSION

The Dormand-Prince method was widely used for solving non-stiff problems. Its implementation is supplied, probably, in all known software libraries. Numerical investigation of this algorithm has been conducted by a lot of authors. In particular, in a monography of E. Hairer and co-authors, there is noticed, that the Dormand-Prince method gives "Excellent numerical results ..." as applied for solving non-stiff problems [2]. In this paper we confined applying this method to finding solution of stiff problems and by the test case showed increase of efficiency due to applying additional stability control and also by calculations with an alternating order. Stability control allows significantly reduce unjustified recoveries and hence increase efficiency of calculations. Essentially, stability control expand possibilities of the Dormand-Prince method applying to moderate stiff problems.

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Simulation of Electro-Hydraulic Drive with Ampulized Hydraulic System

Ozerskiy A. I.
Candidate of the Technical Sciences (PhD), chief of the department “Heat-and-power engineering and applied hydromechanics”,
Don State Technical University
Rostov on Don, Russia
e-mail: kaf tepenergo@iem.donstu.ru

Shoshoashvili M. E.
Doctor of Technical Sciences, professor, chief of the department “Mechanotronics and Hydropneumoautomatics”
South – Russia State Technical University (Novocherkassk Polytechnic Institute)
Novocherkassk, Russia
e-mail: aprim.srstu@mail.ru

Abstract— The method of simulating dynamic modes of operation of electro-hydraulic drive with ampulized hydraulic system (AHS) has been presented. The results of computer simulation and the data of experimental research of the modes of starting a drive when filling the channels of hydraulic machines and pipe-lines of AHS have been shown.

Keywords— computer simulation of a power drive; hydraulic drive systems with electric sources of power; dynamic modes of operation; starting.

I. Introduction and statement of the problem

Simulation of dynamic modes of operation of hydraulic systems (HS) and equipment with positive-displacement hydraulic machines (PDHM) is one of the most urgent and complex problems of contemporary hydraulic machine engineering. Investigations of dynamic modes of operation of such systems and equipment were carried on by T.M. Bashta, V.N. Prokofjev, S.S. Rudnev and other home and foreign scientists. Despite the fact that a substantial amount of investigations were devoted to creating and improving the methods of simulation and calculation and also experimental investigation of these systems and equipment, many problems haven’t been solved yet. For example, dynamics of high-speed spatial currents of fluids in hydraulic channels of positive-displacement hydromachines operating cavities of which are filled or discharged during their starting, stopping and also during the transitional modes of machines operation practically are not subject to proper simulation. It is due to complex processes of fluids movement in supply and discharge channels of these hydraulic machines and also in working channels, for example, in the distribution units of the machines: at fluid flowing when it fills the system of rotating channels with the time-varying area of the cylinder window hole of the rotor-piston pump. These processes are accompanied by ruptures of fluids continuity, diffusiveness of the flow front, unsteadiness of flow, vorticity, turbulence, discontinuous flows, gas saturation and cavitation [1]. These processes haven’t been studied well enough due to difficulty of their description and also due to difficulty of direct observations and measurement of their hydrodynamic parameters.

The distinctive feature of dynamic modes of operation of electro-hydraulic drive systems with PDHM are the processes of motion of liquid and gas-liquid media with movable boundaries moving in hydraulic channels of the pipe-lines and machines of the hydraulic system. The research problems for such processes are referred to the problems of hydrodynamics with movable contact ruptures. Contact ruptures are understood here as surfaces in fluid through which there is no flow of any substance mass and where there is rupture of the fluid main parameters: density, temperature, viscousity, concentration of any substance dissolved in fluid and so on[2]. The phenomena under consideration may involve typical for the present studies the processes of discharging and filling with working fluid hydraulic channels of positive-displacement machines that constantly accompany their work. The similar phenomena also occur under cavitational modes of working fluid flow in the channels of the mentioned hydromachines when due to drop of fluid pressure in the channel there appears rupture of fluid flow continuity and so on. One of the main tasks when studying the peculiarities of the processes under consideration is to determine the laws of motion of exactly movable ruptures (boundaries of media partition).

The analysis of perspective directions of increasing reliability and profitability of the power positive-displacement hydraulic drive of machines and equipment operating under trying conditions: dust and gas loading of the atmosphere, explosibility and fire hazard of the environment, considerable overloading, vibration, etc. has shown the expediency of the approach of “ampulization” of their hydraulic systems. The principle is based on the total isolation of their operating fluids and gases from the environment and replacement of air as an operating body by some inert gas, for example, nitrogen or helium [3]. For regulating these ampulized hydraulic systems
(AHS) an injector (with adjustable nozzle) installed at the inlet of the system booster pump can be used. To provide cavitation free modes of starting and running such hydraulic drive systems (especially at minimal volumes (0.5-1.0 %) of gas cavities of tanks for storing operating fluids) it is necessary to take into account the fact of displacement of free fluid surface in tanks. The latter can be explained the fact that the position of the given surfaces determines gas pressure in gas cavities of tanks of these systems, and, therefore, pressure of fluid at the inlet of the booster and main pumps. The value of this pressure, as is known, determines not only the condition of cavitation free operation of these pumps but provides stability and reliability of the whole power drive [1].

Efficiency and positional accuracy of the power drive are determined by the provided accuracy of the given (rated) change of coordinates of its actuating mechanisms and also the rated pressure of fluids on their working surfaces. In view of this, during computer simulation of the processes investigated here it is necessary to calculate coordinates of movable boundaries and also pressure on the contact surfaces of working fluid with not only gas in tanks but with surfaces of power elements of the drive, for example, with surfaces of piston power hydraulic cylinders. This determines quality of simulation processes and will make it possible to raise positional accuracy of hydraulic drive systems with PDHM.

The practice of solving the similar problems shows that instead of the traditional in hydraulics Euler approach we should apply here Lagrange approach [4, 5]. The latter, as we know, is more common but more complex than Euler approach, as it is used in the cases when the boundaries of fluid are movable. Euler approach is traditionally applied in hydraulics for solving permanent problems of hydraulic calculation of sections of channels and machines filled with fluid and limited by immovable surface areas. The coordinates of these surfaces and fluid pressure on these surfaces are usually known from the problem situation. Application of Euler approach in hydrodynamic problems in these cases, as is known, results in solving the system of nonlinear algebraic equations (Bernoulli equations [6]) relative to average flow speed in the considered immovable points of the channel section. Application of Lagrange approach in the investigated cases results in Cauchy problems for the systems of ordinary differential nonlinear equations of the second order relative to the coordinates of movable fluid surfaces. Such equations, as it is shown in [2], are generalized Bernoulli equations [6] for the case of flowing fluid with movable boundaries. The systems of these equations are only solved with using computer.

II. Peculiarities of calculation methods and the investigated processes

In [2, 5, 7, 8] we have presented the method, based on Lagrange approach, for calculating dynamic characteristics of hydraulic systems with jet and vane machines in the process of filling with and discharging operating fluid of hydraulic channels of these machines and the mains. The suggested method of solving hydrodynamic problems of power drive with PDHM and also the methods of computer simulation of dynamic modes of its operation are also based on Lagrange approach.

With the modes, close to the rated ones, theoretical value \( Q_{H,T} \) of fluid supply by a positive-displacement pump, and its derivative \( \dot{Q}_{H,T} \) with time, unlike a vane pump, don’t directly depend on the difference \( \Delta P_{H,T} = P_{H,BX} - P_{H,RX} \) of fluid pressure \( P_{H,BX} \) at the outlet of the pump and the pressure \( P_{H,RX} \) at the pump inlet. They are determined only by degree of rotation, angular velocity and angular acceleration of the pump shaft. In the given method the presented values are determined accordingly by the equations:

\[
Q_{H,T}(t, \varphi, \dot{\varphi}) = \sum_{i=1}^{n} q_i(t, \varphi, \dot{\varphi}) = \sum_{i=1}^{n} q_i(t, \varphi, \dot{\varphi}) \cdot \phi_i = \frac{2\pi}{z} (i-1) \tag{1}
\]

\[
\dot{Q}_{H,T}(t, \varphi, \dot{\varphi}) = \sum_{i=1}^{n} \dot{q}_i(t, \varphi, \dot{\varphi}) \cdot \phi_i = \frac{2\pi}{z} (i-1) \tag{2}
\]

Here \( q_i(t, \varphi, \dot{\varphi}) \) is the capacity of each i-th cylinder of the hydraulic pump; \( z \) – is the number of its cylinders; \( \varphi(t), \dot{\varphi}(t), \ddot{\varphi}(t) \) – are degree of rotation of an electric motor shaft, its angular velocity and angular acceleration accordingly. We should notice that here \( q_i(t, \varphi, \dot{\varphi}) \) are not analytical functions. These are piecewise continuous functions, consisting of positive sections of sinuous lines shifted one relative to the other by an angle of \( \frac{2\pi}{z} \) [1]. In the given method their values were calculated during computer simulation on the basis of ratios determining \( h_i \), velocity \( \dot{h}_i \) and acceleration \( \ddot{h}_i \) of each i-th pump piston:

\[
h_i(t) = \frac{D}{2} \lg \gamma(t) \left[ 1 - \cos \varphi(t) \right] \tag{3}
\]

\[
\dot{h}_i(t) = \frac{D}{2} \lg \gamma(t) \sin \varphi(t) \dot{\varphi}(t) \tag{4}
\]

\[
\ddot{h}_i(t) = \frac{D}{2} \lg \gamma(t) \left( \cos \varphi(t) \dot{\varphi}(t)^2 + \sin \varphi(t) \ddot{\varphi}(t) \right) \tag{5}
\]

In these equalities: \( D \), \( m \) – is the diameter of a circle of a cylinder block on which cylinders’ axles are located, \( \gamma(t) \) – is the angle of inclination of the block (disc) with the axis of rotation of the pump shaft. Here, designations and admissions, traditional for the theory of positive-displacement axial-piston hydraulic machines, have been adopted [1].

In the proposed method dynamic characteristics of electro-hydraulic drive (electrohydromechanical) system with a positive-displacement pump are determined by the location
\( x(t) \), velocity \( \dot{x}(t) \) and acceleration \( \ddot{x}(t) \) of the front and rear portion of fluid flow. The distinctive feature of operation of the given system consists in that in all the cases, in the end, its dynamic characteristics will depend on the change of the angle \( \varphi(t) \) of turning of an electric motor shaft, its angular velocity \( \dot{\varphi}(t) \) and angular acceleration \( \ddot{\varphi}(t) \) according to the equalities:

\[
\dot{x}(t, \varphi, \dot{\varphi}, \Delta p_H) = \frac{1}{\sigma} \frac{Q_H}{\eta_H} \left( t, \varphi, \dot{\varphi} \right) \eta_H(\Delta p_H) \quad (6)
\]

\[
\ddot{x}(t, \varphi, \dot{\varphi}, \ddot{\varphi}, \Delta p_H) = \frac{1}{\sigma} \frac{Q_H}{\eta_H} \left( t, \varphi, \dot{\varphi}, \ddot{\varphi} \right) \eta_H(\Delta p_H) \quad (7)
\]

Here \( \sigma \) is a cross-sectional area of the channel along which at the given point of time the front of fluid flow with the coordinate of \( x \) is moving; \( \eta_H(\Delta p_H) \) is a pump volumetric efficiency.

With this, functions \( x_1(t, \Delta p_H) \) and \( x_2(t, \Delta p_H) \), determining position of the operating fluid level in a tank and also position of the front of the fluid flow filling hydraulic channels of the mains and HS pumps accordingly are calculated in the course of numerical solution of the problem. Let us note that the dependence of \( x \), \( \dot{x} \), and also \( \ddot{x} \) on the value of \( \Delta p_H \) in HS with positive-displacement pump is realized in so far as volumetric efficiency of the given pump depends on this value.

**III. Description of the experimental complex, calculation results and experimental evidence**

Experimental complex (fig.1) with the model of AHS consisted of the tank containing nitrogen, compressor (vacuum pump), injector, boosting vane pump and also the main positive-displacement pump with EAD. The power drive also included: positive-displacement hydraulic motor and also hydraulic clutch with a fan of working fluid cooling system of the drive. The HDS model provides adjustment with the help of injector having a variable geometry of a nozzle and an inlet into the mixing chamber. Injector feeding was performed both from independent high-pressure source of fluid (Kärcher), and from a positive-displacement pump through additional branch channel of the main (pressure) pipe-line downstream the pump.

![Fig. 1. View of the experimental complex.](image)

![Fig. 2. The operating fluid consumption: 1 – downstream the pump; 2 and 3 – in injector and motor pipe-lines.](image)

![Fig. 3. Speed of operating fluid in the channel downstream the positive-displacement axial-piston hydraulic pump (effect of each piston is shown).](image)
The system of operating fluid pressure measurement consisted of pressure sensors of BOCH REXROTH HM 13 10/250 type and a system data collection - BOCH BT MAC 8–15/C–PM–4AX4. The investigations of the processes of the system launching in the modes of filling its hydraulic channels with operating fluid at consequent start of an injector and a vane pump have been carried out. The results of simulation and experimental data are presented in fig. 2 – 5. Fig. 2 – 5 present the results of computer simulation of dynamics of launching and regulating HDS with positive-displacement hydraulic motor by the way of changing an injector nozzle diameter. During 0.5 sec. after the moment of the system starting an injector nozzle diameter changed from 1 mm till 3 mm. Comparatively small (in comparison with expedient) values of hydroblow reduction (from 12 Mpa to 8 Mpa) at ED starting are explained by the fact that a nozzle of the given diameter “squeezes” the channel when launching ED. However, availability of an injector results in pressure fluctuations (like a hydroblow) and reduces the total level of pressure in the pressure part of the pipe-line. Fig.5 shows the dynamics of fluid pressure changes downstream a vane boosting pump at the inlet of the main positive-displacement pump at small values of the capacity (1%) of the tank gas cavity.

**Conclusion**

The results of full-scale and computer experiments have shown that the proposed methods allow, with reasonable for practical use accuracy (15-20%) to simulate dynamic modes of operation of electro-hydraulic drives with ampulized hydraulic systems on the stage of their designing. The technique makes it possible to simulate properly dynamic processes of joint operation of the adjustable injector, vane boosting pump, positive-displacement hydraulic pump and electric motors as sources of mechanical power. The outlet power element here may be: a positive-displacement hydraulic motor, a hydraulic cylinder or a rotating unit.

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Modeling of Dynamics and Stochastic Processes - the Major Component of the Manual on Software Engineering for the Control Systems

Troyanovskyi V.M.
Department "Informatics and computer software systems". National Research University "MIET"
National Research University "MIET"
Moscow, Russia
e-mail: troy40@mail.ru

Abstract— Problems associated with the creation of a textbook on software engineering for control systems are considered. Modeling of dynamics and stochastic processes highlighted as most important problem. Subject area, the prototype of discipline, hierarchy of systems and mathematical methods are defined. System-related restrictions are discussed, the implications of their improper accounting are considered. Brief description of Requirements to textbook on software engineering for control systems is given. Special attention is given to modeling.

Keywords— modeling; software engineering; control systems; complex dynamical systems; stochastic processes

I. INTRODUCTION

Education and training in the field of Software Engineering received much attention all over the world. An each new application requires own individual program. The scale of development of software before and after the 70 -ies of the twentieth century differ by several orders of magnitude. In 2007, the Russian translation of the book came out, which had the name "Recommendations for teaching software engineering and computer science at universities" [1] (hereinafter referred to as "Recommendations"). Global experience teaching software engineering at universities and colleges, since 1968, generalized here.

In the "Recommendations" states that "software engineering is a relatively young discipline", the book "... will benefit to developers of educational materials (textbook writers, etc.)" and "agencies are encouraged to analyze their own needs and to adapt accordingly the curriculum."

Subject area of this work can be defined as the creation of a textbook on software engineering for control systems. In light of the theme of our conference [2] the greatest interest in the spectrum of problems in the subject area is simulation of the dynamics and stochastic processes.

Problem situation defined by the following circumstances:

• discrete mathematics, as a recommended scientific basis, does not cover dynamics and stochastic processes;
• analysis of textbooks and modeling systems [2] indicate the absence of any in-depth analysis of dynamical systems, which operate in the conditions of random influences;
• such knowledge was given to students in the preparation of engineers; their absence in the preparation of bachelors exacerbates the problem of training qualified specialists.

This determines the importance of developing of textbook on Software Engineering for Control Systems (SECS).

II. SUBJECT AREA AND PROTOTYPE OF DISCIPLINE

A. Specialization

In [1] states: "the study of computer science, together with a certain subject area, will be extremely useful." As such we have chosen the control system as subject area (Fig. 1).

![Fig.1. Components and relationships within the system](image)

An important detail: software in the control system is an integral part - an important, but still - part of the overall system that interacts with all other components. And here proximity to software engineering, to architecture, to interfaces - can be traced very clearly. When teaching students to pay attention to modeling and architecture, as well as interfaces, which is done usually. But have not yet talked about the import consequence analysis of random processes and noise in such systems [3, 4].

B. Prototype of discipline

Over the years, Russian universities preparing software engineers majoring in 2204. Author developed the course "Software of control systems" (SCS) to prepare these professionals in MIET. This course was come about 20 years ago. It was introduced into the curriculum by the decision of the Academic Council MIET. During this time, > 1000
specialists was trained, 1 doctoral and 4 Ph.D. dissertations was defended; the textbook "Information control systems and applied theory of random processes" [5] was published by "Gelios - ARV".

In developing the course, personal research and production results of the author was used; content of this course is maintained and improved by scientific research, performances at major international conferences [6-8]. The hierarchy of the processes studied is shown in Fig. 2.

Fig. 2. Hierarchy of systems and mathematical methods

The horizontal line in Fig. 2 indicates the level of systems, which satisfies the requirements specified in the "Recommendations". However, no dynamics and stochastic processes do fall into account of experts who prepared the "Recommendations". This immediately cuts the upper levels of control systems, starting with the direct digital control. In the SCS, part of the course begins from here and it is the most important for the future of specialization and competent professional software development.

III. SYSTEM-RELATED CONSTRAINTS

A. Restrictions themselves

All the systems mentioned above the dotted line, operated under the following restrictions (Fig. 3):
1. Real time - we have only last data.
2. Stochastic impacts require using of statistical methods.
3. Dynamics converts the input signals into outputs, changing not only the magnitude but also the shape of the signal. And every reaction is a weighted mixture of last individual inputs.
4. Limited surveillance intervals together with stochastic effects may worsen any statistical evaluations.

Fig. 3. Restrictions in total System

Here it is necessary to add the use of discrete-continuous transformations, and take the all this into account together.

B. The central knot of problems

Stochastic processes - Dynamics - limited interval of observation. This is the central knot of problems.

Attraction of statistical methods actualizes the problem of differences in averaging on set and on time (Fig. 4).

Fig. 4. Statistical estimations on the set and along realization

Statistical methods use (obviously or not obviously) the set of events, values or realizations. Independent counts should be taken into consideration when the set is cut across ensemble of statistically independent realizations. Besides, capacity of the hypothetical set can be infinite.

On the practice, the researcher always works with single realization of the limited length. At the same time the counts, chosen from private realization, may be correlated, and their number is always limited.

C. Important terminological remark

We want to emphasize in the terminology that there is a difference when we analyze using averaging over the set and averaging on time. Here, following Bendat [4], we will use term "the covariation function" for result of averaging over set, and "the correlation function" - as the result of averaging on time.
There are also some comments on similar necessity in the book of Ljung [9].

IV. CONSEQUENCES OF INCORRECT ACCOUNTING CONSTRAINTS

Here are two simple examples.

It is known that at summing up already five independent values with uniform distribution, distribution of their sum tends to the normal.

But it is the ideal representation, which is well confirmed by the analysis of likelihood of statistical hypothesis with the A.N. Kolmogorov’s criterion.

In practice, when we work with realization of limited length, it is required hundreds and thousands of counts for successful distribution estimates. This fact is easily seen by modeling (Fig. 5).

![Fig. 5. Hypothetical distribution on set and the histograms for sequences of finite length](image)

Another example is calculation of the average value estimation. For realization of limited length, Results of the analysis and modeling, given here (Fig. 6), show that corridors of convergence could be very different in the case of independent samples and correlated samples.

![Fig. 6. Confidence intervals for the calculation of the average along realization of random process](image)

We may find even more effects at the solution of identification problem. Some of them are illustrated in [?], together with the correct algorithms for solving the problem of identification taking into account the mentioned restrictions.

If we do not turn a blind eye on these factors, then we must light the relevant issues in process of teaching.

V. REQUIREMENTS TO TEXTBOOK ON SOFTWARE ENGINEERING FOR CONTROL SYSTEMS

As follows from the above, we should create a new textbook on software engineering for control systems. The most important requirements are as follows:

- Introduction of additional theoretical topics on the dynamical systems and stochastic processes;
- Level of presentation content of these sections must be available for engineers;
- Creation of interactive demonstration programs to illustrate the most important tenets of the theory;
- Creation of interactive demonstration programs to illustrate the most important tenets of the theory;
- Use the group method of designing software, which students must create for labs.

VI. CONCLUSION

Control systems are the important subject area, where software engineering is necessary. Traditional mathematical methods for constructing programs here are insufficient. This is due primarily with the need to take account the dynamics and stochastic processes in the control systems. Therefore, textbook on software engineering must be supplemented by special sections in the part of the theory, and especially, in the part of modeling.

REFERENCES


Using Information Technology for Computer Modelling of Nonlinear Monotonous Impulse Control System with Uncertainties

Tseligorov N.A.
Russian Customs Academy, Rostov branch, 344000, Rostov on Don, Av. Budenovsky, Dom 20, Russia
nzelig@rambler.ru
+7(632)218-07-12

Tseligorova E.N.
Don State Technical University
344010, Rostov on Don, Gagarin square, Dom 1, Russia
celelena@yandex.ru

Mafura G.M.
OOO «Rostovgiproshaht»
344010, Rostov on Don, St. Krasnoarmeiskaya, Dom 157, Russia
mafurag@hotmail.com

Abstract — This article considers the use of computer modelling for investigating the effect of parametric uncertainty on the robust stability of nonlinear impulse control system (NICS). A one dimensional mathematic model of NICS is considered. The criterion for absolute stability is converted to a criterion equation, which can be analyzed with ease. For transfer functions n=1 to 3 the polynomial equations are provided in symbolic form. This transfer functions are expressed through polynomial coefficients for the numerator and denominator. For the transfer function n=3, a macros is provided. This macro, which has been implemented in Visual Basic for Applications, makes it possible to get the numerical values of criterion equation’s coefficients. The resultant criterion equation can be further investigated using either approximate or analytical (definite) methods. The root locus method (an approximate method) is applied to verify stability. In order to achieve this, MatLab and a specially implemented program complex is used.

An illustrated example on the investigation of robust absolute stability of NICS is given. The investigation of robust absolute stability of NICS is achieved by transitioning from the interval polynomial coefficients of the transfer function to the criterion equation on the basis of the results of the strong Kharitonov’s theorem. Maple is used to find the roots of the criteria equations. Then the stability of the system in question is evaluated. A comparison of results from MatLab and the specialized program complex has been carried out. A region of robust stability for the control system in question has been illustrated.

Keywords— nonlinear impulsive control system, absolute stability, uncertainty, robust stability, interval polynorm, root locus, criteria absolute stability.

I. INTRODUCTION

In practice, the control systems for various purposes will inevitably have to face various difficulties caused by uncertainty. Uncertainty is defined as incomplete or inadequate information about the conditions of the solutions, the presence of chance or opposition. Uncertainty can be caused by exogenous factors such as wear, changes in temperature etc. or endogenous factors such as errors during the design of mathematics models or simplification of the mathematical model [1]. Uncertainty can negatively affect the effectiveness of a control system or even lead to loss of stability. Robust control is a field of control theory that studies the design problem of maintaining invariance of system properties such as stability and performance under large perturbations. The robust approach is advantageous because it allows the use of interval methods which do not require the probabilistic characteristics or precise values of the input parameters. The study of NICS is done on a specially designed program complex [2].

II. STATEMENT OF PROBLEM

The criterion of absolute stability of a nonlinear impulse control system (NICS) with monotonous characteristics can be described by the following inequality [1]

\[ \mathbb{Re}\left\{ q(1-e^{-j\sigma}) W(j\sigma,0) + k^{-1} \right\} > 0, \]  

(1)

Inequality (1) should be satisfied for all frequencies \( \sigma \) in the interval between 0 and \( \pi \) provided that Popov’s parameters \( q \geq 0 \) are real. The nonlinear element (NE) characteristic \( \Phi(\sigma) \) satisfies the following criteria (absolute stability’s equilibrium position is being considered)

\[ 0 \leq \frac{\Phi(\sigma)}{\sigma} \leq k, \quad \Phi(0) = 0, \]  

(2)

More often than not, studies on nonlinear control systems are carried out on idealized nonlinear elements which, unlike real world nonlinear elements, have monotonous statistical characteristics[2]. In such situations, the methods discussed in this work can be used to extend the region of stability and
consequently improve the control system’s working characteristics [1].

The use of criteria (1) for testing the absolute robust stability of NICS is complicated by the transient frequency characteristic $W(j\sigma)$. Using the $w$-transform it is possible to reduce the absolute stability test of NICS to checking if the polynomial is Hurwitz stable [3]. The robust stability can be tested by verifying Kharitonov’s polynomials [4].

### III. Solution of Problem

#### A. Mathematical model for testing the absolute stability of NICS

The pseudo frequency criteria transfer function (1) takes form as illustrated below after application of $w$-transform

$$\text{Re}(1+q\frac{2j\nu}{1+j\nu})W(j\nu) + k^1 > 0, \forall \nu \in [0,\infty] \tag{3}$$

Where $w = j\nu$, $\nu = \frac{2\pi T_0}{2}$ - relative pseudo frequency, $T_0$ - sampling interval.

The transfer function can be illustrated as follows

$$W(j\nu) = \frac{\alpha_0(v) + j\beta_0(v)}{\alpha_2(v) + j\beta_2(v)} \tag{4}$$

Substituting (4) in (3), the following criteria expression is gotten

$$k[\alpha_0(v)\alpha_2(v) + \beta_0(v)\beta_2(v)(1+\nu^2)] + 2q[\alpha_0(v)\alpha_2(v) + \beta_0(v)\beta_2(v)\nu^2 - 2q(\alpha_0(v)\beta_0(v) - \alpha_0(v)\beta_0(v))\nu] + [\alpha_2^2(v) + \beta_2^2(v)](1+\nu^2) = 0 \tag{5}$$

Using the criteria expression (5), it is possible to get the polynomial expression in symbolic form for any transfer function polynomial degree ($n$).

For $n=1$, the transfer function is illustrated below

$$W(j\nu) = \frac{ja\nu + a_0}{jb\nu + b_0} \tag{6}$$

The polynomial expression (5) in symbolic form:

$$P(x)|_{x=x_1} = k[a_1x_1^2 + (a_1a_2 + a_1b_1)x + a_1b_0] + 2q[a_1x_1^2 + (a_1a_2 + a_1b_1)x + a_1b_0] + [b_1^2x^2 + (b_1^2 + b_2^2)x + b_2^2] \tag{7}$$

For $n=2$ the transfer function has the following form:

$$W(j\nu) = \frac{-a_2x^2 + ja\nu + a_0}{-b_2x^2 + jb\nu + b_0} \tag{8}$$

For $n=3$, the transfer function is illustrated below

$$W(j\nu) = \frac{-ja\nu^3 - a_2\nu^2 + a_1\nu + a_0}{-jb\nu^3 - b_2\nu^2 + jb\nu + b_0} \tag{9}$$

Polynomial expression (5) in symbolic form:

$$P(x)|_{x=x_1} = k[a_1x_1^3 + (a_1a_2 + a_1b_1)x + a_1b_0] + 2q[a_1x_1^3 + (a_1a_2 + a_1b_1)x + a_1b_0] + [b_1^3x^3 + (b_1^3 + b_2^3 - 2b_2b_1)x + b_2^3] \tag{10}$$

The expressions (6)-(10) make it possible to get the polynomials necessary for verifying the absolute stability of NICS, without intermediate calculations, using known numerator and denominator polynomial coefficients of the transfer function (4). The necessary polynomials can be gotten by using Excel macro written in VBA. The following is the macro code for $n=3$

```vba
Sub processcoeff()
    Dim a1, b1, a0, b0, a2, b2, a3, b3, k, q
    Dim coeff_x_4, coeff_x_3, coeff_x_2, coeff_x_1, coeff_x_0
    a0 = Range("B1").Value
    a1 = Range("B2").Value
    a2 = Range("B3").Value
    a3 = Range("B4").Value
    b0 = Range("B5").Value
    b1 = Range("B6").Value
    b2 = Range("B7").Value
    b3 = Range("B8").Value
End Sub
```
For Hurwitz stability of polynomial $P(x)$, it is necessary that the following conditions are met\cite{6}:

- the number of times the sign across the sequence of coefficients of the polynomial $P(x)$ changes should be even. In other words, the coefficient of the leading term and that of the constant term should be positive.

- The number of times the sign changes across the sequence $V(\bullet) = V(1, 2, 4, \ldots, 2p, \ldots)$ of the main minors of matrix, which is derived from the polynomial $P(x)$, should be equal to $n$.

The determinant $V_{2p}$ is constructed as follows:

$$V_{2p} = \begin{vmatrix}
0 & a_0 & a_1 & a_2 - p - 1
0 & b_0 & b_1 & b_2 - p - 1
0 & b_0 & b_1 & b_2 - p - 1
0 & b_0 & b_1 & b_2 - p - 1
\vdots & \vdots & \vdots & \vdots & \vdots
\end{vmatrix}, \quad p = 1, 2, \ldots, 2n,$$

Where $b_i$ - coefficients of the first derivative of polynomial $P(x)$.

In Juri's innorny method, the condition that the polynomial roots should lie in the open left half plane can be expressed using a matrix $\Delta_{2n-1}$ of size $(2n-1)*(2n-1)$. The matrix should be innor positive. The matrix is built using the following scheme\cite{5}:

$$\Delta_{2n-1} = \begin{bmatrix}
1 & -a_{n-1} & -a_{n-2} & \cdots & -a_2 & -a_1 & b_0 & b_1 & b_2 & \cdots & b_{n-2} & b_{n-1} \\
0 & -a_{n-1} & -a_{n-2} & \cdots & -a_2 & -a_1 & b_0 & b_1 & b_2 & \cdots & b_{n-2} & b_{n-1} \\
0 & -a_{n-1} & -a_{n-2} & \cdots & -a_2 & -a_1 & b_0 & b_1 & b_2 & \cdots & b_{n-2} & b_{n-1} \\
0 & \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \vdots & \vdots \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & b_0
\end{bmatrix},$$

where $b_i$ is the coefficient of the first derivative of polynomial $P(x)$.

Sturm method suggests the formation of a Sturm sequence and checking the difference between the number of times the sign changes in the sequence when $x=0$ and $x=\infty$\cite{3}.

**Graphical-Analytical methods**

Approximate methods involve the calculation of the polynomial's roots. The most commonly used method is the root locus method. In this method, the calculated roots are shown on a complex plane\cite{7}.

The classical root locus polynomial expression is as follows:

$$A(x) + hR(x) = 0,$$
Where \( A(x), B(x) \) - polynomials, \( h = ck \) - variable parameters.

The above equation is a special case of a more general expression [8]:

\[
A(x) + h_1 R(x) + h_2 C(x) = 0 \quad \text{(9)}
\]

Equation (9) is a result of combining (6) and (8).

\[ h_1 = k \cdot a \quad h_2 = 2qk \]

In order for the NICS in question to be stable, the branches of the root locus should not fall in the real positive axis of complex plane [3].

C. Mathematical model for testing the robust stability of NICS

The robust absolute stability of a NICS can be verified using the four Kharitonov polynomials [4]. The four polynomials can be expressed as follows:

\[
P_1(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + \ldots
\]

\[
P_2(x) = a_0 + a_1 x + \bar{a}_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + \ldots
\]

\[
P_3(x) = \bar{a}_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + \ldots
\]

\[
P_4(x) = \bar{a}_0 + a_1 x + \bar{a}_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + \ldots
\]

Criterion expression (5) is transformed into a system of Kharitonov’s polynomials. If the upper and lower boundaries of interval parameters of system under verification are known, then, using the laws of interval arithmetic, it is possible to get the system of polynomials for analytic or graphical verification.

If the graphical analytical method, using expression (9) and Kharitonov’s polynomials (10), the cloud of roots in the complex plane is gotten. The position of the cloud determines whether the system in question is absolutely and robustly stable.

Illustrative example

Consider a NICS whose transfer function has the following interval coefficients:

\[
W(w) = \frac{w^3 + (1.0.2)w^2 + (0.4.12)w + (0.1.0.3)w}{w^3 + (1.2.36)w^2 + (1.0.20)w + (0.2.0.8)} \quad \text{(11)}
\]

The characteristics of the nonlinear elements are found within the interval [0;1,5]. Popov’s parameter q is equal to 1.

Consider the transfer function (11) with the following nominal coefficient values

\[
W(w) = \frac{w^3 + 1.5w^2 + 0.8w + 0.2}{w^3 + 2.4w^2 + 1.5w + 0.5}
\]

A stability analysis is done using MATLAB and the special program complex. The result is as follows:

According to the above illustrated root locus diagrams, the NICS under consideration is stable.

In order to verify the robust absolute stability of the NICS (11) with intervals while taking into consideration the monotonous nonlinear characteristics, the coefficients in (9) are substituted with values from (11) thus the polynomial \( P(x) \) is gotten. The maximum values for coefficient q = 1 and k = 1.

\[
P_{\text{max}}(x) = 0.06 - 0.26x + 0.41x^2 + 0.54x^3 + 4x^4;
\]

\[
P_{\text{min}}(x) = 0.88 + 1.55x + 11.6x^2 + 19.46x^3 + 4x^4.
\]

Using the values above, the corresponding system of Kharitonov’s polynomials (12) are gotten:

\[
P_1(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 = 0.06 + 1.55x + 11.6x^2 + 0.54x^3 + 4x^4;
\]

\[
P_2(x) = a_0 + a_1 x + \bar{a}_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 = 0.06 - 0.26x + 11.6x^2 + 19.46x^3 + 4x^4;
\]

\[
P_3(x) = \bar{a}_0 + a_1 x + a_2 x^2 + a_3 x^3 + \bar{a}_4 x^4 = 0.88 + 1.55x + 0.41x^2 + 0.54x^3 + 4x^4;
\]

\[
P_4(x) = \bar{a}_0 + a_1 x + \bar{a}_1 x + a_2 x^2 + a_3 x^3 + \bar{a}_4 x^4 = 0.88 - 0.26x + 0.41x^2 + 19.46x^3 + 4x^4.
\]

The roots of Kharitonov’s polynomials (12) are gotten using MAPLE . The results are presented in the following tables.
As seen in the tables above, the Kharitonov’s polynomials do not have any real positive roots and therefore the control system in question is robust and absolutely stable. Illustrated below is a graph of the region of robust, absolute stability of the NICS in question.

IV. CONCLUSIONS
The authors of this work have presented an approach of investigating the robust and absolute stability of nonlinear impulsive control systems with monotonous nonlinearities. This approach makes it possible to effectively estimate the influence of uncertainty, parameter Popov and nonlinear elements’ characteristics on the region of stability. Matlab has been used to verify the results of the special program complex. The original data is prepared in VBA which allows the conversion of symbolic polynomial equation coefficients into numeric coefficients.

References


Analysis and Forecast of Sea Level Anomalies
Spatio-Temporal Variability in the Barents Sea

Zaporozhtsev I. F., Sereda A.-V. I.
Department of Higher Mathematics and Computers Software
Murmansk State Technical University
Murmansk, Russia
e-mail: zaporozhtsev.if@gmail.com

Abstract— In the article developing technique of short-term prediction of sea level anomalies spatial distribution is presented. It is considered in multivariate time series analysis context. Mathematically proved technology of numerical analysis of natural processes in the Arctic is certain to be interesting for different specialized fields professionals of scientific studies (oceanologists, meteorologists, biologists, ecologists, etc.) and in practical activities, such as fishery, gas-and-oil producing industry, delivery logistics, etc., in the Arctic region. The methodology for prediction of spatial distributions of sea level anomalies we are suggesting can also be applied to other ocean surface characteristics forecast with gridded regularly obtained satellite and/or surface measured data as input. It is based on multivariate time series analysis, clusterization techniques and linear algebra numerical methods.

Keywords— sea level anomalies, multivariate time series, singular spectrum analysis, clustering, short-term forecast, gridded data, satellite measurements, spatio-temporal distribution.

I. INTRODUCTION

Complex study of temporal variability of ocean surface characteristics is important problem to deal with in either practical or theoretical context. The first oceanography data digitization was carried out within the limits of international project GODAR [2] which aim was to reconstruct and store observations and measurements information for last hundred years. Accuracy estimation and development of computer technology for data quality control was also suggested. “Climatic Atlas of the Barents Sea 1998: Temperature, Salinity, Oxygen” and “Climatic Atlas of the Arctic Seas 2004: Part I. Database of the Barents, Kara, Laptev, and White Seas - Oceanography and Marine Biology” are the results of that work.

Those publications are useful as information source of average values of some characteristics calculated for long period of time (decades). But mentioned works are difficult to use for short-term forecasting because of data irregularity both in time and space. Inter-agency complex information system for a wide range of marine activities was launched in Russia in 2005. Its operational units and experts provide daily profiles and forecast for the most valuable characteristics. They are obtained from international meteorological center NCEP/NOAA being calculated with global hydrodynamic models of ocean and atmosphere. It is known that sea level anomalies can be considered as integral characteristic of sea surface influenced with many factors. Thus, modern Russian and foreign technologies and systems to analyze sea level anomalies distribution are only regional. In addition, corresponding differential equations have many parameters that are difficult to be determined with appropriate (or acceptable by practice) accuracy. As a result, multivariate time series analysis is likely to be efficient way to solve short-term forecasting problems as mentioned above.

II. DEFINITION OF GRID

Let \( \Delta = \Delta_x \times \Delta_y \) be a regular grid specified for rectangular area \( \Omega = [a,b] \times [c,d] \subset \mathbb{R}^2 \), where

\[
\Delta_x = \{ x_k \mid a = x_0 < \ldots < x_n = b, \quad x_k = x_{k-1} + h_x, \quad k = 1,2,\ldots,n \};
\]

\[
\Delta_y = \{ y_k \mid c = y_0 < \ldots < y_m = d, \quad y_k = y_{k-1} + h_y, \quad k = 1,2,\ldots,m \}.
\]

Since grid node values of any characteristic at particular time point are convenient to be represented by a matrix and geographical coordinates are useless for further calculations, the grid can be defined as a set of index pairs (row and column numbers) for corresponding nodes:

\[
G = [1,d_x] \times [1,d_y] \subset \mathbb{N}^2,
\]

where \( d_x = m + 1 \) and \( d_y = n + 1 \).

III. BASIC FORECAST METHOD

Basic forecasting tool in the research is \( K \)-continuation of multivariate time series based on multivariate singular spectrum analysis (MSSA [5]). The main purpose of MSSA is to decompose the original series into a sum of series, so that each component in this sum can be identified as either a trend,
periodic or quasi-periodic component (perhaps, amplitude-modulated), or noise. This is followed by a reconstruction of the original series. MSSA technique is performed in two stages, both of which include two separate steps as follows:

1) decomposition
   - data embedding which can be regarded as a mapping that transfers the given multivariate series into lagged vectors space; the result is trajectory matrix of multivariate time series being Hankel matrix;
   - singular value decomposition of trajectory matrix to get basal vectors of space generated by rows of the matrix and a sum of elementary matrices;
2) reconstruction
   - grouping corresponds to splitting the elementary matrices into several groups and summing the matrices within each group;
   - diagonal averaging is to transform each group matrix to the form of a Hankel matrix which can be subsequently converted to a time series.

$L$-continuation is carried out by linear recurrent formula for all the series of multivariate system simultaneously. The key assumption of this forecasting technique is a requirement of the new row added to trajectory matrix (as the last one) being in the space generated by its rows before adding. The new row contains one time step ahead forecast for each univariate time series.

It is known that multivariate singular spectrum analysis is more efficient in comparison with its univariate analog if all the time series are concerted. This feature means the similar structure of additional model constructed for each time series separately. Because of natural process study, assumption of consistence is obvious for time series corresponding to neighbouring nodes of grid $G$.

IV. CLUSTERING TECHNIQUE

Grid nodes are divided into clusters according to clusterization method suggested by authors of this article. Assume that a cluster is a set of nodes corresponding to simply connected subregion of area $\Omega$. Each node of $G$ provides time series with the same start point, time step and length (time points number). Thus, each cluster with cardinality of $s$ generates multivariate time series with $s$ components of length, for example, $T$:

$$F_T = (F_T^1, ..., F_T^s).$$

It is known that being applied to time series clustering problem Euclidean distance measure is very restrictive in comparison to expert judgment (human perception) of time series similarity. Some authors suggest to use cross-correlation coefficient to obtain meaningful clustering results [3,4].

Clustering technique accepted in the article is based on the following ideas:

1. Area $\Omega$ is rectangular, therefore primary clusters can be only rectangular. They have predetermined size.
2. Cross-correlation coefficient calculated for any pair of nodes (for the pair of corresponding time series or their fragments with specified length) of the same cluster is certain to be not less than some predetermined value (threshold for high positive correlation). If primary cluster does not satisfy this requirement, it is divided into four clusters (the smallest possible cluster has only one node).
3. The greatest value of cross-correlation coefficient for any pair of nodes corresponds to zero lag (it is referred to as dynamics of one node process has no delay relative to another). If primary cluster does not satisfy this requirement, it is divided into four clusters (the smallest possible cluster has only one node).
4. Primary rectangular clusters can be combined under rules of greedy algorithm: new cluster is formed from a pair of primary clusters that have common space boundary and the greatest value of the least cross-correlation coefficient calculated for all possible pairs of their nodes (one node from each cluster).

V. FORECAST ACCURACY MEASURE

Cluster nodes values forecast

$$\tilde{F}_h(t + k - 1), \ k = 1, ..., h$$

for each time point $t$ is also a multivariate time series calculated by linear recurrent formula of MSSA (multivariate singular spectrum analysis [5]) at horizon $h$ applied to time series $F_N$ of length $N < T$:

$$\tilde{F}_h(t + k - 1) =$$

$$= \text{MSSA}^k(F_N(t - N), ..., F_N(t - 1)) =$$

$$= \text{MSSA}^{k-1}(F_N(t - N + 1), ..., F_N(t - 1)), \text{MSSA}(F_N(t - N), ..., F_N(t - 1))).$$

Here, we use normalized root mean squared error (NRMSE) to measure the forecast accuracy:

$$\varepsilon^h_{F_T, \tilde{F}_h} =$$

$$= \max_{1 \leq s \leq s} \frac{1}{D(T)} \sqrt{\frac{\sum_{j=0}^{k-1} (F^j_T(t + j) - \tilde{F}^j_h(t + j))^2}{h}},$$

$$D(T) = \max_{1 \leq s \leq s} \{ \max_{t < T} F^s_T(t) - \min_{t < T} F^s_T(t) \}. $$
VI. FORECAST CORRECTION PROCEDURE

MSSA forecast results correction technique is based on time series approximation with TARX model [6]. In this case it is used not for \( F_T \) values, but for cluster one step ahead forecast errors. Forecast error of the particular node and time point is defined as the difference between prediction and corresponding value of \( F_T \). The cluster error is calculated as an average of node errors within the cluster at time point \( t \) for one step ahead forecast carried out with MSSA.

MSSA forecasting method uses special autoregressive model to approximate multivariate time series corresponding to particular cluster. Since the aim here is to employ some spatio-temporal effects and dependancies between different clusters, it appears more relevant to account for some explanatory variables in addition to simple autoregressive model. For instance, one step ahead forecast errors observed in several clusters and for different points in time in the past. Assume that we take into consideration four regimes (as a number of neighbours of each nonboundary node of the grid \( G \), \( p \) clusters to correct the forecast of the chosen one and \( t \) for the most lagged time series values relative to time point \( t \). The cluster error after MSSA forecast is to be approximated with the following TARX formula with determined regime \( r \), \( r = r(t) \in \{1, \ldots, 4\} \), being a function of \( t \):

\[
e_i(C) = \beta_0 + \sum_{j=1}^{t} \beta_j e_{t-j}(C) + \sum_{i=1}^{p} \sum_{j=1}^{t} \beta_{ij} e_{t-j}(C_i)
\]

Authors also suggest some recommendations to choose clusters \( C_i, i = 1, \ldots, p \) to be appropriate to correct results for chosen cluster \( C \) which is referred to as a corrected cluster. Any \( C_i \) can be named a correcting cluster.

It is obvious to choose the most stable (consistent) clusters \( C_i \) which nodes provides only high positively correlated time series to time series of the selected cluster.

Let’s define some characteristics that can be used to determine correcting clusters:

1. **Cross-correlation coefficient (is to be maximized)** for pair of clusters is defined as the least value of that coefficient for any pair of nodes (one node from corrected cluster and one node from correcting cluster). As previously, the greatest value for pair of nodes (not clusters) can be obtained for nonzero lag. The only requirement is that correcting cluster dynamics is not permitted to have a delay relative to corrected cluster dynamics.

2. **Sum of cluster gradients scalar products (is to be maximized)**. Sum of all nodes gradients (finite differences of characteristic values for the pair of the nearest nodes) is determined horizontally and vertically at specified time point. Then calculate scalar product of gradients of potential correcting cluster and corrected one. Continue for several sequential time points before the first point of required forecast. Finally, add the results. The greatest sum reveals the most appropriate correcting cluster.

3. **Ration of singular values**. This characteristic represents some level of potential correcting cluster stability (consistency) for long time period (global time scale stability). Select a fragment of cluster multivariate time series. Create trajectory matrix for each univariate fragment and perform its singular value decomposition. Determine two node which provides the greatest and the least first singular value. Then make up ratios of the first and the second singular values for these two nodes. Continue for pairs 2-3, 3-4, etc. If ratios in pairs (for nodes with the greatest and for the least considered singular value) differ significantly cluster is not stable (consistent).

4. **Sum of variances (is to be minimized)**. This characteristic is introduced as measure of local time scale stability. For each node \( h \) differences of sequential time series values before the first forecast point are calculated. Then they are normalized by average (separately, its own for each node). Next step is computing the variance of those values of all cluster nodes for the first difference, then for the second, etc. Resulting \( h \) variances are added to get the final value.

Regime value in TARX model can be obtained as cluster gradient approximated to one of four possible directions.

VII. INPUT DATA FOR EXPERIMENTS

As stated in the article, heading input data is a set of sea level anomalies maps corresponding to particular area in the Barents Sea. A map is defined as spatial distribution of the characteristics reconstructed in specified grid nodes at chosen time point.

Area \( \Omega \) is restricted by 71°N – 76.4°N and 25°E – 44.7°E. Data source is international project Aviso [1] which have been distributing altimetric data worldwide since 1992. Since that date, satellite altimetry has evolved in parallel with the user community and oceanography. Nowadays reference portal located in France provides data, articles, news and tools to satisfy users requests concerning altimetry domain. Time period to deal with contains 365 sequential time points ended with August, 12th, 2013. Time series values vary from -15 to +15. The same data can be obtained if you know the mapping between degrees and Aviso counters. Use values 764 – 823 for latitude and 75 – 134 for longitude.

According to counters (resolution) and selected area, grid \( G \) is 60 by 60 nodes.

Primary forecast algorithm test for each cluster has the following steps:

1. Multivariate time series with length \( T = 365 \) is created.
2. Smoothing by moving average with window length equal to 5 is carried out for each univariate time series separately.
3. Forecast horizon \( h \) is accepted to be 5.
4. Select time point $t^*$ to be the first point of forecast.

5. Specify parameter $u$ as number of points for correction model ($u = 50$). The first correction model point is $t_0 = t^* - u$.

6. To make correction $u$ MSSA forecasts are used. Each MSSA forecast (Fig. 1) takes $T$ sequentially selected point with the best value of $L$ (MSSA parameter, number of trajectory matrix rows) and one time step ahead forecast error is calculated (to obtain $u$ values of error as a result).

![Fig. 1. Time spans of MSSA forecasts and correction](image)

7. One time step ahead forecast error is calculated by linear TARX model for $t^*$. Result forecast values for $t^*$ are adjusted by that error value. Adjusted numbers are used further in MSSA linear recurrent formula to get results up to $t^* + h$.

VIII. SOFTWARE AND EXPERIMENT RESULTS

Software tool for our prediction methodology is a rich client application implemented in Java in Eclipse RCP IDE that provides technology to develop user-friendly, flexible and highly customizable environment for experiments dedicated to solve forecasting tasks. It can be used either to get and visualize third-party information or to carry out real-time data mining calculations as decision support system. This rich client application can be deployed on a local machine, it can interact online with Web-resources and run stand-alone without a network connection.

Clustering algorithm results can be illustrated by Fig. 2 for sample grid of 20 by 20 nodes. Each node is represented with small rectangle. Initially it was divided into 16 clusters. Bold bounding rectangles are used for primary clusters (each of 16 clusters was divided into 4 primary clusters). Numbers show indexes of primary clusters that are retained because they are final clusters.

![Fig. 2. Primary clusters and combined resulting clusters](image)

Resulting clusters tend to grow horizontally for the chosen data as shown in Fig. 3.

![Fig. 3. Two coloured resulting clusters](image)

Number of clusters differs depending on the selected time span (results for grid of 60 by 60 are shown in Fig. 4).

- **time span** $T_1$: 236 clusters;
- **time span** $T_2$: 223 clusters;
- **time span** $T_3$: 195 clusters;
- **time span** $T_4$: 232 clusters;

![Fig. 4. Number of clusters for different time spans](image)

MSSA forecasts and TARX correction was carried out for some stable clusters. The grid $G$ (60 by 60) was divided into 4 regions and the greatest cluster was found in each of them. These four clusters (Fig. 5) have identical structure (set of nodes) for each time span mentioned above.

![Fig. 5. The greatest stable clusters in four regions of $G$](image)
Cluster from northwestern region (31st cluster) was chosen to be corrected cluster at some time point (t = 160). Fig. 6 represent table of values for different clusters characteristics. This table is used to define correcting clusters. List of columns identifiers is the following:

1. Cluster number.
2. Number of matched cluster gradients (5 is maximum possible value) for pair of the considered cluster and the 31st.
3. Cluster cardinality (number of nodes).
4. Square root of sum of variances.
5. Cross-correlation coefficient for pair of the considered cluster and the 31st.

As the compromise settlement, we can state the 32nd cluster to be the correcting cluster for the 31st. The 2nd and the 38th clusters have worse results but they are also better than others are.

IX. CONCLUSION

This article provides some basic ideas of developed by authors methodology of short-term forecast of sea level anomalies distribution using MSSA and TARX as forecasting tools and cross-correlation and spatial neighbouring criterion for grid nodes clusterization.

Some results are shown to represent the usage of the methodology for area in the Barents sea.

Further experiments and comparison with currently used methods will be carried out by authors in several years.

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Software Complex “OPTCON-M” for Atomic-Molecular Clusters Potential Optimization

Anikin A.S., Gornov A.Yu.  
Laboratory of optimal control  
ISDCT SB RAS  
Irkutsk, Russia  
anton.anikin@htower.ru

Andrianov A.N.  
Department of system and applied software  
Keldysh Institute of Applied Mathematics of RAS  
Moscow, Russia  
and@a5.kiam.ru

Abstract—The software complex OPTCON-M is considered, approaches and techniques that increase the reliability of the finding of a global extremum are suggested, the results of computational experiments on Morse potential optimization for clusters with record dimensions are presented.

Keywords—global optimization, numerical methods, parallel computing, Morse potential

Unconstrained minimization problem continues to be one of the main problems in the theory of optimization. Growing performance of modern computer provides opportunities for numerical study wide range of large-scale practical problems. One of such problem is finding low-energy atomic and molecular clusters. Such clusters can be obtained by minimizing the different potential functions - Morse, Lennard-Jones, Dzugutov and several others.

These potentials have a number of features that complicate their optimization. For example, the complexity of Morse potential optimization problem is associated with an astronomical increase in the number of local extrema - for the structure with 147 atoms, experts assessments is about $10^{60}$ [1]. However, modern optimization algorithms, running on high-performance computer systems can successfully find probable ("putative") solutions, which, seemingly, is a global extremes.

In the paper authors presents a program complex “OPTCON-M” for finding low-energy molecular-atomic clusters. This complex contains computational technologies, based on the Big-Bang [2], Basin-Hoping (MSBH), “Forest” and some other global methods. Quasi-Newton L-BFGS method and different versions of conjugate gradient method (Hestenes-Stiefel, Fletcher-Reeves, Polak-Polyak-Ribiere, Liu-Storey, Dai-Yuan, Dai-Liao, Hu-Storey and other [3]) are used for local optimization. Cauchy’s and Powell methods are used for correction of finded minimum.

Implementation of all methods made by authors with C++ language, program complex can works on Linux, Mac OS X and Windows platforms. Program code was build and tested with GCC, ICC and CLang compilers. Some of global optimization methods has effective parallel implementations, which made with using OpenMP, MPI and CUDA technologies. This allows running the software complex on a wide range of modern computing systems, including hybrid.

All described methods were deeply tested during big number of computational experiments. In this experiments was founded global minimums of Morse potential for clusters with sizes up to 250 atoms ($\rho = 3$). At present time the maximum size of cluster with known minimum is 240 atoms, this result can be founded in works of Y. Feng [4] and J.M.C. Marques [2]. The minimum from J.M.C. Marques now is better and was obtained by using Big-Bang method on supercomputer. The authors obtained this “best-of-known” minimum with MSBH method, using Big-Bang method, unfortunately, not allowed us to find global extremum for this cluster. Also, with using MSBH method we obtained new “best-of-known” global minimum for cluster with 241-250 atoms. All extremes were obtained by authors on personal workstations without using of supercomputers.

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The Architecture and Features of the Workbench for Domain of Ore Transportation in the Mines – Bundled Software “Rudopotok”

Chudinov G. V.
Aerology and Thermal Physics Department
Mining Institute of UB RAS
Perm, Russia
e-mail: gleb.chud@gmail.com

Kashnikov A. V.
Aerology and Thermal Physics Department
Mining Institute of UB RAS
Perm, Russia
e-mail: alexey.kashnikov@gmail.com

Mal’tsev M.S.
Aerology and Thermal Physics Department
Mining Institute of UB RAS
Perm, Russia
e-mail: mario-marat@mail.ru

Abstract—Architecture of workbench and its main features on pair with design decisions are reviewed. They contribute to the development of special software on basis of simulation system with focus in setting it on the subject area (domain) – ore extraction and transportation in underground part of mines. Article represents implementation process of proposed model (introduction of ore transformations an oreflow concept for simulation continuous conveyor-hopper transport in DES environment) and UI features in bundled software “Rudopotok”

Keywords — tool, UI, architecture, construction, model, network, ore extraction, transportation, conveyor, simulation

I. INTRODUCTION

In the post-industrial era science and specialized program tools play important role. Their use brings a competitive advantage and allows companies to increase their profits.

At the same time the success of the product and the efficiency of its use are determined not only by reliability, but also by the subjective usability. In turn, the understandability of the software largely depends on the natural representation in the program domain concepts and relationships between them. This is true at least for the user interface, but not only.

Based on research in the field of software development, mining, production and transportation of minerals (PI), a classic agent-based simulation model created and implemented in the "Rudopotok" [1, 2, 3, 4]. The project is developed in the AaTF department of MI UB RAS. Its special feature is the focus on the subject area in order to improve the naturalness of the program and depth of user experience - mining specialists.

A. Subject area

The core part of the program is detailed modelling and simulation for the transportation processes in mine network that is represented by mining areas (blocks) and bunker-conveyor system. The last one is used for ore underground conveyor movement up to endpoint – shafts. (Fig. 1). All simulation results are processed to provide recommendations for the mine design and equipment’ placement.

Moreover, we need to make natural representation of the transportation process, taking into account technical constraints imposed by mining equipment, because they have a significant effect on the applicability of the model. In particular, it is necessary to pay attention to technological and organizational downtime, production scheme, as well as streaming character of moving ore on conveyors and its capacity constraints.

Ore extraction scheme is presented by stratified camera system with shearer mining complexes. We need the possibility of applying an experimental equipment, such as a flexible conveyor or many self-propelled cars. Transportation is carried out for the mine conveyors with different performance and with ore accumulation in in the intermediate bunkers. It is also necessary to allow simulating the scheme with several unloading conveyors and shift their belt movement direction.
B. Analogs

There are static methods of calculation of ore mining [5]. Also, there are papers describing the dynamics of the process based on Petri nets [6] and some others [7, 8]. However, they have several drawbacks. First, do not take into account the time component needed for detailed planning. In addition, they do not consider the physical limitations. Often concentrate on moving other type of PI on a conveyor network, without attention to the processes of production and reception capacity constraints of real equipment, such as conveyor belt and hopper volume. Therefore, complete solution to all noted problems and specifics does not exist.

In addition, a large number of mining methods of PI, kinds of mining operations do not allow use of already existing solutions. Must be able to expand and build model to account for the specifics of the particular conditions. Therefore, it is advisable to use an agent-oriented paradigm [9].

There are software packages, such as Repast, Net.Logo, etc. [10] to facilitate the development of an application of ready-made components. The most developed is considered to be AnyLogic [11]. However, the cost, the degree of development and the need for in-depth development of both the specific model and the rich user interface, nullify their benefits.

II. Rudopotok Features

“Rudopotok” allows storing transport networks for mines after building and editing them. The last two aggregated actions are possible via clicking and moving appropriate visual objects and operations with them on UI. On complete transport scheme after automated checking of inputted parameters for whole network, we can run not only single simulation experiments, but also their series. Computation experiment allows to collect and to obtain statistical data on the objects of the transport scheme. Therefore, we can view the results in graphs and tables (Fig. 2).

Additionally program animate processes of extraction and transportation of ore and all the way around the mine. It calculates optimum parameters such as minimally required amount of bunker transhipment point, the average effective capacity of the conveyor – all based on a series of computational experiments.

![Graphs simulation results on schema objects.](Fig. 2)

III. System Architecture

The basic concepts and design decisions were improved along with software development and the domain knowledge extraction (ore transportation in underground part of mine). This fully corresponds to the iterative nature of agile software development.

In the operation of the system is logical to distinguish static aspect, describing the basic elements of the model, and dynamic - performed operations, and useful analytical part. Processes in the shaft shown in conveyor transport schema (object-oriented). It specifies the structure of the transport network - blocks, conveyors, transfer points and the links between them (Fig. 3).

A. Dynamical part

Modeled in detail the process of extraction of ore in mining areas, presented in blocks. Algorithms implemented in relevant objects (combine, self-propelled car). Naturally modeled in detail the operation of machines (working stroke, moving, ore extraction, outgoing, unloading in ore passes and to cars), their interaction and mining stages (Fig. 4). As input parameters, the actual physical and technical data mining machines, obtained from their passports.

![Scheme mining ore in the chamber by combine and self-propelled car.](Fig. 4)
B. Ore

The main object of interest in the program is the movement of ore, starting from its production and finishing lifting ore on the ground by shafts. In terms of simulation – ore is the main entity, need to be represented on the one hand natural, and the other - quite effective. After talking with experts revealed that the ore has properties such as weight / volume and qualitative content of mineral in it. Customer needs this information.

However, any special concepts to simulate the movement of PI through conveyor-bunker system and self-propelled machines, transfer bunker and ore passes, did not exist. Also must take into account that during PI move through pipelines need to control the height of the ore, to prevent overflow pipeline - this causes an essential equipment downtime and loss of enterprise profit.

C. Ore arithmetic/transformation

Thus, there are two views of the ore. One - the final volume called a bunch of ore (OrePile) and characterizes the quality and weight required for accounting by self-propelled cars and bunkers. Other - of a certain length and height, as well as weight and quality, located on the conveyer (OreSegment). In addition, they must be converted between each other, including among themselves on overload from the bunker-loader in a self-propelled car. From the cars to ore passes, from ore passes on the conveyer, of the conveyer into the bunker, with the accumulation of ore in it.

Ore arithmetic operations involves heaps of ore, such as merging and splitting in a certain proportion. Moreover, convert piles of ore into the conveyor segments, and merge / separation into smaller segments or large segments of the conveyer, and the transformation of segments in the heap of ore bunkers at accumulation (Fig. 5).

![Fig. 5. Ore presentation with operations. Left (violet) – ore pile. Right - (orange) – ore segments.](image)

Strongly influenced by the decision to use specialized classes to represent the qualitative indicators, such as mass, volume, performance, speed, instead of the traditional real values. This greatly simplified the questions to convert units of measurement and increased reliability of software.

In addition, it became necessary to improve classical discrete-event simulation (DES) and avoid its discreteness to accommodate ore streaming nature on conveyors. Thus, when sufficient bandwidth of the hopper it should be not ore at any time. At the same time, straightforward using of DES indicates the presence of small amounts of ore in the bunkers on the border of time steps – it causes errors and not correct/valid – in real we must have continuous flow.

D. Oreflow

Overcoming the limitations of DES for streaming nature require the use of finite decomposition paradigm when modeling step divided into smaller substeps of arbitrary length. So appear of the notion of flow of ore (OreFlow). It is a sequence of simple flows ore productivity during the time step, while having quality and weight, i.e. characteristics of the ore heap (OrePile) (Fig. 6, left).

![Fig. 6. Production intensity. Left - incoming / outgoing. Right - structure.](image)

At the same time, for oreflow were applied the merge / separation operations. Their importance was discovered later to solve the general problem of simulation overload ore through one hopper intermediate point (PP), coming from several pipelines and discharged several pipelines (Fig. 6, left).

Usually hopper used to merge multiple streams of ore on one pipeline, greater productivity - for example, the trunk. Sometimes you need to unload ore from the hopper to the conveyer several branches - you need when filling pipelines and having more uniform performance.

E. Ore flow on conveyors

Solving the most common problems with an arbitrary number of incoming and outgoing conveyors elegantly turned out in the framework of streaming arithmetic. When entering the bin has a complex input stream of ore. In the middle (in the bunker) are unloading devices (UD), bandwidth limiting and separating the flow of ore to several complex outflows. When their performance is not enough, the ore is stored in a bunker in a natural way. The advantage of the solution is the ability to change the performance of UD at the boundaries of time steps and the ability to dynamically control the process of moving the ore in the mine and control filling of conveyors.

Thus, to represent the movement of ore used concepts connected entity, defined for them arithmetic, allowing a natural way to express complex behavior of objects with conveyor-bunker working logic. This takes into account the capacity of the conveyor, bunkers and unloading device performance.
IV. TECHNICAL DECISIONS

A. Ore presentation on conveyors and optimization

To overcome the technical limitations of memory volume and to optimize the speed of calculation a number of improvements were taken. In particular, ore segments adjacent to each other and of equal height and quality are combined into a single segment. To simplify verification of conveyor belt filling the concept anticircuit was introduced. It determines how much space is left on height for loading ore. Depending on the source of incoming ore to conveyor, ore can either wake up beyond it, leading to undesirable consequences in terms of the process of mining, or accumulate in the bunker, waiting for the next available space. At the exit, we have a two-dimensional model of the conveyor belt (Fig. 5).

Fig. 7. Ore presentation on conveyor belt.

B. Optimization of ore presentation. Facts

In fact, experience has shown that the use of linear segments and heaps of ore on the computer difficult. There are problems with rounding integers, limited memory on your computer (especially with decreasing time step) and the need to control height restrictions. In particular, for the simple scheme RU-4 (30-40 + 30-40 PP pipelines, 10 blocks units) and the time step of 10s. The program took away more than 4 GB of memory. In addition, tens of minutes required for one run. Made optimizations make it possible to run much faster and use less memory (~ 1GB for complex networks).

V. CONCLUSIONS

Briefly presents the development "Rudopotok", which is a specialized tool for working with the subject area of mining - mining and transportation of ore in underground mines of the conveyor-bunker way. Showing the architectural features of modeling the process of moving ore and its simplification by crystallization of concepts and give them a natural look. This way of presenting the ore can be considered as an analytical template to work with similar areas. “Rudopotok” took the stage calibration, verification, validation; tested on JCS Evrokhim networks and BKPRU-4 JSC Uralkali.

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Determination of Surface Roughness Using Three-Dimensional Graphics

A. Dairbayev, B. Belgibayev, S. Dairbayeva
Scientific-Research Institute of Mathematics and Mechanics
Al-Farabi Kazakh National University
Almaty, Kazakhstan
e-mail: dairal@mail.ru; bbelgibaev@list.ru; sabina.dairbaeva@mail.ru

Abstract—Roughness of the inner surface of the concrete shaft spillways of hydrotechnical constructions can produce a significant impact on the turbulence of the water flow in the swirler. This can lead to the formation of "oblique waves", vortex shedding and water streams overlapping of water streams. And these phenomena increase shaft wear and lead to its destruction. The situation is exacerbated by the fact that the roughness measurement of the inner surface of the shaft is very inconvenient, eventually its destruction is caused, and potholes, chips and cracks are formed. The proposed method of determination of the roughness is based on three types of measurements. This is the measurement of the geometric dimensions of the physical model of the surface roughness, 3D Laser Scanning and the use of photographic images processed in 3D Max system. The latter method is rather new and can be applied in different fields of science. The discrepancy in the outcomes of the roughness determination does not exceed 5%.

Keywords—hydrotechnical constructions, shaft spillway, tangential swirler, roughness surface, oblique waves, overlapping, tacheometer.

I. INTRODUCTION

Determination of surface quality and surface roughness is an urgent task in many areas, particularly in hydrotechnical constructions (HTC). This happens due to the fact that the roughness of the inner surface of the concrete shaft spillways can make a considerable impact on the turbulence of the water flow, especially in the initial section in the swirler, as over a period of time its destruction occurs. Therefore, it is especially important to monitor the condition of the entire HTC.

At the present time there are many new technologies in the field of waterworks scanning. These technologies are based on the use of laser scanning systems. Laser scanning technology is based on a high-precision measurement of the distance from the laser rangefinder, located in the 3D scanner, to the surface of the scanned object and the determination of two angles (horizontal and vertical), which decide on the vector direction from the laser rangefinder to the scanned object's local coordinate system. The problem of wide application of the laser scanner is its high cost, so in practice digitial tachymeters, which have the same functions as the laser scanners, are normally used. The only difference is that although accuracy of measurements made with modern electronic tachymeters is comparable with 3D laser scanners, the scanner performance is up to thousand times higher.

Laser scanners can greatly simplify the work on creation of an accurate 3D-model of an existing object. As a result of the measurements, we obtain the spatial coordinates of an array of points (point cloud), the position of which is determined on the surfaces of objects within the working area of the scanner.

The basic purpose of 3D scanning of HTC consists primarily in determination of the operational surface roughness, detection of potholes, chips, cracks and visible shaft spillways erosion and getting the picture of the HTC model with its subsequent monitoring (Fig. 1).

![Fig. 1. 3D-model of the spillway dam](image)

The importance of measuring the surface roughness is in determination of the state of the shaft surface, where the water flow turbulence occurs, causing the formation of "oblique waves", vortex shedding and overlapping of water streams, which lead to increased shaft wear up to a complete destruction of the dam.
II. MATERIALS AND METHODS

The turbulent flow regime is characterized by intense mixing of the fluid in the transverse direction (across the stream) and longitudinally (along the length of the flow) directions. In the boundary layer are the swirles formed which penetrate the turbulent core, increasing the intensity of mixing of individual fluid particles forming cross flows. The turbulence usually is formed when some critical Reynolds number exceed. According to the Nukiradze graph, such condition is can appear when the coefficient of hydraulic friction will depend only on the surface roughness (Fig. 2, curve 5) [1]. So, in this way a self-similar region or zone of the quadratic resistance is formed.

![Fig. 2. Nukiradze graph](image)

As it is seen in Fig. 2, In Re < 2300 (lgRe <3,36) line 1, we have laminar where λ depends only on the Reynolds number and is independent of wall roughness.

When Re> 2300 ÷ 4000 (lgRe = 3,36 ÷ 3,6) curve 2, there is the fast transition from laminar to turbulent flow. Curve 3 is characterizes the dependence of λ on the Reynolds number for surfaces which roughness amplitude is less than the thickness of the laminar water film near the wall. Next the curves λ and Re diverge. Hydraulic friction coefficient λ depends on the roughness and Re (zone curves 4-5).

Roughness has the main impact on the coefficient of hydraulic friction and is determined by the amplitude (absolute roughness Δ in Fig. 3) [1].

Also, the coefficient of hydraulic friction essentially depends on the position the roughness and shape. Therefore, concepts of equivalence and relative roughness were introduced.

The offered method of determining the roughness is based on three aspects of measurements. This is the measurement of geometric dimensions of the surface roughness of the physical model in a plaster cast, 3D laser scanning and the use of the photographic images processed in 3D Max systems.

Methods of determining the roughness using a physical model proved inaccessibility of measurements inside the shaft spillway.

Fig. 3. Types of roughness

The procedure consists in the measurement of surface roughness on a physical model by means of a micrometer. The produced plaster cast allows to compare the surface roughness, which was obtained with the help of 3D laser scanning and photographic images processed in 3D Max systems, with the real surface roughness of the object. For this purpose, a grid of thin plexiglass with corresponding geometrical dimensions of length and width was placed over the plaster cast (Fig. 4). The height (depth) was determined with a micrometer.

![Fig. 4. Plaster cast surface of HTC (18 to 25cm), cast partition with a grid (a pitch 0.5 cm).](image)

Although there are many methods, techniques and devices, including contact and contactless methods, for determination of surface roughness, generally when measuring the surface of micron range, we used the simplest method, sufficient for purity of the experiment, especially as the measurements were made in the millimeter range [2, 3]. As a result, the received point cloud was processed in AutoCAD, Matlab, 3D Max systems, and 3D laser scanning system (Fig. 5).

The principle of 3D scanning using a digital tachymeter is quite well-known, however, the results processing is carried out in different ways [4]. In our case, for the processing of scanning data the multifunctional software Topcon Image Master for IS is used.

Scanning, measurement of point cloud (Fig. 6) and photographing of the object are produced by means of the WiFi connection between the laptop and the tachymeter.
Determination of surface roughness by photographic images is relatively new and little explored. The basic idea of this method is to obtain photographic images of the surface roughness, processing it in the system of three-dimensional coordinates, getting the point cloud and modeling using the known tools. For this, a program such as PhotoModeler can be used [5].

The advantage of the method is obvious. First of all, it gives an opportunity to scan not the whole area, but the part where the surface damage is visually spotted. This is possible after receiving video or photo materials of the investigated surface, especially in hard-to-reach places. Besides, this method can be applied in the determination of surface roughness in the "micro" and "nano" range, avoiding the use of various time-consuming and quite expensive methods.

III. RESULTS

For creation of roughness in 3Ds Max systems we photograph a fragment of the cast of the shaft spillway concrete surface. Initially, we create an object, a concrete wall, for instance, and then import the image photographed before. Then we immediately set to work on modeling (Fig. 8).
By using 3Ds Max functions measuring the roughness parameters is possible, but application of Topcon Image Master Program is preferable, because there you can get the coordinates of points of the received cloud. In order to compare these methods and determine the surface roughness it is necessary to convert the object model from Autodesk 3Ds Max into Topcon Image Master Program. To do this, we get the object meshed, receive a point cloud, process it with Topcon program and obtain the coordinates of points (Fig. 9, 10).

Fig. 9. Processed point cloud by means of Topcon program.

Fig. 10. The coordinates of points.

Having a point cloud it is possible to determine root mean square value of the roughness and analyze the quality of surface applying the known methods and formulas.

As a result of research was produced three models to determine surface roughness and quality (Fig. 2, 4, 6).

Fragment surface roughness graphs shown in Fig. 11. Graphs were constructed according to the point cloud of the roughness, when measured with a the physical model, tachymeter and photographs.

Fig. 11. Fragment surface roughness graphs

IV. CONCLUSIONS

Analyzing the results and comparing figures 4, 5 and 7 we draw the following conclusions:

- the surface roughness obtained by means of the geometric dimensions of the surface roughness of the physical model in a plaster cast, also 3D laser scanning using the tachymeter, and the use of photographic images processed in 3D Max System are identical;

- the discrepancy in the results of scanning and measurement of the physical model is 3-4 %;

- the discrepancy in the results of processing of photographic images in the system of three-dimensional graphics and measurements of the physical model is up to 5-6 %;

- on the basis of the research data it is possible to create workstations for monitoring HTC.

REFERENCES


Software OPTCON-A for Solving Nonconvex Problems of Parametric Identification of Dynamical Systems

Gornov A. Yu.
Laboratory of Optimal Control
Institute for System Dynamics and Control Theory of SB RAS
Irkutsk, Russia
e-mail: gornov@icc.ru

Abstract — We present the software OPTCON-A, which is intended for the computational solving of nonconvex problems of parametric identification of dynamical systems. A number of applied problems from the different areas, such as flight dynamics, robotics, energy, economy, ecology, medicine and nanoscale physics was successfully solved by using this software. The results of numerical experiments are produced.

Keywords — Software, parametric identification, dynamical systems, optimization methods.

The problem of parametric identification of dynamical systems can be considered as a special finite-dimensional optimization problem with a functional computed on the solutions of an ordinary differential equations system, and as an optimal control problem with the control which is do not depend on the time variable. This problem is non-convex in the general case. Its solution is difficult to obtain by using classical mathematical approaches based on the theory of mathematical programming and the Pontryagin Maximum Principle.

The report discusses the functional content of the software OPTCON-A, which is intended for the computational solving of nonconvex problems of the investigating class. The library of algorithms includes both methods of global search and local methods that are used to improve the accuracy of solutions in the neighborhood of local extrema (see, for example, [1]). A set of nonlocal methods includes parabolas method which is based on a combination of coordinate descent algorithm with algorithms of one-dimensional search, tunneling method which efficiently allows to look through local extrema, spherical search method based on direction finding of global reduction function, the nonlocal method of Powell-Brent. Local algorithms include several variants of the conjugate gradient method and the LBFGS method. We use the modified adaptive algorithms proposed in [2] for the numerical approximation of gradients. Service part of the software includes a set of standard integration methods, aimed at both non-rigid and rigid systems (DOPRI5, DOPRI8, RADAU, RADAU5, LSODA algorithms and others). It is implemented the dialogue system allowing us to customize algorithmic parameters, construct computational multimethod scheme, verify the accuracy of integration and system's discretization, and perform post-optimization analysis for organizing the interactive modes.

The properties of proposed software are investigated by applying a collection of test problems. A number of applied problems from the different areas, such as flight dynamics, robotics, energy, economy, ecology, medicine and nanoscale physics was successfully solved by using this software. The results of numerical experiments are produced.

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REFERENCES

Universal Software for Conversion Discrete Sequences to Continuous Relationships

Mityukov V. V.
Software Engineer of Computer and Information Department
Ulyanovsk Higher Civil Aviation School (Institute)
Ulyanovsk, Russia
e-mail: v.mityukov@gmail.com

Abstract— In the tasks of modeling and computational experiments, it is desirable to use as possible universal algorithms. In this paper we propose a similar approximation algorithm given in tabular or graphical specified relationships of implementing further operation of differentiation and integration is.

Keywords— numerical method; linear equations; homogeneous system; LU-decomposition; programming system

Approximation of such an algorithm based on the traditional linear model – \( y(x) = \sum C_j \cdot \phi_j(x) \), composed of fragments analytically calculated – basis functions \( \phi_j(x_j) \) \((j = 1, 2, \ldots n)\), for example, members of a power series, or member of a number of Chebyshev, Fourier series, ... May be added that the results of operations of differentiation and integration of this linear model are also linear.

Results are determined by interpolation or smoothing conditions [1] in system of points \( x_i \), \((i = 1, 2, \ldots m)\). Interpolation conditions – this is the exact compliance of equals \( y(x_i) = y_i \) at these points. While smoothing minimizes the sum of squared deviations of \( y(x_i) \) by \( y_i \) at specified points (least squares method). Both of these conditions lead to systems of linear algebraic equations. If there are measured values of the inclines of tangents and/or values of the integrated areas \( Y_i \) at certain intervals, there are no obstacles for the addition of the original system of equations, rows (equations) \( y'(x_i) = y'_i \) and \( Y(x_i, x_j) = Y'_i \).

Versatility algorithm achieved on the basis of the conditions of existence of non-zero solution of the homogeneous linear system with the matrix \( H \), that is, the condition \( \det(H) = 0 \) [2]. Initially the original system of linear equations is extended to homogeneous form. Then, the prepared matrix \( H \) is applied algorithm of its LU-decomposition, without moving the bottom line. Accumulated in the bottom right zeroed Block matrix (row or column), linear combinations of discrete values, determines the desired value of the result. The results obtained allow two categories of linear representation:

1) with the calculated coefficients of the a priori defined basis functions \( \phi_j(x) \)
2) with calculated weight functions for a priori given discrete values \( y_i \).

Preliminary testing of the above algorithm is performed in an office program "MS Excel". Introduced a set of discrete data to the receiving system of basis functions, chosen approximation method to set the necessary values of the constants \( m \) and \( n \), the results prescribed category. Building the augmented matrix \( H \), its processing and calculation results stated above were performed by software. The necessary macros and subroutines implemented in embedded programming language VBA, with output to display on tables and charts.

REFERENCES

Simintech for Automated Process Control System Development

Parshikov I., Baum F., Petukhov V., Shchekaturov A., Timofeev K.
3V Services, LLC
117105, Moscow, Varshavskoye shosse, building 1, office 13
RUSSIA
e-mail: info@3v-services.com

Abstract— One of the basic and challenging tasks in development of automated process control systems is the development of a control system that includes many cooperating subsystems. Evolution of microprocessor technology and increase in computational capabilities of controllers allows to implement more sophisticated and complex control algorithms with regard to all system measured variables. Sophisticated and complex control programs comprising a large number of control algorithms, controllers, software protection solutions and interlocks can be executed in real-time mode under control of real-time operating systems (RTOS). As the complexity of programs increases, software developers need new up-to-date development tools. In particular, it is essential to provide verification of control programs by the preliminary mathematical simulation of process flows and control processes.

Keywords— APCS, control system, PLC, SimInTech.

I. INTRODUCTION

The nuclear power plant is a complex object featuring the automated process control system that is not a standalone system but operates as a part of more complex system. Design solutions required for the APCS development should be based on the best practice considering operation of the NPP as a whole. That is why, it is critically important that the complex dynamic model of the object should be used for development of the control system.

The SimInTech process systems dynamic modeling environment is the multi-purpose automated computational system for complex modeling of events and processes at nuclear power plants and also at any other process facilities.

The SimInTech software suite allows to implement the model-oriented design approach that gives the developer the following advantages:

1) local modeling of operation of algorithms and controllers together with the object model at any stage of life cycle to enable preliminary debugging and testing at the design stage;

2) automatic and verified translation of algorithms to the target system while excluding the human factor that may affect team work of programmers and process engineers;

3) remote monitoring of algorithms execution in the process of testing of the hardware and software complex of the automatic control system (ACS HSC) and final debugging and setting of controllers;

4) automated code generation that allows to dramatically reduce the repeated iteration process of algorithm debugging required to achieve the final bug-free state;

5) exclusion of the human factor aspect by developing the control system model and algorithms in the same development environment;

6) process animation used in development of video frames that allows to set up controller variables, control algorithms in the process of operation of the complex model and correct functioning of algorithms.

This Project is based on the existing design and debugging experience of algorithmic programming and software solutions for the reactor building automated control system (RB ACS) at the operating NPP. This Project is also based on the end-to-end design approach – using the unique development environment to develop the control system algorithms, automatic generation of these algorithms to the target system, development of software for the programmable logic controller and transfer of this software to the end user, i.e. to the hardware of the operating NPP.

SimInTech software has been improved to development APCS software.

II. HARDWARE-SOFTWARE SYSTEM

Hardware-software system for reactor compartment automatic regulating system includes two control racks with backed up processor modules. Processor modules are combined within two independent LANs integrating computation means for each of the two channels. Each channel is composed of:

- low-level processor modules;
- archive server;
- engineering top-level station;
- gateway for data transmitting to external systems;
- functional units ensuring data collection from sensors and generation of control signals to controls (gate valves, pumps).

Topological layout of computation means is presented in Fig. 1.

![Topological layout of computation means](image)

**Fig. 1.** Typical layout of hardware-software system

Low-level processor modules provide direct calculation of regulators. Processor modules and archiving servers are configured on the basis of serial x86-compatible computers with OCPB QNX 6.5 installed and executable real-time environment NordWind (a part of SimInTech).

Processor modules interrogate functional units, acquire and process collected data, generate control signals and, in addition, transmit collected data via LAN to the archiving server.

Archiving servers provide writing of signals acquired by low-level processor modules in archive, and access to written data from the side of top-level software.

The gateway enables controllable access to data in the system from the side of external systems.

Engineering station is to control Windows OS and is configured on the basis of serial x86-compatible computer. Top-level software based on SimInTech is installed on that, which provides the following composed function:

- making up process and diagnostics algorithms in graphical form;
- generation and preview of process and diagnostics video frames;
- entering setting coefficients for models of regulators functioning at the low level;
- hardware configuration;
- emulation of operating modes of hardware-software system for reactor compartment automatic regulating system;
- scanning of process and diagnostics information archives;
- acquisition of status data on process equipment, software and hardware facilities related to the hardware and software system;
- display of process and diagnostics alarms on video frames;
- execution of service functions.

Software developed within SimInTech enables emulation of all operating modes of hardware-software system for reactor compartment automatic regulating system and can be optionally installed on PC not included into the set of the hardware and software system. In general, the system can serve 29 regulators with 100 Hz sampling rate and writing of over 5000 real-time archive parameters.

### III. PROVISION OF AUTOMATED PROCESS CONTROL SYSTEM SIMULATION

To provide the functional for designing APCS the following options have been implemented in SimInTech during its simulation:

- channel restoration system;
- execution of a sub-model/writing a signal against a preset condition;
- optimization of serial sorting of a model.

#### A. Channel restoration system

As a rule a control system includes a large amount of flip-flops, integrators and other units that are provided with both calculated state variables and operator-configurable...
parameters (time constant, gain factors, etc.). In the process of operation variables and parameters contain current values resulting from calculations and accumulation of history of parameter changes made by the operator. On start-up of the system these values are set up by default on the basis of their initial values. If the system is rebooted, then values accumulated as a result of operation will be lost and replaced with initial ones.

In case of operation of two or more similar parallel control channels (with the same processor modules and the same control algorithms) to back up one of those in case of rebooting, values of state variables and parameters in channels will be different, and the channels will transmit different control commands against the same input signals (with the same parameters of controlled object). To achieve a unified state of the channels a time will be required, within which internal variables of a channel to be rebooted will accumulate approximately the same values as variables in control channels operating without a stop, and the operator will introduce changed parameters.

Implemented channel restoration system, on entering a new parameter by the operator, will save the state of its parameters into a file, while processor module will be read out by it in the process of rebooting; then parameters and current state variables will be copied from the processor module of a control channel operating in parallel. Thus, buffer variables and their checking for correctness during execution of a submodel against a preset condition are running only in the moment the button is pressed by the operator rather than continuously. At the same time adjustment ratios are copied from the buffer variable into operating one only when the two following preconditions are met: system checking is successful and operator’s confirmation is obtained.

Such algorithms are placed in sub-models, which are run only on generation of an external condition, thus, allowing processor time to be essentially saved.

This system and its algorithms have been developed to ensure adjustment of control by operator in standard mode without stop and re-programming of processor modules.

To exclude that an option of execution (there are more than 8000 available tuning parameters in this example) of sub-models and/or signal writing against an external condition has been implemented.

Modification of composed function of SimInTech modeling core is carried out to implement adjustment ratio entry system. Processing of new ratios entry in the system relies on the low level of APCS in order to ensure protection against incorrect entry of parameters. Single test of a new parameter at one cycle of algorithm running) is executed as follows: the operator enters a new parameter value that is transmitted to the controller, then it is checked for correctness followed by display of testing results. Then the operator either accepts the new parameter value by pressing the confirmation button, or cancels the entry. New parameter value checked in the controller and confirmed by the operator replaces the old one and is accepted for operation.

Fig. 2. Video Frame of Pressure Controller (Selection of Measurement Channel)

Implemented channel restoration system, on entering a new parameter by the operator, will save the state of its parameters into a file, while processor module will be read out by it in the process of rebooting; then parameters and current state variables will be copied from the processor module of a control channel operating in parallel.

This algorithm excludes delays in restoration of values of parameters and variables and starts operation of a restored channel without any mismatch at outputs with operating channels (“impact-free” mode).

B. Execution of a sub-model/writing a signal against a preset condition

Continuous waiting “for writing” available in the parameter entry system for a large number of parameters from the operator (actually, from a video frame), as well as “no-load” operation of check algorithms for entered parameter correctness will result in vain essential consumption of processor time and in performance loss.

If adjustment is required, the operator can activate a video frame of a needed controller and enter a new parameter value...
in a required interface. Entered value is sent to the processor module and written in buffer variable and checked for correctness. In case all checks are successfully completed, the operator is suggested via the video frame interface to confirm the parameter entry by pressing the second button (otherwise the entry is blocked). On confirmation, the new checked value in the processor module is copied from the buffer variable into the selected parameter variable. Starting from this moment only the new parameter is actually enabled.

Fig. 4. Video Frame for Adjustment of Parameters of Standard Level Controller in Pressurizer

C. Optimization of serial sorting of a model

Implementation of this option excludes any cycle-wise delay when using signal writing and reading units within one processor module.

When designing a set of algorithms of different degree of complexity, which shall operate together, those, as a rule, are divided into functional plans using some criteria. Each functional plan is a conceptual completed algorithmic unit that includes input and output signals. Output signals of a functional plan are calculated in this algorithm, written in signals (named project variables) and used as inputs in other functional plans.

With such a task assigned, output variables of all functional plans are calculated in every cycle of calculation, and their calculated values will be used at particular inputs of other functional plans in the next cycle of calculation. If signal path passes though N functional plans, then N cycles will be required for generation of a “correct” output signal of the extreme algorithm, which slows down operation of the automated control system and degrade the quality of control.

In SimInTech environment “binding” of different functional plans in a single algorithm and optimization of sorting of project units have been implemented (actually, expanding of all functional plans located in different sub-models, on one plane), in the process of which no delay for cycle(s) is occurred, when a calculated variable is used within the same processor module.

IV. CONCLUSIONS

Presented experience of designing and adjustment of algorithms and software for reactor compartment control system for NPP in operation confirms the effectiveness of a mixed-mode development of control system with integrated dynamic model of an object in uniform design environment. Main advantage of such approach lies in verification of control programs by means of preliminary mixed-mode mathematical simulation of processes and control algorithms.

The applied method of throughout design allows control system algorithms, on being designed, to be automatically generated for a target system with the next following creation of software for PLC and its handing-over to end consumer, i.e., hardware of NPP in operation.

The following options have been implemented in SimInTech: channel restoration system, execution of a model against a preset condition, controller parameters enter algorithms, optimization of serial sorting of a model and channel validity check. Modernization performed allows NPP APCS to be simulated in full.

Technology of APCS design in SimInTech enables optimization of design solutions, unification and duplication of a project, improvement of grade of manufacture, CAPEX and OPEX decrease and creation of a soft version of a project.

References


Using ISMA Simulation Environment for Numerical Solution of Hybrid Systems with PDE

Shornikov Yu. V., Bessonov A. V., Myssak M. S., Dostovalov D. N.
Automation and Computer Engineering Department
Novosibirsk State Technical University
Novosibirsk, Russia
e-mail: shornikov@inbox.ru, abv.poste@gmail.com, maria_myssak@mail.ru, dostovalov.dmitr@mail.ru

Abstract — A class of hybrid systems (HS) with system of partial differential equations is considered. Architecture of instrumental environment is designed in accordance with CSSL standard. Algorithms of finite difference method for the transition from PDE to ODE system are given. Universal data structure for storing HS models has been designed and proved. Example of specification and analysis of ozone concentration models is given.

Keywords - Hybrid system, system of PDE, software architecture, autogenerated parsers, antlr4, finite difference method.

I. INTRODUCTION

Modern systems of instrumental simulation usually have an extensive set of subject-oriented specification languages. They use unified analysis algorithms due to using a common mathematical software. In this paper we propose a new system architecture of ISMA (that in Russian means Instrumental Facilities of Machine Analysis) based on the methodology of hybrid systems (HS). This article examines a new application of ISMA – systems of partial differential equations (PDE) with constraints. PDEs are used to describe processes in the chemical-technological systems, elasticity problems, etc. To achieve this goal a series of consecutive problems is solved: the textual specification of ISMA environment models expanded by constructions describing PDEs; a special data structure for storing the model in memory is developed; approximation algorithms are implemented for transition from a system of PDE to ODE system. Analysis of ODE system is performed by methods included in the library of the environment.

II. CLASS OF SYSTEMS

There are many systems (mechanical, electrical, chemical, biological, etc.), the behavior of which can be conveniently described as a sequential change of continuous modes [1]. These systems are referred to as hybrid or event-continuous. Each mode is given by a set of differential-algebraic equations with the following constraints:

\[
y' = f(x, y, t), x = \varphi(x, y, t),
pr : g(x, y, t) < 0,
t \in [t_0, t_1], x(t_0) = x_0, y(t_0) = y_0,
x \in R^N, y \in R^N, t \in R,
f : R^N \times R^N \times R \rightarrow R^N,
\varphi : R^N \times R^N \times R \rightarrow R^{Nc},
g : R^N \times R^N \times R \rightarrow R^5.
\]

The vector-function \( g(x, y, t) \) is referred to as event function or guard. A predicate \( pr \) determines the conditions of existence in the corresponding mode or state. Inequality \( g(x, y, t) < 0 \) means that the phase trajectory in the current mode should not cross the border \( g(x, y, t) = 0 \). Events occurring in violation of this condition and leading to transition into another mode without crossing the border are referred to as one-sided. Many practical problems are characterized by stiff modes, and the surface of boundary \( g(x, y, t) = 0 \) has sharp angles or solution has several roots at the boundary. Numerical analysis of such models by traditional methods is difficult or impossible, as it gives incorrect results. Therefore it is necessary to use special methods to detect events accurately.

This class of systems is expanding by the addition of boundary conditions for PDEs [2]. Continuous behavior of HS is determined by the systems differential-algebraic equations and PDEs. In the proposed implementation the equations with the maximal order not higher than second are considered. Applied algorithms do not impose a restriction on number of variables – i.e. their number is theoretically unlimited. Nevertheless should take into account that the introduction of each new variable leads to a tremendous increase in the number of equations generated as a result of the finite differences method. Therefore the real limit on the number of variables is imposed by computing resources: computer software as well as computer itself. The considered equations are nonlinear type. The linear equation are also supported and regarded as a narrow equations type.
In this paper we consider the type of nonhomogeneous PDE. The coefficients used in partial differential equations considered in this paper can be either constant or variable. This paper discusses the parabolic type equations. Boundary conditions of considered problems must be rectangular area $\Omega$ – rectangle, parallelepiped, etc.

Thus, the proposed expansion of the instrumental environment designed for the analysis of PDE type equation (2): heterogeneous, non-linear, second order, with constant and variable coefficients, with an unlimited number of variables $N$ and limited by $N$-dimensional rectangular grid.

$$\frac{\partial z}{\partial t} = \psi \left( x, z, t, p, \frac{\partial z}{\partial p}, \frac{\partial^2 z}{\partial p^2} \right),$$

$$x = \varphi(x, t),$$

$$pr: g(x, t) < 0,$$

$$x(t_0, p) = x_0, z(t_0, p) = z_0,$$

$$t \in [t_0, t_n], p = \left[ p_0, p_n \right],$$

$$\frac{\partial z_0}{\partial n} = \bar{z}(p),$$

$$x \in R^N, z \in R^N, t \in R, p \in R^N,$$

$$\varphi: R^N \times R \rightarrow R^N,$$

$$\psi: R^N \times R^N \times R \times R^N \times R^N \rightarrow R^N,$$

$$g: R^N \times R \rightarrow R^N,$$

where $n$ denotes the normal to the boundary and $\bar{z}(p)$ is a given function.

III. ARCHITECTURE OF ISMA

Development of simulation languages, simulators, simulation systems, etc. is essentially influenced by the CSSL (continuous system simulation language) Standard 1968 [3]. Although forty years old, the structures defined in CSSL Standard are used up to now. End of 90ties, CSSL extended to implicit systems, while a new modelling language, Modelica, was introduced. In principle, the modelling paradigm changed from signal flow – oriented modelling (explicit systems) to power – oriented modelling (implicit systems), from “causal” signal modelling to “acausal” physical modelling. The early CSSS standard determined basic necessary features for a simulator, the late developments to implicit systems fixed extended features for simulation systems – both referred as classical CSSL features. In 1968, the CSSL standard set first challenges for features of simulation systems, defining necessary basic features for simulators and a certain structure for simulators.

The CSSL standard also defines segments for discrete actions, first mainly used for modelling discrete control. So-called DISCRETE regions or sections manage the communication between discrete and continuous world and compute the discrete model parts. For incorporating discrete actions, the simulation engine must interrupt the ODE solver and handle the event. For generality, efficient implementations set up and handle event lists, representing the time instants of discrete actions and the calculations associated with the action, where in-between consecutive discrete actions the ODE solver is to be called. In order to incorporate DAEs and discrete elements, the simulator’s translator must now extract from the model description the dynamic differential equations (derivative), the dynamic algebraic equations (algebraic), and the events (event i) with static algebraic equations and event time, as given in Fig. 1 (extended structure of a simulation language due to CSSL standard). In principle, initial equations, parameter equations and terminal equations (initial, terminal) are special cases of events at time $t = 0$ and terminal time. Some simulators make use of a modified structure, which puts all discrete actions into one event module, where CASE – constructs distinguish between the different events.

Simulation environment of complex dynamical and hybrid systems called ISMA is developed at the department of Automated control systems of Novosibirsk state technical university (Russia) [4].

Specification of hybrid systems is carried out using graphical and symbolic languages that are the system content of instrumental environment. Analytical content is provided by numerical methods and algorithms for computer analysis corresponding to the chosen class of systems and methods for solving these models. ISMA environment is developed subject to simplicity of description of dynamical and hybrid models in the language that is maximally close to the object language. Main features of ISMA are the following:

- Composition of hybrid models is carried out in visual structural-textual form;
- Structural form of model description corresponds to the classical description of systems by block diagrams and includes all necessary components such as integrators, accumulators, amplifiers, signal sources, nonlinear elements and others;

![Fig. 1. Extended structure of a simulation system due to extensions of the CSSL standard with discrete elements and with DAE modelling](image-url)
- Language of symbolic specification is approached maximal to the language of mathematical formulas;
- Special module for specification of problems of chemical kinetics in the language of chemical reactions which automatically translates them into a system of differential equations;
- A variety of traditional and original numerical methods included methods that are intended for the analysis of ODE systems of medium and high stiffness;
- Computer simulation in real time;
- Graphic interpreter called GRIN provides a wide range of tools for analysis and visualization of simulation results such as scaling, tracing, optimization, displaying in the logarithmic scale and phase plane;
- Extension of system functionality by adding new typical components and numerical methods.

Architecture of ISMA software package (Fig. 2) is designed in accordance with CSSL to unify existing mathematical program software for analysis of problems in various object domains: chemical kinetics, automation, electricity, etc.

IV. A NEW DESCRIPTION LANGUAGE OF HS MODELS WITH PDEs

One of the many approaches used is ISMA to describe HS models is textual representation. For this purpose a special language LISMA (Language of ISMA) is developed [5]. And context-free grammar of LL(2) class is designed for LISMA. However existing description tools are not suitable enough to model boundary value problems of PDE systems. Therefore new language structures are introduced to describe specific elements.

Before the development of grammar of language elements a comparative analysis of multiple peers was made. In these grammars the following characteristics were emphasized: flexibility and extensibility, usability, ease of perception, the corresponding mathematical description. Using these criteria multiple languages were evaluated with the ability to describe models with PDE equations. The main ones are the following: FlexPDE, Wolfram Mathematica, gPROMS, EMSO, ASCEND. In many languages to describe the partial derivative functional style is used, in which the derivative is a function of several arguments. Based on review and analysis of mentioned simulation environments LISMA has been extended by description of boundary value problems with PDEs. This extended grammar was developed in the ideology of inheritance.

To describe a system of differential equations, boundary conditions and initial values a new LISMA language features are introduced. Explicit declaration of variables that should be subjected to discretization is introduced. For this purpose a special structure is used with grammar written in the Backus-Naur form as follows:

$$\text{apx}_\text{var} \rightarrow \text{'}\text{var}' \text{var}_\text{ident} ' (' \text{DecimalLiteral}, '!', \text{DecimalLiteral} ')\text{apx}_\text{var}_\text{tail}'$$

$$\text{apx}_\text{var}_\text{tail} \rightarrow \text{'}\text{apx}' \text{DecimalLiteral} \mid \text{'}\text{step}' (\text{FloatingPointLiteral} | \text{DecimalLiteral})$$

For example, the following expression corresponds to the given grammar:

$$\text{var} \ x[0, 20] \ \text{apx} \ 30;$$
$$\text{var} \ y[0, 30] \ \text{step} \ 0.5;$$

Fig. 2. Architecture of ISMA
In this structure boundaries of the variable are defined in square brackets. The following constructions are the keyword `apx` (short for approximation) or the keyword `step`. Keyword `apx` used if we want to break the considered domain of definition for a fixed number of segments, thus realizing the priority execution speed. We use the keyword `step` if step size is important – an accuracy priority. Number of segments and step size are written following the keyword.

Several elements are introduced in the description of the equations. First, it is an explicit indication of variables that affect the equation on the left side of the equation. This record type is optional and can be omitted as before on the left side to specify variables in parentheses. Partial derivatives are described in a functional style. Letter `D` is used as function name – the most concise version, which is not lost in code, mostly lowercase. The arguments used name of a differentiable function, the variable on which the derivative is taken and the order of the derivative. If the derivative is first-order, the latter argument is omitted suggesting that it is taken equals to 1 by default. This approach to the description of the derivative satisfies all the previously entered criteria: it allows you to use all sorts of variables which should be differentiated; it does not contain descriptive information duplication and laconic, and thus it is practical and easy to perception; and finally it is easy to relate to mathematical description. As a result, the description of the PDE as follows:

```
partial_operand \rightarrow \textquotesingle'D'\textquotesingle Identifier \textquotesingle','\textquotesingle Identifier \\
\textquotesingle','\textquotesingle DecimalLiteral\textquotesingle? \textquotesingle'
```

Below is an example of this language construct:

```
c1' \textquotesingle= Kh*\text{D}(c1,x,2) + \text{D}(Kv*\text{D}(c1,z), x); \\
c2' \textquotesingle= \text{D}(c1,x,2)*\text{pow}(x,2);
```

For numerical solution of PDEs by FDM is necessary to determine the boundary conditions – values of the derivative at the edges of the grid under consideration. It looks as follows:

```
edge \rightarrow \textquotesingle'edge\textquotesingle \textquotesingle'edge_eq\textquotesingle \textquotesingle'on\textquotesingle Identifier \textquotesingle'edge_side\textquotesingle \textquotesingle';
edge_eq \rightarrow Identifier \textquotesingle='\textquotesingle (FloatingPointLiteral | DecimalLiteral)
edge_side \rightarrow \textquotesingle'left' | \textquotesingle'right' | \textquotesingle'both'
```

Construction contains a partial derivative equation with a certain value on the right side. This allows you to specify a description for a particular variable value and the type of border: left, right or both. Below is an example of all three types of boundary conditions:

- `edge \text{D}(c1, x) = 0 \text{ on left};`
- `edge \text{D}(c1, x) = 20 \text{ on right};`
- `edge \text{D}(c1, y) = 0 \text{ on both};`

Lexical and syntactic analyzers for modified language are developed using the library antlr4. This library is ideal for problems of fast and efficient automatic construction of parsers. Under the ISMA project it is decided to use Antlr4, because it is quite applicable to the existing grammar and own work to create parsers require significant investment in the development and documentation. In addition, experience in using Antlr4 can be successfully applied in other projects.

V. Unified Description Section in ISMA Environment

After the language grammar is defined, a data structure for storing models in memory after parsing should be developed. This data structure must be universal for all types of model specification. With several ways to describe HS – graphics, text or block diagrams, we should be able to lead each of them to a single universal form, which subsequently may be transmitted to solver input. This approach simplifies the task of unification of ISMA software. For a more specific application of the simulation environment ISMA it is necessary to develop a graphical part responsible only for model specification. In this description module the modules of calculation and graphical interpretation remain unchanged.

When designing such a data structure many factors should be taken into account. This is necessary to ensure that upon presentation of new conditions the whole system of modeling was not inapplicable. Thus, the developed data structure should be easily expandable. Adding new elements to the model should not be a need to rewrite large parts of the system. Furthermore, the model should excludes redundancy. The appearance of redundancy in the description of such complex structures as the model of a hybrid system with a differential-algebraic equations and PDEs is a potential source of errors. In addition, the model must be easily divided into blocks and must be easy to use. In order to accommodate these properties subject-oriented approach is chosen in the design of the data structure for storing HS model. The implementation language is Java.

The data structure represents a set of closely related classes which can be divided into four types (Fig. 3):

- equation description classes;
- expression description classes;
- discrete behavior (states and transition conditions) description classes;
- entire model description classes;

Expressions are a sequence of elements called tokens. Tokens are both operands and operators. Two types of sequences to write expressions are supported: infix and postfix (inverse polish notation). Postfix notation is useful for computing values on the stack and is used for calculations in
step semantic analysis to calculate values of the constants and initial conditions. If the expression contains only operators of algebraic is considered algebraic. If the expression contains logical operators it refers to a type of conditional expression used in the description of the conditions of transitions between states. Algebraic expressions used in the description of the right sides of all considered types of equations: algebraic, differential, PDEs, and constants. All of them serve to describe continuous behavior of certain state of the hybrid system. Within each state there exists the so-called variable table that stores equations and variables. For description of the states and conditions of the transitions between them responsible the appropriate type of classes. Collection of states, conditions of transitions between them, and a set of instantaneous action at the entrance to a condition is called hybrid automaton. Hybrid automaton has an initial state, which corresponds to the time \( t = 0 \). Complete set of all of the above classes called the HS model.

For solving PDE in the ISMA environment approximation of equations for difference grid by finite differences method is used. This method is used to solve systems with rectangular boundaries. In such problems FDM has a sufficiently high accuracy. At the same time it wins in speed other methods. Consider the algorithm transition from of PDE to a system of ordinary differential equations.

**Step 1.** Construct a list of all variables for discretization. At this stage special structure for describing variables of storing type of discretization and accuracy (number of elements of grid) is analyzed.

**Step 2.** Divide equations into two groups: permanent and approximated. Here you need to select the equation that must be converted to the difference analogue – is analyzed right-hand sides and identifies those who are in the right part of the required variables.

**Step 3.** Construct N-dimensional grid. For all variables for sampling the number of elements for which they are divided is defined. The product of these values is the dimension of the grid.

The number of equations to be obtained by the algorithm corresponds to the equation:

\[
N = n_p \prod_{i} n_i \tag{3}
\]

where \( N \) is the number of approximating equations, \( n_p \) is the number of PDEs, \( n_i \), \( i = 1, \ldots, m \) is the number of grid points for each variable approximated.

Numerical approximation of derivatives is performed by the formulas:

\[
\frac{\partial u_j}{\partial \zeta} = \frac{u_{j+1} - u_{j-1}}{2\Delta \zeta}, \quad \frac{\partial^2 u_j}{\partial \zeta^2} = \frac{u_{j+1} - 2u_j + u_{j-1}}{(\Delta \zeta)^2}, \quad 1 \leq j \leq N \tag{4}
\]

**Step 4.** Apply boundary conditions. For each variable boundary conditions under which the simulation and approximation takes place must be specified. At this stage the variables in the initial and final nodes of the grid (relative to the current variable) are replaced by the indicated boundary values. If not then the default is zero.

**Step 5.** Set initial conditions for all equations.

**Step 6.** Transition from the grid to the ODE system. Here you need to go over all grid points. Thus it is necessary to put a unique identifier for each new equation while maintaining a connection that has been set by difference equations. As a result for each equation in each grid a copy of it in the system of ODE will be created and the initial condition \( (t = 0) \) will be specified.

VI. SCHEME OF MODEL INTERPRETATION AND SOLVING

Four basic levels of working with model can be distinguished: the interpretation of the input specification of the model, controller, solver, graphic interpreter. The Fig. 4 presents the first two levels in more detail.

Level of interpretation is responsible for converting the model described by the input specification of the universal representation HS. After model is input to simulation environment in text specification before the numerical solution the model passes through a series of stages of analysis. The first two stages – the lexical and syntactic analysis. They are conducted by facilities of the parser generated library antlr4. If the model is correct, we have an abstract syntax tree (AST). Bypass AST and further retrieval of information allows you to fill a unified data structure a model description HS. This is done using a variety of services:

- service of sequential approach syntax tree (design pattern "visitor");
- conversion service from infix into postfix notation and vice versa;
- value calculator of constants and initial conditions – a stack machine for the Polish-inverted notation;
- service of model validation – semantic analysis.
They depend on three variables: the vertical position $z$, horizontal $x$, and from time to time $t$. Equations take into account the horizontal diffusion, advection, and non-uniform vertical diffusion. A mathematical model has the following form

$$\frac{\partial c_i}{\partial t} = K_k \frac{\partial^2 c_i}{\partial x^2} + \frac{\partial}{\partial z} \left( K_z (z) \frac{\partial c_i}{\partial z} \right) + R_i (c_i, c^2, t), \quad (i = 1, 2),$$

where

$$K_k = 4 \cdot 10^{-6}, K_z (z) = 10^{-8}, e^{ij/5},$$

$$R_1 (c_i, c^2, t) = -k_1 c_i - k_2 c_i c^2 + 7.4 \cdot 10^{-6} \cdot k_3 (t) + k_4 (t) c^2,$$

$$R_2 (c_i, c^2, t) = k_i c_i - k_2 c_i c^2 - k_4 (t) c^2,$$

$k_1 = 6.031$, $k_2 = 4.66 \cdot 10^{-16}$,

$$k_3 = \begin{cases} \exp (-22.62/\sin(\pi t/43200)), & \text{if } n_p u \ t < 43200 \\ 0, & \text{if } n_p u \ t \geq 43200 \end{cases},$$

$$k_4 = \begin{cases} \exp (-7.601/\sin(\pi t/43200)), & \text{if } n_p u \ t < 43200 \\ 0, & \text{if } n_p u \ t \geq 43200 \end{cases}.$$

This system is a hybrid and has two states $st_1$ and $st_2$ with transition condition $t \geq 43200$ (Fig. 5).

Boundary conditions $\frac{\partial c_i}{\partial x} = 0$ at $x = 0$, $x = 20$, $\frac{\partial c_i}{\partial z} = 0$ at $z = 30$, $z = 50$. Initial conditions are:

$$c_i (x, z, 0) = 10^6 \alpha (x) \beta (z),$$

$$c^2 (x, z, 0) = 10^2 \alpha (x) \beta (z),$$

where

$$\alpha (x) = 1 - (0.1x - 1)^2 + (0.1x - 1)^4/2,$$

$$\beta (z) = 1 - (0.1z - 4)^2 + (0.1z - 4)^4/2.$$
Computer model in the ISMA is:

```
// Constants
const k1 = 6.031;
const k2 = 4.66* pow(1, -16);
const pi = 3.1416;
const time = 0;

// Variables to be sampling
var z[30, 50] step 5;
var x[0, 20] step 5;

// Equations
k3 = exp(-22.62/sin(pi*time/43200));
k4 = exp(-7.601/sin(pi*time/43200));
Kh = 4* pow(10, -6);
Kv = pow(10, -8) * exp(z/5);
C1 ' = Kh* D(C1, x, 2) + D(DKV1, z) + R1;
C2 ' = Kh* D(C2, x, 2) + D(DKV2, z) + R2;
DKV1 = Kv * D(C1, z);
DKV2 = Kv * D(C2, z);
R1 = k1*C1 - k2*C1*C2 + 7.4*pow(10, 16) * k3 + k4*C2;
R2 = k1*C1 - k2*C1*C2 - k4*C2;

// Boundary conditions
edge C1=0 on z both;
edge C1=0 on x both;
edge C2=0 on z both;
edge C2=0 on x both;

// Initial values
C1 (0) = pow(10, 6) * (1 - pow(0.1*x-1, 2) + pow(0.1*x-1, 4)/2) * (1 - pow(0.1*z-4, 2) + pow(0.1*z-4, 4)/2);  
C2 (0) = pow(10, 12) * (1 - pow(0.1*x-1, 2) + pow(0.1*x-1, 4)/2) * (1 - pow(0.1*z-4, 2) + pow(0.1*z-4, 4)/2);

// Change of state
state st1 (time>43200) {
    k3=0;  k4=0;
} from init;
In this example blocks of model description are marked by comments: constants, variables to be sampling, algebraic equations, the system of PDE, boundary conditions, the initial value (the Cauchy problem) description of the state st1. Variable x will be divided into 20 parts, and the variable divided into z 40. The result is a grid dimension of 800. In this example, state change occurs at the value of time t = 43200. The resulting chart dynamics of the concentration of the reactants are presented in Fig. 6. and Fig. 7. Fig. 8 shows interface of new textual models editor. He is represented by two windows: code editor and window for output debug information.
```

**VIII. CONCLUSIONS**

In this paper a new class of hybrid systems, continuous dynamics of which is defined by a system of DAE and PDE with boundary conditions, within ISMA instrumental environment is introduced. The architecture of ISMA is considered. New elements of LISMA language for description of PDE and boundary conditions language are presented. Grammar of new language inherited from the old language and is also context-free. Data structure for storing unified
representation model is designed. It allows you to expand the scope of ISMA application without changing computational part of the system. Steps of parsing and transition to the solver are discussed in detail. An example of solving model of ozone concentrations is given, text model is obtained and numerical calculations are carried out.

REFERENCES


Abstract—The report presents a software, which includes heuristic algorithms for solving nonconvex optimal control problems with control of the relay type. We submit the results of computing experiments.

Keywords—Relay optimal control problems, global extremum, random coverings method, Shepard's algorithm, genetic search method.

The global extremum search of functionals, which are defined on trajectories of dynamical systems, is one of the most difficult extreme tasks. The development of the approaches, oriented to obtain globally optimal solution for nonconvex optimal control problems (OCPs), is still an important problem.

This paper presents a software for the numerical investigation of nonconvex relay OCPs. The package consists of three algorithmic components: Shepard's algorithm [1], genetic search method [2] and the random coverings method [3]. It is proposed generating algorithms for the control functions of the relay type, allowing to receive a different number of switching points. This algorithms are used for creating of stochastic initial and admissible controls which are necessary for the effective operation of the developed software. The mathematical expectation of the number of switching points, consistently generated by iteration of the algorithm, is equal to given algorithmic parameter.

One of the most reliable mathematical methods for optimization finite-dimensional problems are methods of coverings, based on the hypothesis that the growth rate of objective function is limited. This hypothesis is formalized as estimations of Lipschitz constant for function and its derivatives. The construction of proposed coverings method, in full accordance with tradition, is reduced to generate a sequence of sampling points (in this case, the relay controls) and the corresponding sequence of sets, which should cover the attainability set.

The genetic search method, based on using of the original crossover and mutation mechanisms for constructing relay controls, allows research multietremal OCP with deep consideration of the specific tasks of this class.

Shepard's method is focused on the construction of data approximation for the objective functional values for different stochastic controls that can significantly reduce the computational cost of finding the minimum value of the objective functional.

The study of efficiency of proposed algorithms with different values of algorithmic parameters and the comparison with the multistart method [4], used for solving nonconvex OCP, are carried out. The testing results of the developed software allow us to demonstrate the performance of introduced algorithms for relay optimal control problems.

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Analysis of the Use of FACTS Devices of Different Types and the Ability to Bring Parameters of Power Quality to GOST R 54149-2010

Balabanov M. S.
Chief engineer
«International Energysaving Corporation»
St. Petersburg, Russia
e-mail: balabanovms@iescorporation.org

Abstract—The article contains the analysis of the ability of the UKRM (FACTS devices) of different types to correct network characteristics to a normalized values, in terms of the main indicators of the quality of electric power.

Keywords—FACTS; Smart Grid; RPCS

Globally, there is growing interest in the rapidly developing in the last decade direction of the transformation power industry based on a new technological basis by creating active-adaptive networks called Smart Grid. [1]

Basic cluster of the Smart Grid system are the devices that are related to technology of controlled AC transmission systems, - Flexible Alternative Current Transmission System (FACTS) [2].

FACTS is one of the most promising electric-grid technologies, the essence of which is that the electrical network is converted from passive electricity transport device into device, that is actively participating in the management of operation and modes of electrical networks.

First generation FACTS devices (FACTS-1) include devices that provide voltage regulation, as well as the required degree of compensation of reactive power in electric networks (Shunt Capacitors, automatic capacitors, harmonic filter, automatic harmonic filter, synchronous compensator, shunt reactor, automatic shunt reactor, series compensation system, short circuit current limiters, thyristor switched capacitors, thyristor controlled reactor, static var system, controlled shunt reactor, controlled series compensation system, phase shifter).

The most recent second generation FACTS devices (FACTS-2) include devices that provide control of mode parameters based on fully controlled power electronics devices (IGBT transistors, IGCT - thyristors, etc.). FACTS-2 has a new control quality - vector control, when regulated not only the quantity but also the phase of the voltage vector of electric network (STATCOM, ASC…). Transcription names of types of FACTS devices is presented in Table 1 [3, 4].

<table>
<thead>
<tr>
<th>Product</th>
<th>Distinguishing mark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactive power compensation system</td>
<td></td>
</tr>
<tr>
<td>Shunt Capacitors</td>
<td></td>
</tr>
<tr>
<td>Automatic capacitors</td>
<td></td>
</tr>
<tr>
<td>Thyristor switched capacitors</td>
<td>TSN</td>
</tr>
<tr>
<td>Harmonic filter</td>
<td>HF</td>
</tr>
<tr>
<td>Automatic harmonic filter</td>
<td></td>
</tr>
<tr>
<td>Synchronous compensator</td>
<td></td>
</tr>
<tr>
<td>Thyristor controlled reactor</td>
<td>TCR</td>
</tr>
<tr>
<td>Shunt reactor</td>
<td></td>
</tr>
<tr>
<td>Automatic shunt reactor</td>
<td></td>
</tr>
<tr>
<td>Static var system</td>
<td>SVC</td>
</tr>
<tr>
<td>Controlled shunt reactor</td>
<td>CSR</td>
</tr>
<tr>
<td>Synchronous static var compensator of reactive power based on a voltage converter</td>
<td>STATKOM</td>
</tr>
<tr>
<td>Asynchronized synchronous compensator including a flywheel</td>
<td>ASK</td>
</tr>
<tr>
<td>Synchronous static longitudinal compensator of reactive power on the voltage Converter basis</td>
<td>SSLC</td>
</tr>
<tr>
<td>Network settings control devices</td>
<td></td>
</tr>
<tr>
<td>Series compensation system</td>
<td>SCS</td>
</tr>
<tr>
<td>Controlled series compensation system</td>
<td>CSCS</td>
</tr>
<tr>
<td>Thyristor controlled phase-shifting transformer / phase-turning system</td>
<td></td>
</tr>
<tr>
<td>Phase-spanning transformer</td>
<td></td>
</tr>
<tr>
<td>Converters of current type</td>
<td></td>
</tr>
<tr>
<td>The HVDC on conventional thyristor</td>
<td>The HVDC on STATCOM basis</td>
</tr>
<tr>
<td>Asynchronized synchronous Electromechanical frequency Converter</td>
<td></td>
</tr>
<tr>
<td>Longitudinal-transverse regulation devices</td>
<td>Joint (parallel-sequential) power flow controller (based on two STATKOMs or two EMPC connected in parallel-series)</td>
</tr>
<tr>
<td>Limiting device short-circuit currents</td>
<td>Current-limiting device</td>
</tr>
</tbody>
</table>

In most cases, the issues of ensuring the quality of electricity to the regulated GOST R 54149-2010 performed with the help of devices of reactive power compensation (UKRM). Table 2 shows the analysis of the ability of the UKRM of various types to correct network characteristics to
the normalized values of the basic parameters of quality of electric power.

### TABLE II. THE VARIOUS TYPES UKRM ABILITY OF BRINGING THE ELECTRICITY QUALITY TO GOST R 54149-2010

| The basic parameters of quality of electric power, GOST R 54149-2010 | Frequency deviation | Slow voltage change | Voltage fluctuations | Flicker | The nonsinusoidal of voltage | Voltage unbalance in three-phase systems | Signals voltage, transmitted through the electric grid | Voltage interruptions | Voltage and overvoltage | Failures of voltage and overvoltage | Optimization of flow distribution on losses, loading, stability parameters |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CSR | − | + | + | − | − | − | − | − | − | − | − | + |
| STATKOM | − | + | + | + | + | + | + | + | + | + | + | + |
| AF | − | + | + | + | + | + | + | + | + | + | + | + |
| SVC | − | + | + | + | + | − | − | + | + | + | + | + |
| TSC | − | + | + | + | + | − | − | − | − | + | + | + |
| TCR | − | + | + | + | + | − | − | − | − | + | + | + |
| SSLC | − | + | + | + | + | − | − | − | − | + | + | + |
| CSCS | − | + | + | + | + | − | − | − | − | + | + | + |
| JPEC | − | + | + | + | + | − | − | − | − | + | + | + |

**Conclusion**

In the first phase implementation of FACTS devices without the use of higher-level control systems is possible by targeting these devices to the needs of a specific object without covering the entire grid goals.

In the future, there is ability to adjust these devices to perform more extensive tasks in combination with other devices and activities. It also implies the possibility of upgrading these devices.

The economic benefit from the set of Smart Grid solutions is only possible in a systematic and comprehensive approach. Now, when the introduction of Smart Grid architecture on the territory of Russia is at the initial stage, it is necessary to start from the bottom of this system, implementing the FACTS wherever they individually will bring maximum economic effect, and that it will be integrated into the “smart grid” later.

The greatest interest in this respect is the devices of reactive power compensation with the use of modern power electronics, as the most suitable for a large number of tasks of Smart Grid.

To facilitate complexity of calculations in the course of project implementation, the choice of the type and characteristics of the UKRM currently widely used mathematical models of various software packages. On the territory of Russia there is a software package RastrWin admitted by the system operator, developed by experts of the Federal state Autonomous educational institution of higher professional education "Ural Federal University named after the first President of Russia Boris Yeltsin". But software package RastrWin does not perform a series of calculations (especially dynamic), unlike software packages of foreign production, for example DigSilent, or the system ANSYS, which is one of the most powerful and popular finite element settlement systems in the world. But even the use of several software packages does not allow the engineer to fully automate the process of designing and constructing of FACTS devices.

Additional restrictions on the validity of the mathematical modeling imposes the selection of characteristics of analyzer of electricity quality and correctness of performed measurements.

It is preferable to use portable devices, carrying out measuring and recording power quality that were set out in GOST R 54149-2010 [5], in accordance with GOST R 51317.4.30 Class A [6]. This class is most preferred on the basis of the requirements of precise measurements, such as checking compliance with the standards that are quality-setting standards for electricity, as well as the fulfillment of the terms of contracts providing for the possibility of resolving disputes through measurements, etc.

As practice shows wrong measurements of quality of electricity lead to severe consequences, such as:

- lower power of UKRM on the effect of flicker and voltage deviation;
- non-compliance with GOST R 54149-2010 after installation UKRM by: the coefficient of nonsinusoidal voltage curve, the coefficient of n-th harmonic component of voltage, the asymmetry coefficient of voltages on reverse order;
- the possibility of failure of the capacitor banks by overheating;
- And many others.

The urgency of creation of a "smart grid" within the boundaries of the unified national power grid of the Russian Federation and separate objects is substantiated not only by the lack of a developed concept (on the basis of foreign
experience, but taking into account Russian specifics), but a lack of software systems that reflect all the features of the global industry for the design of FACTS devices. Currently, none of the software product, both domestic and foreign, does not reflect the full range of equipment of FACTS, its main characteristics, limitations on use, simulation of the final result on the fact of commissioning of the equipment. Lack of special software packages to alleviate calculations designer and high qualification requirements for engineers constrain the pace of implementation of energy-efficient modern equipment. Introduction of FACTS devices on particularly important facilities is of paramount importance, as it allows to correct the interference by high-precision equipment, extending the life of the entire fleet of equipment (including cables) to ensure high reliability requirements (survivability of power supply system).

REFERENCES


[5] GOST R 54149-2010 Norms of quality of electric energy in power supply systems of General purpose

System-Level EMI Verification and Analysis
Using Simulation Methods

Gryaznov Mikhail
Samsung Electronics Co. LTD,
Samsung R&D Institute Russia
Moscow, Russia
m.gryaznov@samsung.com

Khripkov Alexander
Samsung Electronics Co. LTD,
Samsung R&D Institute Russia
Moscow, Russia
a.khripkov@samsung.com

Abstract—As a step to integrate electromagnetic interference (EMI) analysis into design process of electronic devices, this paper proposes novel EMI modeling method. Frequency-domain simulation approach and methods of accuracy improvement using experimentally based EMI source model are employed. Methodology is experimentally verified on test samples with logic data signals and DC/DC converters.

Keywords—EMI, simulation model, frequency domain, behavioral models, DC/DC converters, IBIS model, Thevenin circuit

I. INTRODUCTION

In practical designs, digital circuits are defined as SPICE and IBIS models and analysis is done in time-domain. Obtained time-responses are transformed into frequency domain using Fourier transform (FFT) for spectrum representation.

Behavioral modeling of the conducted EMI is presented in [1]. With the parameters extractions based on numerical methods [2] or measurement [3], the system can be simulated in time domain [2]. Simplicity of circuit construction and availability of SPICE and IBIS-models are advantageous for these methods, however several drawbacks are limiting applicability for EMI analysis.

S-parameters of PCB and device structures are extracted for the purpose of EMI analysis. Time-domain simulation requires extensive computational resources for S-parameters calculation at large number of frequency harmonics, inverse FFT for time-domain circuit simulation and then FFT for the frequency spectrum representation. Therefore, time-domain EMI simulation for optimization purpose is time consuming.

Another drawback is simulation errors, caused by numerical noise of the Fourier transform. Typical EMI analysis task involves signals with over 100 dB differences of amplitudes between EMI noise generator and Line Impedance Stabilization Network (LISN) connection. Dynamic range of transient solvers and FFT is not sufficient, thus, intrinsic simulation errors may undermine EMI analysis accuracy and produce unreliable results.

Frequency domain approach [4], [5] allows significant reduction of time and computational resources for EMI analysis by avoiding FFT and convolutions of all signals. This EMI modeling method is faster and more reliable.

It would be beneficial to develop generic frequency-domain approach and methods of accuracy improvement using experimentally based EMI source models. Until now, EMI analysis of commercial DC/DC converters is problematical: no SPICE models are available from vendors; behavioral models of pulsed DC/DC converters don’t include information required for EMI analysis.

This work is devoted to application of frequency-dependent simulation models for EMI noise sources and EMI analysis of complex systems using these simulation models. Developed models and frequency domain analysis are applied to practical design cases for evaluation of EMI simulation accuracy.

II. EMI SIMULATION MODELS

A. Methods to reduce complexity

At the first step, reducing simulation complexity is done by discretization and de-featuring of conductors and dielectric structures. Structures of the electronics system are analyzed in EM simulation tools; obtained S-parameters were included in a circuit simulation environment for system analysis. Combined circuit and structure-level simulations allows separately analyze effects of components and structural variations.

Due to the high number of PCB and structure components linked with each other, de-featuring is done before carrying out the 3D field calculation. Most components have negligible influence on circuit behavior modeling and calculation time is reduced remarkable by their removal.

The identification analysis of relevant components is performed by evaluating sensitivity of the transfer function in dependence on every single structure and circuit element. Electrically small non-resonant structures are evaluated by the transfer function calculated at a few harmonics; resonant structures required Eigen-mode calculations to ensure that parasitic resonances are not altered. The threshold level of every transfer function indicates components which are critical in their placement. It is very important for this calculation to consider shielding planes and ground connections, as they show major influence.
In engineering practice, simplification is typically done manually by experts in the system electrical behavior and EMI characteristics of components [6]. In this work, complexity reduction of EMI simulation models is automated using statistical analysis in simulation tools.

B. EMI simulation accuracy improvement

Accuracy of radiation EMI estimation is achieved only for models based on experimental data for radiation EMI levels and for experimentally measured currents on cables. Following factors are limiting simulation accuracy:

- Near field coupling of the EMI receiving antenna and anechoic chamber characteristics.
- Model for LISN connection to the power cables and the model for test cables.
- Accuracy of experimentally measured EMI data used for calibration of models.
- Trade-off of simulation accuracy versus simulation time.

Development of accurate EMI simulation models requires a sequence of work steps, refining the EMI simulation results as shown in Table I.

<table>
<thead>
<tr>
<th>Test</th>
<th>Experimental and simulation goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement of impedances and transfer functions at interconnection points</td>
<td>Verify parasitic resonances, and impedances at modules connections</td>
</tr>
<tr>
<td>Obtain the correlation between currents on the components, cable harness and radiated EMI field strength</td>
<td>Verify EMI test setup model: EMI measurement for RF generator connected to the components and cable connections</td>
</tr>
<tr>
<td>Measurements of conducted and radiated EMI</td>
<td>Verify simulation models for EMI sources and system-level EMI model</td>
</tr>
</tbody>
</table>

Simulation models are validated for the test conditions of automotive equipment [9]. Measurements took place in absorber-lined shielded enclosures (ALSE). The device is fixed on a grounded metallic table bonded to the enclosure (Fig. 1). The device is connected to cable harness and LISN as shown in Fig. 2. A measurement antenna is arranged one meter in front of the setup. Absorber-lined walls are represented in simulation model as perfectly matched layer boundaries.

C. Validation of EMI simulation accuracy

This recommended practice for modeling and simulation results validation defines three types of validation cases: canonical, benchmark, and standard [7]. Standard problems and other means of obtaining a reference are described in [8] together with a procedure to compare the resulting data sets.

In practical case, no reference data is available. Therefore, validation is possible by using self-referencing models, created by making changes to the primary model’s computational setup that should be transparent to the user and provide the same exact answer as the primary model. It should be noted that each of these changes to the primary model only validates a specific portion of that model and so it is appropriate to use as many changes as possible.

In the geometry-based self-reference approach, the goal is to create self-referenced models by modifying the primary model geometry in such a way that the changes in the result can be simply predicted. This approach to validation is limited to the user’s understanding of the problem and its expected behavior.

Accuracy evaluation shall be done by defining resonant characteristics of the transfer function for the EMI noise propagation. Resonant frequency is highly sensitive to geometry or component value changes. Therefore, EMI simulation accuracy degrades if the transfer function has resonances.

As an example, consider radiation EMI peaks caused by 1.8 m long cable harness (Fig. 2). Experimentally measured radiation EMI (Fig. 3a) has peaks at frequencies: 45 MHz, 120 - 135 MHz, 210 – 235 MHz, 300 - 330 MHz. These peaks are created by parasitic resonances between EUT case, cables and the metal table and defined as follows. The cable length (~1.8m) is sufficiently long to present a number of series and

![Fig. 1. EMI test setup for automotive equipment [9]](image1)

![Fig. 2. Simulation model for EMI test chamber](image2)
parallel resonances (Fig. 3b). Each series resonance frequency has maximum radiation EMI. Each parallel resonance frequency has minimum radiation EMI levels. Approximately, radiation EMI peaks occur at cable length \( L = \frac{\lambda}{4} + n^* \frac{\lambda}{2} \), where \( n = 0, 1, 2, \ldots \).

Fig. 3. Experimentally measured radiation EMI (a), Impedance at the cable to EUT connection (b)

Deviation of component values may cause up to 30 dB variation of EMI level at any fixed frequency. That could be illustrated with the transfer function of an elliptic filter (Fig. 4) with nominal component values and with ±5% deviation.

Fig. 4. Effect of resonant transfer function deviation on accuracy

D. EMI simulation models for logic IC

Frequency-dependent source model is based on Thevenin equivalent circuit (Fig. 5). For the logic IC, it is extracted from the IBIS models using time-domain calculations. PRBS signal is used as a data source with length corresponding to required frequency step. Determining the frequency-dependent impedance is done by simulating IBIS models loaded with two predefined impedances \( Z_{L1}, Z_{L2} \) sequentially. Voltage and current time-domain diagrams are transformed into frequency domain.

Frequency dependent amplitude \( V_s \) and impedance of the source \( Z_s \) are defined from equations (1), (2). Thus, frequency domain noise source is constructed with frequency-dependent output power and output impedance.

\[
V_{L1,2} = \frac{Z_{L1,2}}{Z_{L1,2} + Z_s} V_s, \quad (1)
\]

\[
Z_s = \frac{Z_{L1,2}(V_{L1,2} - V_s)}{V_{L1,2} - V_{L1,2}} V_s = V_{L1}(Z_{L1} + Z_s)/Z_{L1}, \quad (2)
\]

Fig. 5. Frequency-dependent source model is based on Thevenin equivalent circuit

For most practical cases, frequency dependence of the impedance can be neglected by modeling only the real part of impedance \( Z_{r1} \). This frequency-dependent noise source is replacing IBIS models in the PCB EMI model, further analyzed in the frequency domain.

AC-analysis is recommended if nonlinear elements are excluded from the circuit, i.e. when all components are represented as frequency-dependent sources, S-parameters or linear lumped components. AC-analysis is based on linear matrix operations. Therefore, minimum calculation error is introduced into the simulation. This is reducing simulation time and requirements for computational resources.

Consider an example of signal crosstalk calculation on a test PCB with three lines as shown in Fig. 6. Central line (Port 1) is connected to the IBIS-model of data source. Two outer lines (Port 2, 3) are passively loaded “victims”, routed at different distances from the central line to test simulation predictability. PCB model is calculated using S-parameters. Slow data rate 500 kBps with a very fast signal slew rate ~ 1 ns is used for clarity purposes.

Spectrum of the data source and transfer function of the test PCB are shown in Fig. 7. Fig. 8 illustrates noise spectrums of two “victims” calculated by the Fourier transform of the interference signal in time domain; Fig. 9 - spectrum directly calculated in the frequency domain. Simulation time for time domain 289 sec, for frequency domain – 1.56 sec.

According to Fig. 7, spectrum of the data source is monotonously decaying, transfer function is increasing 20 dB per decade. Due to that non-resonant behavior, it is unrealistic to have sharp peaks in the spectrum of interference signal. That spectrum should have almost constant intensity up to 300 MHz.
due to equal decaying and increasing of the data source spectrum and transmission function respectively. In the range 300 – 400 MHz, transfer function is constant; therefore, the spectrum of interference signal shall decay at frequencies above 300 MHz as shown on Fig. 9. Spectrums calculated in the time domain (Fig. 8) have significant errors.

![Fig. 6. Test layout for the interference signal calculation](image)

![Fig. 7. Spectrum of the data source and transfer function of the test PCB](image)

![Fig. 8. Spectrums of the interference signal calculated in the time domain](image)

Frequency domain calculation has features relevant to physical behavior, but the spectrum obtained in the time domain simulation has peaks caused by the Fourier transform noise and unrealistic shapes.

E. EMI simulation models for pulsed DC/DC converters

Construction of EMI noise source model for pulsed DC/DC converter shall be based on experimental measurements for the source impedance and voltage spectrum. Measurements of the voltage noise time-diagrams or frequency spectrums shall be done for various load impedances of the DC/DC converter.

The first method is the EMI measurement of the test structure and constructing equivalent simulation circuit comprising all components of an interference propagation path. In the next step a near field probe measurement identifies all EMI sources, frequency-dependent power sources with the specified impedances are placed into the circuit model. Parameters of the frequency-dependent power sources are defined using method described above. De-embedding is done using the $S$-parameters of the analyzed test structure.

Measurement setup and photo of the test layout with an isolated DC / DC converter ADuM 5401 [10] are shown on Fig. 10. ADuM 5401 is operating at a frequency 180MHz. Violations of PCB layout rules caused exceeding of maximum permissible level of interference at harmonics of 180 MHz and 1440 MHz. Model was created for the structure analysis, and then PCB changes were made. The modified structure was analyzed using the power values of the measurements of the old structure. In the next step the modified structure was also measured. The results are shown in Table II.

<table>
<thead>
<tr>
<th>freq, MHz</th>
<th>Measurement data, dBuV/m</th>
<th>Simulation data, dBuV/m</th>
<th>Δ, dB</th>
<th>Δerr, dB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Old PCB</td>
<td>New PCB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>41.4</td>
<td>23.5</td>
<td>17.9</td>
<td>14.5</td>
</tr>
<tr>
<td>1440</td>
<td>36.9</td>
<td>29.2</td>
<td>7.75</td>
<td>16.8</td>
</tr>
</tbody>
</table>

Δ is a difference between EMI radiation levels for old and new versions of the PCB, calculated for measured and simulated EMI radiation levels. Δerr is difference between corresponding Δ values for measured and simulated results. Δerr is used to estimate accuracy of simulations.

The drawback of that approach is a need of EMI measurements in an anechoic chamber, which is time and
resources consuming. Another problem is - the more changes you make - the higher modeling error occurs.

Improved method of the DC / DC converter analysis requires EMI measurements on a reference layout, using only spectrum analyzer and LISN. Parameters of this reference layout shall be de-embedded for reconstruction of the simulation model. After that, DC/DC EMI source model shall be included into the device power circuit to be analyzed.

The reference layout of the DC / DC converter ADuM5401 was fabricated and tested using the measurement setup as shown in Fig. 10. Frequency-dependent simulation model for the DC/DC converter (Fig. 11) based on experimentally measured spectrums of ADuM5401 is listed in Table III.

<table>
<thead>
<tr>
<th>Freq</th>
<th>Vdd1, dBuV</th>
<th>Viso, dBuV</th>
<th>Icoup, dBuA</th>
</tr>
</thead>
<tbody>
<tr>
<td>180MHz</td>
<td>70.9</td>
<td>68.1</td>
<td>28.3</td>
</tr>
<tr>
<td>360MHz</td>
<td>71.1</td>
<td>77.4</td>
<td>27.1</td>
</tr>
<tr>
<td>720MHz</td>
<td>60.8</td>
<td>62.7</td>
<td>14.5</td>
</tr>
<tr>
<td>1.44GHz</td>
<td>50.6</td>
<td>43.7</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Fig. 10. Measurement setup for the reference layout (a), Test PCB for the DC/DC converter ADuM5401 (b)

Fig. 11. Frequency-dependent simulation model for the DC/DC converter

III. CONCLUSION

This paper is devoted to methodology of EMI design rules integration into R&D process. Simulation models for conducted and radiated EMI of electronics devices, methods for accuracy improvement and validation are disclosed. Based on experimental results for controlled testbed setups, frequency-dependent models for logic IC and DC/DC converters and the principle of separating the EMI source and propagation paths, a new and practical method to construct EMI models of the complex system is proposed and verified.

Developed method of frequency-dependent model construction can be used to predict the EMI noise generated by electronics devices regardless of their complexity. It is very helpful to optimize electronic system design by providing an EMI prediction tool at the design stage and perform backwards circuit specification for target EMI noise attenuation and filtering.

REFERENCES

Energy-Economic Analysis of Hybrid System for Remote Pond Supply

Jevtić M., Tomović M., Klimenta D. and Novković D.
Faculty of Technical Sciences Kosovska Mitrovica
University of Priština in Kosovska Mitrovica
Kosovska Mitrovica, Serbia
miroljub.jevtic@pr.ac.rs, milan_tomovic@yahoo.com, dardan.klimenta@pr.ac.rs and djordje_novkovic@vektor.net

Abstract— In this paper, the energy-economic analysis of isolated hybrid system that uses hydropower and photovoltaic system is carried out. As a case study, the trout pond at the river Radovanska Reka near Boljevac in eastern Serbia was taken. Energy-economic analysis of hybrid system is carried out for two cases: (i) the tubular turbine of micro hydro power is with fixed blades; (ii) the tubular turbine is redesigned – impeller is optimized for higher flow (using software ANSYS CFX) and guide vanes are movable. Energy-economic analysis of system is performed using the software HOMER. Based on performed simulations the optimal configuration of the system is selected.

Keywords—HOMER, ANSYS CFX, renewable sources of energy, hybrid system, tubular turbine, modeling, designing

I. INTRODUCTION

To power supply the isolated rural and remote areas the hybrid systems consisting of the available renewable energy and diesel generators are used [1-5]. These hybrid systems are optimized to meet the needs of the consumer areas with the most optimal configuration in terms of technical features and cost. In hybrid systems, renewable energy sources are: wind turbines, hydro turbines, PV panels, biofuels and biomass generators. In addition, in the systems are used batteries, fuel cells, converters and electrolysers.

The aim of this paper is to carry out the energy-economic analysis of a hybrid system to power supply a remote trout ponds and to propose a new configuration under the new load diagram of electricity consumption. The trout pond is located on the river Radovanska Reka in eastern Serbia [2].

Before the reconstruction, the hybrid system was consisted of a micro hydro power plant of 6,4 kW, diesel generator sets of 12 kW and battery banks. Trout pond production was increased and new consumers were connected, such as ice maker and oxygenator. Therefore, it was required: (i) to increase the total renewable energy production; (ii) to increase the renewable energy in summer months, and (iii) to optimize the reconstructed hybrid system.

The tubular turbine, which is installed in micro hydro power plant built at the retention pool (Fig. 1), was designed with fixed vanes and fixed blades of the impeller. Therefore, it was able to work only with flow which could deviate up to 15% of designed flow.

This means that in the summer (when the flow in river is reduced) micro hydropower does not operate and production of electrical energy was carried out from the diesel generator, which is more costly. Therefore, it was carried out the reconstruction of turbine in order to increase the production and extend the operation of turbine in the summer months when flow is lower than designed flow.

Authors of this paper were performed directly and inverse analysis of above-mentioned turbine by using of computers mechanic of fluids [6]. By using the software ANSYS CFX the numerical simulation of flow in existing tubular turbine was performed. Based on the performed CFD simulations the performances of existing tubular turbine were obtained numerically: the new design requirements were defined and, initially, the new geometry of the impeller and guide vanes were approximately defined. Then, it was carried out the fine tuning the calculated geometry by applying a series of successive simulations and by gradually correcting the geometry, until the optimum geometry, for the project regime. On the basis of last obtained CFD simulation, the performances of optimized turbine were obtained. These performances, compared with the performances of existing turbine, were significantly improved. In Fig. 2 and 3 the operating characteristics of the turbine before the modification and after the modification are given. Fig. 4 shows the network of modified turbine, which was formed during the calculation.

This paper was based on research conducted within the project TR33046.
Fig. 2. Operating characteristics of turbine before modification: P-power, H-head, η-efficiency.

Fig. 3. Operating characteristics of turbine after modification: P-power, H-head, η-efficiency.

Fig. 4. The grid in zone of impeller and guide vanes.

From Fig. 2 and 3 the significant improvement of performances of the turbine after modification can be seen: optimal power of turbine is increased from 6.4 kW to 8.5 kW; at reduction of flow by about 15 percent below the optimal operating regime, the efficiency of both turbine modifications is significantly reduced (which is a characteristic of all tubular turbines); the optimal flow of turbine is increased from 265 ℓ/s (before modification) to 350 ℓ/s (after modification).

In order to enable the operation of turbine in summer, at low flow rates (up to 30% of the designed flow), guide vanes are mounted as movable.

II. ENERGY-ECONOMIC ANALYSIS OF THE HYBRID SYSTEM VARIANTS

Energy-economic analysis of the hybrid system variants was performed using the software HOMER. In Fig. 5 the scheme of observed hybrid system (given in HOMER) is shown. In order to perform an energy-economic analysis, it is necessary to define the daily load profile of system, enter data on the renewable energy sources (hydro and PV module) and data on the components of hybrid system: diesel generator, inverters and batteries.

Fig. 5. Scheme of hybrid system of the pond Radovanska Reka.

Models of the hybrid system components, which are implemented in HOMER, are given in Table I [7].

III. THE ENTERED DATA INTO HOMER

Daily load profile. A typical daily load profile for January is shown in Fig. 6.

Fig. 6. Daily load profile of the pond Radovanska Reka (month of January): a – working days; b – weekends.
TABLE I. MODELS OF THE HYBRID SYSTEM COMPONENTS

**PV Array**

\[ P_{\text{PV}} = f_{\text{PV}} Y_{\text{PV}} I_T I_S \]

- \( f_{\text{PV}} \) - PV derating factor,
- \( Y_{\text{PV}} \) - rated capacity of the PV array (kW),
- \( I_T \) - global solar radiation (beam plus diffuse) incident on the surface of the PV array (kW/m²),
- \( I_S \) - 1 kW/m², which is the standard amount of radiation used to rate the capacity of the PV array.

**Hydro turbine**

\[ P_{\text{hydr}} = \eta_{\text{hydr}} \rho_{\text{water}} g h_{\text{net}} Q_{\text{turbine}} \]

- \( \eta_{\text{hydr}} \) - turbine efficiency,
- \( \rho_{\text{water}} \) - density of water,
- \( g \) – gravitational acceleration,
- \( h_{\text{net}} \) - net head,
- \( Q_{\text{turbine}} \) - flow rate through the turbine.

**Diesel generator**

\[ F = F_0 Y_{\text{gen}} + F_1 P_{\text{gen}} \]

- \( F \) - generator’s fuel consumption,
- \( F_0 \) - fuel curve intercept coefficient,
- \( F_1 \) - fuel curve slope,
- \( Y_{\text{gen}} \) - rated capacity of the generator (kW),
- \( P_{\text{gen}} \) - electrical output of the generator (kW).

**Battery bank**

\[ C_{\text{bw}} = \frac{C_{\text{rep, batt}}}{N_{\text{batt}} Q_{\text{lifetime}} \eta_{\text{rt}}} \]

- \( C_{\text{rep, batt}} \) - replacement cost of the battery bank (dollars),
- \( N_{\text{batt}} \) - number of batteries in the battery bank,
- \( Q_{\text{lifetime}} \) - lifetime throughput of a single battery (kWh),
- \( \eta_{\text{rt}} \) - round-trip efficiency.

**Economic modeling**

\[ C_{\text{NPC}} = \frac{C_{\text{ann, tot}}}{\text{CRF}(i, R_{\text{proj}})} \]

- \( C_{\text{NPC}} \) - total net present cost,
- \( C_{\text{ann, tot}} \) - total annualized cost,
- \( i \) - annual real interest rate (discount rate),
- \( R_{\text{proj}} \) – project lifetime,
- \( \text{CRF}(\cdot) \) - capital recovery factor.

\[ \text{CRF}(i, N) = \frac{i (1+i)^N}{(1+i)^N - 1} \]

- \( i \) - annual real interest rate,
- \( N \) - number of years.

\[ \text{COE} = \frac{C_{\text{ann, tot}}}{E_{\text{prim}} + E_{\text{grid, sales}}} \]

- \( \text{COE} \) - levelized cost of energy,
- \( C_{\text{ann, tot}} \) - total annualized cost,
- \( E_{\text{prim}} \) - total amounts of primary load,
- \( E_{\text{grid, sales}} \) - energy sold to the grid per year.

The average daily consumption of electric energy during the year is 25 kWh, peak power is 4.7 kW and the load factor is 0.287.

**Solar and photovoltaic (PV) module.** Mean monthly values of solar radiation with an index of transparency are shown in Fig. 7. Data on the intensity of solar radiation are taken from NASA [8] based on latitude and longitude for the municipality Boljevac [9].

![Fig. 7. Mean monthly values of solar radiation and clearness index, in Boljevac area.](image-url)

Other data of PV modules that were used in the simulations are: the life of PV panels is 25 years, the loss factor is 88.8%, slope angles are 40 °, and azimuth is 0 °. With these parameters Yingli polycrystalline solar panels of power rating of 245 W were selected [10]. Investment costs and replacement costs of solar panels are 900 $ and 900 $/kW, respectively, while the annual operating and maintenance costs are 15 $/year [10]. For purposes of simulation, the solar panel powers of 1, 2, ..., 12 kW were used.
Water energy and hydro module. In Fig. 8 the histogram of monthly medium flow of water in the river Radovanska Reka is shown [11].

Water from the retention pool is directed to tubular turbine with the pipe diameter of 500 mm and length of 8 m. The range of flow turbine before reconstruction is from 220 to 265 ℓ/s and after reconstruction from 90 to 350 ℓ/s. Net water head at turbine is 2.9 m. The lifetime of micro hydro power plant is 25 years, predicted investment costs and replacement costs are 1000 $ and 1000 $/kW, respectively.

Annual operation and maintenance costs are 2.5% of the investment costs.

Diesel generator. Three-phase diesel generator of 12 kW is used [12]. The price of diesel fuel is current market price which is 1.84 $/ℓ. Investment costs, replacement costs, operation and maintenance costs are 2200 $, 1500 $ and 0.025 $/year, respectively [12].

Inverter. The selected inverter is StecaGrid 3000 [10, 13] for a rated voltage of 845 V. The lifetime of the inverter is 25 years and efficiency is 98.6%. Investment costs and replacement costs are 328 $ and 328 $/kW, respectively, and the annual operating and maintenance costs are 0 $/year [10]. Powers of the inverter, which are used in the simulation are 1, 2, ..., 6 kW.

Batteries. The selected batteries are Trojan T-105 [14]. Trojan T-105 battery is designed for cyclic operation, where the rated voltage is 6 V, capacity is 225 Ah (1.35 kWh), and the total energy is 845 kWh. Investment costs, replacement costs, operation and maintenance costs of batteries are 69 $, 69 $ and 0.25 $/year [15] and the numbers of batteries used in the simulation process are 2, 4, 8, 16, ..., 80.

IV. RESULTS OF ANALYSIS AND DISCUSSION

After 2184 simulations and after 55 seconds of the computer operation HOMER displays the categorized solutions of system, ie, systems in order of profitability from most profitable to the less cost-effective.

The results for optimal configuration of system, costs of individual system components, as well as the monthly average electric production are given in Table II, Fig. 9 and Fig. 10 (for turbine with fixed guide vanes) and in Table III, Fig. 11 and Fig. 12 (for turbine with movable guide vanes and optimized impeller geometry).

TABLE II. POWER, COST AND ELECTRICAL ENERGY GENERATION OF SYSTEM COMPONENTS BEFORE RECONSTRUCTION

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (kW)</th>
<th>Total Cost ($)</th>
<th>Generated Electrical Energy (kWh/god)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>11</td>
<td>12,009</td>
<td>16,337 (41%)</td>
</tr>
<tr>
<td>Hydro</td>
<td>6,4</td>
<td>8,445</td>
<td>23,414 (58%)</td>
</tr>
<tr>
<td>Generator</td>
<td>12</td>
<td>6,235</td>
<td>458 (1%)</td>
</tr>
<tr>
<td>Trojan T-105</td>
<td>72</td>
<td>11,013</td>
<td>/</td>
</tr>
<tr>
<td>Inverter</td>
<td>5</td>
<td>1,640</td>
<td>/</td>
</tr>
<tr>
<td>System</td>
<td>29,4</td>
<td>39,343</td>
<td>40,209 (00%)</td>
</tr>
</tbody>
</table>

Fig. 9. Cash Flow Summary of System Components During Project Life Time (before reconstruction).

Fig. 10. Monthly Average Electric Production of System Components.

TABLE III. POWER, COST AND ELECTRICAL ENERGY GENERATION OF SYSTEM COMPONENTS AFTER RECONSTRUCTION

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (kW)</th>
<th>Total Cost ($)</th>
<th>Generated Electrical Energy (kWh/god)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>7</td>
<td>7,642</td>
<td>10,396 (21%)</td>
</tr>
<tr>
<td>Hydro</td>
<td>8,5</td>
<td>10,104</td>
<td>38,239 (77%)</td>
</tr>
<tr>
<td>Generator</td>
<td>12</td>
<td>10,742</td>
<td>829 (2%)</td>
</tr>
<tr>
<td>Trojan T-105</td>
<td>48</td>
<td>7,342</td>
<td>/</td>
</tr>
<tr>
<td>Inverter</td>
<td>4</td>
<td>1,312</td>
<td>/</td>
</tr>
<tr>
<td>System</td>
<td>27,5</td>
<td>37,142</td>
<td>49,464 (00%)</td>
</tr>
</tbody>
</table>

Fig. 11. Cash Flow Summary of System Components During Project Life Time (After Reconstruction).
From Tables II and III it follows that the reconstruction of the turbine, where the geometry of the impeller is optimized and fixed vanes are replaced with mobile, affects on the hybrid system parameters. Power and produced energy of hydro turbine were increased, Power of PV panels is reduced (due to higher production from hydro turbine in the summer months), the total annual energy production is increased and the cost of the system is reduced. Number of batteries is much lower.

The results of cash flow summary and monthly average electric production, which are given in Figures 11 and 12, confirm previous conclusions.

V. CONCLUSIONS

For power supply the trout pond that is built near the remote mountain rivers economical solution is a hybrid system of renewable sources of energy. The main source of renewable energy is water that comes out of the retention pool of the pond. In order to maximize the energy, it is necessary to optimize the turbine (that is usually tubular propeller, due to the small water head) and complete hybrid system.

As shown in this paper, using the software ANSYS CFX and CFD numerical simulation of flow in the existing tubular turbine, the actual performance of turbine can be determined and better performance, based on the redesign of the impeller and the guide vanes, can be suggest.

Optimization of hydro turbine directly affects the performance of the entire hybrid system: the higher power and energy of the system is given, the cost of the system is reduced, the number and power of other components (PV panels, batteries, inverters) is reduced. Software HOMER is very useful for economic and technical analysis of such systems and other variants of hybrid systems.

REFERENCES

Forecasting of Daily Electric Power Consumption of Power Grid with Using Technocenosis Model

Platonova E.V.
Department «Electric power engineering»
Khakas Technical Institute - branch of Federal State Autonomous Educational Institution of Higher Professional Education "Siberian Federal University"
Abakan, Khakas Republics, Russia
email: eplatonova@yandex.ru

Chistyakov G.N.
Department «Electric power engineering»
Khakas Technical Institute - branch of Federal State Autonomous Educational Institution of Higher Professional Education "Siberian Federal University"
Abakan, Khakas Republics, Russia
email: chist2@yandex.ru

Abstract - The authors propose an adaptive model for short-term forecasting of electric power consumption using mathematical apparatus of parametric rank parametric H-distributions. The model may be used both for electric power systems in the whole, and for individual participants in the wholesale power market. Effectiveness of the model for forecasting the hourly electric power consumption was estimated for Khakas power grid.

Keywords – forecasting, electric power consumption, technocenosis model, rank parametric H-distribution, the software package Mathcad.

1. INTRODUCTION

System operator generates and uses its own forecasts for ensuring of reliability of Unified electric power system of Russia in the formation of the forecast dispatch schedule for supervisory of the control territories. Temporary planning hierarchy is divided into three main intervals: long-term planning (from one month to a year in advance), short-term planning (market "day-ahead"), operational management regimes (balancing market). Predictive values of power consumption are usually done at all time intervals with successive refinement of the results of calculations with decreasing lead time.

To ensure normal operation of the wholesale power market in the planning "day ahead" there is a short-term forecast both of total electric consumption of the power grid and electric consumption of each market participant. The volume of raw data and forecasting models may be different. The accuracy of the forecast calculations depends not only on the reliability of the electric power grid modes, but also on the reliability of the wholesale market. In turn, the accuracy of forecasting depends on the quality of the mathematical model used, correctly reflecting the daily fluctuations of electric power consumption, which in many cases is a complex non-stationary process.

The works of many Russian and foreign researchers [1-7] are devoted to the solving of forecasting of electric power consumption. For short-term forecasting of electric power consumption tasks, there are the most common factograph extrapolation forecasting methods, including univariate and multivariate, linear and nonlinear, stationary and non-stationary, traditional and nontraditional. Thus, up-to-date data analysis methods, mathematical statistics, correlation and regression analysis, the theory of artificial neural networks, the theory of relational databases.

Despite the variety of using forecasting methods, of electric power consumption, every time the choice of method is determined by the particularities of the solving task (by specifics of the object forecasting, by features of the information used, by way of using the method in practice and the complexity of its implementation). Therefore the search for new approaches and the development of modern efficient models, which satisfy a number of requirements, are remained actual.

An effective model should cover all major prediction intervals, make forecasts of the required quality, should be based on the use of modern methods of data analysis and forecasting, should be adaptive, should fully use the computational power of modern computers, should have visualization tools, must be able to have its further improvement.

The proposed for consideration the adaptive model for short-term forecasting of power consumption utilises the technocenosis approach with using mathematical apparatus of parametric rank H-distributions. Calculations and mathematical modeling are carried out using software products such as Mathcad, Statistica, MS Excel.

2. THEORETICAL BASE OF SHORT-TERM POWER CONSUMPTION MODELING

In the works [8-11] the term "technocenosis" was introduced and technocenosis approach was developed to
research electric power systems, including the simulation of electric power consumption. In these works cenosis (community) simulates a totality of electric power consumers in a factory shop, plant, region, economic sector (community facilities). Technocenosis approach to simulation (forecast) lies in the fact that the electric power consumption of the object community we consider not in isolation, but it is related to other objects, which are systematized hierarchically on electric power consumption.

The difference of the proposed model from the famous ones consists of the fact that as a basis of technocenosis approach to simulate of daily energy consumption (forecast) there are the using of operational data of hourly electric power consumption the power grid, corresponding to its daily schedule load.

Electric power consumption research is carried out in the form of rank: the rank \( r \) is appropriated to each analyzed period. In electric power consumption forecasting "day-ahead", one hour is taken as the period of analysis. As objects of valuation, the values of hourly electric power consumption are adopted (which are considered as objects of the community). Time intervals are day-night (considered as cenosis).

The rank \( r = 1 \) is appropriated to each period (hour) of maximum (peak) power grid load, and a nonincreasing function \( W(x) \), which has been adopted as the basis for construction of rank parametric \( H \) - distribution is a two-parameter hyperbola:

\[
W(x) = W_1/x^\beta, \quad (1)
\]

here \( x \) – continuous analogue of integer \( r \);
\( \beta \) – characteristic rank coefficient, which determines the degree of the distribution curve steepness;

\[
W_1 = W_{\text{max}}(1) \quad \text{– a constant, which is considered to be the power consumption in the period (hour) of maximum (peak) power grid load.}
\]

Changing the parameters \( A_x \) and \( \beta \) in time is formalized by the surface of rank parametric \( H \) - distribution:

\[
W(r, t) = \frac{W_1}{r^\beta(t)} = \frac{a_1 + b_1(t)}{r^\beta(1 - e^{-\beta t})}, \quad (2)
\]

here \( t \) - time period;
\( a_1, b_1, \beta_1, T \) — constants of approximating equations.

The meaning of forecasting, based on the expression (2), consists actually in forecasting of area (point) under the rank parametric \( H \) - distribution, which can be corrected in time by rank parametric \( H \) - distribution configuration, which in turn is the upper bound of volume (in time) of the total daily electric power consumption of the power grid (forecast verification). There is forecasting algorithm for parameters of daily electric power consumption:

1) The hourly electric power consumption is ranked during the every known day-night of prehistory \( t \) (lead period);
2) The indicators of rank distribution are calculated by formula (1) for rank row \( (x = r) \);
3) The significance of projection curve of rank parametric \( H \) - distribution is determined on the horizontal axis per day-night, preceding day-night forecast (estimated rank):

\[
r_{i|j} = (W_{i|j}/W_{i|j}^*)^{1/\beta}, \quad (3)
\]

here \( W_{i|j}^* \) – significance of the first point of rank parametric \( H \) - distribution per day-night, preceding day-night forecast, MWh; \( W_{i|j} \) – ranked significances of daily electric power consumption per day-night, preceding day-night forecast, MWh;
\( \beta_i \) – rank coefficient for each hour per day-night, preceding day-night forecast;
4) It is accepted, that the calculated rank for short-term forecast is not changed and the hourly forecast of daily electric power consumption is made:

\[
W_{in} = W_{in}/r_{i|j}^\beta, \quad (4)
\]

here \( W_{in} \) – forecast significance of the first point of rank \( H \) - distribution, MWh; \( \beta_n \) – forecast significance of rank coefficient.

3. PRACTICAL APPLICATION OF MODELS

A. The primary processing of statistical data

Simulation of electrical power consumption was made on the example of Khakas power grid in the software package Mathcad, using statistical data of telemetry and telemeasurement of operative information complex CK-2003 for three months.

To obtain a complete picture of rank parametric \( H \) - distribution for each group of objects, three-dimensional surface (shown fig. 1) were constructed.

Fig. 1 shows the stable form of rank surface: at the beginning of each month there is a gradual decline, and at the end of each month there is increasing of electrical power consumption.
For combinations of indicators rank parametric $H$-distributions the concordance coefficients have been calculated: $K_1 = 0.925$ и $K_2 = 0.92$. Obtained coefficients describe high degree of interconnectivity of objects. On the base of the coefficients one can conclude, that daily schedule of hourly electric power consumption for Khakas power grid can be considered as technocenosis and in short-term forecasting of hourly day-night electric power consumption it is acceptable technocenosis approach, using mathematical apparatus of rank parametric $H$-distributions.

Approximation of obtained rank parametric $H$-distributions of empirical data was obtained with the help of method of rank forecasting analysis, with the estimation and specification.

B. Approximation of rank parametric $H$-distributions

A two-parameter hyperbolic form, according to the formula (1) was given as a standard method of rank analysis.

Approximation was carried out twice: by method of the least modules and by method of the least squares. The magnitude of maximum deviation, magnitude of the sum of deviations and total magnitude of the relative error by method of the least modules are significantly lower than by method of the least squares. In this case, there is a reason to recognize that the method of the least modules is more correct to use.

By means of the function $\text{REZ}$ the resultant function was defined (shown fig. 2).

For the purpose of hourly electric power consumption forecasting for power grid it had been used Gauss-methods (G-methods), based on the Gaussian mathematical statistics. Forecasting was performed using various durations of electric power consumption prehistory. In detail calculations were performed with the duration in 2, 4, 7, 10 day-nights. The best forecasting results have been obtained with a history of 10 day-nights.

C. Forecasting of electric power consumption in technocenosis using Gauss-methods

With the use of the software package Mathcad the following operations have been performed consistently:

1) Taking the logarithm of source data with allocation of trend by method of the least modules and its removal;
2) Allocation, smoothing by Gauss-method of hourly median and minimum levels of electric power consumption;
3) Graphical representation of hourly median and minimum levels of electric power consumption (shown fig. 3);
4) Testing Cochran's hypothesis about homogeneity of variances for hourly power consumption;
5) Calculation of hourly average variances values;
6) Forecasting of electric power consumption with a 95% confidence interval, considering trend for the next day-night;
7) Comparison of electric power consumption forecast with actual electric power consumption (shown fig. 4).

D. Analysis of the forecast results

Analysis of the balances for compliance with normal distribution law has confirmed the correctness of the
The best length of prehistory for forecasting of hourly electric consumption of the power grid was 10 days, and in this case the error values of the median significance were minimal. The results obtained demonstrate a high accuracy of the forecast model using the technocenosis approach. It should be noted that the proposed method, as well as any other prediction method does not ensure a wholly or near accuracy. It is explained by impossibility to take into account all the factors, influencing the electric power consumption. If we consider the most significant factors, the forecast is more accurate for objects, which work with greater stability. For the objects that become unstable, the forecast accuracy is very low.

4. CONCLUSION

The practical results of the simulation were considered on the example of forecasting of electric power consumption of the Khakas power grid. It should be noted that the proposed model was also tested for the electric power consumption forecasting of the separate participants at wholesale power market. It was forecasted electric power consumption at the market “day-ahead” for energy retail companies and for qualified consumers, who are part of the Khakas power grid.

The proposed model has flexibility and possibility of its further improvement. The system of the forecasting allows using some additional information (both on the influencing factors, and on the electric power consumption of different subdivisions) and the additional methods of forecasting.

REFERENCES

Uniformed Mathematical Model of 3-Phase Transformer with Single Magnetic Core and It’s Computer Implementation

Pustovetov M. Yu.
Science-Investigating and Testing Center "Cryotransenergo"
Rostov State University of Transport Communications
Rostov-on-Don, Russia
e-mail: mgsn2006@rambler.ru

Abstract—Uniformed mathematical model of 3-phase transformer with single magnetic core for different variants of primary and secondary windings connections using wye and delta schemes at every of 12 phase shifts using clock notation is proposed and described. Computer implementation of model and examples of computer simulation results for some schemes and vector groups are shown. Used a hybrid approach to build a visual computer model of transformer: circuit-design and in the form of block diagrams.

Keywords—modeling methodology, 3-phase transformer, clock notation, current, delta scheme, mathematical model, computer model, phase shift, vector group, voltage, wye scheme.

I. INTRODUCTION

Modeling methodology involves the following steps:

1. Analysis applications requiring solution by computer simulation to determine devices requiring description in the form of mathematical models.
2. Development of a mathematical model of the device
3. Develop and debug a computer model of the device
4. Using a computer model of the device for applications, including as part of the model is more or less complex technical system.
5. Analysis of the results of computer simulations.

To analyze the modes of operation of power systems and electrical equipment with 3-phase transformer is convenient to use a mathematical model (MM) of the device, which allows to obtain the results of calculations with different variants of the phase windings connections at all of the twelve vector groups under clock notation. Accordingly [1] common connections for 3-phase transformers are recommended with vector groups 0, 1, 5, 6, 11 and additional connections with vector groups 2, 4, 7, 8, 10. But in [2] the example of simulation for transformer with scheme and vector group YNd9 is suggested. It is widespread practice when for 12- or more pulse rectifier feeding two or several phase shifting 3-phase transformers are uses. Each of the phase shifting transformers has a secondary side winding with different from another transformer scheme and vector group, having identical for either transformer primary winding [3, 4]. Phase shift between supply voltages of secondary windings provides mitigation of some high frequency harmonics on the input of the rectifier. In particular, it is the way of improving the shape of the current consumption of the network and the power factor. A similar result is achieved by using different schemes and vector groups for primary windings of each phase shifting transformers while identically secondary windings [5].

Thus, despite the fact that electromagnetic processes in a single transformer is substantially not dependent on the scheme and vector group of windings, while simulating processes in electrical power systems or power electronic devices where there are 3-phase transformers with different schemas and vector groups, simulation may be incorrect if the vector group doesn’t take into account properly.

II. RELATED WORKS

In group 3-phase transformer design, unlike a construction with single magnetic core common to the three phases, is not considered magnetic coupling between phases due to its significant weakening. MM of 3-phase transformer at SIMULINK, called Three-Phase Transformer 12 Terminals [6], allows you to connect the findings phase windings in an arbitrary manner, including getting all 12 vector groups. It is only known to the author MM with this capability. But this is made up of three MM of 1-phase transformers, that is, strictly speaking, is not suitable to describe the 3-phase transformer with a single magnetic core.

Similar way is used for simulating two phase shift transformers feeding 12-pulse rectifier with schemes Yy and
Dy [5]: MM for each of 3-phase transformers is assembled from three MM of 1-phase transformers in OrCAD.

Another variant of the 3-phase transformer MM in the software SIMULINK is Three-Phase Transformer Inductance Matrix Type (Two Windings) [7]. This describes the MM for the case of 3-phase transformer with single core. Iron losses were taken into account. The possible for this MM schemes and vector groups stated only as YNy0, YNd1, YNd11, Dyn1 and Dyn11. Simulation results reported in [4] are based on MM [7].

III. PROPOSED MATHEMATICAL MODEL DESCRIPTION

In this paper author propose the development of unified MM of 3-phase two winding transformer with single magnetic core, covering all 12 standard vector groups by clock notation.

MM of 3-phase transformer equations can be written as (1), where: indices a, b, c denote belonging to respective phases; v - phase voltage, V; i - phase current, \( L_a \) - phase winding leakage inductance, \( \mu \) \( r \) - phase winding resistance, Ohm; \( w \) - the number of turns in phase winding. 1 denote the indices belonging to the primary winding of the transformer , and the indices 2 - to the secondary. \( e_{a1} \), \( e_{b1} \), \( e_{c1} \), \( e_{a2} \), \( e_{b2} \) and \( e_{c2} \) - phase electromotive forces in primary and secondary windings.

\[
\begin{align*}
\begin{cases}
\frac{v_{a1} - r_{a1}i_{a1} - L_{a11} \frac{di_{a1}}{dt}}{dt} &= v_{a01} \\
\frac{v_{b1} - r_{b1}i_{b1} - L_{b11} \frac{di_{b1}}{dt}}{dt} &= v_{b01} \\
\frac{v_{c1} - r_{c1}i_{c1} - L_{c11} \frac{di_{c1}}{dt}}{dt} &= v_{c01}
\end{cases}
\end{align*}
\tag{1}
\]

For each of the phases of the voltage drop in the magnetization branch of the primary winding connected in series with the main inductor \( L_m \) and iron losses resistance \( r_m \) (similarly as in the T-shaped equivalent circuit):

\[
\begin{align*}
v_{a01} &= -e_{a01} = L_m (i_{\mu}) \frac{2}{3} \left[ \frac{di_{a1}}{dt} + \frac{w_2}{w_1} \frac{di_{a2}}{dt} \right] - \frac{1}{2} \left( \frac{di_{b1}}{dt} + \frac{w_2}{w_1} \frac{di_{b2}}{dt} \right) + \frac{r_m}{2} \left( \frac{i_{a1} + \frac{w_2}{w_1} i_{a2}}{dt} - \frac{1}{2} \left( \frac{i_{b1} + \frac{w_2}{w_1} i_{b2}}{dt} \right) + \left( \frac{r_2}{w_1} i_{c2} \right) \right) = L_m (i_{\mu}) \frac{di_{a1}}{dt} + r_m i_{\mu};
\end{align*}
\tag{2}
\]

where \( i_{\mu} \) - the current in the magnetizing branch of transformer phase.
\begin{equation}
\begin{aligned}
v_{b1} &= -e_{b1} = L_m(i_{\mu b}) \frac{2}{3} \left[ \frac{di_{b1}}{dt} + \frac{w_2 di_{b2}}{w_1 \frac{dt}{dt}} \right] - \\
&\quad - \frac{1}{2} \left[ \left( \frac{di_{a1}}{dt} + \frac{w_2 di_{a2}}{w_1 \frac{dt}{dt}} \right) + \left( \frac{di_{c1}}{dt} + \frac{w_2 di_{c2}}{w_1 \frac{dt}{dt}} \right) \right] + \\
&\quad + r_m \left[ \left( i_{b1} + \frac{w_2}{w_1} i_{b2} \right) - \frac{1}{2} \left( i_{a1} + \frac{w_2}{w_1} i_{a2} \right) \right] + \\
&\quad + \left( i_{c1} + \frac{w_2}{w_1} i_{c2} \right) \right] = L_m(i_{\mu b}) \frac{di_{b2}}{dt} + r_m i_{\mu b}; \\
v_{c01} &= -e_{c01} = L_m(i_{\mu c}) \frac{2}{3} \left[ \frac{di_{c1}}{dt} + \frac{w_2 di_{c2}}{w_1 \frac{dt}{dt}} \right] - \\
&\quad - \frac{1}{2} \left[ \left( \frac{di_{a1}}{dt} + \frac{w_2 di_{a2}}{w_1 \frac{dt}{dt}} \right) + \left( \frac{di_{b1}}{dt} + \frac{w_2 di_{b2}}{w_1 \frac{dt}{dt}} \right) \right] + \\
&\quad + r_m \left[ \left( i_{c1} + \frac{w_2}{w_1} i_{c2} \right) - \frac{1}{2} \left( i_{a1} + \frac{w_2}{w_1} i_{a2} \right) \right] + \\
&\quad + \left( i_{b1} + \frac{w_2}{w_1} i_{b2} \right) \right] = L_m(i_{\mu c}) \frac{di_{c2}}{dt} + r_m i_{\mu c}.
\end{aligned}
\end{equation}

Proceeding from the theory of groups, which is based on phasor diagrams of the transformer, the sign " \text{"} " \text{"} in comments to the system of expressions (1) corresponds to the case when the primary and secondary windings are disposed on the same core leg and the same wound. The sign " \text{"} " \text{"} corresponds to the case of opposite direction of winding coils on the same core leg or change the start and end of one of the windings relative to another. " \text{"} " \text{"} Sgn should be used for schemes and vector groups Dy11, Yd11, Yy0, Dd0, and " \text{"} " \text{"} to Dy5, Yd5, Yy6, Dd6. Hereinafter wye scheme may be changed to wye with neutral.

IV. MATHEMATICAL MODEL VERSIONS WITH PERMUTATION OF THE PHASES

Versions of the equations of MM for 3-phase transformer for cases when there is a permutation of the phases of the secondary winding relative to the primary are possible. At first lets modify the expressions (2) - (4) by changing the phase indices \text{"} a, b, c \text{"} at the secondary winding currents and their derivatives respectively to \text{"} b, c, a \text{"}. The system of equations (1) it is necessary to make the changes (8). That is, the indices at the voltage drops in the magnetization branch of the primary winding of each phase are replaced: in the phase \text{"} a \text{"} to \text{"} c \text{"}, in the phase \text{"} b \text{"} to \text{"} a \text{"}, in the phase \text{"} c \text{"} to \text{"} b \text{"}. Here we have the input signals from the primary winding MM to the secondary winding MM, which explains the reverse phase indices change: \text{"} b, c, a \text{"} at \text{"} V_{01} \text{"} respectively for \text{"} a, b, c \text{"}.

\begin{equation}
\begin{aligned}
v_{a01} &= -e_{a01} = L_m(i_{\mu a}) \frac{2}{3} \left[ \frac{di_{a1}}{dt} + \frac{w_2 di_{a2}}{w_1 \frac{dt}{dt}} \right] - \\
&\quad - \frac{1}{2} \left[ \left( \frac{di_{b1}}{dt} + \frac{w_2 di_{b2}}{w_1 \frac{dt}{dt}} \right) + \left( \frac{di_{c1}}{dt} + \frac{w_2 di_{c2}}{w_1 \frac{dt}{dt}} \right) \right] + \\
&\quad + r_m \left[ \left( i_{a1} + \frac{w_2}{w_1} i_{a2} \right) - \frac{1}{2} \left( i_{b1} + \frac{w_2}{w_1} i_{b2} \right) \right] + \\
&\quad + \left( i_{c1} + \frac{w_2}{w_1} i_{c2} \right) \right] = L_m(i_{\mu a}) \frac{di_{a2}}{dt} + r_m i_{\mu a}; \\
v_{c01} &= -e_{c01} = L_m(i_{\mu c}) \frac{2}{3} \left[ \frac{di_{c1}}{dt} + \frac{w_2 di_{c2}}{w_1 \frac{dt}{dt}} \right] - \\
&\quad - \frac{1}{2} \left[ \left( \frac{di_{a1}}{dt} + \frac{w_2 di_{a2}}{w_1 \frac{dt}{dt}} \right) + \left( \frac{di_{b1}}{dt} + \frac{w_2 di_{b2}}{w_1 \frac{dt}{dt}} \right) \right] + \\
&\quad + r_m \left[ \left( i_{c1} + \frac{w_2}{w_1} i_{c2} \right) - \frac{1}{2} \left( i_{a1} + \frac{w_2}{w_1} i_{a2} \right) \right] + \\
&\quad + \left( i_{b1} + \frac{w_2}{w_1} i_{b2} \right) \right] = L_m(i_{\mu c}) \frac{di_{c2}}{dt} + r_m i_{\mu c}.
\end{aligned}
\end{equation}

These permutations are reflected in the expressions (5) - (7). In other words, such a change of phase indices is made when entering the signals from secondary winding MM to the primary winding MM. In addition to this, in the comments to
\[ e_{a2} = \frac{w_2}{w_1} v_{e01} + L_{oa2} \frac{di_{a2}}{dt} \]

\[ e_{b2} = \frac{w_2}{w_1} v_{e01} + L_{ob2} \frac{di_{b2}}{dt} \]

\[ e_{c2} = \frac{w_2}{w_1} v_{e01} + L_{oc2} \frac{di_{c2}}{dt} \]

(8)

In version of MM, containing (5) - (8) equations, "+" sign in front of the right side of (8) should be used for schemes and vector groups Dy7, Yd7, Yy8, Dd8, and "+" to Dy1, Yd1, Yy2, Dd2.

Final modification of the equations (2) - (4) is an exchange phase indices \(a, b, c\) at the secondary winding currents and their derivatives respectively to \(c, a, b\), whereby we get (9) - (11).

\[ v_{a01} = -e_{a01} = L_m (i_{\mu}) \frac{2}{3} \left[ \frac{di_{a1}}{dt} + \frac{w_2}{w_1} \frac{di_{a2}}{dt} \right] - \frac{1}{2} \left( \frac{di_{a1}}{dt} + \frac{w_2}{w_1} \frac{di_{a2}}{dt} \right) \]

\[ + \frac{r_m}{2} \left( i_{a1} + \frac{w_2}{w_1} i_{a2} \right) \]

(9)

\[ v_{b01} = -e_{b01} = L_m (i_{\mu}) \frac{2}{3} \left[ \frac{di_{b1}}{dt} + \frac{w_2}{w_1} \frac{di_{b2}}{dt} \right] - \frac{1}{2} \left( \frac{di_{b1}}{dt} + \frac{w_2}{w_1} \frac{di_{b2}}{dt} \right) \]

\[ + \frac{r_m}{2} \left( i_{b1} + \frac{w_2}{w_1} i_{b2} \right) \]

(10)

\[ v_{c01} = -e_{c01} = L_m (i_{\mu}) \frac{2}{3} \left[ \frac{di_{c1}}{dt} + \frac{w_2}{w_1} \frac{di_{c2}}{dt} \right] - \frac{1}{2} \left( \frac{di_{c1}}{dt} + \frac{w_2}{w_1} \frac{di_{c2}}{dt} \right) \]

\[ + \frac{r_m}{2} \left( i_{c1} + \frac{w_2}{w_1} i_{c2} \right) \]

(11)

We also need to in the comments to the system of equations (1) to make the replacement indices in each phase at voltage drops in the magnetizing branch of the primary winding as shown in (12): in phase \(a\) to \(b\), in phase \(b\) to \(c\), in phase \(c\) to \(a\).

In version of MM, containing (9) - (12) equations, "+" sign in front of the right side of (12) should be used for schemes and vector groups Dy3, Yd3, Yy4, Dd4, and "+" to Dy9, Yd9, Yy10, Dd10.

\[ e_{a2} = \frac{w_2}{w_1} v_{e01} + L_{oa2} \frac{di_{a2}}{dt} \]

\[ e_{b2} = \frac{w_2}{w_1} v_{e01} + L_{ob2} \frac{di_{b2}}{dt} \]

\[ e_{c2} = \frac{w_2}{w_1} v_{e01} + L_{oc2} \frac{di_{c2}}{dt} \]

(12)

V. FEATURES OF THE MATHEMATICAL MODEL, IT'S COMPUTER IMPLEMENTATION AND SIMULATION RESULTS

Described by (1) - (12) MM is applicable in case of asymmetry of parameters of phase windings of the transformer (assuming the same for all phases of \(L_m\) and \(r_m\) ) and at unbalanced load. The account of the saturation of the magnetic circuit caused by the main magnetic flux is possible. The main magnetic flux of each phase of 3-phase transformer (for simplicity, we consider the three-leg core) passes through it's own one phase leg of magnetic core. In transformer’s MM is appropriate to use for each phase of its magnetizing current, i.e., the three dependencies \(L_m(I_{\mu1}), L_m(I_{\mu2}), L_m(I_{\mu c})\).

This approach allows us to take into account features of the harmonic content of the phase voltages and currents for
different types of connection schemes (an example of the simulation results shown in the table I).

When debugging a computer model of the equations (1) - (12) in the sense of matching to vector group, it is necessary to check the phase shift of the primary and secondary voltages at no-load conditions, as well as the results at nominal (loaded) conditions for the ratio of the values of current in primary winding and a transformed current in the secondary winding.

Examples of computer simulation of voltages and currents of the 3-phase transformer at different vector groups and other things being equal (frequency of 50 Hz sine wave, $w_1 = 330$, $w_2 = 57$, the nonlinearity of the magnetization curve is not considered, balanced active-inductive load) are shown in Fig. 1 and Fig. 2 , where the curves are marked as follows : 1 - line-to-line voltage of the primary winding $u_{a1} - u_{b1}$; 2 - line-to-line voltage of the secondary winding $5(u_{a2} - u_{b2})$; 3 - line-to-neutral voltage of the primary winding $u_{a1}$; 4 - line-to-neutral voltage of the secondary winding $5 \cdot u_{a2}$; 5 - phase current of the primary winding $50 \cdot i_{a1}$; 6 - phase current of secondary winding transformed to the primary $50 \cdot i_{a2}^\prime$.

The fig. 3 shows a view of the hierarchical block containing the model of three-phase transformer. Fig. 4 - 8 show the inner content of the hierarchical block: models of primary and secondary windings of transformer formed on the circuit engineering principle and the model of magnetizing branch, made in block diagram form.

<table>
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<th>$f$ (Hz)</th>
<th>$V_{1ma}$</th>
<th>$V_{2ma}$</th>
<th>$V_{mab}$</th>
<th>$I_{1ma}$</th>
<th>$I_{1mab}$</th>
<th>$I_{2ma}$</th>
<th>$I_{pma}$</th>
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<td>171,4</td>
<td>473,7</td>
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<td>6,2</td>
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<td>1,9</td>
<td>0</td>
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</tbody>
</table>

**Table I**

Harmonic Content of Voltage and Current for Computer Model of 3-phase Transformer 240 kVA Dy at Nominal Conditions When Powered Primary Winding by Sinusoidal Line Voltage and Nonlinear Magnetization Curve is Taken into Account

![Fig. 1](image1.png)

Fig. 1. The results of computer simulation of voltages and currents for 3-phase transformer with the scheme and the vector group Yy8.

![Fig. 2](image2.png)

Fig. 2. The results of computer simulation of voltages and currents for 3-phase transformer with the scheme and the vector group Yy4.

![Fig. 3](image3.png)

Fig. 3. Hierarchical block, symbolizing the three-phase model of the transformer T-164 with the scheme and the vector group Dy7. The left is a list of parameters whose values are transmitted to the internal circuitry of the model.

![Fig. 4](image4.png)

Fig. 4. The model of the secondary winding of phase A transformer Dy7.
VI. EXPANSION OF THE COMPUTER MODEL OF 3-PHASE TWO WINDING TRANSFORMER COMPUTER

MODEL TO THE POSSIBILITIES OF MODELING ZIGZAG SCHEME

Connect "zigzag" is used when possible uneven load in phases with the presence of common mode currents. Since modern electric drive and power schemes have proliferated multigang units and frequency converters based on multilevel inverters an autonomous voltage, the demand are mathematical and computer models of three-phase three-winding transformers and transformers with windings connected on a "zigzag". Such a model can be claimed on the basis of mathematical and computer models of three-phase two-winding transformer with a single magnetic core.

Known computer models of three-phase three-winding transformer and three-phase transformer with a primary winding connected to "zigzag" in MATLAB Simulink. The disadvantage is that the models are built on the basis of three single-phase three-winding transformers.

Of [1] it follows that each phase winding at connection scheme "equal-leg zigzag" is formed from two identical half-windings connected in series. Moreover, the shift in EMF between half-windings is 60 electrical degrees. For transformer with Dz0 we can say that in one of the half-windings EMF shifted with EMF of primary winding as group 1 (backlog at 30 electrical degrees). And another half-winding has shift as 11 group (lead of 30 electrical degrees).

At first, obtain a computer model of three-phase three-winding transformer Dyy1 - 11, wherein there are two identical secondary windings.

Received acceptable simulation results for transformer Dyy1 - 11, we can begin to compile the model Dz0. To do so, the findings of the hierarchical block, symbolizing the three-winding transformer, connect as follows (fig. 9): beginnings of phases of the secondary winding, the ends of which are connected in one point attached to the ends of other similar phases of the secondary winding. Beginnings of the last phases are connected to the phases of load.
When connecting the secondary winding on a "zigzag" model gives magnitude voltage across the secondary winding of 1.15 times less than in the case of "star" connected secondary winding, which is true. Example of results obtained at sinusoidal voltage is shown in Fig. 10.

The developed computer model is suitable for non-standard connection groups with the scheme "not equal-legs zigzag." The model is possible taking into account nonlinearity of magnetization curve.

Presented in the report results is the part of the work performed by the author under the proposed thesis for the degree of Doctor of Technical Sciences. As a part of this work has also developed computer models of three-phase induction motor, single-phase transformer, saturable reactor, thyratron, power electronic convertors. They are used for the simulation of industrial and railway transport electric drive modes, including dynamic thermal modes of induction motor under feeding with asymmetric power voltage.

VII. CONCLUSIONS

Uniformed MM of 3-phase transformer (two windings) with a single magnetic core, covering 12 standard vector groups in a clockwise notation (for wye and delta schemes) is developed.

The model takes into account iron losses. Accounting for the nonlinearity of the magnetization curve is produced individually for each phase, thus achieving the correct simulation of the harmonic content of voltages and currents.

Computer implementation of the MM of 3-phase transformer designed by means of Pspice provides 12 terminals of the windings, thus achieving the possibility of its use in any circuit diagram.

On a computer model successfully passed test modes confirming strong magnetic coupling of transformer phases at presence of a single magnetic core such as follows.

Test Mode 1. Upon excitation coil located on one of the rods in the unexcited windings of open other rods will be induced substantial EMF (slightly less than half of the applied voltage, in accordance with the parameters of the transformer). For example, upon excitation of one phase winding of the primary open-loop test is conducted with the other two phases of the primary winding and the secondary winding open-loop phases.

Test Mode 2. Same as above, but with shorted windings other rods (in which a shorted winding unexcited rods there are significant currents). The model is shorted unexcited phase primary winding to the ground. Phase secondary winding can be all open or secondary winding loaded at rated load.

Computer models of transformers has been successfully tested in circuits with non-sinusoidal (PWM) supply voltages, including scheme IIIy.

An extension of the mathematical and computer models for three-phase three-winding transformer and circuit zigzag are achieved.

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The Generation of Multidimensional Stochastic Process of Perturbation in the Problems of Railways Rolling Stock Dynamics

Savoskin A. N.
Electric trains and Locomotive Department
Moscow State University of Railway Engineering
Moscow, Russia
e-mail: elmechtrans@mail.ru

Akishin A. A.
Electric trains and Locomotive Department
Moscow State University of Railway Engineering
Moscow, Russia
e-mail: elmechtrans@mail.ru

Abstract—During the movement of trains on the tracks it’s exposed to the perturbation in the form of railway track irregularities causing oscillations of mechanical parts. This raises the problem of the generation of multidimensional stochastic process disturbances, given the matrix of correlation functions or spectral densities. For this was created the forming mechanism in the temporary realm. With help, According of this mechanism was performed the generation of multidimensional random process in the temporary realm

Keywords—the generation of multidimensional stochastic process, perturbing factor causing railway vehicles oscillation, the forming mechanism in the temporary realm

For the solution of the problems of dynamics of railway rolling stock you need to generate a multivariate Gaussian stationary stochastic process of perturbation \( y(t) \) known for its characteristics - matrix auto and mutual correlation functions \( R_{yi}(\tau) \) or matrix spectral and reciprocal spectral densities \( G_{yi}(j\omega) \).

For this purpose usually use formative mechanism [1], its structural diagram shown in figure 1. This mechanism consisting of \( m \) uncorrelated white noise generators (WNG\(_1\) + WNG\(_m\)) and \( 0,5 \, m (m + 1) \) linear sustainable minimal phase filter with the specified frequency character-

\[ x_i(z) \]
\[ x_i(z) \]
\[ x_i(z) \]
\[ x_i(z) \]
\[ x_i(z) \]
\[ x_i(z) \]
\[ x_i(z) \]
\[ x_i(z) \]

Fig. 1. Structural scheme of forming mechanism in the operator realm

In the software implementation, each WNG\(_i\) generates a discrete sequence of numbers , \( x_i[nT] \), \( n = 1, 2, ..., N \) and \( T \) - sampling increment, distributed by the Gaussian law with the spectral density equal to one. This sequence \( x_i[nT] \) is not correlated with each other.

This process is necessary converted into a multidimensional Gaussian stationary stochastic process with a
given matrix of spectral densities \( \| G_{yi} (j\omega) \| \) with the size \( i \times u = m \times m \), where \( i = 1, 2, 3, ..., m \) and \( u = 1, 2, 3, ..., m \).

As an algorithm for solving this problem offers the following procedure.

1). Since the output process are discrete, then necessary first obtain a matrix of discrete spectral density \( \| G_{yi} (z) \| \) output process \( y(nT) \) by discrete Laplace transforms

\[
X(z) = Z\{ x(nT) \} = \sum_{n=0}^{\infty} x[n]z^{-n}, \quad \text{где} \quad z = e^{qT} = e^{pT}
\]

(1)
of the matrix of correlation functions \( \| R_{yi}(nT) \| \):

\[
\| G_{yi} (z) \| = Z\{ \| R_{yi}(nT) \| \}.
\]

(2)

2). Formulate the matrix \( \| G_{yi} (z) \| \) in the following form:

\[
\| G_{yi} (z) \| = \| W^*(z) \| \| W_{iu}(z) \| \| G_{xi}(z) \|
\]

(3)

where \( \| W^*(z) \| \) — is a matrix of discrete frequency characteristics, hermitian coupled with a matrix \( \| W_{iu}(z) \| \): \( \| G_{xi}(z) \| \) — the matrix is singular spectral density uncorrelated signals at the output of the generators of white noise with the size \( m \times m \):

\[
\| G_{xi}(z) \| = \begin{bmatrix}
1 & 0 & 0 & \ldots & 0 \\
0 & 1 & 0 & \ldots & 0 \\
0 & 0 & 1 & \ldots & 0 \\
\ldots & \ldots & \ldots & \ldots & \ldots \\
0 & 0 & 0 & \ldots & 1
\end{bmatrix}
\]

3) Get the matrix \( \| W_{iu}(z) \| \) with the help of procedure "factorization" expressions (3) and convert it into the matrix of the impulse characteristics with the help of the inverse discrete Laplace transformation.

4) To calculate the output process with the help of integral convolution.

4) To calculate the output process \( \eta_{iu}(x = vt) \) with the help of integral convolution

\[
y_{iu}(nT) = \int_{0}^{\infty} k_{iu}(nT - \zeta) x_{iu}(\zeta) d\zeta.
\]

where \( T = \frac{\Delta x}{v} \)

\[
\int_{0}^{\infty} k_{iu}(nT - \zeta) x_{iu}(\zeta) d\zeta.
\]

Fig. 2. Structural scheme of forming mechanism in the temporary realm
The implementation of this algorithm can be executed in the new scheme forming mechanism (figure 2), containing impulse response \( k_{iu} (nT) \) and integrators that performs the calculation of integral convolution (5).

As an example, present the generation of four-dimensional Gaussian stationary stochastic process disturbances in the form of vertical and horizontal irregularities \( \eta_{iusl} (x = vt) \) of the left and right rails, causing oscillations in railway vehicles. Here \( i = s = 1 \) corresponds to the vertical irregularities; \( i = s = 2 \) - horizontal; \( u = l = 1 \) corresponds to the left, and \( u = l = 2 \) - the right wheels. As a result, the numbering of the matrix will have a dimension of \( 4 \times 4 \).

In [3] was performed approximation by analytical expressions auto and mutual correlation functions and the spectral and the reciprocal spectral density of such a multidimensional stochastic process.

We cite an expression for the correlation functions to the form, corresponding to the differentiable stochastic process \( \eta_{iusl} (x = vt) \):

\[
R_{iusl}(\tau) = S_{iusl}^2 \sum_k a_{kiusl}^2 \exp \left[ - (\alpha_{kiusl})^2 (n_{iusl}^* \Delta x)^2 \right]
\times \cos \left( \beta_{kiusl} n_{iusl}^* \Delta x \right)
\]

where \( n_{iusl}^* = n - n_{ciusl} \) \([m]\); \( a_{kiusl}^2 \) - the part of the variance \( S_{iusl}^2 \) stochastic process, coinciding with \( k \) component of the correlation function \((k=1, 2, 3, 4)\), and \( \sum_k a_{kiusl}^2 = 1 \); \( \beta_{kiusl} \) \([-\text{m}^{-1}] \) and \( \alpha_{kiusl} \) \([-\text{m}^{-1}] \) - the frequency of the maximum and the relative damping factor \( k \) component of the correlation function \( R_{iusl}(\tau) \); \( n_{ciusl} \Delta x \) \([m]\) - the shift of the maximum of mutual correlation functions, relative to the origin.

If \( \beta_{kiusl} \) is zero, equation (6) will contain exponential component. If \( n_{ciusl} \Delta x \) is zero, stochastic processes \( \eta_{iusl} (x = vt) \) are not correlated, i.e. statistically independent. Also \( n \Delta x_{ciusl} = 0 \) corresponds to the analytical expression of the autocorrelation function.

Perform direct discrete Laplace transforms of the expression (6) in the software package MatLAB with the help of command "iztrans" and get the expression for the discrete spectral densities in the form:

\[
G_{iusl}(z) = S_{iusl}^2 \sum_k a_{kiusl}^2 \times \left\{ \exp \left[ - \alpha_{kiusl}^2 \Delta x \right] \right\} \exp \left[ - \beta_{kiusl} \Delta x \right] z \times \left\{ \exp \left[ - \alpha_{kiusl}^2 \Delta x \right] \right\} z^2 + 2 \left\{ \exp \left[ - \alpha_{kiusl}^2 \Delta x \right] \right\} \cos \beta_{kiusl} \Delta x z + 1 \right\} \]

(7)

Factorize (7) in software package MatLAB using the operator "factor", we find an analytic expression for the matrix elements of the transmission functions:

\[
W_{iusl}(z) = S_{iusl}^2 \sum_k a_{kiusl}^2 \times \left\{ \exp \left[ - \alpha_{kiusl}^2 \Delta x \right] \right\} \exp \left[ - \beta_{kiusl} \Delta x \right] z \times \left\{ \exp \left[ - \alpha_{kiusl}^2 \Delta x \right] \right\} z^2 + 2 \left\{ \exp \left[ - \alpha_{kiusl}^2 \Delta x \right] \right\} \cos \beta_{kiusl} \Delta x z + 1 \right\} \]

(8)

Performing the inverse \( z \)-transform for \( W_{iu}(z) \) with help of the command "iztrans" switch over to the matrix of the impulse response:

\[
k_{iu} \{n \Delta x\} = S_{iu} \sum_k a_{kiusl} \times \left\{ \exp \left[ - \alpha_{kiusl} \Delta x \right] \right\} \cos \left[ \beta_{kiusl} (n \Delta x - \tau_{iusl}) \right] - \exp \left[ - \alpha_{kiusl} [(n + 1) \Delta x - \tau_{iusl}] \right] \}
\]

\[(n = 1, 2, ..., N; \ \Delta x = \nu T)\]

(9)

Comparison of the impulse response characteristics, based on this expression and correlation functions (6) with the values of the parameters, given in [3], show that these processes are close enough.

The difference between them is that in the first stage, the damping of the impulse response faster than the correlation functions. Then, when \( n \geq 50 \) this damping is slowing down (\( \Delta t = 0.185 \ s \)).

For example in Fig. 3 shows such a comparison for the autocorrelation function and impulse response horizontal irregularities of the right rail and mutual correlation
function and impulse response vertical irregularities of the left and horizontal irregularities of the right of rails.

According found impulse characteristics with the use of integral convolution was performed the generation of multidimensional random process in the temporary realm Fig.2 with parameters $\Delta x = 0.185\,m$ and $N = 5400$.

The results of generation one of the sets of realizations of four-dimensional stochastic process geometric irregularities of railway (Fig. 4), made according to the described algorithm, show, that generated random processes "average" close to the source.

For a more detailed comparison, perform the correlation and spectral analysis of random processes according to the method described in [3], and compare them with the specified schedules of correlation functions and spectral densities of the real track, presented in [3].

For example, figure 5 shows some graphics for auto and mutual correlation functions, and in figures 6 and 7 corresponding auto and of the mutual spectral density. These graphs, built on the generated implementations have normal convergence with the specified set. Some variance explained by the peculiarities of the functioning of white noise generators, and also the errors of the spectral analysis.
Fig. 5. The autocorrelation function of the irregularities of the track: the left vertical rail (a) and right rail horizontal (b); mutual correlation function between vertical and right horizontal irregularity rails (c); right vertical and left horizontal irregularities of the rails (d); generated - solid lines; analytic expression is dotted line.

Fig. 6. Spectral density irregularities of the left vertical (a) rail and right rail horizontal (b); generated - solid lines; analytic expression is dotted line.
Thus, we propose an algorithm of generation of multidimensional geometric irregularities of the rail track. Using this algorithm you can generate such irregularity at different speeds with any length of implementation and discretization step. This allows you to numerically solve it in a temporary area of the multidimensional problem of the dynamics of rolling stock with nonlinear characteristics spring suspension.

Reference

Hardware and Software System for Modeling
PWM and PPM Signal for Telemetry System

Baiguanysh S., Alimbaev A., Mirmanov A.
Department of Radio Engineering, Electronics and Telecommunications
S.Seifullin Kazakh Agrotechnical University
Astana, Kazakhstan
e-mail: mirmanov.a@mail.ru

Abstract — In this article The problems of building new telemetry system for geophysical investigations of petroleum and gas drills while process of drilling are considered. The using of hardware-software complex based on NI equipment to studying this problem is shown. The programming code and experimental device to shaping information sequence of telecommunication system with microwave transmitter and pulse phase modulation is developed.

Keywords — Telemetry, PTM, microcontroller, unhomogeneous media.

I. INTRODUCTION

Technology development and operation technology of petroleum and gas drilling is the most important area of science and industry. Drilling wells is difficult, and in some cases dangerous process.

Currently, cable-free telemetry systems and standalone devices are widely used to solve various geological, technological and technical problems in the process of drilling directional and horizontal wells, studying the parameters of the geological section, their development in difficult geotechnical conditions and exploitation of oil and gas, coal, ore and special wells of various minerals deposits. [1]

II. RESEARCH PROBLEMS

Abandoning the old transmission methods and equipment associated with the decision of a large systemic problem. Enumerate the problem situations and resolved conflicts

1. Frequency band.
2. Radiowave propagation in an inhomogeneous medium with a large signal attenuation.
3. Modulation type and waveform.

Modernization and improvement of the existing equipment are not able to solve all these problems, because the method of transmitting data is a restriction itself. From this, it follows the urgency of developing fundamentally new approaches to design methodology and operation of telecommunications systems in geophysics.

These problems were partially resolved in research on the circuit and constructive realization of powerful Gunn oscillator. For example, in [1], circuit and constructive description of the generator module were given, and in [2] - its performance characteristics were described. The possibility of erratic diode’s work in resonator chamber was noted and developed measures to stabilize the power system module that finally led to the stable generation of radio pulses [3]. In article [4] an approach to the study of the behavioral generator module was developed and identified patterns that would reveal the possible use of the module not only in short-range radar, but also in data transmission. Nanosecond microwave pulses are successfully used for sensing pipes and defect detection [5]. While the pipeline itself is a kind of ultra-boundary waveguide that provides all types of waves. Data transmission in the ultra-boundary waveguides has not been investigated because of the large attenuation and lack of technological applications in the past. However, recently in geophysics it became necessary for improving efficiency and reducing resource consumption of geophysical works [6].

In the papers, cited above the first two problems were considered, questions relating to the type of modulation and waveform considered only in context. Considering the high probability of inhomogeneities in the communication channel affecting the shape and amplitude of the signal, it is necessary to conduct research on the generating of an information signal applied to the works mentioned above. In filling environment, it is impossible to use ordinary pulse transmission systems, because while passing through the communication channel videopulse signals integrity will be compromised. SNR for signals of different shapes in the filling environment changes significantly [7]. For data transmission, radiopulse and noise-like signals can be used.

III. TRANSMITTING MODULE OF THE TELECOMMUNICATION SYSTEM

Gunn oscillator [6] consists of two nodes:

- modulating signal formation unit of rectangular shape;
- waveguide resonator.

Waveguide resonator where the Gunn diode are set forms a microwave unit. Rectangular modulating signal-generating unit is designed for excitation of Gunn diode by pulses of different duration and duty cycle Electrical block diagram of generation module is shown on figure 1.

Figure 1. Block diagram of the generator module
IV. HARDWARE-SOFTWARE SIMULATION COMPLEX

In this work, the PPM signal was formed implemented by software-hardware complex based on National Instruments equipment (Fig. 2), which includes:

1) Training Lab Station NI ELVIS II
2) Development board with Freescale's microcontroller
3) Modular PXI test platform
4) LabVIEW software
5) IDE Freescale CodeWarrior for HCS12

Figure 2. Hardware-software complex

NI ELVIS II platform is a bundle of virtual instruments for academic and research laboratories. NI ELVIS II can solve some problems by installing specialized boards for telecommunications, fiber-optic technology, microcontrollers, electronics, etc.

Using NI ELVIS II with Freescale HCS12 microcontroller from the company AXIOM provides great possibilities for exploring the basic architecture of HCS12 microcontrollers. It is also possible to study the basics of embedded systems development not only on HCS12 microcontrollers, but also based on other architectures. As well one of the main advantages is the availability of software for writing the code itself and its subsequent in-circuit debugging. Branded IDE Freescale CodeWarrior for HCS12 performs both of these tasks. It includes: the compiler, linker and debugger. The latest version of CodeWarrior is available on the official website freescale.com. Free trial version allows you to write programs in assembly language without any limitations and the language C / C++ with the restriction on the size of the firmware.

Hardware-software complex PXI-1044 National Instruments Company with a set of modules is used to visualize the operation process of the microcontroller, in conditions close to the microwave signal transmission in a heterogeneous environment. The package includes:

A) Generator to 3.3 GHz – required for formation of a high-frequency signal and transmitting it into the waveguide

B) Vector spectrum analyzer to 3.3 GHz – required for investigation of the signal passed through the circuit. This module can explore the frequency spectrum of the high-frequency signals, distortion and noise at the output of tract.

C) Programmable preamplifier. Since the signal in the path can be greatly weakened, it needs to be strengthened for better transmission through the tract.

V. PROGRAM IMPLEMENTING MODULATION

To demonstrate the basic capabilities of the platform was developed a program of controlling PWM module via ADC module.

Microcontroller control program was developed in order to analyze the changes in the shape of the signal depending on the modulation parameters.

To analyze the modulation implemented MC9S12C32 microcontroller program was developed. The algorithm presented in Figure 3.

Figure 3. Algorithm of the program
Main algorithm performs initialization PWM module and an analog-digital converter module of the microcontroller. As well RTI module is initialized. At the next step, the interrupts from RTI module are enabled. Then the program loops and does nothing.

When an interrupt occurs, the CPU core ceases to perform the main algorithm, and goes to the interrupt handler subroutine. Subroutine performs analog-to-digital conversion, obtained value sets PWM duty cycle. Then the program exits from an interrupt handler.

Figure 4 shows a connection diagram for the PWM study complex. The microcontroller is programmed using the programmer module. The one of the ADC channels connected to a signal of the function generator. The output signal is taken from PWM zero channel, and the input signal is the zero ADC channel.

Figure 4. Connecting complex to experiment with PWM and ADC modules

VI. SIMULATION RESULTS

Results of the experiment are represented by waveform and spectrum of the signal at the output of the PWM module. PWM signal is shown by red color, and the signal on ADC input is blue.

Figure 5 shows the result of the voltage changes at the ADC input. Increasing the voltage can change the PWM duty cycle.

Figure 5. PWM signal with different duty cycle

Figure 6 shows the result of the impact of the harmonic signal at ADC channel.
VII. CONCLUSIONS

Thus, PPM generation unit was implemented by using considered hardware-software complex, as part of a project to develop a data transmission system via inhomogeneous media used in geophysical studies.

Study of signal parameters, the type of modulation, simulation and experimental research will lead to a new method for transmitting telemetry data, which in turn will contribute to resource efficiency of geophysical works and its cheapening.

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Simulation Models for Studying the Multiprocessor Systems

Efimushkina N.V., Orlov S.P.
Computer technology department
Samara State Technical University
Samara, Russia
e-mail: nvefimushkina@mail.ru

Abstract - The paper describes the high-performance computing systems simulation models, such as the multiprocessor systems of different structures, as well as the subsystem of memory of these systems. The sets of input and output data are given. The samples of the screen form for the simulation models are shown. The software is designed by students under the guidance of authors and is successfully applied in SSTU during for several years. Software product’s authors were awarded with the certificates from the Russian national competition of student’s works in natural sciences.

Key-words - multiprocessor system, memory, simulation modeling.

I. INTRODUCTION

Modern computers and systems are characterized by the complex architectures and sophisticated operating modes. Methods of the computing systems theory are applied to study the specifics of the systems. The most reliable results might be obtained by the experiments on the computing systems functioning under the real or close to real conditions. High complexity of the real computer architectures makes the process of learning very hard for the student.

II. PROBLEM FORMULATION

The most perspective methods of simulation modeling are the methods which are based on the functional specification of the system presented in the form of algorithm called as simulation (algorithmically) model. The program contains the procedures that imitate the states of the system and the processes for evaluation of the system requirements. Simulation models reproduce the work of the system according to the foregone properties of the elements which models in their turn are also combined into corresponding structure. Scalability is one of the most important properties of simulation modeling. Proposed approach allows studying the systems of any complexity considering the impacts of different factors and reproducing the most typical situations.

Simulation models provide qualitative information about the system properties to make reasonable design decisions. In order to make the application of the described method more valuable and understandable for students, simulation models should be visualized by implemented user interfaces.

The correct choice of parameters and attributes which should be used to describe the structure and the possible states of the objects inside the model is the core problem of its development. The chosen attributes should provide the basic properties of computers’ functioning on the one hand and to reduce the number of secondary factors which complicate the perception of the model on the other hand.

III. PROBLEM SOLUTION

The number of problems had been solved while developing models:

1) Choosing the basic elements of the system which have to be displayed in the model;
2) Definition the specification level of the object parameters;
3) Assessment of the model adequacy.

During for the solution of the first problem as the research objects were chosen:

a) The central part of the multiprocessor system containing the central processors and memory modules;
b) The multilevel memory subsystem.

It was necessary to display the basic elements of the systems which define the features of their functioning. For example, in the multiprocessor systems the major elements are the processors and the related random access memory modules. The conflicts arising at the access of the several processors to one memory module, can significantly affect system productivity. The memory subsystem has a hierarchical multilevel structure. Such a structure also is investigated in the considered models.

The choice of the set objects parameters was another problem in developing models. They have to provide the explanation of the main functioning features of the high-performance computing systems and their devices. Thus, it is necessary to reject the minor factors which complicate the perception.

Described approach has led to use the simplified models of the systems. So, peripheral devices aren’t displayed.
Models contain the minimum quantity of the elements which are enough for explanation of object work.

IV. THE DESCRIPTION OF MODELS FOR STUDYING THE MULTIPROCESSOR SYSTEMS

Models represent the software package of the various structure computer systems simulation models. It is intended for carrying out the laboratory classes on the subject "Architecture of the high-performance computing systems" for the computer science bachelors. The software can be useful for the similar architecture real computer systems research. It allows studying the organization of computing processes in the central part of the multiprocessor systems, and also in their memory subsystem. There is an opportunity to research the most various factors influencing on these devices and systems productivity. The software provides an assessment of the temporary characteristics. It includes simulation models for such systems as:

1) The fixed structure multiprocessor system;
2) The multiprocessor system with a variable structure;
3) The multilevel memory subsystem.

The multiprocessor systems are based under construction on the identical devices: processors, RAM modules, etc. They work under control of the general operating system. The central part of such systems consists of several processors and the memory modules connected by a communication network (as shown in fig. 1) [1, 2].

![Microprocessor System Central Part](image)

Fig. 1 The microprocessor system central part

Nowadays, the various structures of such networks are developed. In offered article connection "everyone with everyone" is considered.

One of the most important problems of the multiprocessor systems is the conflicts in the central part, arising at the access of two and more processors to one memory unit. Such access, as we know, can lead to the information distortion in the RAM and data mistakes. The semaphore principle is used for their elimination. The first processor addressed to memory, takes it and sets a flag. All the other processors requests are put in the queue. Such queue service is carried out with using some of known disciplines. From the point of the whole system the conflicts lead to increase the task solution time and decrease the processors efficiency due the resources (RAM) release waiting.

Research conflicts in the computer systems are one of the important problems of the computing systems theory. Analytical methods of this problem solution are based on the closed stochastic networks theory and are characterized by the complex expressions and valuable errors [3]. The system simulation model working in a multiprogramming mode, allows researching her behavior at any structure and any service discipline. Such a model is also realized in offered creation. Three processors and three RAMS are presented in it. The bigger amount of the devices will complicate model and system studying.

Input data for modeling are:
1. The number of the tasks processed by the system;
2. Each task parameters:
   2.1. The number of tasks processing stages (execution and RAM access).
   2.2. The execute time and RAM access time.
   They can have the following ratios:
   2.2.1. The execute time is more in 2, 5, 10 times the RAM access time;
   2.2.2. The execute time is equal RAM access time;
   2.2.3. The execute time is less in 1, 5, 2, 3 times the RAM access time;
3. Order of the processors accesses to the RAM.

The following modes are investigated:
3.1. Each processor works only with the own RAM (the RAM has the same number, as the processor);
3.2. Each task works with the all RAMS in the set order.

Model results are presented as:
1. The trace of tasks executions for the each processor;
2. Total processors waiting times and task holding times which are shown near each processor during modeling;
3. The processors efficiency coefficients.

The model allows to research two main operating modes:
a) Each processor works only with the own RAM;
b) Each processor works with the all RAMS.

The first mode doesn't cause the conflicts and is an etalon for the second one. If the processors work with the all RAMS, it is necessary to set an order of their accesses to the memory modules. At three processors and the RAM the order can be set in six different ways. In the model it appears by the revealing lists. The screen form for such operation is given in fig. 2.

Several tasks service is imitated in the model. For each of them the execute stage of processor and the memory access is carried out. Thus the temporary charts of processors
The number of processors;  
2) The number of RAM modules;  
3) The number of tasks;  
4) The execute stages quantity;  
5) Duration of execution;  
6) The access latency of memory;  
7) The order of accesses to memory unit.  
The model allows receiving the following results:  
1) The processors operation clock cycles quantity;  
2) Their idle time clock cycles quantity;  
3) The processor efficiency coefficients;  
4) Each processor conflicts quantity.  
It is possible to change number of the processors and number of RAM modules from 2 to 10. The number of the tasks varies from 100 to 1000. The quantity of the execute stages, the execute times and the access memory times change from 1 to 10 steps. Initial data set screen form for complex containing the five processors and RAM is provided on fig. 4.

The functioning processor is painted on the model scheme by its own the color. If the processor stands idle, it is signed by red color. The addressed RAM is painted over by the corresponding processor color. If the RAM is free, its color is white.

After model start in the form center the chart showing a condition of each processor in each step begins being under construction: blue color designates the account, green – the memory access and red – idle time.

During modeling the next statistics is obtained:
1) The processor operation cycles quantity;  
2) The idle time cycles quantity;  
3) The efficiency coefficient;
4) The number of conflicts.

The modeling process screen form is presented in fig. 5.

The described model provides to research the influence of the number of processors and the RAM, and also parameters of tasks on the system characteristics.

In a latest model the architecture of the multiprocessor UMA SMP computer system with the bus organization, the memory subsystem containing following main devices is investigated:

a) The main memory (RAM);

b) The cache memory;

c) The local memory.

Input data for modeling are:

1) The number of processors;

2) Total the number of memory access instruction;

3) Rate of read/write operations in the general mix;

4) The multiprocessor computer system configuration:
   - Without cache and local memory;
   - With cache memory;
   - With cache and local memories.

5) RAM, local and cache memory capacities in lines;

6) RAM, local and cache memories read and write latencies in clock cycles;

7) The number of lines copied in a cache and local memory for once (quantity of lines in the block).

The model results are represented as:

1) The executed instruction and cycles quantities;

2) The average time of executed instruction;

3) The system bus average efficiency;

4) The processors cache misses quantity;

5) The local memory misses quantity;

6) The executed instruction average quantity.

The model uses the principle "locality of references". In it information census from the bottom level in the top is carried out by the consecutive addresses blocks of lines. The general structure of a subsystem is represented on the screen in the fig. 6. The system without local memory screen form is given in fig. 7.

The model allows researching the influence of the following system characteristics: the number of processors, the memory structures, and also the programming structure (the access memory instructions ratio). There is an opportunity to define effective conditions for the system operation, and also the maximum number of processors for similar structures.

![Fig. 5 The modeling process screen form](image)

![Fig. 6 General memory subsystem structure](image)

![Fig. 7 System without local memory structure](image)
V. CONCLUSION

The program complex contains three typical multiprocessor systems models. It is used in laboratory classes on subject "Architecture of the high-performance computing systems". Simulation models are developed with use of the universal environments (Delphi and C ++). Models were simplified to reproduce the functioning of main computer elements, their structures and operational states, and visualized to make material more understandable for the student. The experiments that can be conducted using the models help to analyze the computer parameters and find out the optimal operating modes with provided input information.

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Virtual Laboratory Training Module: Programming of Machining on CNC Lathes under 3D Model Using HSM Technology Elements

Platonov V.V.
Mechanical engineering and metallurgy technologies
Department
Khakas Technical Institute
Abakan, Khakas Republic, Russia
Email: pvv_hti@mail.ru

Fomin D.Yu. and Medko V.S.
Construction material technology and material science
Department
St. Petersburg State Polytechnic University
St. Petersburg, Russia
Email: dmitryfmn@yandex.ru, v.medko@yandex.ru

Abstract— High Speed Machining (HSM) technology is considered by authors as most prospective technology in machining field in future. Investment on machines and cutting tool for HSM technology is too high to use it directly in educational process. Authors develop laboratory training module for education purpose in universities which based on simulating of machining process in SprutCAM system.

Keywords— high speed machining, CNC lathe, educational laboratory module, simulating, SprutCAM system

I. INTRODUCTION

High Speed Machining (HSM) is the innovative technology, which offer reduce production time and in the same time increase precision of machining. Under HSM reducing chronometrical time of process achieves by using intensive cutting parameters and common simplification production process. Main rule for success in HSM technologies is the correct choice of factors participating in production process: lathe, CNC system, cutting tool, CAM system using HSM support, employee qualification skills.

Statistic survey (made by IBAG company) at in German, Japan and USA industrial society had resulted: 20% respondents suggest HSM is most prospective technology of the future [1].

Thus HSM took second place by importance after automatic preproduction systems. 60% of German and 90% of Japan enterprises have plan to invest in HSM technologies. This digits show us importance of HSM technologies and knowledge.

CNC Lathe for HSM is special equipment which approx. 2-2.5 times more expensive than standard CNC machines. Technological fixtures for HSM are also several times more expensive than for standard CNC processes.

Financial question for Russian higher education is too important which exclude possibilities to use HSM machining centers in mass educational purposes. This problem can be solving out in industrial cooperation using modern simulating system.

II. BASE FOR DEVELOPING EDUCATIONAL LABORATORY MODULE

Development of HSM technology and organizing high technology production been realize on base SLL “Abakan-Plast” where in cooperation with Khakas Technical Institute startup flexible production of press forms. This project at the same time is experimental production and educational base for students/specialist majoring in CAD/CAM knowledge. Practice and laboratory trainings under discipline “CNC Lathes” are held on the factory (fig. 1).

A. Equipment

Now day our education facility consists of 7 CNC machines:
• vertical milling machine 65A60, CNC system “NC-201M”, additional liquid cooling for spindle bearing, parameter S1 till 2 500 rpm;
• milling machine FD-106 MAKINA (Japan), CNC system “NC-302” with impulse control actuators feeds SDC series, high speed motor-spindle IBAG (24 000 rpm, runout not more 2 micron) (fig.2);

Fig. 2. Milling machine FD-106 MAKINA

- vertical milling machine 2C150ПМФ4 CNC system NC-210, drive system HA-HM series, electrical accelerator head IBAG (40 000 rpm);
- special milling machine for finish HSM small workpieces on the base of universal milling machine 6720, CNC system “NC-220”, drive system HA-HM series, motor-spindle 24 000 rpm (Taiwan);
- CNC machining center VM850 (China), CNC system Siemens SINUMERIK 828D, motor-spindle 12 000 rpm;
- CNC machine 16К20, CNC system NC-220, drive system HA-HM series.

Staff includes 5 people – all young specialists’ mechanical engineering and metallurgy technologies department of Khakas Technical Institute.

B. General laboratory equipment and software

In parallel with educational training center was organized laboratory - computer class for programming CNC system type NC-200. Each computer of this laboratory connected with concrete CNC machine. Computer works as simulator for CNC machine in purpose to prepare machining technologies for CNC machines, develop operating program.

On each computer in addition to CAD/CAM program set up virtual machine with emulator of CNC system NC-210. Laboratory computers and lathes are organized in one network. Network use to design parts by using 3D models under CAD system and then to gather it into nodes. CAM system use to generate machining technology using 3D model, to simulate machining process, to create operating programs and after all procedures to transfer operating program by virtual network to the CNC machine (emulator CNC system). On the emulator we can control machining process by using graphic display. Also computer class offer to learn PLC programming language for programming electro automatic devices for CNC machines.

C. CAM system

We use SprutCAM® because this is CAM system high automation level system. By the way to create operating program we have to define 3D model of the product, preform and fixture. In next step we have to form machining stages. For the each stage we have to define common machining parameters e.g. the angle of cutting, height of crest. According to input parameters system automatically will calculate and define optimal trajectory. During the simulating process preforms happed us real unit from stage to stage. Geometry changes from stage to stage.

Procedures for generating operating program for CNC machine include:
• import of geometrical model;
• generate models of preform, part and fixture;
• determine machining stages and parameters;
• generate operating program for CNC machine.

Program automatically installs basic recommended parameters for each machining stage and dependently of geometry requirements for new technological process.

Correction regarding parameters is possible on each design stage of technological process.

Interface of SprutCAM system is flexible regarding design of machining stages with no limitations. Each made modification cause changes of schematic figures on display.

D. CNC lathe simulator: virtual machine, emulator

Emulator works under DOS in real time mode on virtual machine - VMware Player (fig.3). Operation system requirements: Windows 2000/XP, Windows 7. CNC system is produced by Balt-system.

Fig. 3. Emulator
Functionality: development and correction of operating programs for machining

III. LABORATORY MODULES

A. Module “Operating program for 2D contour”

Purpose: automated design of an item in CAD system, generating technological process for machining and development of operating process in SprutCAM 2007.

Procedures:
1) Construct a curve in “Kompas Graphic” CAD system and transform it to SprutCAM 2007 or generate 2D geometry directly in SprutCAM 2007;
2) Generate 2.5D milling technology in SprutCAM 2007;
3) Retrieve operating program in ISO mode of CNC system “NC-210”, write graphic display to it;
4) Transfer operating program to emulator of CNC system (by virtual network);
5) Run machining program and observe it by graphic display.

B. Module “Operating program by 3D model”

Purpose: automated design of technological process for producing press-forms from tempered steels (HRC 55) directly by 3D models in SprutCAM 2007 with elements of HSM technology.

Procedures:
1) Import 3D model (*.igs) to SprutCAM 2007;
2) Assign surfaces for machining (in cooperation with lecturer);
3) Assign lathe, cutting tool, parameters for machining according to HSM technology requirements and recommendations;
4) Simulate machining process;
5) Retrieve operating program in ISO code using postprocessor;
6) Correct cutting mode, zero point, write graphic display;
7) Transfer operating program to emulator of CNC system (by virtual network);
8) Run machining program and observe it by graphic display.

IV. PRACTICAL EXAMPLE

Proposal: develop machining process for item “punch” (fig.4).

Fig. 4. Item “punch”

Procedures:
1) Run SprutCAM7 in administrator mode;
2) Assign CNC lathe from program base “parameters” → “lache”: three-coordinate milling machine;
3) Assign 3D model of part for machining on appropriate tab. Information in tab “3D model” introduce as a tree-catalog “preform” → “part” → “fixture”. Import to each tab appropriate file with 3D model in *.igs data;
4) Install imported items on coordinate axes;
5) Assign machining parameters in tab “technology” → “create new”;
6) First stage: milling of the groove under the removal ring. Use function “2D contour”. Click to create tab → determine work zone for model, working surfaces, limitation zone → click “working proposal”;
7) Hold “Shift” and choose all outside contour elements → click “curve”. Project drawing will change according fig.5;
8) Double click by generated project to open tab “corrections” → use “equidistant” mode for automatic tool radius corrections;

9) Correction of machining parameters: tab “geometrical parameters” → choose cutter tool, type → length → diameter;

10) Correction cutting mode: tab “modes” → feeding options, cooling if necessary. Advice to use “feeding auto calculation” tab to increase precision;

11) Correction in tab “approach” (fig. 6) to set up safe surface. Choose overrun, approach, trajectories;

12) Parameters corrections: tab “parameters” (fig.7) → correct parameters depending tool and item characteristics;

13) Assign machining strategy: tab “strategy”(fig. 8) → user can choose 2 variants of applicable strategy: machining by “wells” - each hole cut to a predetermined depth consistently or machining “by layer” – tool cut all hole on the same depth stage by stage;

14) Correction of machining field: “machining field”;

15) Correction of machining transitions: tab “transitions”;

16) Simulating: stages 1-15 are done, display shows preform (fig. 9).
17) Generate operating program: tab “file” → “generate post processor” → tap complete button;

18) Correct code of operating program: add and delete lines as it show on fig.10;

19) Run virtual machine with installed emulator → download operating programm in MP2 memory field → observe operating programm on display.

V. CONCLUSION

We hope that represented laboratory module will help to organize educational process in the field HSM technology under main and additional educational program, international semester, exchange programs.

REFERENCES

Fault-Tolerance in Redundant Distributed Hardware-Software Multi-Agent Systems

Igumnov A. V.
Information and Control Systems Department
St. Petersburg State Polytechnical University
St. Petersburg, Russia
e-mail: Alexei.Igumnov@gmail.com

Abstract— The developed model of redundant distributed hardware-software multi-agent system (MAS) defines new fault-tolerance strategy which is based on replication of tasks and actuators of the existing multi-agent systems as well as on an introduction of redundant sets of executive containers for execution of both tasks and software agents. The developed fault recovery methodology presented in the article includes communication protocol for components of MAS which enables task execution and actuators usage independently of its deployment in a particular executive container and fault-recovery procedures. The developed model as well as fault-recovery methodology was validated by the stated and proved theorem on fault-tolerance property of a redundant distributed hardware-software MAS. The application of logical-and-probabilistic methods to evaluation of reliability indexes of MAS is examined in the article. The criteria of serviceability and new probabilistic methods to evaluation of reliability indexes of MAS are developed. The computing experiment required for reliability function synthesis with logical-and-recovery methodology was validated by the stated and proved recovery procedures. The developed model as well as fault-recovery methodology presented in the article includes introduction of redundant sets of executive containers for actuators of the existing multi-agent systems as well as on a tolerance strategy which is based on replication of tasks and hardware-software multi-agent system (MAS) defines new fault-tolerance property of a redundant distributed hardware-software MAS.

Keywords— multi-agent system; fault-tolerance; fault-recovery; redundancy, operability function, reliability, imitation modelling.

I. INTRODUCTION

Several benefits of multi-agent systems (MAS) declared by an artificial intelligence theory are the reason of an increasing interest in application of agent-oriented technologies for development of various industry hardware-software systems.

One of the most important properties of industry system (e.g. control system) is its reliability. Existing methodologies such as DarX [1], AAA for broker teams [2], Sentinels approach [3] ensure fault-tolerance only in case of failures of agents and hosts required for execution of software agents. Moreover, existing methodologies are not able to provide any theoretical assessment of guaranteed reliability of MAS, thus its effectiveness is proved only experimentally. Known methods of determination of reliability of MAS described in [4] and [5] enable calculation of probability of survival in case of failures of several hosts of a network on which the said MAS is deployed.

The purpose of the described research is to ensure fault-tolerance of MAS in cases of software failures of agents and particular tasks of agents, hardware failures of hosts required for execution of software agents and hardware failures of actuators which are defined as special hardware components required for interaction of agents with an environment. To make MAS and agent-oriented technologies applicable for real world industry systems it is required to guarantee a specified level of reliability of MAS. Thus increasing of reliability indexes is not enough and there is a need in a method for theoretical assessment of reliability level of MAS guaranteed in case of application of the fault-recovery methodology.

II. HARDWARE-SOFTWARE MULTI-AGENT SYSTEM MODEL

A. Hardware-Software Multi-Agent System Model

The presented model of hardware-software multi-agent system is based on such elements of the MAS model developed for FATMAS methodology [6] as agents, tasks supposed to be executed by agents and resources required for execution of particular tasks. Let’s assume that all agents of MAS are implemented as software components. Thus we have introduced a set of additional components called agent platforms (AP). We define AP as a hardware-software component required for both execution of software agents and provision of services required for agent interaction. As MAS is typically situated in some environment and moreover MAS is designed to operate with the said environment we have also introduce a set of special resources called actuators (ACT). We define an actuator as a hardware-software component required for interaction of agents with an environment. It’s worth noting that the said mentioned interaction with an environment is required for performing of particular tasks. We also assume that all resources required for performing of tasks except of ACTs may be provided by each agent or AP and thus exclude a set of resources from the MAS model.

We define a distributed hardware-software MAS as an ordered set $MAS = \langle T, A, HWP, HWR \rangle$, where $T$ is a set of tasks, $A$ – a set of agents, $HWP$ – a set of APs, $HWR$ – a set of ACTs. The configuration of MAS is defined via following set of predicates:

- $confTaskAgent(t, a)$ determines whether a particular task $t$ belongs to a particular agent $a$;
**B. Fault-Tolerance Strategy and Redundant Hardware-Software Multi-Agent System Model**

FATMAS methodology [6] has introduced duplicating of tasks instead of duplicating of non-critical agents for the first time in the art. However FATMAS also utilizes duplication of critical agents if all tasks of these agents could not be performed by any other agent due to resource inaccessibility.

We have defined AP as a component responsible for execution of software agents. Now we shall explicitly state that AP is a universal executive container for software agents, i.e. any AP is able to execute any agent of MAS. Similarly we treat each agent of MAS as a universal executive container for any MAS task. Based on this assumption there longer is no reason to replicate (i.e. to create a full copy) existing agents and APs. Thus fault-tolerance shall be achieved through replication of functional components only, i.e. such components which functions could not be performed by any other component.

It’s suggested to build a fault-tolerance strategy based on replication of functional components of MAS such as tasks and actuators and an introduction of redundant sets of universal executive containers such as software agents and APs. To define a configuration of the redundant MAS based on the developed strategy it is required to define a deployment of tasks on a set of agents, a deployment of agents on a set of APs and an accessibility of particular actuators for particular APs.

We define a redundant distributed hardware-software MAS as an ordered set $RMAS = \langle TT, RT, RA, RHWP, THWR, RHWR \rangle$, where $TT$ is a set of task types, $RT$ – a set of tasks, $RA$ – a set of agents, $RHWP$ – a set of APs, $THWR$ – a set of actuator types and $RHWR$ is a set of actuators. The configuration of the MAS is defined via predicates as follows:

- $confTypeTask(tt, t)$ is true if a type of a task $t$ is $tt$;
- $confHwrHwp(hwr, hwp)$ determines whether a particular ACT $hwr$ is accessible for a particular AP $hwp$, i.e. for all tasks of all agents deployed in AP $hwp$.
- $reqHwrTask(hwr, t)$ determines whether a particular ACT $hwr$ is required for performing of a task $t$;
- $confAgentHwp(a, hwp)$ determines whether a particular agent $a$ is deployed in a particular AP $hwp$;
- $confTaskAgent(t, a)$ determines whether a particular task $t$ belongs to a particular agent $a$;
- $confAgentHwp(a, hwp)$ determines whether a particular agent $a$ is deployed in a particular AP $hwp$;
- $reqTHwrTTask(thwr, tt)$ determines whether an actuator of a particular type $thwr$ is required for performing of a task of a particular type $tt$;
- $confHwrHwp(hwr, hwp)$ determines whether a particular actuator $hwr$ is accessible for AP $hwp$.

The univocal correspondence exists between the set of task types $TT$ of the redundant MAS and the set of tasks $T$ of the existing MAS so that all tasks of type $tt$ of the redundant MAS are equal to a particular task of the existing MAS and may replace each other in case of failures. Similarly, the one-to-one mapping exists for the set of actuator types $THWR$ and the set of actuators $HWR$ of the existing MAS. The developed model is described in details in [7] and [8].

Only one task in a replication group, i.e. a set of tasks of a similar type, shall exert influence on the MAS environment during its execution. Such task is called an active replica of a particular type. It’s worth noting that one and only one active replica for each task type shall exist in redundant MAS.

III. FAULT-RECOVERY METHODOLOGY

A. Communication Protocol.

Each task of MAS is assumed to be able to request execution of another task or to utilize a particular actuator during its execution. To apply the fault-tolerance strategy to the existing MAS transparently we introduce new communication protocol based on message processing which shall enable execution of an active replica of a particular type as well as usage of an actuator of a particular type independently of its deployment in particular executive containers.

The communication between components of MAS is message-based and function send(msg(args), dest) indicates that a message msg with parameters args is sent to a component dest. We suggest that a receiver of message shall be strongly bounded based on type of originator component. Thus an agent is able to send a message to AP if and only if the said agent is deployed in this AP. Similarly AP is able to send a message only to its agents. Also it’s assumed that there is no limitation on message based communication between APs. We introduce some special values of available destination. Each component is able to send a message to a parent component in accordance with MAS hierarchy (i.e. from a task to an agent in that this task is deployed and from an agent to its AP) by specifying the up value as a destination. We assume that each AP shall be able to communicate with all APs of MAS by sending a message to the best destination.

Each agent of the redundant MAS shall have a database (DB) with following tables:
• deployment table contains records for all tasks located in the agent linking the task and its type;
• active replicas table contains records for all active replicas located in the agent linking the type of active replica and the corresponding task.

Each agent platform of the redundant MAS shall have a DB with following tables:
• deployment table contains records for all tasks located in all agents of the agent platform linking the task, its type and the agent in that the task is deployed;
• actuators table contains records for all accessible actuators linking the actuator and its type;
• active replicas table contains records for all task types of MAS linking a particular task type and either the agent of the AP if the active replica of this type is located in this agent or the remote AP if the active replica is deployed in one of agents of the remote AP.

If a particular task of the redundant MAS requires execution of another task of type tt it sends the pfm(tt) message to its agent specifying the up destination. The coordinated handling of the pfm(tt) message by all components of MAS results in execution of an active replica of the required type tt:
• on reception of the pfm(tt) message the agent will execute the active replica of the type tt if it is located in this agent in accordance with the active replicas table of its DB, otherwise the agent will send the pfm(tt) message to its agent platform;
• on reception of the pfm(tt) message the agent platform will determine whether the active replica of the required type tt is located in a particular agent of this AP or in one of agents of a particular remote AP in accordance with the active replicas table of its DB, then AP will finish a processing by sending the pfm(tt) message to either its agent or the remote AP.

If a particular task of the redundant MAS requires utilization of an actuator of a particular type thwr it sends use_hwr(thwr) message to its agent which will route the received message to its AP without any further processing. On reception of the use_hwr(thwr) message AP will find an accessible actuator of the thwr type in accordance with the actuators table of its DB and will perform the requested action.

B. Fault-Recovery Procedures

Fault-recovery procedures are required to deal with mentioned above failures that lead MAS to inability to perform one of tasks. We state that databases of agents and APs shall contain records only for components that are not in failure. It’s assumed that failures of all components shall be detected to perform an appropriate fault-recovery procedure. If a detected failure results in an inability to perform an active replica of a particular type then new replica shall be found and activated. The procedure of activation of new replica shall be performed iteratively in accordance with components hierarchy: firstly by a component responsible for failure detection, then by its parent and finally by coordinated actions of all agent platforms.

If an agent detects a software failure of its particular task t of type tt it will perform the a_r_tfail(t) procedure comprised:
• remove records related to the task t from DB;
• request its AP to remove all records related to the task t from DB;
• if the failed task t is the active replica of type tt then if there exists another agent’s task t* in accordance with the deployment table then activate it as new active replica by modification of the active replicas table otherwise send a request for new replica activation to its AP via req_atask(tt) message.

An agent platform processes req_atask(tt) message received from one of its agents by performing h_r_tfail(tt) procedure comprised following steps:
• if there exists a task t* of type tt located in agent a* of AP then activate the task t* as new active replica of type tt by modification of active replicas table and send a request to the agent a* to perform a modification of agent’s active replicas table;
• if AP is not able to find a task of type tt located in one of its agent, AP will send a broadcast request for replica activation to all remote APs via req_atask(tt) message.

An agent platform process req_atask(tt) message received from one of remote APs similarly to the h_r_tfail(tt) procedure defined above. However if AP is not able to find a task of the required type it will not issue new req_atask message because the received broadcast message indicates that the procedure of new replica activation by coordinated actions of all APs has been already initiated. If the new replica is activated by AP hwp it sends a broadcast atask_announce(tt, hwp) message. On reception of this message each AP updates the active replicas table so that a record for task type tt indicates that the active replica is located in one of agents of AP hwp.

An agent platform is responsible for detection of software failures of its agents. If an agent platform detects a failure of its agent a it performs h_r_afail(a) procedure comprised:
• remove records related to all tasks located in the agent a from the deployment table;
• determine a set of task types such that the active replica of each type from the said set is located in the agent a in accordance with the active replicas table;
• perform h_r_tfail(tt) procedure for all task types from the said set of task types to activate new replicas.

If an agent platform detects a failure of an actuator hwr of type thwr it performs h_r_hwrfail(hwr) procedure comprised:
• remove a record related to the actuator hwr from the actuators table;
• if there is any other available actuator hwr* of type thwr then fault-recovery is not required as processing of the use_hwr(thwr) request can be performed with the hwr*;
• determine a set of failed tasks of agents of AP such that each task from the said set requires utilization of an
actuator of type \( thwr \), remove records related to tasks from the said determined set from DB and request to remove corresponding records from DBs of agents;

- determine a set of failed task types such that the active replica of each type is deployed in one of agents of AP and belongs to the determined set of failed tasks;
- perform \( h_r_tfail(tt) \) procedure for all task types from the said determined set of failed task types to find and activate new replicas.

If an agent platform detects a failure of a remote AP \( hwp \) it performs \( h_r_hwpfail(rhwp) \) procedure comprised:

- determine a set of task types related to failed active replicas located in one of agents of the failed AP \( hwp \) in accordance with the active replicas table;
- perform \( h_r_tfail(tt) \) procedure for all task types from the determined set of task types to activate new replicas;
- for each new replica activated in one of agents of AP \( hwp \) by the \( h_r_tfail(tt) \) procedure send a broadcast \( atask_announce(tt, hwp) \) message to inform all remote APs about changes in deployment of active replicas.

It’s worth noting that \( h_r_hwpfail(rhwp) \) procedures shall be performed only by one of APs that has detected a failure.

C. Theorem on Fault-Tolerance Property of Redundant Distributed Hardware-Software Multi-Agent System

To validate the developed fault-recovery methodology we have stated and proved the theorem on fault-tolerance property of a redundant distributed hardware-software MAS. We define that a task \( t \) is in an operable state if and only if it is not in software failure, the agent \( a \) in that the task \( t \) is deployed is not in software failure, AP \( hwp \) in that the agent \( a \) is deployed is not in failure and the task \( t \) has an access to actuators of all required types and said mentioned actuators are not in failure.

Theorem. The redundant MAS will recover from detected software failures of agents and tasks and from hardware failures of agent platforms and actuators if following conditions are met:

- if software failure of a task \( t \) which is the active replica of type \( tt \) is detected then there exists another task \( t^* \) of type \( tt \) which is in an operable state;
- if software failure of an agent \( a \) is detected then for each task \( t_i \) which is deployed in the agent \( a \) and is the active replica of type \( tt_i \) there exists another task \( t_i^* \) of type \( tt_i \) which is in an operable state;
- if hardware failure of an agent platform \( hwp \) is detected then for each task \( t_i \) that is deployed in one of agents of AP \( hwp \) and is the active replica of type \( tt_i \) there exists another task \( t_i^* \) of type \( tt_i \) which is in an operable state;
- if hardware failure of an actuator \( hwr \) of type \( thwr \) is detected then for each task type \( tt_i^* \) which requires utilization of an actuator of type \( thwr \) there exists a task \( t_i^* \) of type \( tt_i \) which is in an operable state.

Proof. Let’s consider a failure of the task \( t \) of type \( tt \) detected by the agent \( a \) in which the task \( t \) is deployed. Let’s assume that the agent \( a \) is deployed in AP \( hwp \). In accordance with stated conditions there exists a task \( t^* \) of type \( tt \) that is in an operable state. The task \( t^* \) may be deployed in the agent \( a \), in one of agents of AP \( hwp \) or in one of agents of a remote AP \( rhwp \). All records related to the failed task \( t \) are removed from DBs of the agent \( a \) and AP \( hwp \) by the \( a_r_tfail \) procedure.

If the task \( t^* \) is deployed in the agent \( a \) then in accordance with the \( a_r_tfail \) procedure it will be activated as new replica with a modification of the active replicas table of agent’s DB. As new active replica \( t^* \) is deployed in the same agent as the failed one no further modification of DBs of APs is required.

If the task \( t^* \) is deployed in agent \( a^* \) of the remote AP \( rhwp \) then on reception of the \( req_atask(tt) \) message from the agent \( a \) AP \( hwp \) will perform \( h_r_tfail(tt) \) procedure which will result in an activation of task \( t^* \) with a modification of active replicas tables of AP DB and DB of agent \( a^* \). As new active replica \( t^* \) is deployed in the agent \( a^* \) of the same AP \( hwp \) no further modification of DBs of other APs is required.

If the task \( t^* \) is deployed in agent \( a^{**} \) of the remote AP \( rhwp \) then on reception of the \( req_atask(tt) \) message from AP \( hwp \) AP \( rhwp \) will activate the task \( t^* \) with a modification of the active replicas tables of AP and agent \( a^{**} \) DBs. AP \( rhwp \) will also send the broadcast \( atask_announce(tt, rhwp) \) message which processing by each AP of MAS will result in modification of the active replicas table of AP DB. Thus independently of deployment of the task \( t^* \) the redundant MAS will recover from the failure of the task \( t \).

Let’s consider a failure of the agent \( a \) detected by AP \( hwp \) in which the agent \( a \) is deployed. All records related to all tasks deployed in agent \( a \) will be removed from AP DB by the \( h_r_afail(a) \) procedure so that DB will not contain any records related to failed components. AP \( hwp \) will determine all task types related to active replicas deployed in failed agent \( a \) in accordance with the active replicas table and will perform the \( h_r_tfail(tt) \) procedure for each type. In accordance with stated conditions of the theorem there exists a task \( t^{**} \) of type \( tt \) for each task \( t_i \) deployed in the agent \( a \) if it is the active replica of type \( tt_i \). As was proved for the case of task failure the \( h_r_tfail(tt) \) procedure will activate new replica of type \( tt \) independently of its deployment in executive containers of MAS. Thus all active replicas that are in failure due to the failure of the agent \( a \) will be replaced with new replicas and the redundant MAS will recover from the failure of the agent \( a \).

Let’s consider a failure of the actuator \( hwr \) of type \( thwr \) detected by all APs for that the said actuator is accessible. Each \( hwp \) that has detected the failure of the actuator will perform the \( h_r_hwpfail(hwr) \) procedure. Execution of this procedure by AP \( hwp \) will result in removing of all records related to the failed actuator \( hwr \) from the actuators table of AP DB. Let’s suppose that there is no other actuator of type \( thwr \) accessible from AP \( hwp \). In accordance with the \( h_r_hwpfail(hwr) \) procedure all records related to tasks deployed in agents of AP that are in failure due to an unavailability of an actuator of the required type \( thwr \) will be removed from both DB of AP and DBs of agents. Moreover for each active replica deployed in one of agents of AP which is in failure caused by an
inaccessibility of an actuator of type \( thwr \) the \( h_{r\_ffail} \) procedure will be performed. As was proved for the case of task failure the \( h_{r\_ffail}(tt) \) procedure will activate new replica \( t^* \) of type \( tt \) independently of its deployment in executive containers of MAS. In accordance with stated conditions of the theorem a task \( t^* \) that in an operable state exists for each task type \( tt \) that requires utilization of an actuator of type \( thwr \). Thus all active replicas that are in failure due to the failure of the actuator \( hwr \) will be replaced with new replicas and the redundant MAS will recover from the failure of the actuator.

Let’s consider a failure of AP \( rhwp \). Let \( hwp \) be one of APs that has detected the failure. The execution of the \( h_{hwpfail}(rhwp) \) procedure by AP \( hwp \) will result in determination of a set of active replicas deployed in one of agents of the failed AP \( rhwp \) and in execution of the \( h_{r\_fail}(tt) \) procedure for each said determined active replica that is in failure due to the failure of AP \( rhwp \). As was proved for the case of task failure the \( h_{r\_ffail}(tt) \) procedure will activate new replica \( t^* \) of type \( tt \) if there exists the task \( t^* \) of type \( tt \) which is in an operable state. In accordance with stated conditions of the theorem for each task \( t_i \) which is deployed in one of agents of AP \( AP \) and is the active replica of type \( t_i \) there exists another task \( t^*_i \) of type \( tt \) which is in an operable state. Thus each active replica that is in failure caused by the failure of AP \( rhwp \) will be replaced with new replica and the redundant MAS will recover from the failure of the agent platform \( rhwp \).

IV. RELIABILITY ASSESSMENT

The stated and proved theorem on fault-tolerance property of redundant MAS validates the developed fault-recovery methodology. Application of agent-oriented technologies to industrial systems requires obtaining of a guaranteed level of MAS reliability. Thus there is a need to develop a method for theoretical assessment of reliability level of MAS guaranteed in case of application of the said fault-recovery methodology.

Logical-and-probabilistic methods enable synthesis of a reliability function of a system in an analytic form [9]. These methods require formation of logical operability function which determines a state of the whole system based on states of its components and are based on transformation of the said operability function to such form which allows replacement of logical operators with arithmetical operators and logical variables with corresponding probabilities of no-failure [9]. To enable utilization of logical-and-probabilistic methods for assessment of reliability of redundant MAS we have developed the methodology for formation of an analytic logical operability function of the said redundant MAS.

As each task of the existing MAS is assumed to implement unique functionality and each task type of the redundant MAS corresponds to one and only one task of the existing MAS we have stated the criteria of serviceability as follows. The redundant MAS is not in failure if and only if for each task type there is a task of this type which is in an operable state.

Based on the stated serviceability criteria we introduce definitions of a minimal functional configuration (MFC) and a minimal operable configuration (MOC). We define MFC as an ordered set \( <MFC, MWR> \), where \( MFC \) is a set of tasks, \( MA \) – a set of agents, \( MHWP \) – a set of APs. Each MFC shall represent one of the shortest paths of successful operation [9] without considering the necessity of actuators utilization. Thus a set \( MT \) shall include one and only one task of each task type from a set \( TT \) of task types. Moreover a set \( MA \) shall include only such agents in that at least one task from a set \( MT \) is deployed. Similarly a set \( MHWP \) of APs shall include only such APs in that at least one agent from a set \( MA \) is deployed.

MFC contains a minimal set of tasks required for successful operation of the redundant MAS as well as sets of agents and APs required for execution of these tasks. The formal MAS model includes a set of actuators required for performing of tasks. Thus we define MOC as an ordered set \( <MFC, MWR> \), where \( MFC \) is a minimal functional configuration, \( MWR \) – a set of actuators of MOC. Each MOC is based on one of MFCs, moreover multiple MOCs may and shall be formed from one MFC. MOC shall represent the shortest path of successful operation in accordance with logical-and-probabilistic method [9]. Thus a set \( MWR \) of actuators shall meet following conditions:

- for each actuator type from a set \( THWR \) of actuator types the set \( MWR \) shall include at least one actuator;
- each actuator from the set \( MWR \) shall be accessible for at least one AP from a set \( MHWP \) of APs of MOC;
- the set \( MWR \) shall satisfy the requirement of availability of actuators of all required types for each task from the set \( MT \);
- for each actuator from a set \( MWR \) shall exist such AP from a set \( MHWP \) for that this actuator is only one accessible actuator of this particular type;
- for each actuator from a set \( MWR \) shall exist such AP from a set \( MHWP \) for that this actuator is accessible and an actuator of this type is required for performing at least one task deployed in one of agents of this AP.

If all components of MOC are not in failure and all other components of the redundant MAS are in failure the whole MAS is not in failure because operability of all components of MOC is enough for successful operation of MAS. Moreover in a considered case a failure of one of MOC components will lead to the whole MAS failure due to an inability to perform a task of at least one task type. Thus MOC can be treated exactly as the shortest path of successful operation if and only if all mentioned above conditions are met.

In accordance with logical-and-probabilistic method the logical operability function may be formed as disjunction of conjunctions, wherein each conjunction represents one of the shortest paths of successful operation [9]. Thus a logical operability function of the redundant MAS shall be determined in following manner.

\[
\bigvee_{\forall MOC} \left[ \left( \land_{\forall t \in MTC} w(t) \right) \land \left( \land_{\forall a \in MA} w(a) \right) \land \left( \land_{\forall hwp \in MHWP} w(hwp) \right) \land \left( \land_{\forall hwr \in MWR} w(hwr) \right) \right] \tag{1}
\]

In (1) \( MOC \) is a minimal operable configuration, \( MT, MA, MHWP \) are respectively sets of tasks, agents and APs of MFC used for construction of particular MOC, \( MWR \) is a set of actuators of MOC, \( t, a, hwp, hwr \) are respectively a task, an
agent, AP and an actuator of the redundant MAS, \( w(t) \) is a logical function representing a state of particular component.

The formal methodology for formation of an operability function of the redundant MAS is presented in [8]. The formation of the operability function of the redundant MAS in the form (1) enables application of logical-and-probabilistic methods for transformation of the operability function and synthesis of a reliability function in an analytic form.

V. IMITATION MODELLING

The purpose of the performed computing experiment based on imitation modeling is to proof that utilization of the developed fault-recovery methodology will guarantee the level of reliability equal to the theoretical reliability assessment calculated with logical-and-probabilistic methods based on an operability function formed in accordance with all determined minimal operable configurations of the redundant MAS.

Let’s consider test redundant hardware-software MAS with a set of task types \( TT = \{t_{10}, t_{20}, t_{30}\} \), a set of tasks \( RT = \{r_{110}, r_{210}, r_{310}\} \), a set of agents \( RA = \{a_{12}, a_{22}, a_{32}, a_{32}\} \), a set of APs \( RHWP = \{h_{13}, h_{23}, h_{33}\} \), a set of actuator types \( THWR = \{r_{110}, r_{210}, r_{310}\} \) and a set of actuators \( RHWR = \{r_{111}, r_{211}, r_{221}, r_{311}, r_{321}\} \). The MAS configuration is as follows:

- \( confTypeTask \) is true on a set \( \{t_{110}, t_{120}, t_{210}, t_{310}, t_{320}\} \).
- \( confTypeHwr \) is true on a set \( \{r_{110}, r_{120}, r_{210}, r_{220}, r_{310}, r_{221}\} \).
- \( confTaskAgent(t, a) \) is true on a set \( \{t_{110}, a_{12}, t_{120}, a_{22}, t_{210}, a_{32}, t_{310}, a_{32}\} \).
- \( confAgentHwp \) is true on a set \( \{a_{12}, h_{13}, a_{22}, h_{23}, a_{32}, h_{33}\} \).
- \( reqHwrTTask \) is true on a set \( \{r_{110}, t_{110}, t_{120}, t_{210}, t_{310}, t_{220}\} \).
- \( confHwrTTask \) is true on a set \( \{r_{110}, h_{13}, r_{122}, h_{13}, r_{122}, h_{13}, r_{122}, h_{33}, r_{122}, h_{33}, r_{122}, h_{33}, r_{122}, h_{33}\} \).

The test MAS configuration is shown in Fig. 1. The obtained outcomes of the performed computing experiments for two disparate redundant MASs are presented in Table I and in Fig. 2. The second redundant MAS is equal to the first one described above except of increased redundancy level.

<table>
<thead>
<tr>
<th>Time</th>
<th>Probability of No-Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( PA_1(t) )</td>
</tr>
<tr>
<td>1</td>
<td>0.999563</td>
</tr>
<tr>
<td>10</td>
<td>0.962195</td>
</tr>
<tr>
<td>20</td>
<td>0.872160</td>
</tr>
<tr>
<td>30</td>
<td>0.757702</td>
</tr>
<tr>
<td>40</td>
<td>0.637612</td>
</tr>
<tr>
<td>50</td>
<td>0.523370</td>
</tr>
<tr>
<td>60</td>
<td>0.421105</td>
</tr>
</tbody>
</table>

VI. CONCLUSIONS

The developed model of distributed hardware-software multi-agent system defines MAS as:

- a set of tasks representing and implementing unique functionality of the system;
- a set of agents required for performing of tasks;
- a set of agent platforms required for execution of software agents;
- a set of actuators required for interaction of agents with an environment in order to perform particular tasks;
- a deployment of tasks on a set of agents;
- a deployment of agents on a set of agent platforms;
- an accessibility of particular actuators for particular agent platforms.

The developed model of redundant distributed hardware-software MAS explicitly defines software agents and agent platforms as universal executive containers and separates universal and functional components such as tasks and actuators. The model defines new fault-tolerance strategy based on replication of all functional components and on introduction of redundant sets of executive containers.
The developed fault-recovery methodology defines fault-recovery problem as a problem of search and activation of new replica of a task of a particular type in case of inability to perform the active replica of this type caused by detected failure. The methodology introduces new communication protocol that enables task execution and actuators utilization independently of its deployment in executive containers of MAS. The methodology defines fault-recovery procedures required to deal with detected failures of software agents, tasks, agent platforms and actuators.

The stated and proved theorem on fault-tolerance property of redundant MAS defines a set of conditions and validates that in case of fulfillment of said conditions the redundant MAS will recover from failures of tasks, agents, agent platforms and actuators though performing of developed fault-recovery procedures defined.

The methodology for construction of an analytic operability function of a redundant MAS defined by the developed model enables utilization of logical-and-probabilistic methods for synthesis of reliability function representing a probability of no-failure in an analytic form. The theoretical assessment of probability of no-failure is important for analysis of existing multi-agent systems as well as for synthesis of multi-agent systems with guaranteed required level of reliability.

The performed computing experiments based on imitation modelling of MAS components behavior in accordance with developed fault-recovery procedures have validated that the developed fault-recovery methodology ensures the level of reliability equal to the theoretical assessment.

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The Ministry of Education and Science of the Russian Federation
National Mineral Resources University
Saint-Petersburg, the Russian Federation

The article provides a synthesis of the distribution of temperature field in the isotropic rod on the basis of impulse response functions — the Green’s function. The mathematical modeling of the principle performed on the hybrid supercomputer using NVidia CUDA technology. On the basis of mathematical modeling were made the conclusion of the possibility of optimizing the temperature conditions in the system under control. Also, were made the conclusions about the number of heating elements and the number of members of the Fourier series.

Keywords — synthesis; system analysis; mathematical model.

I. INTRODUCTION

Synthesis of program controls carried out on the basis of process models by formalizing requirements in the form of single or multi- target conditions (equalities, inequalities) submitted requirements minimizing quality functionals. Analytical solutions of the heat operator were used for the relationship between the controlled axes (factors). Or difference schemes for their respective tasks. That allows us to get a large variety of program control algorithms. Such algorithms with appropriate generalization can be designed to create systems with locally optimal or locally - oriented control. Approach to the synthesis of locally - optimal control for temperature processes can be based on heat conduction problems using finite difference schemes. These schemes allow “algebraize” optimization problems of control synthesis. This in turn will provide an opportunity to bring them to the solution of a countable number of finite-dimensional mathematical programming problems. In modal image analytical solution is infinite or finite linear combinations of “modes”. As a set of exponential - periodic basis functions and time coordinates.

Approaches to the synthesis of stabilizing controls can be considered on the basis of variant target conditions and resolution of mathematical programming problems by numerical methods. This problem was solved by A.N.Tikhonov and A.A.Samarski when considering the first boundary value problem, which mathematical model is given by the following equations [1]

\[ \begin{align*}
    u_t &= a^2 u_{xx} + f(x,t), \quad 0 < x < l, \quad 0 < t \leq T, \\
    u(0,t) &= \mu_1(t), \quad 0 \leq t \leq T, \\
    u(l,t) &= \mu_2(t), \quad 0 \leq t \leq T, \\
    u(x,0) &= \varphi(x), \quad 0 \leq x \leq l.
\end{align*} \]  

(1)

Where: \( t \) - time; \( x \) - the point location (X axis coordinate) of the temperature sensor; \( \xi \) - a point-location (X axis coordinate) of a heating element; \( f(x,t) \) - the operation input at the point “x”; \( a^2 \) - thermal diffusivity of the material for the object of control.

II. THERMODYNAMIC PROCESSES MODELLING WITH GREEN FUNCTION.

The Green function (2), reflecting the behavior of the temperature field at any time anywhere in the control object was obtained. Bringing her A.N. Tikhonov A.A. Samarski investigated the question of convergence of Fourier series, which decomposes to the Green's function [2, 3].

\[ G(x,t) = \sum_{n=1}^{\infty} \frac{2}{n \pi} \sin \left( \frac{n \pi x}{l} \right) \sin \left( \frac{n \pi t}{l} \right) e^{(-a^2 \frac{n \pi}{l})^2 t} \]  

(2)

Where \( n \) - number of members of the Fourier series; \( l \) - rod length; \( t \) - time; \( x \) - point location (coordinate along the X axis) of the temperature sensor; \( \xi \) - point location (coordinate along the X axis) of the heating element; \( \tau \) - the time of inclusion of the point source; \( a^2 \) - thermal diffusivity of the material for the object of control.

Thus, formula allows the calculation of the behavior of the temperature field at an arbitrary point of isotropic rod at an arbitrary time. However, for the research of temperature field over time a function of the initial heating must be considered, because the temperature value is a sum of values of the Green's function at the current time and the function of the initial heating [4, 5].

Thus, for analysis of the temperature field is necessary to apply the formula (3), considering the initial heating function [4]:

\[ \begin{align*}
    T(x,y,t) &= \sum_{n=1}^{\infty} \sum_{l=1}^{\infty} \frac{2}{n \pi} \exp \left[ \left( -\frac{n \pi}{l} \right)^2 t \right] \sin \left( \frac{n \pi x}{l} \right) \sin \left( \frac{n \pi y}{l} \right) \xi_l + \\
    &+ \sum_{n=1}^{\infty} \sum_{l=1}^{\infty} \frac{2}{n \pi} \exp \left[ \left( -\frac{n \pi}{l} \right)^2 (t - \tau_p) \right] \sin \left( \frac{n \pi x}{l} \right) \sin \left( \frac{n \pi y}{l} \right) \xi_l \varphi \left( x, \tau_p \right). \end{align*} \]  

(3)
III. CONTROL OBJECT MODELLING WITH CUDA TECHNOLOGY

Consider the simulation process on the example of the control object, consisting of a cylindrical rod, of negligible thickness and length "l_1", and the heating elements "k" and temperature sensors "d" located on it. Then, we model behavior of the temperature field in the isotropic rod on a hybrid supercomputer using CUDA technology. The input values of the system: l_1=10 meters, k =100 units, d=100 units, T_{base}=1...5000 C◦, a_2=0.00024 m^2/s, \nu, p, \varepsilon {1,2,3,4,5,6,7,8,9}, t=1 second. Mathematical modeling time is set on 170800 seconds (48 hours).

Required to determine the time after which a metal loses properties of solids. Mathematical modeling of this temperature field is not possible on a standard PC due to extremely high computational complexity. For these purposes, we take 96 GF108 core processor based on the graphic calculator GT 630. It should be noted that the structure of the CUDA chip is different from the structure of the processors for PC.

Intel Nehalem processor contains four independent processor cores, each of which has full functionality of the CPU. This kernel will be able to handle traps, work with input – output devices, so it can fully support the operating system. Each core contains a first-level caches for data and instructions, contains the logic sampling instructions and data second level cache. All cores are symmetrically attached to the third level cache and to QPI (Quick Path Interconnect) - system of processors connection to the chipset. They are attached to the IMC (Integrated Memory Controller) – communication system with memory, which came to replace the north bridge.

In some versions of modern Intel processors integrated graphics controller is present [8, 9].CUDA chip is the GF108 processor having 32 stream processors (Fig. 1).

Also it has two caches of 32 KB and 256, respectively, with 128-bit bus width. This chip provides two gigabytes of RAM per processor. It also had the ability to support cluster flow modeling and SIMD-instructions. Now, let’s take a look on the block of code (Fig. 2), that calculates the temperature field.

It should be noted that a reserved area of memory has been allocated to preserve memory capacity (Fig. 3). After copying the data to the computer processor using software operator cudaMemcpyDeviceToHost had happened the slash memory allocation for computation organization of vector data types for (i = 1; i <= d; i++) {
    // Code for calculating the temperature field...
}

Fig. 2. Block of code, responsible for temperature control.

Thus, the last code fragment ensures the functioning of the module only on the first processor of the calculator. Changing the first parameter of the function you can perform calculations on other calculators, if available in the system. Also, the combination of these parameters allows you to create control software for high-performance systems based on calculators NVidia Tesla. However, due to the fact that Tesla calculators have built of 4 processors with 2000 cores each, you must make an additional stream operation calculation. The slash memory usage allowed in addition to the calculation of the temperature field experimentally, discover the required number of members of the Fourier series required for a target precision. The system does calculations for 1000, 100 and 10 members of the Fourier series. Results of mathematical simulation on a supercomputer and on a personal computer are shown in Table 1. As can be seen from the table, values are the same, but the time spent on calculations much less. Hence, the mathematical modeling of automatic control systems will significantly increase productivity. To a large extent this is necessary for real-time systems.

On the base of the results of the isotropic rod temperature field mathematical modeling we can draw the following conclusions.

1. With minimal impact (0.1 W) on the control object the isotropic rod lost its physical properties of solids on 8652 second experiment.
The mathematical modeling results analysis shows that the simulation of automatic control and progression systems, including robust control can be significantly extended by the use of hybrid supercomputers. Their application will not only expand the number of control actions, but also the modeling process time.

REFERENCES

Development of Road Sign and Road Marking Recognition Algorithm for Active Vehicular Safety Systems

Maiorchik A. V.
Department of Computer Systems & Software Engineering
St. Petersburg State Polytechnical University
St. Petersburg, Russia
e-mail: aleksa@yandex.ru

Abstract—Proposed recognition algorithm of road markings and road signs and software component for modeling and simulation of active vehicular safety systems. Area of application of the results of the study are active safety vehicles, control systems and unmanned vehicles unmanned aerial vehicles, as well as navigation systems. Distinctive features of the proposed algorithm is the possibility of automatic recognition and evaluation of road signs in real-time, identification of small objects, excluding the possibility of affine transformations of the objects, the unification algorithm to detect road markings and signs.

Keywords—complex active safety system, image processing, mathematic modeling, pattern recognition, road signs.

I. INTRODUCTION

The main research purpose is the creation of the algorithm for road marking and road sign detection for active vehicular safety systems. Application areas of the research are active vehicular safety systems, control systems of unmanned aerial vehicle and navigation systems.

II. DEVELOPMENT OF THE RECOGNITION ALGORITHM

A. Description of the recognition algorithm

Proposed recognition algorithm of road markings and road signs and software component for modeling and simulation of active vehicular safety systems. The algorithm includes the following steps:

- noise removal on the video frame;
- detection of road marking on the video frame using the Hough transform to find lines;
- image color filtration using RGB or HSV spaces [2];
- detection of round and triangular objects using the Hough transform to find lines and circles;
- road sign identification [1,3].

The stage of road sign identification includes the following sub-steps:

- if the target country is unknown then identification is performed using shared European sign base, where signs have only slight difference. Else proceed to step of model’s type classification (nonlinear algebraic equation, ordinarily differential equations, algebraic-differential equations);
- country identification is performed, based on the following road sign features: shape, border color and thickness, type, color, size, image rotation and background color;
- identification of road signs belonging to one specific country is made by using Haar-like features.

B. Results of a study of the recognition algorithm

Proposed algorithm has been tested on a road sign recognition system, named “Crosswalk”.

To perform color filtration images have been transformed to HSV space. H, S, V threshold values for red, blue and yellow colors were picked up experimentally for different weather conditions and luminance. S, V coordinates are in the range of 0-255; H is in the range of 0-179. Coordinates range values corresponding to the red color: 0<H<19, 145<H<179, 60<S<255, 20<V<255. Coordinates range values corresponding to the blue color: 105<H<155, 60<S<255, 16<V<255. Coordinates range values corresponding to the bright yellow color: 30<H<36, 200<S<255, 35<V<90.

For the purpose of specific sign identification Haar algorithm has been used, which builds up a cascade of object’s features to identify it. To create a training sample of images opencv_createsamples utility has been used. opencv_haartraining utility has been used for training the classifier-cascade.

Fig. 1 shows an example of correct “Crosswalk” road sign.
The algorithm was tested on the video frames from the car video recorder. Video recordings were made in the afternoon, in the evening, at night and during rain. Results showed that the percentage of detected signs is 95.6%, number of false positive cases – 1.

III. CONCLUSIONS

In this paper we propose improved algorithm for road marking and sign recognition for modeling and simulation of active vehicular safety systems. The key feature of this algorithm is search area reduction using color filtration, object recognition (by shape) and road marking features, which allows to deal with two separate tasks (road marking and sign recognition). Distinctive features of the proposed algorithm is the possibility of automatic recognition and evaluation of road signs in real-time, identification of small objects, excluding the possibility of affine transformations of the objects, the unification algorithm to detect road markings and signs.

REFERENCES

Abstract—Features of modelling, designing and research of units and machine-tool systems are in-process resulted. The models executed with application of software MATLAB for problems within the limits of performance of researches of static and dynamic character are observed.

Keywords—hydrostatic bearing systems; dynamic characteristics; package; linear model; nonlinear model

I. INTRODUCTION

The dynamic characteristics of hydrostatic bearing systems (HB) are determined by set of the interconnected mechanic-hydraulic processes occurring under change of load or at action of periodic forces, arising at the processes of cutting (for metal-cutting machine tools).

II. COMPARATIVE INVESTIGATIONS

The purpose of dynamic calculation under change of load of HB is a determination of spectral properties of HB [1], major of which is the value of damping of the free oscillations, and calculation of the parameters of adjusting RC-chain, which is necessary for its increasing. The analysis of nonlinear HB model, described of a system of the ordinary differential equations, in view of impossibility of their analytical solution, is carried out by the procedures of numerical integration, with the help of a MATLAB package. Simultaneously with it the opportunity of application of linear model for such transients processes calculation is considered, that more simply allows to determine damping property of a HB and to establish parametrical border of qualitative change of transient processes from oscillatory to non-periodic.

As it is shown by the comparative analysis which has been carried out for typical parameters HB, linear model is well enough for approximate transient processes in case of a HB with the force closing and gives an essential divergence with nonlinear model in case of an open HB [2]. It is remarkable, that the linear model gives the results decreased by value of a static mistake at negative loading (25-30 %) and increased (10 %) - at positive loading, what is connected with nonlinear stiffness properties of HB, - the stiffness decreases at reduction of loading and grows at its increase.

III. CONCLUSION

The non-linearity of damping and stiffness characteristics also influences on oscillatory properties of a HB, particular, - on its amplitude - frequency characteristic at stationary periodic loading, what allows not only to estimate amplitude of displacement and reactions, but also to determine quantity of stationary modes and to investigate their stability.

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Integrated Data Model for Managing a Multi-Service Dynamic Infrastructure

Volkov A.N.
Head of Automats dept.
SPbSPU
St. Petersburg, Russia
volkov-and@yandex.ru

Efimov V.V.
Operations Manager
RingCentral Inc.
San Mateo, CA, USA
2vadim@inbox.ru

Mescheryakov S.V.
Professor
SPbSPU
St. Petersburg, Russia
serg-phd@mail.ru

Shchemelinin D.A.
Operations Director
RingCentral Inc.
San Mateo, CA, USA
dshchmel@gmail.com

Abstract — The challenges of managing a multi-component distributed infrastructure with dynamically growing business services in IT company is described. Standard approaches to configure the automated management tools, including both in-house and 3rd party software products, are discussed. Conceptual configuration model for integrating the distributed databases and applications, which doesn’t require creating a separate integrated DB, is proposed. The advantages of new approach to system integration are shown through the example of real-world implementation.

Keywords — distributed infrastructure, big data, integrated model, configuration management.

I. INTRODUCTION

Most of big IT companies are multi-service and are hosted in distributed data centers with a virtualized cloud infrastructure. The multi-host components for provisioning particular business services have both in-house and 3rd party applications installed. Managing remotely a big multi-service infrastructure is challenging. Existing management tools are usually the software products of external vendors, which are not open source and their databases are not compatible to each other. So, the integration of all management tools is needed for more efficient control of business processes.

RingCentral (RC) as a big international IT company is not an exception. It provides multiple IP telecommunication services for more than 300K customers in North America and Europe, including voice calls, voice mails, faxes, conferencing, SMS, mobile platform and other services. RC multi-service infrastructure consists of over 3.5K hosts, which are located in 4 data centers in the USA and Europe, and is dynamically growing across business service components and platforms.

II. RC MULTI-SERVICE CLOUD INFRASTRUCTURE

RC cloud environment has rather complicated structure, including hardware and virtual machines, software assets and deployments, environment-specific configuration. To describe new concept, the following terms and conditions are taken into account.

Host is either a hardware or VM or blade or network switch, each with operating system or firmware, having its own dedicated configuration, such as CPU, RAM, HDD, network bandwidth, etc.

Configuration Item (CI) is an asset type, such as OS, application, memory. Each CI has its own product line of Builds (Revisions), for example OS product line is MS Windows XP, Vista, 7, 8, etc.

Configuration is a set of relationships between Hosts, CIs and Revisions, e.g. which particular system is installed on a certain host with exact CI values. Such configuration gives more knowledge, better visibility and can be used for management integration in a big distributed cloud infrastructure [1].

III. INTEGRATED DATA MODEL

Conceptual configuration model is shown in Figure 1. In real life the Hosts, CIs and Builds are heterogeneous. Hardware and virtual hosts can be managed in different inventory tools. Same for CIs – in-house and 3rd party software assets are being managed separately.

The main purpose of the Integrated Data Model is to establish relationships between management tools that own the Hosts, CIs and Builds. In RingCentral Company, the following in-house and external products are used, which are popular in other IT companies as well:

- RackTables as Inventory Tool [2]
- Jenkins as Asset Build and Management Tools [3]
- Incident Management Portal (RC product)
- Change Management Portal (RC product)

Fig. 1. Conceptual Configuration Model
IV. TECHNICAL IMPLEMENTATION

Integrated data model is designed at RingCentral Company as shown in Figure 2. Each part of data exists in a single authoritative source of data – one physical DB per management tool. This is done for synchronization and security purposes.

Integration between tools is implemented on application level in addition to DB. Web applications have both backend and frontend. Client application supports authentication via sessions and cookies and, thus, is the communication hub for the management tools via Ajax requests. The user himself (his web session) is one of the integration points between the management tools. Authorization is verified on behalf of each particular tool using the existing session. If the user is not logged in or doesn’t have permissions to one of the tools, this particular data will not be available. This is also helpful to resolve security issues.

Data access is provided via REST API of a management tool. Write access is allowed for the push updates coming from other integrated tools. For example, when a certain change request in the Change Management Portal is marked as completed, the push update command is automatically sent via user browser to the Monitoring System to modify the status of affected host from maintenance back to production.

To comply with HTTPS security protocol, the Cross Origin Resource Sharing (CORS) is used. That means if an integrated tool uses HTTPS, all the others are also switched to HTTPS.

V. CONCLUSION

New approach to the integration of management tools is implemented at RingCentral Company providing the following benefits:

- Management of a big distributed data and business processes in a dynamic multi-service IT company is much more efficient when all the management tools are integrated in one information system.
- No need to create a separate integrated DB and migrate data from distributed data sources.
- Integrity of management data, as it is stored only in one DB instance but can be modified from various tools.
- Security and reliability, since the data access from user session is differentiated among management DBs.
- Compatibility with IT standards, such as REST API, Ajax and CORS, that are used in modern frameworks.

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