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The forming cyclic loads on the offshore structures during ice field edge fracture

Формирование циклических нагрузок на шельфовые сооружения при разрушении льда

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Abstract. The non-stationary process of ice breaking at the contact of the edge of a drifting ice field (IF) and the sea ice-resistant platform (IRP) can lead to dangerous vibrations and potentially dangerous dynamic loads on this offshore structure. Extreme resonant oscillations of the platform base can cause not only violations of the regular functioning of the object, but also significantly reduce the reliability of the structure and its durability, causing fatigue fracture in the structure of the IRP or its equipment, also such process can change the bearing capacity of the soil under the platform foundation. Dynamic ice destruction is a complex process, and the development of models of this phenomenon requires a well defined methodology and research procedure. The dynamic reaction of the structure on impact of the ice field depends on a combination of many factors: the size and flexibility of the impacted leg of the platform; the ice loading velocity, temperature and physical-mechanical parameters of ice, and others. The object of this research is the physical processes involved in the real system "IF-IRP" - the energy transfer from the moving ice fields to the control volume of ice in the contact area, accumulates the elastic energy received to its critical level in this volume and causes its destruction with a certain frequency. The most important property of the object of study, i.e. the subject of the research, is the mechanism of ice fracture in the zone of interaction of two basic elements of the system: the ice field and IRP. The aim of the study is to identify and describe the regularities of formation of cyclic ice loads on the structureand describe the process, taking into account the phenomenological features of sea ice fracture as a mechanism for converting the kinetic energy of the ice field into the elastic energy spent on to deviations leg of the platform and the energy spent on destructing the ice.

Аннотация. Нестационарный процесс разрушения льда на контакте кромки дрейфующего ледового поля (ЛП) и морского ледостойкого основания (МЛО) может привести к опасным вибрациям и потенциально опасным динамическим нагрузкам на шельфовые сооружения. Такие явления значительно снижают надежность сооружения и его долговечность, потому что вызывают усталостные разрушения в элементах конструкции и изменения несущей способности грунта под фундаментом платформы. Учитывая актуальность проблемы, данная статья посвящена процессу функционирования системы «дрейфующее ледовое поле − морское ледостойкое основание». Целью исследования является выявление и описание причины и закономерностей формирования циклической ледовой нагрузки на сооружение, описывающих процесс с учетом феноменологических особенностей разрушения морского льда. Метод исследования, примененный в данной работе - изучение результатов полномасштабных и лабораторных экспериментов, а также теоретических научно-исследовательских работ, связанных с процессами взаимодействия ЛП-МЛО, включая и работы автора. Объектом исследования является механизм преобразования кинетической энергии ледового поля в энергию упругих отклонений сооружения и энергию, затраченную на разрушения льда. Показано, что периодичность циклов разрушения льда регулируется достижением предельного значения удельной энергии разрушения льда в его сжатом объеме на контакте с сооружением. Рекомендуется эту характеристику применять в качестве критерия разрушения льда и продолжить исследовать ее стабильность и воспроизводимость в экспериментах для определения ее параметров.

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Introduction

Significant attention from the researchers in the field of investigation of ice formation interaction with shelf structures during the development of the problem was directed upon the analysis of calculation methods for the maximum ice load. So, periodical updating of standards and norms for the procedures for defining the parameters of the ice load calculation formula was obtained as a result of such investigations. Several years ago, such update was made for the Russian Code SP 38.13330.2012 [1] and the International Normative Document ISO/DIS 19906 [2]. The Russian norms provide no recommendations for the calculation of the dynamic impact of ice; the international norms provide the directions to consider this case.

The process of ice load formation began to be seriously investigated after the discovery of significant and hazardous vibrations for structures and personnel, including dangerous oscillations for drilling equipment located on operating platforms within the Cook Inlet, lighthouses in the Gulf of Bothnia, drilling platforms at Caspian, Asov Sea and Bohai Gulf, and ice-resistant platform structures within the Sakhalin region.

The first experimental works for the investigation of the vibration of marine structures were made in natural conditions for the real marine drilling platform in the Cook Inlet. The first scientists investigating this problem were Peyton [3] and Blenkarn [4].

In this period, the records on saw-tooth ice load upon supports of railway/road bridges [5, 6] and water dams [7] were obtained and also investigations were actively conducted on the vibration of the lighthouses within the Gulf of Bothnia [8, 9]. The reason for beginning these investigations was due to the fact that in this area in 1966, drifting ice fields budged and destroyed the lighthouse Tainio (Finland) [10]. The caisson of the lighthouse was set at a depth on 14 m on to sand bottom and overturned due to contact with a rocky ledge. In 1969, the Nygran Lighthouse was destroyed due to drifting ice fields (Sweden) [10]. The 2.5meter diameter lighthouse tower was damaged at 1-meter deep under the sea level; however, there was no displacement of the foundation. In 1974, the Kemi Lighthouse (Finland) was fractured at the upper section due to strong vibration [11]. In 1977-79 the reinforced concrete foundation of a drilling platform that has a shape of a polyhedron with 8 m diameter was damaged on the Azov Sea shelf [12]. There are many other cases of marine lighthouse foundation destruction in shallow waters. Serious damages exhibited by steel truss-type drilling platforms under the influence of single year ice fields within the Bohai Gulf and the destruction of one of such platforms disposited here have forced scientists in China and engineers from other countries to begin investigating this problem carefully. Specific analysis of the dynamic influence of ice fields acting upon the truss type platforms has shown that as a result of the tensile fatigue that occurs as a cyclical ice load, steel struts and bracings on platforms were destroyed. These events provided the conditions for increasing the values of oscillation and flexible deviation of the platform, therefore personnel were not able to operate subject to such conditions [13, 14, 15].

It shall be noted that the dynamic interaction of ice and marine structures is usual not only for flexible structures with small transversal supports. In winter 1985-1986, the Molikpaq Platform, with a 54 000-ton caisson and a 111-m^2 foundation, located within the Beaufort Sea, was influenced by 1 x 2 km drifting multi-year ice field [15, 16]. In compliance with the analysis, it was defined [17] that as a result of a 0.5 - 3 Hz vibration caused by 30 minutes of ice destruction at a contact zone, the platform was put into critical condition close to shear stability loss over the foundation soil surface. Pore pressure in sandy soil core foundation increased and this led to its liquefaction. In this regard, the bearing capacity of the foundation under the caisson reached its critical minimum value. At the time such results were unexpected for specialists. So, it can be supposed that there is a serious probability of shear of reinforced concrete caissons of lighthouses' foundations located within the Gulf of Bothnia subject to the same conditions as the Molikpaq Platform. The destruction of tower structures can occur due to fatigue as a result of a long-term cycle load, the same as the destruction of steel elements of lattice structures of drilling platforms within the Bohai Gulf. In recent years, the problem of the influence of cyclical loads on the strength of foundations has been present in oil platforms in the Sakhalin Shelf. [18].

The investigation of formation and development of vibration caused by ice impact shall be continue because the inevitable transition to deep waters on the one hand, and the necessity to increase the dimensions (and weight) of the underwater section of structure (in order to eliminate wave impact on the drilling equipment) on the other hand. This will lead to the flexibility of the structure as a whole (subject to provision of required strength of the structure) which will increase the negative impact of cyclic loads on the overall structural strength, and this requires that designers use materials with higher fatigue strength, ensuring its service life. In the last years, designers of marine wind generators have been faced with this problem when developing foundations for Baltic Sea areas [19,20].

However, as it was noted by some authors at the end of the last century and at the beginning of the new century [21,22,23], no details of structure and ice interaction process providing the vibration were developed up to the designing practice application level. Modern scientists have noted that no basic mechanism for the process is clear up to the present time, so the investigation shall be continued [24, 25, 26].

Thus, cyclical action of ice is an important factor in determining the reliability and durability of the IRS and the relevance of this problem remains topical due to two reasons. Firstly, due to the prospects of development of industrial shelf areas. Secondly, due to the absence of normative documents to ensure solutions provide safety and a longer service life of designed structures shelf ice-covered seas.

Given the relevance of the problem, presently it is necessary to achieve a deeper understanding of all the physical phenomena that jointly provide the vibration process of the structure during its interaction with an ice field. The aim of the study is to identify and describe the reasons and regularities for the formation of the cyclic ice loads on the structure, and to describe the process taking into account the phenomenological fracture characteristics of sea ice. Given that the load of ice on the structure reaches its maximum value at the moment of rupture of the ice , search the solution of the task about the frequency of occurrence of the peaks of the contact forces, which cause periodic oscillation of structure should be by studies and analyzed of the mechanism of destruction of ice. So any idea about the formation of ice loads shall be based on a mathematical description of the process of destruction of the edge of the ice field, taking into account the phenomenological characteristics of ice. In this regard, the main objective of this research should be the task of studying the mechanism of destruction of ice, as the environment, which exerts a forcical pressure on marine structures.

Research methods of interoperability issues ice fields and structures on the shelf

On the basis of the aforementioned aims and objectives of the work, the method of research applied in this work is to study the results of full scale and laboratory experiments and also the results of the theoretical scientific-research works related with the processes of the IF-IRP interaction, including the works of the author. The object of study is the mechanism of the conversion of the kinetic energy of the ice floes into elastic energy deviations of structures and the energy spent on the destruction of ice.

The phenomenon of vibration of marine structures during their interaction with a moving ice field, as was shown in the introduction to this work, in the first time was fixed while conducting experiments with full-scale platform in Cook Bay [3.4]. The aim of the first full-scale experiments held by Payton [3] in 1966-68, was to obtain the maximum pressure of ice on the support platform. Here during the study of the force action of ice moving at speeds from 0.5 to 2.1 m/s on cylindrical legs of the platform, 91 cm in diameter, H.R. Peyton found a strong vibration of the structure, which was caused by the destruction of ice. And during the process of interaction of the edge of the Ice field with the platform leg surface, the ice destructed from compression in the contact zone and the ice load on the leg was a "serrated" line with different frequency peaks depending on several factors. Peyton has defined that due to an increase of the ice field velocity, the frequency of ice destruction increased, but the ice load value range decreased.

The phenomenon of the vibration of structures caused by the movement of ice fields showed that it is necessary to take into account the fatigue in the calculations of structural elements, and to very carefully research the factors influencing the forming of vibrations and its development.

Experimental methods of researches regularities of occurrence oscillations of platforms

Blenkarn [4] also has performed investigations within the Cook Inlet in Alaska. Comparing the frequency of self-oscillation of the structure and the ice destruction frequency, he proposed that the "ice field - structure" system can provide the resonance of ice destruction frequency and self-oscillation frequency of the structure.

Thus, the findings were obtained, which give reason to assume the possibility of the emergence of platform resonant oscillations with the fluctuations of the force causing the edge ice field fracture. The nature of these phenomena requires special investigation due to a hazardous decrease of reliability and service life of expensive structures. These experiments can be considered as an accelerator for the development of investigations in the field of cyclic contact destruction of ice.

Given, that very difficult to control the structure and texture of ice in field measurements of ice forces on real constructions, the cutting process of the ice cover by supports have been extensively investigated on models of supports, these impactting on the full-scale ice cover. Simultaneously, the technology of model ice preparation was developed; ice basins were constructed; and technical means for registration of the quickly processes were developed subject tofor application in these areas.

The researche of fracture mechanisms of the edge of natural ice cover during its interaction with the structure models

This type of experimental works was developed by a group of scientists from the beginning of 60th; however, such works are continued in the present time. Natural ice provides the possibility for elimination of serious problems related to physical-mechanical ice modeling, becourse the results can be directly applied for analysis. For several years, starting in 1969, experiments with natural ice performed by J. Schwartz [27], and K.P. Croasdale and others [28–30] was made. During the interaction If-IRS provided the entry multiprocess processes destroying the edge of the ice field, occurring in the contact zone of the front surface of the model. These authors note that in addition to the initial radial vertical cracks and horizontal cracks in the array of ice plates, ice on the contact surfaces are completely crushed. Also, before the support appeared limited volume of highly compressed ice. The ice inside this volume has a lot of cracks, which are directed randomly.Also, before front surface of support occurs forming wedge-shaped volumes of ice, which are extruding by the surface of the support during moving ice field and are sliding in the direction of the upper and lower surfaces of the ice field.

These phenomena were completely approved by Tryde [31], Hirayama and others [32], Vershinin and others [33], Kivisild and Iyer [34], Nevel and others [35], Michel and Toussaint [36], Khrapaty and Tsuprik [37], Kry [38], Taylor [39], Ojima and others [40], Saeki and others [41, 42], Yamashita and others [43], Bekker [44], Karulin [45] and a lot of other scientists. For these experiments subject to detailed investigation of local ice pressure acting upon support and analysis of ice-structure interaction and vibration of structure, special strain gage panels were used, for example, by Sodhi and others [46]. The typical schemes of ice fields edges destruction due its interaction with a cylinder support is shown in Figure 1.

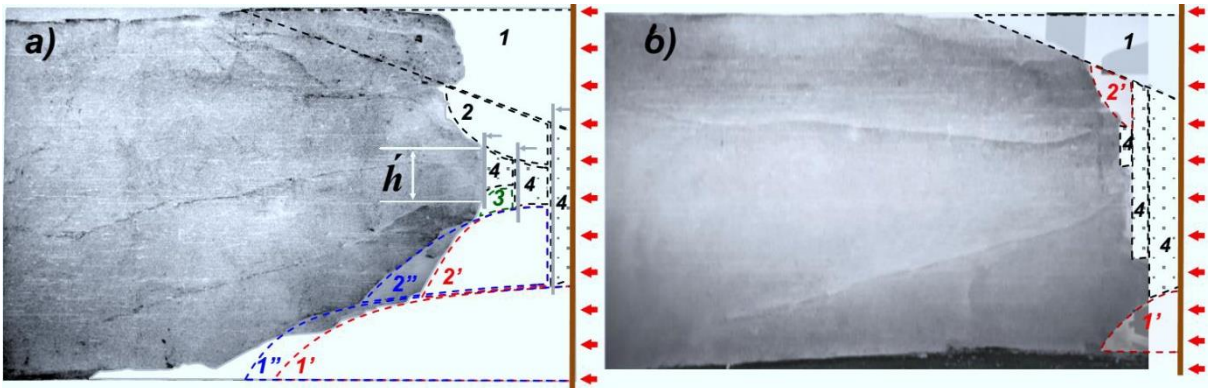

Figure 1. Photo of the natural ice fracture (experiment by the author 1978; Japan Sea) after dynamic introduction a cylindrical model of supportin ice edge:
a) decrease of effective thickness h´ by spalls (1, 2, 3) the sides of the ice plate and crushing of the middle section wedge (4) with model speed V= 3.2 m/sec;
b) – also with model speed V= 2.5 m/sec.

From analysis of the pictures of destruction it can be approved that the mechanism of ice destruction has the most complex character. The part of ice field movement energy at a contact zone of edge ice field and structure support surface is used for ice destruction, i.e. for horizontal and vertical cracks development, shear cracks, crushing of ice and displacement of products of ice fracture out of the contact zone. Energytransferried into the structure provides the deflection from equilibrium and creates the local forces onto its structural elements. The sizes, number and orientation of long vertical/horizontal cracks and shear cracks define the volume of compressed area in front of the support at the middle section of the field inclusive of its depth and height ***h´***. However, these parameters directly depend on the ice strength $\boldsymbol{\sigma_i}$, ice field velocity $\boldsymbol{V_{if}}$ and ice thickness ***h***. But moreover, due to close contact in front of the support, the limited volume of strongly compressed ice (prism area) has appeared in front of the support. Ice within this area is crushing [50].

Laboratory investigation of the cyclical destruction of ice in the interaction process with the structure models

The high price of full-scale measurement of ice forces upon real structures, natural ice and model supports subject to the impossibility of operational updating of the structure and ice field interaction conditions, provides the wide application of laboratory investigations. The first experiments for investigation of ice cover and hydrotechnical structure support surface interaction performed for laboratory model ice were developed by Afanasyev and others [51] at the ice basin of AANII. Two types of ice destruction in front of the support were revealed as a result of these experiments: destruction due to penetration and ice field stability loss. Contact force due to ice penetration is usually greater than in the case of ice field stability loss, so the calculating issue shall be referred to as ice penetration by the support. Besides, it shall be considered that contact pressure is decreased due to an increase of support width; ice destruction type shall be defined by its stability and ice velocity. Generally, a lot of works were devoted to investigation of these factors' influence against the mechanics of ice destruction, including ice pressure distribution laws subject to contact area of different supports. The completeness of physical-mechanical processes subject to contact ice destruction shall be provided by indenters with pressure sensors. It was used in works of Kamesaki, and others [52], Sodhi and others [53], Frederking and others [54], Takeuchi and others [55], Kryzhevich and others [56]. An integral configuration of the tensile contact field was obtained by applying a plastic strain gage film on the support model as it was described by Höderath and others], and tactile film with different colors depending on the pressure value per each section – Takeuchi and others. [58].

However, in spite of performed investigations, no applicable explanation of resonance phenomena, self or forced vibration subject to dynamic impact due to the interaction between ice and structure were revealed. The reasons for such phenomena can be subdivided into two categories: negative damping (Blenkarn, [4]; Määttänen [8]) and resonance (Sodhi [59]). Ice pressure force due to resonance frequency of structure vibration is described for both cases when the frequency of ice pressure force change due to ice destruction has increased the self-vibration of structure (Yue & Guo [23]; Määttänen [11]; L. Wang, J. Xu [61]; Huang & Liu [62]). Both types of structure vibration are usually considered as self-energizing; the mechanism of forced vibration shall be considered as an alternative. During 50 years, the group of scientists (inclusive of Määttänen and Sodhi respectively) has investigated the nature of structure vibration phenomena in order to define resonance or self-energizing or forced vibrations occurring in front of the structure subject to ice destruction load.

The first approach of scientists for justification of a concept explaining the formation of resonance vibration of the structure was based upon the investigation of the critical combination of parameters subject to ice destruction: i.e. its stability, support diameter, ice cover thickness and drifting velocity. ice strength was always considered as a maximum stability value defined by experiments with small samples for uniaxial compression σ_o. Most scientists have considered the dependency of this parameter from ice volume deformation velocity $\acute{\varepsilon}$ (L_{cr}) in front of the support due to ice field movement as a main feature. However in a series of experiments by some authors, this hypothesis has not found a definite confirmation.

The other approach for the ice destruction model in contact with a support was submitted by Sodhi [59]. His conclusions are based upon the results of full scale laboratory experiments with model ice subject to testing of 50–500 mm model piles against an ice load from a 50–80 mm ice field and a drifting velocity from 10 up to 210 mm/sec. Based upon testing results, Sodhi [59] has suggested to consider the resonance vibrations of flexible structures as a result of ice field action with ice destruction frequency, i.e. forced vibrations.

An idealized diagram of ice destruction due to shear was suggested by Sodhi and Morris [60] for description of the ice destruction as a single peak subject to law velocity of the indenter movement. It shall be noted that almost all ice thickness shall be wasted for chipping of the two prisms. Moreover, the length of the chipped section is equal to one third from the total thickness of ice.

The investigation the destruction of ice by mechanism chipping prior Sodhi and Morris [60] and further was performed by very much scientists [26-47], where the strength features of ice due to shear also were studed [60–62]. Chip is one of the dissipation mechanisms (release) of elastic energy of a compressed material by forming the free surface of new cracks. The chip is formed due to the realization the crack of lateral shear and developed within the compressed volume of ice subject to displacement of crack edges located at a definite angle to direction of compressing force. Usually different authors have explained the parameters of contact force of saw-tooth type during the time of interaction as a manifestation of this mechanism (or as per the length of destructed ice area).

The chips are featured with an unstable character that provides local destruction and loss of contact area. As per some works [42], for example, it provides the decrease of real thickness of ice h up to effective thickness h'. Moreover, these autors associate such decrease is referred with ice deformation velocity of ice field.

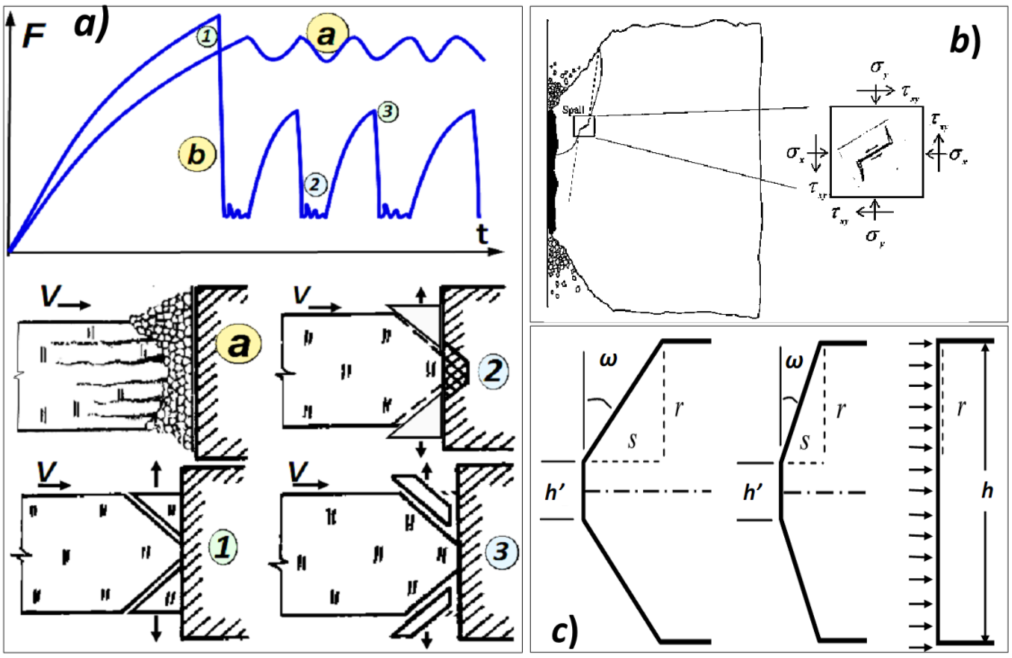

Figure 2. The fracture modes of ice on contact with a leg of structure as per Tsuprik V.G., 1984, [63, 64] a) crushing of ice and extrusion of products breaking the ice from contact area (a); the primary spalls (1) and alternation spalls with crushing of ice in the central part of the ice sheet (2-3). Formation of spall crack within the compressed area of a contact (a) and the diagram of edge leveling due to local spalls and crushing of compressed ice (d) at the central point of wedge as per Taylor and Jordaan, 2012 [65]

The Fig. 2-a shows the types of fracture of the contact edge ice field with the leg of the structure, proposed in 1984 by V.G. Tsuprik [63, 64] based on known results of the few research works done at the time, including studies of the author (Fig. 1). Depending on the strength and speed of THE ice field and the rigidity the legs of the structure, different modes of ice destruction may be experienced: beginning from a continuous soft crushing and extrusion of acrumpled mass of ice to the pure brittle mechanism of spalls of the blocks of ice or alternation spalls with crushing and extrusion of products breaking the ice in the contact area.

Considering the results of different investigations, Taylor and Jordaan [65] have suggested the probabilistic model of ice field edge fracture mechanism (PFM model - probabilistic fracture mechanics). It consists of a probabilistic approach for the initial process of ice field destruction associated with different defects of ice providing chipping of areas within the contact zone of the structure surface (see Fig. 2-b).

The results of all the above-mentioned investigations provides the possible explanation of the relationship between processes of spalling and crushing, when following one after another chipping, which creates a wedge in the ice field edge, where process develops of compressing and crushing i.e. leveling process of the edge line and formation of new large spalls (see Fig. 1; 2-c). Thus the process of crushing is a sequence of small spalls formed within the middle part of the contact area, with their release on the free surface or it occurs in the middle of the contact area in the high pressure zones. All these striped and mutually complementary processes represent the full process fracture of ice in contact with a structure.

Investigation of the parameters of cyclical ice load for real structures in natural conditions

The direct measurement of ice pressure forces using panels provides important initial information for the development of theoretical models for structure design. The first scientists applying such methods were Peyton [3] and Blenkarn [4], who in 1966-1970 obtained the records of ice loads acting upon structures located within the Cook Inlet in Alaska. Määttänen [8,11] has investigated ice forces providing the vibration of lighthouses within the Gulf of Bothnia. Engelbrektson [9, 67] has performed full scale measurements of ice pressure against the Norströmsgrund lighthouse located within the Gulf of Bothnia. He noted that the ice pressure against the support depends on the ice destruction character, i.e. the ice field drifting velocity. Kärnä and Turunen (1990) have suggested the four types of models for an identification of the ice pressure force; they provide different types of structural measures.

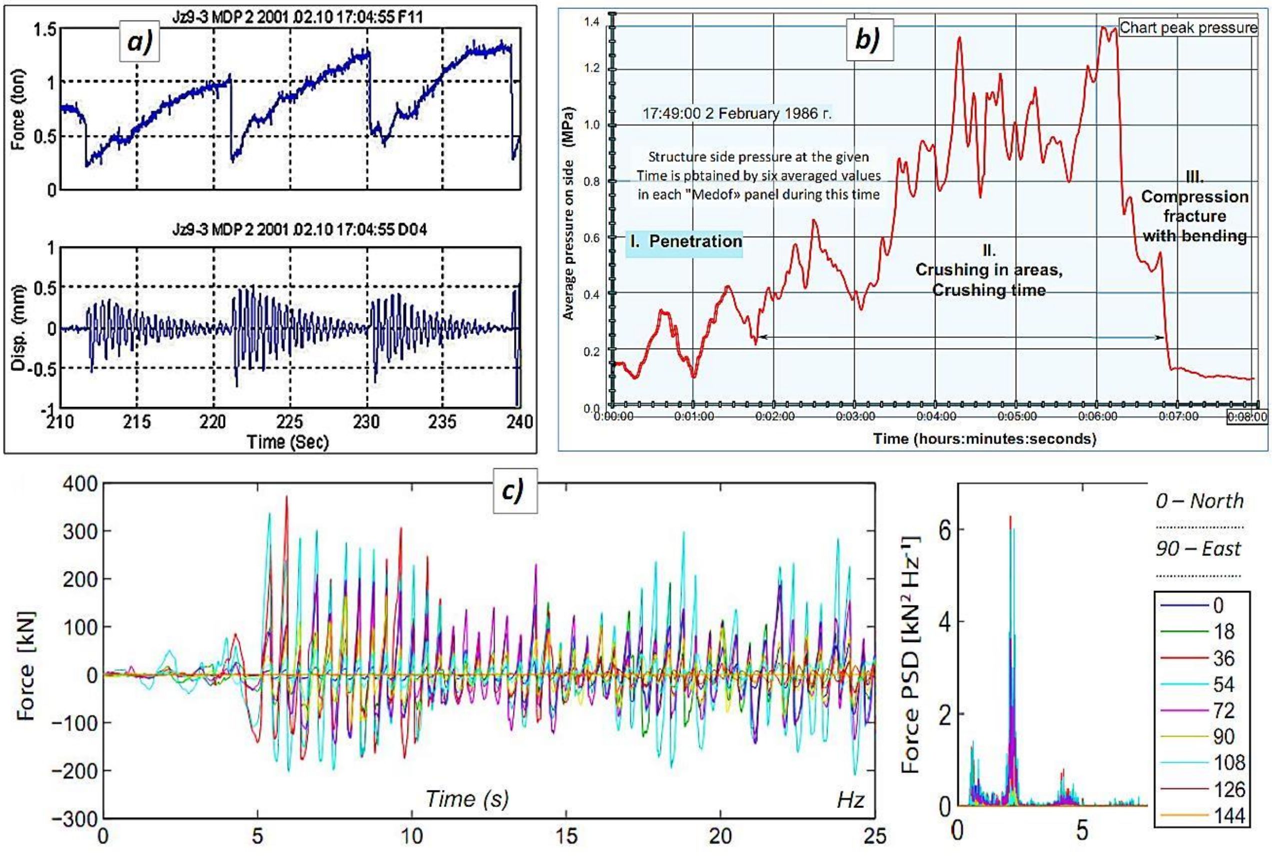

Figure 3. Record of ice loads on legs and vibration of structure subject to cycle destruction of ice: a) - as per Yue et al. [69], b) - as per Vershinin et al. [48], c) - as per Nord et al. [25]

In order to develop this idea D.S. Sodhi [68] in 2000 at the Bohai Gulf and Yue and others [69] have performed the investigation of ice thickness and temperature influence against the upper conversion velocity (***V_2***). These investigations were purposed in qualitative and quantitative analysis of conversion between continuous crushing (CC) and interrupted crushing (IC) on the basis of the model's reaction measurement. These authors have performed full-scale investigations of ice field and structure interaction. These investigations were featured with a simultaneous recording of the ice impact time, its velocity and structure movement. The authors of this investigation [69] have concluded that the contact force shall represent the function of relative shear of structure and relative velocity between structure and ice field edge; moreover, time shall be constant.

Besides the special strain gage panels, in order to perform the investigation of structure vibration, acceleration indicators, tilt indicators, seismographs, etc. were used. They provide the possibility to record the detailed distribution of contact pressure of ice in the contact area, to investigate the functional dependency of peak values of ice force and frequency subject to conditions of ice field and structure interaction. Among these factors area ice field velocity, ice thickness and ice strength. Such methods were used for structures at the Gulf of Bothnia and the Bohai Gulf, as well as the Molikpaq Platform. Some results are given on Figure 3.

This figure shows a static impact of ice and the corresponding vibrations of the platform foundation structure within the Bohai Gulf (Fig. 3-a) as per Yue and others [70], Fig. 3-b shows the typical destruction of an ice field for the Molikpaq platform [48]. Fig.3-c shows the records of ice load acting upon strain gage panels located at the foundation of a lighthouse subject to different angles of ice field drifting and the diagram of ice destruction frequency distribution within the Gulf of Bothnia (see Fig. 3-c) as per [25].

Based upon the brief investigation of ice load cycle parameters for real structures in natural conditions it can be noted that structure vibrations occur as its reaction to ice destruction until a certain depth. In the case of small velocity ice field movement, the transfer of kinetic energy from the ice field to the structure happens as a separate impulse (see Fig. 3-a) that causes the deviation of the structure from equilibrium state and accumulation of elastic potential energy in the contact zone of ice. Ice destruction in this volume release support of structure from ice pressure and construction reconstitutes the statically equilibrium due to elastic potential energy in material of structure support. In the time reconstitutes of happens extruding of ice destruction products from the contact area. Until to new contact can to pass the time depends from ice field velocity and the ice destruction depth. In the case of high velocity of ice field, depending on structure rigidity and strength of ice, the transfer of kinetic energy into potential energy of ice compression with further destruction can provide an increase in structure deviation (see Fig. 3-b), i.e. vibration. In this period of IF-IRS interaction, free fluctuations of the structure are possible. If the frequency of ice destruction with the same parameters is will close to one of the self-vibration frequency of the structure, resonance phenomena can occur (see Fig. 3-c) and such situation can cause loss of stability and destruction. Practically, such phenomena can occur for structures with different rigidity as reaction structure to different combination of main parameters, such as ice field thickness, its velocity and ice strength (Fig. 4).

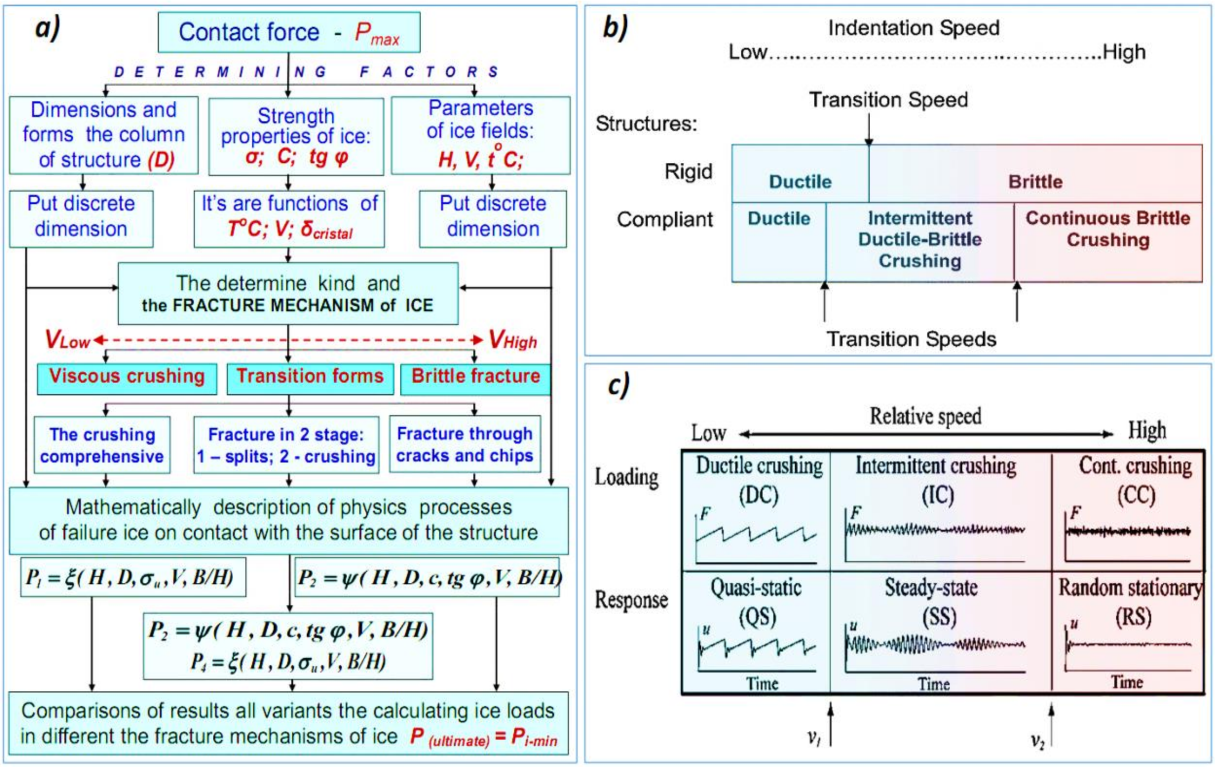

Figure 4 The classification scheme of possible types of destruction of ice with different combinations of factors that determine the fracture properties of ice in the process of interaction of IL-IRS: a) By on studies of Tsuprik.G., 1984 [63,64];
b) –by D. Sodhi, 2000, [68]; c) –by Bjerkås M. and Skiple A., 2005, [66]

Thus, the analysis of the results of the studies of all the phenomena occurring in the process of interaction between IF and IRS both in natural and experimental conditions showed that it can be proven that, depending on the speed of the IF, the rigidity design of IPC and the stiffness (strength) of ice, all possible modes of IF-IRS interaction can be divided into three types. An integrated approach to the classification of all the phenomena described here was submitted in 1984 in the works of V.G. Tsuprik [63, 64]. This provision was later recognized by the majority of researchers, except at very low speed mode when there is creep (fluidity) of ice, and adequate schemes were presented in the works Sodhi [68] (Fig. 4-b) and Bjerkås and Skiple [66] (Fig. 4).

The methods of theoretical modeling of the ice-structure interaction process

The first model of ice fracture in contact with the ice field is the "classic" model, created back in the first half of the 20th century and is currently represented in normative instruments [1, 2] in the form of the " K.T. Korzhavin formula". This model represents the most elemental method of calculation of the maximum value of the contact force of rigid motionless structures with the edge of a drifting ice field.

But, as shown above in this paper, the interaction of ice field and structure can develop according to different scenarios, which are determined by the peculiarities of the fracture of ice depending on its hardness (strength) and loading conditions in each particular case, given the flexibility of the legs of the structure. In terms of methodology and organization, the IRS design should be elaborated by algorithms for ice load calculations, understandable and adequate to all the scenarios of development process of interaction of IF-IRS. Such algorithms should be at least three and they should be based on models that describe the process of interaction between the IF-IRS on three completely different scenarios. For quasi-static processes, peak ice force occurs when the limit is reached, the plasticity of ice and this ice strength criterion is necessary for use in the calculation method of ice load, which should be based on the model of continuous ice fracture and extrusion of the products of ice destruction from the contact area. In other cases, the models of elastic-brittle fracture of ice should apply, or models combining several types of ice fracture. There are possible cases of the emergence of phenomena of autooscillations in the IF-IRS system, caused by the cyclical destruction of ice. To calculate the force of the impact of ice on the structure and its period of oscillation, dynamic equations should be obtained where the limit value of ice strength parameter necessarily should be taken into account, which regulates the transition to the beginning crushing of ice in a stress volume in edge ice field and load-shedding on the structure in case of an excess of the limit value for this parameter.

Data from many experimental observations becomes the basis for the development of an analytical description of the oscillation processes and the structure vibration during its interaction with a drifting ice field. Presently, there are a lot of theoretical models describing the dynamic interaction of ice and structure. Now many models are known: Interaction model subject to insignificant displacement; brittle fracture model; model of continuous crushing and displacement of ice; deformation’s models, for example those with deactivating ligaments; elastic-brittle models based upon Hooke's Law; Mohr-Coulomb model of bulk material; hydrodynamic and spectrum models; negative friction models and relative displacement; model of vortex-induced vibration (VIV); et al. [4, 10–12, 20–26, 31, 48, 49, 74, 80].

For a full and adequate representation of all the possible variants of the mechanical processes occurring during interaction of a drifting ice field with structure, it is probably enough to explore the three "benchmark" types of theoretical models proposed by different authors as a basis for using algorithms of ice load calculations. These three classes of models are very briefly discussed below.

Model of periodical crushing with spalls

Ice fracture by periodic crushing mode is characterized by the formation spalls on the ice field edge and a reduction of the ice thickness up to the effective – $\boldsymbol{h}^{/}$ (as opposed to actual $\boldsymbol{h}$, Figs. 1 , 2), which depends on the ice deformation speed. As the speed of the ice field $\boldsymbol{V_{if}}$ increases, the value $\boldsymbol{h}^{/}$ decreases, as the size of the spalls grows in the zone of ice fracture in contact with the surface of the leg. During alternation of processes of spalls-crushing are occurring recession and increase of the ice load and it has a saw-tooth type because the contact area is changing. Such models have been developed since the late 1960's and the complex interaction process of between IF-IRS was effectively described by the model of a system with one degree of freedom. At the base of such models lies the unified concept of periodic fragmentation of ice at the leg of structure, proposed by H.R. Peyton [3] in the years 1968 and 1969. Matlok and co-authors [69] had used Peyton’s concept and proposed a revolutionary idea that "the fracture of ice occurrs at a certain size” and they presented a model that can describe the reaction of the structure upon impact of an ice field acting at low and high speeds.

In order to demonstrate their hypothesis, many authors apply the Matlock model [69], which describes well enough the fluctuations of the structure close to the relaxation oscillations. A mechanical analogy of this well-known model is shown in Figure 5-a. In this model, moving ice field is presented in the form of a simple beam with many elastic cantilever teeths, that moving with a speed $\boldsymbol{V_{IF}}$ in the direction of a single-mass model of the structure (***M***) with elements of elasticity (***K***) and damping (***C***).The teeths are in contact with a cantilevered elastic-pliable model of support rigidly fixed at its base.This model has the ability to receive "sawtooth" loads on the structure (fig. 5-b), because the destruction of the teeth occurs only for the critical deformation of $\boldsymbol{S_{cr}}$. The $\boldsymbol{S_{cr}}$ value can depend on the speed of the ice field, and the thickness and height of the teeth (fig. 5-a) allows to simulate the strength and elastic properties of ice. Changing the distance between the tines can simulate the length of the breaking ice zone $\boldsymbol{L_{cr}}$ before thecontact surface of the leg of the structure. The length $\boldsymbol{L_{cr}}$ determines the frequency of the ice fracture and, consequently, the period of oscillation structures $\boldsymbol{T}$ in the models of some authors, such as Yue et al. [70] and some others.

Variations of these parameters on this model, a different character (type) of fracture the ice can be obtained, which can vary from visco-plastic to brittle (fig. 5-b) and mainly depends on the speed of the ice field V_{LP} and the stiffness of the ice. The equation of this mechanical process, implemented this model in [69] is written in the form:

$$M\ddot{x} + C\dot{x} + Kx = F(t), \tag{1}$$

This non-inertial model of elastic-brittle type ice fracture simulates the relaxational oscillations of the structure and allows to obtain the ice load by numerical methods in the form of a sawtooth curve, where each peak starts to grow from zero load. This effect is achieved by the fact that the limit value of the deformation of each tooth S_{cr} must be entered in advance in the calculation. The model of Matlok et al. [73], does not allow to "grab" the resonant frequency of the structures because in its mathematical interpretation, the periodicity of the forces as a function of time is not entered.

Significant development of the theory of ice self-induced vibrations in the process of interaction between IF and IRS was achieved by the research of K.A. Blenkarn [4], who in 1970 stated that the structure and ice field must be seen as a system of related elements. Additionally, this researcher, based on the results of the experiments of Peyton [3], who researched the reduction of ice strength by increasing its loading rate (Рис. 5-d), proposed to "consider the ice forces to be a function of the relative velocity between the far-field ice V_{if} and the structure $\dot{X}$". Using these three hypotheses, K.A. Blenkarn [4] proposed to describe the oscillation process in the IF-IRS system under the influence of the force F(v) to apply the known theory of oscillations that uses the equation of motion of the body with "negative damping " [71], which is a function of the relative velocity $V_r = (V_{if} - \dot{x})$ of the two interacting system elements LP-IPC. His model is described mathematically as follows:

$$(M/g)/\ddot{x} + C\dot{x} + Kx = F(V_{if} - \dot{x}), \tag{2}$$

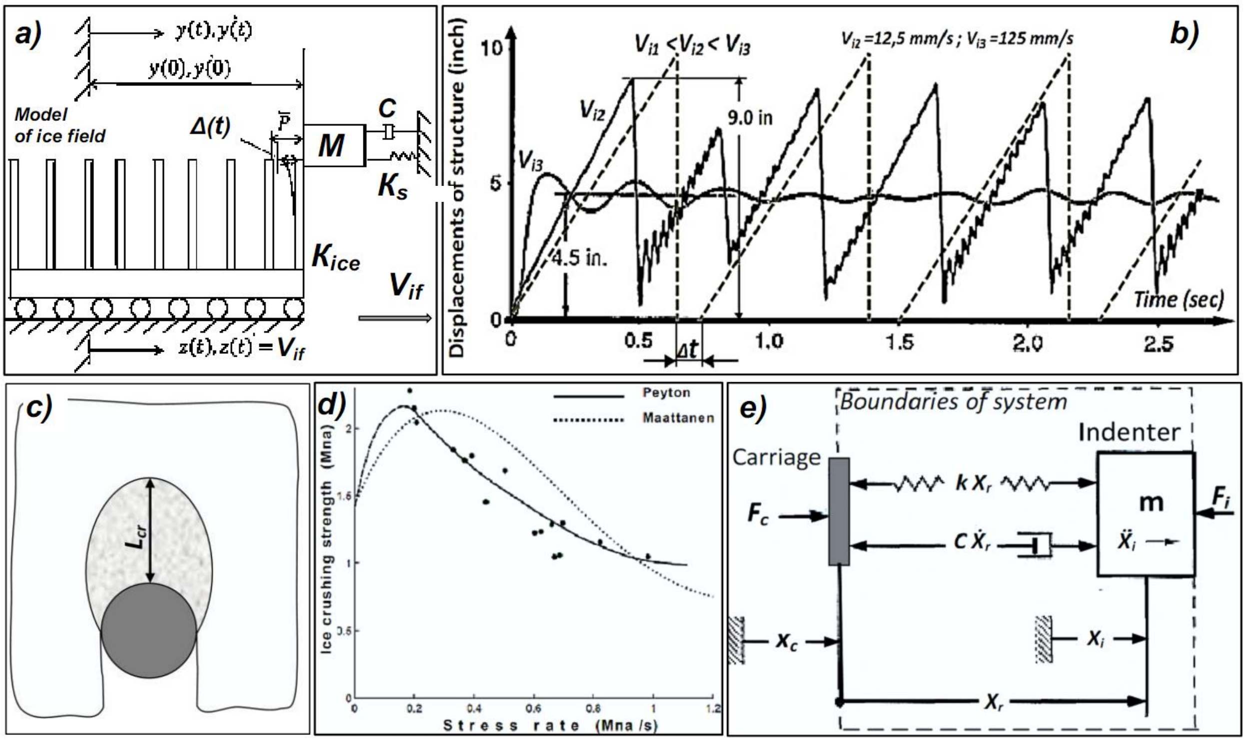

Fig. 5 Models of interaction for IF - IRS system: a, b) –Matlock et al. [69]; c) –Yue et al. [70]; d) –Dependence of strength of ice loading speed as per Peyton [3] and Määttänen [11]; e) –Sodhi model [72]

Next, given the low values of displacements of structures and deformations of ice, K.A. Blenkarn [4] rewrote the force function F as the formula (3), which then was subsituted in formula (2) and formula (4) was obtained:

$$F(V_{if} - \dot{x}) = F(V) - \dot{x}\frac{\partial F(V)}{\partial V} \tag{3}$$

$$M\ddot{x} + \left(C + \frac{\partial F}{\partial v}\right)\dot{x} + Kx = F(v) \tag{4}$$

Thus, the "negative damping" concept entered by K.A. Blenkarn [4] for the system IF-IRS based on the use of the dependencies of ice strength and its download speeds, proposed by H.R. Peyton [3] (Fig. 5-c), explains the emergence of autooscillations in the IF-IRS system. The ice self-excited oscillations in the system occur if the friction coefficient $\partial F/\partial v$ becomes negative and is numerically greater than the structure damping factor ***C***. Then the equation 4 will be the equation for "negative net damping", and the preponderance of negative friction ($\partial F/\partial v$) over positive (***C***) over time will lead to an increase in amplitude of the structure. In addition, K.A. Blenkarn [4] experimentally determined that the frequency of ice load peaks corresponding to the points of ice fracture, is governed by the ice field speed V_{if}, the structure flexibility ***K*** and the rigidity K_{ice}, depending on the relative velocity of the structure and the ice fields V_r (download speed of ice). Blenkarn K.A. [4] also confirmed that a simple case of "intermittent" interaction can be described by the model presented by Matlock et al. [69].

The concept of "negative damping" is received quite widespread among researchers. M. Määttänen in 1977 [11] proposed a mathematical model for the description of autooscillations in the IF-IRS system, which has many degrees of freedom. Here, the model has also been obtained by combining the equation of structure motion and ice load as the relative velocity function $F(V_r)$ in the form of the external friction characteristic. The load was adopted as on Fig. 5-d, where each point on the curve is the limit strength of one sample tested on uniaxial compression with a constant loading speed. This model was further developed by Wang & Xu [61], Vershinin et al. [48] and other researchers. But the concept of "negative damping and self-excited vibration" was constantly subjected to criticism and disagreement by another researcher of this problem Sodhi D.S. [59] for many years. This author considers the oscillations, emerging in the process of IF-IRS interaction and explains its position by the existence of a number of inconsistencies, which challenges the concept of Blenkarn and his followers. The following discrepancies are noted:

– The model with "negative damping" describes an idealized physical process in which at each moment of time is has a place the maximum stress state on the eve of the beginning of the ice crushing in the contact zone, and the initial contact force cannibalizing is determined by the value V_r and the specified strength sample $R_c(\dot{\sigma})$;

– mathematically not permissible, when we are looking for a solution to the time-dependent interaction between solids, but the strength of ice is taken only as point on the "stress-deformation" curve, obtained at the time of the ice sample destruction during testing;

– physically, it means ignoring the real physical-mechanical properties of ice, described by the curve of tests on strength of ice with respect to time when determining a power function $F(t)$ for the equation (1) as a similar dependency curve by Peyton R. [3] (fig. 5- d);

– the concept is not a confirmed hypothesis, because it is based on estimates of the negative damping, rather than specific measurements of key parameters of the process.

Sodhi D.S. [72] offered its interaction model IF-IRS (fig. 5-e). He held very carefully prepared experiments in the "closed" mechanical system that controlled all the factors and ***measured changes of energy*** and values of all variable parameters that could influence the parameters of the interaction model IF and the leg of the IRS. The results of these experiments have shown that the process of interaction between IF-IRS is always a process of dissipation (transfer) of kinetic energy of the IF in ice array and no transfer of energy from the ice field to the structure. On this basis, Sodhi D.S. [72] excludes any possibility of oscillations induced by ice as a result of the negative damping, as proposed Blenkarn [4] and Maattanen M. [11].

Despite the existence of contradictions, considered by the two points of view on a single phenomenon, offering new models as the type considered here, that are formed using the hypothesis of negative damping. In every model, the instant ice crushing strength parameter is considered, and isdefined by tests of small specimens for uniaxial compression and the σ_o parameter of this strength depends on the speed of sample loading, as shown in Fig. 5-d.

The "continuous" and "layer-by-layer" crushing models

The model identified in the header, made up of a separate group of LF-IRS interaction models, was formulated at the beginning of the ice fracture modeling, developed during a long period and used at the present time. First, based onmodels of such type was a "hydrodynamic model" for the fracture of ice by Kurdumov and Heisin, proposed in 1976 [73], shown in Figure 6-a. These authors' model was based on the concept of extruding products of ice fracture from contact zone. Here, a mechanism for breaking the ice is not considered, and the model is based on the hypothesis of the continuous change of the physical state of the ice from the solid phase of the rear sight (intact) of ice to the destructed state in the form of an ice crumb.

In a work of the author [74], it is also represented a developed model of layer-by-layer fracture of ice during dynamic interaction between IF and the supports of the IRS (fig. 6-b). Products destruction of ice occur as the result of the transition of "solid ice“ by in a layer-by-layer mode from a pre-fractured layer, located before the frontal boundary (front) of destruction in to new state as a layer of crushed ice (crumb), which extrudes from the contact area. This transformation is occurring in end process increase of contact pressures in moment reached limit of the volume potential energy deformation accumulated in the pre-fractured layer.

In models of such type is not direct contact with the intact ice during interaction and at least, most of the interaction forces transferred through the layer of crushed ice or ice-crumb, as shown on Figure 6-a,b,c. In the moment where peak pressure will achieved in a compressed layer of damaged ice, occurs crushing this layer and followed by an instantaneous drop of the contact forces, the crushing phase ends and occurs change the type of process on to new process - phase of the clearing. In these types of models the contact force during process interaction variate in accordance with the phase of the crushing and clearing. The effort, required to extruding the fragmented ice In such models, are increased synchronously with the approaching to zero thickness layer of ice crumbs.

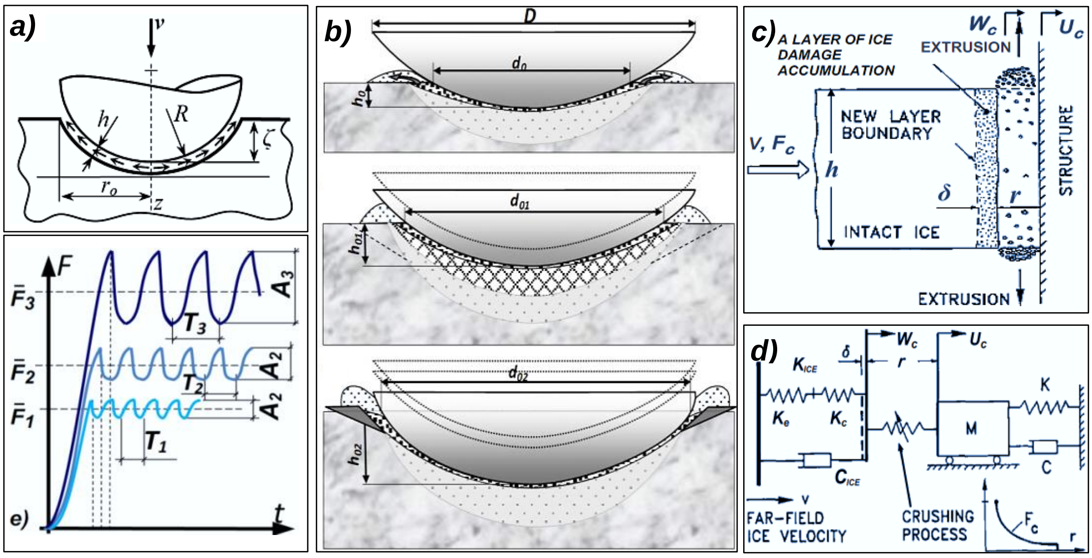

Figure 6. Models continuous crushing: a) – representation of a hydrodynamic model Kheisin et al. [73]; b) – layer-by-layer model of ice fracture by Tsuprik [74]; d),c) – model continuous crushing by Kärnä and Turunen [75]; d) – model destruction of the ice layer by Jordaan and Timco [76]; e) – different of contact force graphics for model of continuous crushing of ice for one speed ice field, but different values ice rigid

The authors of the work [76] use the same approach as in [73-75], introducing the body of ice field in several areas: far from the surface, the ice is in pristine condition (intact ice); closer to the contact surface, ice has a layer badly damaged by cracking; between this layer and the surface, structures are formed by a layer of fractured ice (ice crumbs).

The contact force during the process of interaction IF-IRS in models of this type are weakly changing when the transition fracture process from the phase of crushing to the phase of cleaning, if the strength of ice is low. But with the increasing strength of ice, such models can describe the periodic process of the ice fracture and, consequently, periodic change of amplitude (***A***) and the period (***T***) of the peaks of ice load ***F*** on the structure (Fig. 6-e). Thus, the layer-by-layer mechanism of breaking the ice with a relatively high strength can generate a cyclical ice load on the structure, causing it to wobble. Amplitude and period of oscillation of structure are defined by its rigidity K_D and the rigidity of ice K_{ice}, which depends from the strength of ice R_c and from the conditions of its contact with the structure.

Experimental-theoretical method for dispensing of energy consumption by the destruction of ice

Given that the considered system is closed, the most complete processes of element interaction within this system can be described by using the law of conservation of energy. In such approach, the main energetical processes in the phenomena of oscillations of the IRS are processes of moving the kinetic energy of the ice field into elastic energy deviation of the structure inequilibrium and the elastic energy of compressed volume ice and potential energy dissipated in this part of the ice. At the same time, on the basis of conservation laws, it is clear that in the process of the interaction, part of the kinetic energy of the drifting IF is spent irretrievably on the fracture of ice.

As far as we know, the solutions of task of relaxational oscillations in the IF-IRS system by method for solving the equation of energy balance has not yet been cited. In paper [48] the scheme of energy consumption in the "ice-structure" system was viewed, but in the mathematical description of the dry friction model, the dynamic processes for the ice field and in the structure is described by of two differential equations of motion, related through a common for these elements of unified system by force their contact interaction. But the strength of ice in explicitly form in to the equations is not included. At the same time, in different years a number of researchers have suggested the use of the specific energy of ice fracture ε_{cr} as a parameter of the strength in the calculation of ice load [72, 78–80].

The mechanism of oscillation generation in the system IF-IRS

Consider IF and IRS not as two separate objects, but as a system in which those objects are interacting among themselves, new phenomena are spawned, which are not characteristic for each of these objects outside the system. Such phenomena are the process of the ice fracture and the structure oscillation process. We assume that the size of the ice field is large, its mass and its velocity change slightly during interaction and in the calculation of the values of these parameters, the kinetic energy IF can be considered as unchanged, and its mass and speed as constant values. With these assumptions, the interaction of the elements in the system IF- IRS can be regarded as a function of the active, autonomous, conservative self-excited autooscillation and self-adjusting system of the relaxational type (fig. 7). Usually, the mechanical behavior of this system is described by linear differential equations. But this approach does not take into account the cause of the hesitation, i.e. the nature or source of the emergence of a periodical force.

Previously, the possible scenarios of development of the process of interaction of the elements of the system IF-IRS were analysed. So, if the speed of movement of the ice field VIF= Vi1 is small (fig. 5-b), and ice has high strength RC, the ice load on reliance will have the appearance of individual peaks with gradual rise of force and abrupt it decline in moment of ice fracture. Breach of contact may occur after shift wedge-shaped blocks of ice on the bottom and top surfaces of the ice field (fig. 2-b,c). The structure, freed from the pressure of the ice field will begin to reverse movement towards the ice field, which continues to move, and then all processes in the system reoccur. The beginning of the next contact may come through the time interval Δt (fig. 5-b). When the speed of the ice field (IF) monotonically increases $\boldsymbol{V_{ij}}$**>…. >** $\boldsymbol{V_{i3}}$ **>**$\boldsymbol{V_{i2}}$ **>**$\boldsymbol{V_{i1}}$,load peaks are followed more frequently and at high speed IF and smaller ice strength, the ice load curve has slightly noticeable extremes (a variant of the curve in Fig. 5-b $\boldsymbol{V_{i3}}$).

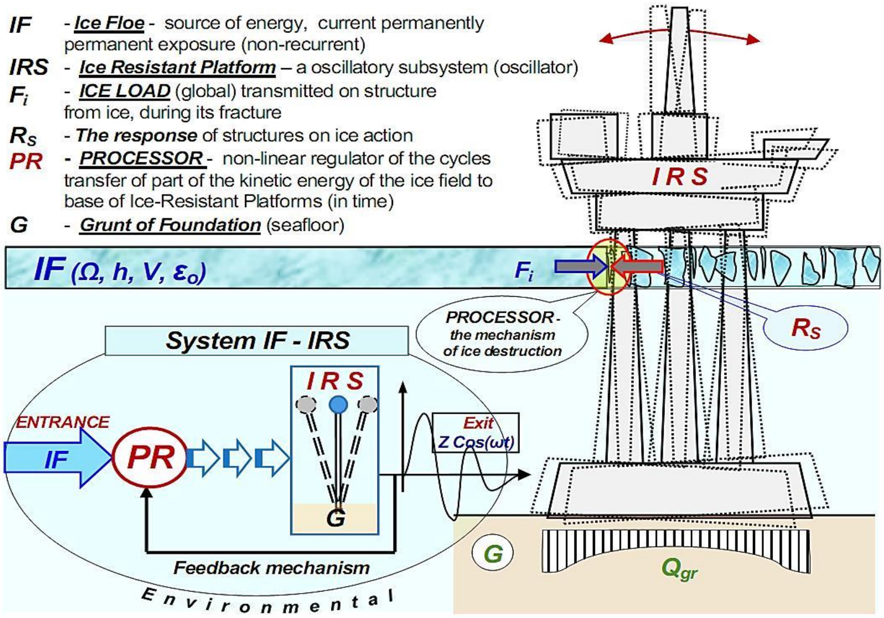

Figure 7 Image and functional scheme of “IF – IRS” system and subsystem “IRS”, in their emergence the autooscillations

Namely, such nature of mechanical processes and such alternation in the IF- IRS system generates a cyclical sequence of increase and decline of ice load on a structure which can lead to a self-exciting oscillation of IRS when exposed to ice fields. At the same time, as can be seen from the theory of vibrations [71], the autooscillation in systems is usually occurring due to periodical transfer of energy from the source to vibrating element of the system, i.e. in our case from IF to IRS.

Therefore, hesitation of the structure will be supported by the injections of energy taken from the moving ice field and there should be a mechanism for dosing of the output kinetic energy of the ice field and its transfer to the structure. Perhaps the authors of work [76] Jordaan I.J. and Timco G.W. speculated in the same manner in their model of ice destruction and therefore they designated the location of the process of transfer of kinetic energy from the ice fields to the structure between the images of these two elements of system IF-IRS. (Fig. 6-d).

Dosing and frequency of transfer of kinetic energy from ice field to structure performed due to the account of the functioning of the processor of the system– during realizing of the mechanism of fracture of ice (PR on Fig. 7), which acting as a ratchet mechanism in a watch or pressure regulator valve a in steam machine – but here as the regulator cycles of hesitation process.

The specific energy of mechanical fracture of ice as a regulator of structure frequency oscillations

Consider the approach to a structure that has the transverse dimension supports (D) and stiffness G_S, an ice field with certain combinations of V_{IF} speed, thickness h and hardness (strength) of ice Gi (Fig. 8-a). Description of the energy transfer process in an array of ice from the leg of structure and the potential energy accumulation mechanism that acting in deformable volume of ice, in this work are taken according to the concept, described in [77, 78].

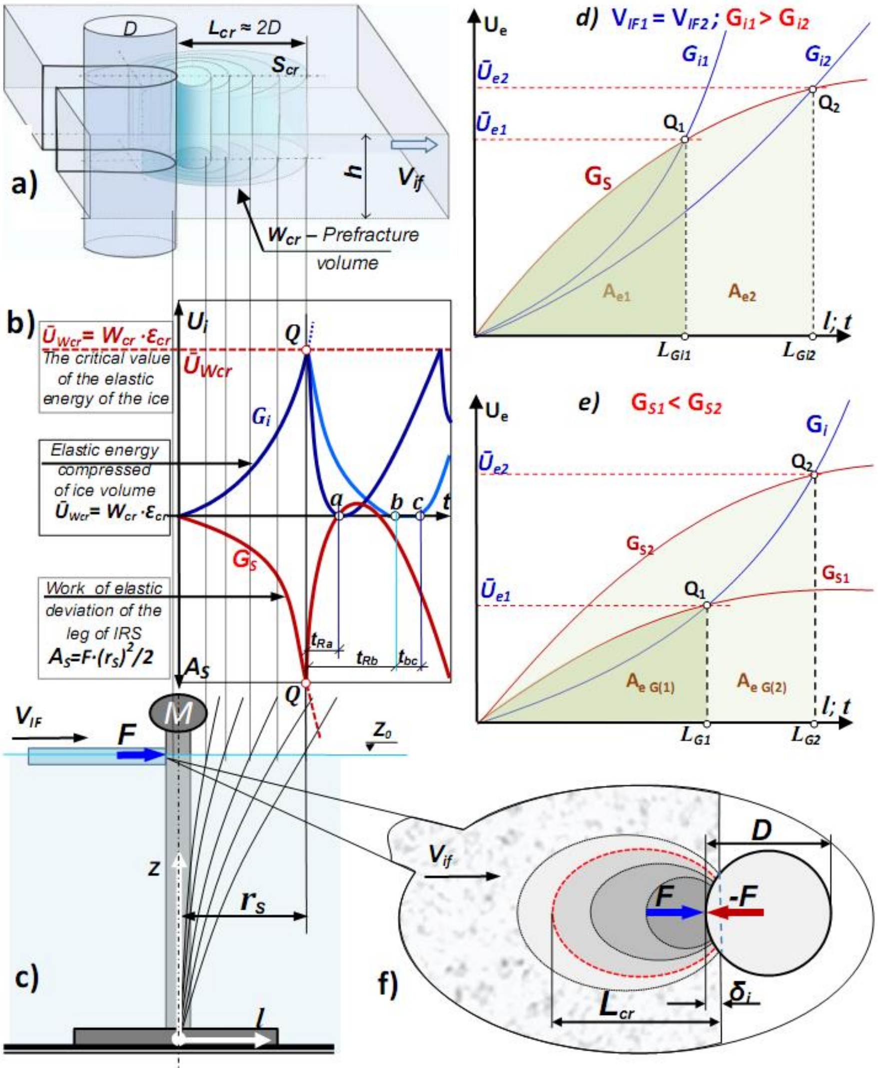

Figure 8. Illustrations the occurrence of cyclic ice loads during process interaction of ice field edge with the surface of leg structure

We write the equation of balance of the ice field kinetic energy consumption $\boldsymbol{\Delta U_{IF}}$ in the contact zone by its transmission into elements of the system IF-IRS, in which it will distributed, in the form of elastic energy ($\boldsymbol{\Delta U_e}$) during the same interval:

$$\Delta \boldsymbol{U_{IF}} = \Delta \boldsymbol{U_e}\,. \tag{5}$$

In the active phase of interaction, the influx of the kinetic energy of the ΔU_{IF} from the IF in the contact area during one loading cycle occurs continuously, the level of potential energy U_{Wcr} in the strained volume of ice field W_{cr} increases (Fig. 8-a,b) and at the same time, work A_S is exerted to reject structures (Fig. 8-b,c). From the conservation laws are known that physical sense have not the full numerical value the value of the potential energy , but the change of its numerical value during deformation , only in this case it represents the energy of the elastic deformation. However, considering the condition of additivity, the dissipation energy ΔU_e of the system equals the sum of energy (of work) used on the elastic deviation of the structure ΔU_S, including the dissipation energy in the material and in the constructions of the structure, and the energy ΔU_{Wcr}, stocked within the ice array at its edge area, including the energy dissipated in ice:

$$\Delta \boldsymbol{U_e} = \Delta \boldsymbol{U_S} + \Delta \boldsymbol{U_{Wcr}} \tag{6}$$

In the process of interaction with the IF-IRS at any moment prior to the time of destruction of the ice in a strained volume, according to Newton’s third law, the balance of the changes in the energies of elastic deformations of the curved leg structure and the compressed volume of ice will take place.

$$\boldsymbol{\Delta U_S} = \boldsymbol{\Delta U_{Wcr}}; \quad \boldsymbol{\Delta U_e} = \boldsymbol{2\Delta U_{Wcr}}. \tag{7}$$

Therefore, the balance – equality (5) in the process of interaction between IF and IRS, subject to (7) may be breached only in 2 cases: due destruction of the structure (stability loss) or due destruction of the ice. Staging of the considered problem here assumes to take into the calculation the size and parameters of sustainability or local strength of structures that withstand the possible greatest ice load. This means that a force that causes the destruction of ice, i.e. ice load on structure, needs to be determined on the basis of the requirement of destructing the ice. Therefore, it is necessary to examine the parameters and conditions for the destruction of the ice that must be included in formula for calculating the boundary conditions for the energety state of the strained ice volume W_{cr}.

A mathematical description condition of the beginning of the destruction of the ice in the final stage of its deformation, not only has a great theoretical value for this unique material, but also a practical importance for solving the problem of ice loads, as described in this work. Here, the magnitude ε_{cr} - specific energy of mechanical fracture of ice was adopted as a criterion of ice destruction. The theoretical basis of this criterion is the theoretical model of layer-by-layer destruction of ice and methods for experimental determination of this value are given in the works [74, 79, 80, 83].

Thus, the key parameter governing the cyclicity of the ice destructed is a critical threshold value of potential energy of deformation ε_{cr} accumulated in the unit volume. The exceeding of this threshold energy shall cause the destruction of the ice and breaking of the contact ice-structure for a while. To achieve critical stress state pre-fracture in the strained volume of ice W_{cr} it is necessary to spend energy (Fig. 8-a, b):

$$\boldsymbol{\overline{U}_{Wcr}} = \boldsymbol{W_{cr}} \cdot \boldsymbol{\varepsilon_{cr}}\,. \tag{8}$$

Changes in the energy state of the interacting elements of LP-MLE system, considering full synchronization in time of the consideration processes (6), occur is due perform work by force $\boldsymbol{F}$ as on the deviation of the $\boldsymbol{r_S}$ support structure in the direction of movement of the ice field ($\boldsymbol{A_S}$ - Fig. 8-c), and on embedding of the support into the edge of the ice field in the opposite direction ($\boldsymbol{A_I}$ - Fig. 8-f) on $\boldsymbol{\delta_i}$ depth.

$$\boldsymbol{\overline{U}_S} = \boldsymbol{A_S} = \int_0^{r_S} \boldsymbol{F} \cdot \boldsymbol{d}(\boldsymbol{r_S}) = \boldsymbol{F} \cdot \frac{\boldsymbol{r_S}}{\boldsymbol{2}}; \tag{9}$$

$$\boldsymbol{\overline{U}_{Wcr}} = \boldsymbol{A_i} = \int_0^{\delta_i} \boldsymbol{F} \cdot \boldsymbol{d}(\boldsymbol{\delta_i}) = \boldsymbol{F} \cdot \frac{\boldsymbol{\delta_i}}{\boldsymbol{2}}, \tag{10}$$

The maximum ice load on the IRS can be determined from equation (8) and (10) describes the limiting value of the potential energy of the elastic deformation in ice volume $\boldsymbol{W_{cr}}$ created by the work of the contact force, provided to the embedding leg of structure in the ice at a depth $\boldsymbol{\delta_i}$:

$$\boldsymbol{F} = \boldsymbol{\varepsilon_{cr}} \cdot \boldsymbol{f}(\boldsymbol{W_{cr}}/\boldsymbol{\delta_i})\,. \tag{11}$$

The dependence of the volume of ice fracture and the depth of an elastic embedding structure in the ice is the subject of a separate study.

Results and Discussion

The important result of all studies should be considered understanding that the phenomenon of fracture of ice is the cause and source of other phenomenon - vibrations of the IRS. The phenomenon of the destruction of the ice during IF-IRS interaction has a dynamic periodic nature and the nature (mechanism) of ice fracture determines the frequency and amplitude of the encountered oscillation in constructions. It is proposed in the work that the experimental-theoretical method of dispensing the energy costs for the destruction of the ice revealed that the essence of the phenomenon of cyclical ice loading is the periodic violations of the energy balance of the two main simultaneous processes of accumulation of elastic energy in the structure deviating and accumulating elastic deformities in ice volume. For the flexible structure by the main parameter, governing the processes of elastic deviation of the IRS and the compression of the limited volume of ice on the front surface of the structure leg is the size of the dose of kinetic energy of the ice field, which is consumed on the work for deviation of the structure and for compression of some amount of ice in the array edge of ice field to its critical level stress state.

According to diagram Fig. 8-b,c, the critical value of ice destruction energy $\bar{U}_i$ in condition of compression ice volume at a contact zone shall be determined for each calculating event by using the ice field thickness h and its velocity V_i (parameters of ice field kinetics) and rigidity (strength) of ice G_i, defined by the parameter specific energy fracture of ice ε_{cr}. A mechanism of regulation of the limiting number of the spent kinetic energy of the ice field, that is, the conditions of equality (5), is based upon the interruption of the energy transfer process from the ice field by a gap of contact IF-IRS after the compressed ice crushed. This mechanism shall be considered as a basic condition for emergence of self-vibration in IF–IRS system. Figure 8-d shows the graphical interpretation of the results obtained for the two different cases of strength parameters of ice fields (stiffness) G_{i1} and G_{i2} interacting with a structure leg with rigidity of G_S. Figure 8-e shows graphs for the case of two structures with varying stiffness (G_{S1}, G_{S2}), interacting with the ice field with constant stiffness ice (G_i). As can be seen in these graphs, the absorption of flux of ice field energy in interaction process in points (Q) interrupting becourse reached of the limit of opportunities its absorption Ue in IF-IRS System. Therefore, the amount of absorbed energy of ice field during the time Δt, i.e. the power transfer of ice field energy is determined by the speed of its movement, V_{IF}, the rigidity of ice G_i, and the stiffness of structures G_s.

Depending on the combinations of all the above parameters, the oscillation mode can be transient, established with constant amplitude and frequency, and random (with random frequency and amplitude).Several scientists have included in the descriptions of their proposed models of interaction between IF with IRS, the processes of energy dissipation in a deformed ice volume and in the material of the leg of the structure [2, 31, 48, 53, 54, et al.], and they considered these processes as independent. They assumed that the probability of the emergence of the critical cycle, i.e. the stabilizing process of auto-oscillation, is related to the fact that in the case of monotonically increasing amplitudes of oscillation in the IF-IRS system, the energy dissipation in the system at the expense of damping is monotonically increased; and through some period of time, the energy dissipation of the system in one cycle must be equal to the energy received by the structure in this period of time from the drifting ice field [48]. Thus, if the frequency of these vibrations match with one of the frequencies of natural oscillations of IRS, the system IF-IRS can present self-exciting oscillation with constant amplitude, and the energy source for these fluctuations is the kinetic energy of the IF.

This mode, in terms of reliability construction, is the most dangerous because of the possibility of resonance phenomena. The combination of the phenomenological events described is a complex cause of dangerous vibrations in offshore structures, which can lead to accidents, and reduced reliability and durability of structures. But for this occurrence, the autooscillation regime must be respected by the two conditions arising from the law of conservation of energy.

Condition A: the amount of the “energy swap ΔU_{IF}" from the ice field in an oscillating element of the system per unit time must not be less than the amount of energy ΔU_e dissipating in the system;

Condition B: the transfer of the "doze energy” must occur synchronously with the frequency of vibrations of IRS, i.e. the power of inertia of IRS in this moment must be zero, or a vector of this force should have the same direction as movement of the ice field and have a value close to zero.

Therefore, emergensing the autooscillations in the IF-IRS system require serious theoretical and experimental evidence, because for their automatic resumption must be require the return of a structure to its neutral position absolutely synchronous with the frequency of the ice fracture. On the basis proposed in this paper, the conception of the energetical description of the interaction process in the system IF-IRS lower an attempt is made to consider the possibility of emergence of autooscillation processes in this system.

Figure 9 shows the diagram of self-excited oscillations in the IF – IRS system subject to an increase of ice field velocity V_{IF} and some decrease of the specific energy of ice destruction ε_{cr} on account of an increased velocity of the ice load. The increase of ice movement velocity V_{IF} leads to an increase in the contribution of "energy swap ΔU_{IF}" through a contact area per time t_s prior to the destruction of the next layer of ice. In this regard, the process of cyclical destruction of ice from an area of a single oscillation (Fig.9-b1) is moving into zone of the intermediate mode (Fig.9-b) and further into an area of stable high speed V_3 (fig.9-b3). Here occurs an almost continuous transformation of the kinetic energy of the field into potential energy of layer compression at a contact zone, its destruction and a displacement of destructed fragments out of a contact zone. The structure obtaining increased energy during a shorter period of time, as per the oscillation theory, shall increase its amplitude.

Implementation of the "Conditions A" is possible for certain combinations of parameters of the ice field and the structure, including: drift speed V_{IF}, its thickness h and the value of ε_{cr}, as well as the stiffness of the IRS G_S and its mass. Given the diversity of the natural environment, this coincidence is always possible because the ice field, which has a very large kinetic energy, will be destroyed in the contact area. Such event always precedes a cycle of accumulating potential energy in the ice array. Energy flux from the ice field will equal to the energy required for fracture of ice because this process is governed by the critical value of the specific elastic energy in an array of ice (Fig. 9-a), which will cause its fracture.

A more complex situation can be with the execution of the "Condition B". Execution of the second condition is possible only if the new contact of the surface structure, after ousting products of ice destruction from the previous cycle of interaction, will begin with the intact ice in point "x" on the Figures 9-b,c. Only in this case, the vector of force pressure ice on his contact with the structure will not receive the resistance from structure which prior to this point was moving against the movement of the ice field. Then the kinetic energy of the ice field will start a smooth segue into the potential energy of the elastic deflection of the structure or "added" to the remnants of the inertial force of a structure, when it returns to the resting state, if was had the transition it oscillation through the resting state ("0"). Therefore, only the execution of events in such order can create conditions for development of the autooscillations in the IF-IRS system.

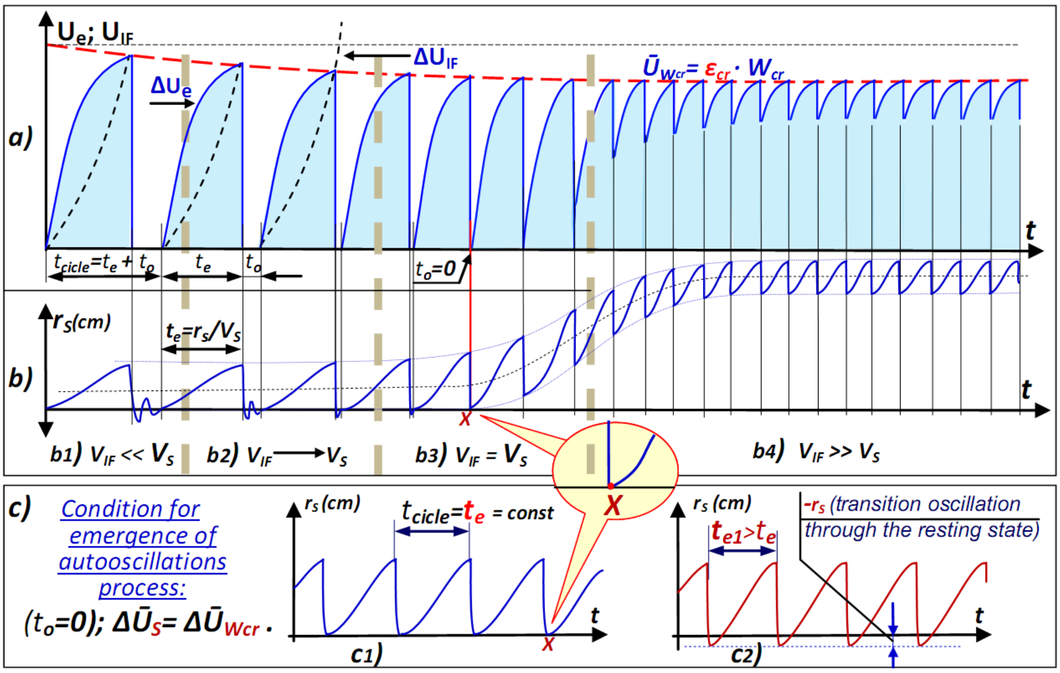

Figure 9 Diagrams of changing of self-excited oscillations of IF-IRS system (a-b) due to increase of velocity movement ice field Vif and view charts of autooscillations process of hard (C1) and flexible structures (C2) according to the theory of oscillations.
Here tcikl is a full time of contact (full cycle); te – a time of active phase load compressed ice and structure; t0 – a time when not contact;

This scenario is also theoretically possible, but in this case, the graph of fluctuations must conform to the type at Fig. 9-c (it can be compared with the schedule of the oscillations of the pendulum in clocks). But it does not correspond to the views of oscillations on the schedules of "self-excited oscillations", recorded in field and laboratory experiments that are listed in many previously published works [4, 9, 11, 13, 25, 70]. At the same time, all these records, possibly, were obtained in the forced vibration mode, as stated in several works of D. Sodhi [60, 72].

Conclusion

In this work, first the energetical concept of the process of emergence of a cyclical load from ice field (IF) to ice resistant structures (IRS) is justified. It is shown that the description of the process of fracture edges of ice fields in the contact zone shall be based on the consideration of energy balance in the system containing these two objects. The process of transferring the kinetic energy from the moving ice field to the structure is presented in this work, in the form of simultaneous development of the two main processes: accumulation of elastic energy in equal shares in deviating of the structure and in the volume of ice in the contact area of the edge the ice field. The essence of the phenomenon of cyclical ice loads on the IRS is shown as periodical interruptions of the monotonous processes of elastic accumulation of energy and its partial dissipation in two elements of the system IF-IRS, caused by the destruction of ice in the contact area and a simultaneous breach of contact between IF and IRS.

The results obtained in the investigations provide a basis for offering the followings conclusions.

1. In phenomenon of the cyclic ice loads the exclusive role plays a fracture mechanism of ice. Presence of such mechanism providing the periodical limitation size (volume) "paging" of energy from ice field to subsystem "IRS" in compliance with the theory of vibration, doing this mechanism as regulator of the period and amplitude oscillation of IRS, and it are limiting increase amplitude during autooscillations. Such mechanism is the main sign of autooscillation system.

2. Periodicity of the ice destruction is defined by the velocity of accumulation of elastic energy deformations of ice at the contact zone of the ice edge and the structure depending on IF velocity, structure's rigidity and friction force between elements of sistem. The fracture, as a spontaneous process releasing potential energy stored elastically in the strained volume of ice, starts in a local micro-volume, where is achieved the violation of equality speed of adding of energy and power of its scattering.

3. The basic parameter determining the frequency fracture of ice, i.e. periodicity of resets accumulated elastic energy in each next elastically compressed volume of ice in a continuous process of interaction of the elements of the IF-IRS system is threshold of the value of the specific energy of elastic compression of ice required to launch of the fracture mechanism of ice in the ice array of edge ice field.

4. Application of the specific energy of mechanical fracture of ice ε_{cr} for calculation of marine ice-resistant platforms on to cycle ice load, seems completely justified and efficient because the energy has a concrete physical sense and better of another parameters of strength correspond to essence of notions about it as about a complex of potential energetical barriers preventing the develop of kinetic processes in materia. The use of energy as an internal state of the material allows to use mathematical methods of mechanics, physics, thermodynamics, elasticity theory, and other fundamental sciences.

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