САНКТ-ПЕТЕРБУРГСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ
ПЕТРА ВЕЛИКОГО

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«INVESTIGATION OF MECHANICAL INTERACTIONS IN THE CIRCUITS SYSTEM WITH ELECTRIC CURRENTS»

(Исследование механических взаимодействий в системе контуров с электрическими токами)

Учебное пособие

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Предисловие.

Настоящее пособие составлено на основе практикума «Теоретические основы электротехники. Теория электромагнитного поля», являющегося четвертым изданием широко известного руководства к лабораторным работам, содержание и структура которого постоянно обновлялись в соответствии с совершенствованием методики преподавания дисциплины, техники измерений, компьютерной обработки экспериментальных данных. Данное же руководство обобщает опыт проведения лабораторных занятий по дисциплине «Теория электромагнитного поля» для студентов Института энергетики и транспортных систем на английском языке.

В данное пособие вошло описание одной из лабораторных работ, выполняемых в лаборатории ТЭМП университета: «Исследование механических взаимодействий в системе контуров с электрическими токами». Содержание работы включает в себя описание лабораторной установки, программу работы, методические указания по обработке экспериментальных данных и выполнению аналитических и численных расчетов, а также вопросы для самопроверки. В приложении приводится форма протокола, в которой записываются экспериментальные данные, а также подробный словарь терминов по теме лабораторной работы.

Лаборатория ТЭМП относится к последней части курса «Теоретические основы электротехники», т.е. рассчитана на работу студентов, имеющих высокий уровень подготовки по данному предмету и достаточный уровень знаний иностранного языка.

Настоящее пособие ставит своей целью помощь студентам в подготовке к выполнению лабораторной работы, усложненной необходимостью общаться с преподавателем, оформлять отчет по лабораторной работе на английском языке.

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LABORATORY WORK

INVESTIGATION OF MECHANICAL INTERACTIONS IN THE CIRCUITS SYSTEM WITH ELECTRIC CURRENTS

Introduction

The aim of the work is studying the methods of measurement and calculation of electromagnetic forces acting in the system of two coils with electric current. The task of the work includes researching an effect which ferromagnetic and conducting bodies produced being placed near a coil carrying a current.

Setup Specification.

There are two identical coaxial round coils in the laboratory set up (Fig.1). Parameters of the coils are as follows: the inner radius R_1=4,4cm, the outer radius R_2=7,9cm. The thickness of the coil is 2,5cm. Every coil has the winding of 510 turns. The interaction forces are measured with the aid of laboratory scales (Fig.2). The force examined equals to the difference of scales readings at current presence and current absence in the coils. The set up allows to move the upper coil. The lower coil is motionless. The coils can be connected to the DC source or to the AC source (Fig.3). The rheostat is applied for correcting the current value. There are A-meter, V-meter and W-meter in the circuit. They are used for measuring the current, voltage and power required for calculating parameters of coils.

Work Program.

1. Getting the dependence of electromagnetic force vs the distance between the coils. Being connected in series the coils are powered by a DC source.
   Four cases should be examined in this experiment. It means that above mentioned dependence is studied at 2 values of current. Anybody will notice that the force of interaction is directly proportional to the current squared.

Besides the force-distance dependence is measured when the coils are connected in series aiding and those in series opposing. (Aiding connection is the connection when currents in the coils are flowing towards or away from marked terminals). One of these experiments corresponds to the force of attraction and the other corresponds to the force of repultion.

Then the examined coils should be connected to the AC source, and the force-distance dependence is measured at aiding or opposing connection and at some value of current.

2. Next experiment is the dettermination of the sign of mutual inductance *M* . We don't know beforehand the sign of mutual inductance. And you should find it out experimentally as follows: set an arbitrary distance between the coils connecting in series aiding, measure the current, voltage and power at the terminals of the circuit *I'*, *U*', *P*'. Then you will change the kind of connection (arranging the series opposing connection). As a result, you will obtain the current, voltage and power at the terminals of the circuit *I''*, *U*'', *P*''. All these data (*I'*, *U*', *P*', *I''*, *U*'', *P*'') anable you to calculate equivalent empedances *z*', *z*'', resistance *R*, reactances *X*', *X*'', inductances *L*', *L*'' according the formulae:

$$z = \frac{U}{I}\,, \qquad R = \frac{P}{I^2}\,, \qquad X = \sqrt{z^2 - r^2}\,, \qquad L = \frac{X}{\omega}$$

And then you can calculate *M* as follows:

$$M = \frac{L' - L''}{4} \qquad (1)$$

M may have plus or minus sign.

3. At the next experiment you obtain the dependence of mutual inductance |*M*| vs the distance *z*. You apply another circuit this time (Fig.4). The upper coil is connected to the source of alternative voltage through A-meter and lower coil – across the high-voltage V-meter. The voltage of mutual induction is $U_2 = \omega M I_1$ (where ω is angular frequency, I_1 is the current in the upper coil), hence

$$|M| = \frac{U_2}{\omega I_1} \quad (2)$$

4. The dettermination of 2^{nd} coil's parameters: the resistance R_2 and inductance L_2. In this case experimental circuit (Fig.3) contains only one coil (2^{nd} coil). You will take readings of V-meter, A-meter and W-meter and calculate z_2, R_2, x_2, L_2 of the coil.
5. The next experiment is finding out the dependence of electromagnetic force vs the distance when one coil is short circuit and the other is connected to the source of alternative voltage.
6. The final part of the labwork is measuring the force of interaction between the coil with DC and ferromagnetic disk. Varing the distance between the lower coil and the disk you should take scails readings . The disk itself is attached to the upper coil. Magnetization of ferromagnetic material leads to the appearance of attractive force between the coil and the disk. The emergence of this force can be explained using the method of images. Reflecting the coil in the near plain of the disk, we obtain the problem of calculation of electromagnetic force acting in the system of two coils at aiding connection (Fig.5).

   Repeat this experiment, connecting the coil to the source of alternative voltage. Anybody will notice that the force of interaction is less then that in first case because of eddy currents, being induced in the disk. Eddy currents create repulsive force.
7. The similar experiment should be done with aluminium disk and the coil with AC. Eddy currents occur in the aluminium disk. The repulsive force, created by eddy currents, acts on the coil disposed near the disk.

Theoretical Calculation of Electromagnetic Forces

In order to find the mecanical force due to a magnetic field one can use the expression[1]:

$$f_g = \left(\frac{\partial W_m}{\partial g}\right)_{i=const} \quad (3)$$

So, the force equals to the derivative of the magnetic energy W_m with respect to the varying coordinate g. The magnetic energy of the system of two coupled coils with currents i_1 and i_2 equals

$$W_m = 0{,}5L_1 i_1^2 + 0{,}5L_2 i_2^2 + M i_1 i_2 \ , \quad (4)$$

where L_1 and L_2 are the inductances of first and second coils respectively, M is the mutual inductance. From (3), (4) it follows that the force of interaction of two coupled coils, connected in series ($i_1 = i_2$), may be calculated as

$$f_z = i^2 \frac{\partial M}{\partial z} \ , \quad (5)$$

where z is the distance between coils (Fig.1).

(L_1 and L_2 don't depend on the coordinate z).

The mean value of electromagnetic force F_z is expressed by the formula :

$$F_{zm} = I^2 \frac{\partial M}{\partial z} \ , \quad (6)$$

where I is the RMS of alternating current flowing in the coils.

The mutual inductance M as a function of varying distance z, is obtained experimentally. The experimental curve $M(z)$ should be differentiated graphically.

The mean value of the force F_m , acting on the coil, supplied by sinusoidal voltage when the second coil is short-circuit, may be calculated as follows:

$$F_{zm} = -I_1^2 \frac{\omega^2 M L_2}{R_2^2 + \omega^2 L_2^2} \frac{\partial M}{\partial z} \quad (7)$$

where I_1 is the RMS of alternating current flowing in the first coil,

R_2 is the resistance of the second coil,

ω is a angular frequency of the current.

Experimental Data Handling in the Report of the Labwork.

All functions obtained experimentally, should be represented as the graphs. Calculated dependences should be plotted too and be compared with experimental ones. The distance dependence of the force, acting on the coil with DC at the presence of ferromagnetic disk, should be compared with the distance dependence of the force of interaction of two coils with DC, connected in series aiding.

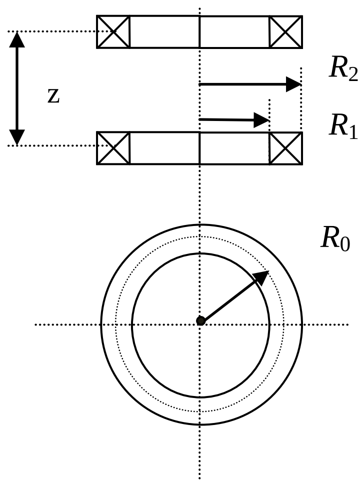

Fig. 1

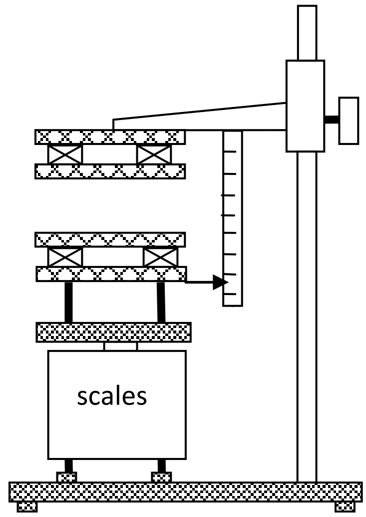

Fig. 2

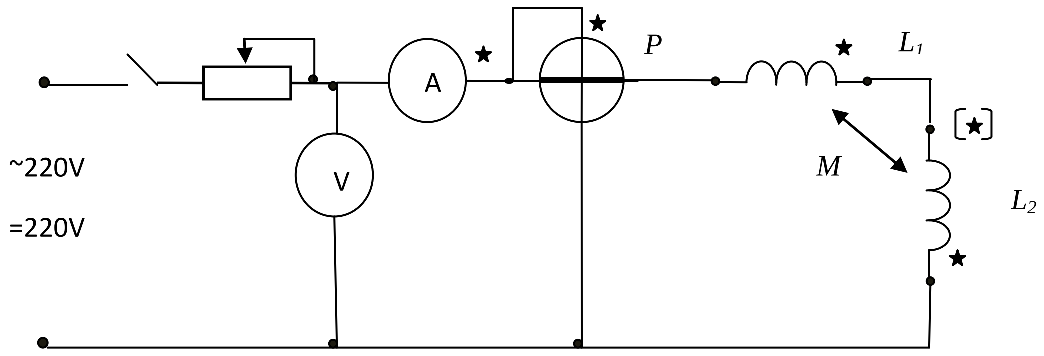

Fig. 3

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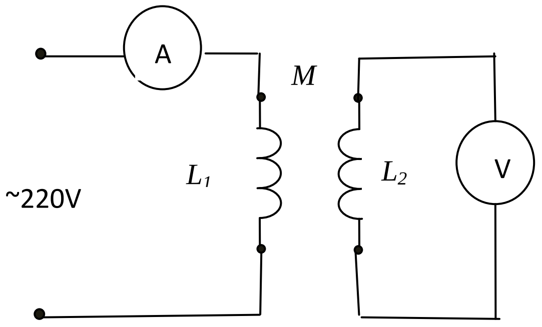


Fig. 4

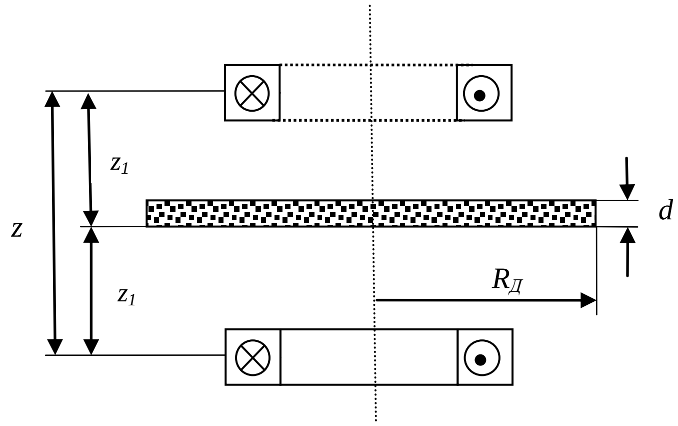


Fig.5

Using Software *Qfield* for Research of Electromagnetic Forces.

Class of problem

The first step is create the problem. We should choose **Magnetostatics** formulation of the problem for DC source and **AC magnetic** formulation for AC source. Both formulations use vector magnetic potential ***A***.

The geometric models of the systems

Since the coils and disks have axial symmetry, we can consider a 2D axisymmetric models of the systems. The geometric model of the two coils is shown in Fig.6, the coil and the disk model is shown in Fig.7.

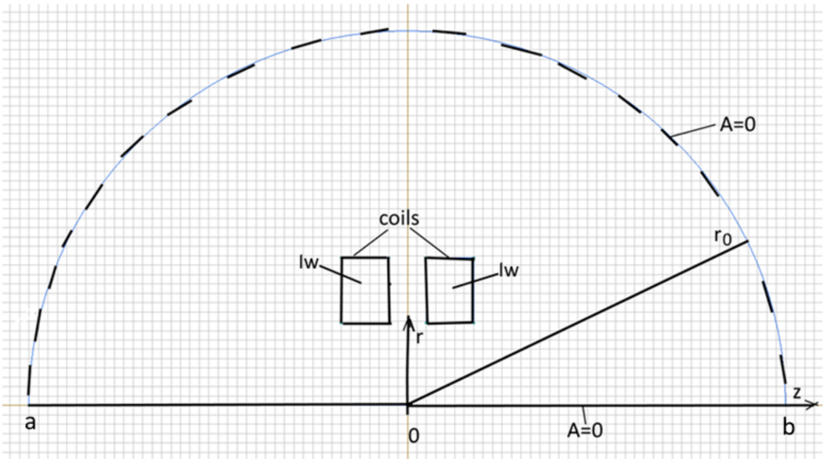


Fig.6

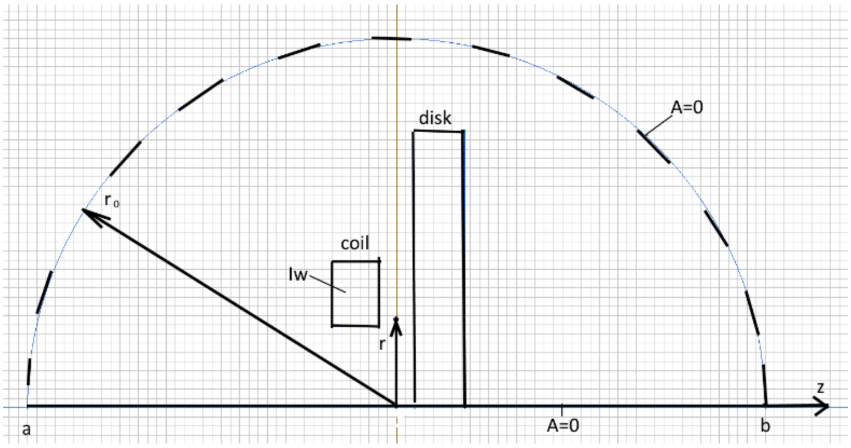


Fig.7

In these figures, the line *ab* is a line of axial symmetry. On this axis the vector magnetic potential ***A*** is zero. Artificial outer boundary of the models is a semicircle (dashed line). The radius r_0 of the semicircle in Fig.6 should be approximately 10 times greater than radius R_2 shown in Fig.1 and the radius r_0 in Fig.7 should be greater than radius $R_Д$ shown in Fig.5. We accept that the vector potential is zero on artificial outer boundaries. To simulate a short circuit of one of the coils, we use position "Electrical circuit" in the menu of the problem. In the resulting electrical circuit we set short circuit of the coil.

Initial data for calculation

Magnetomotive force *MMF=Iw* (*I* is measured current, *w=510*).

Current frequency: 50 Hz.

The relative magnetic permeability of air, copper windings and aluminum disk μ = 1.

The relative magnetic permeability of the steel disk μ = 1000.

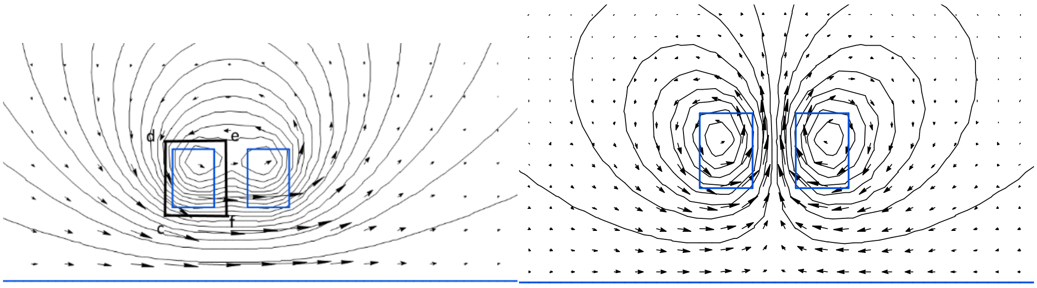
Electrical conductivity of steel σ = 10,000,000 S / m.

The electrical conductivity of aluminum σ = 37000000 S / m.

The coils are wound with insulated wire, so the conductivity of the material of the coils in the transverse direction is zero.

Results

The calculation results may be presented as: Field Lines, Vectors, Color Map. The example of the Vectors for adding coils is shown in Fig.8a, for opposite coils in Fig.8b.



a) b)

Fig.8

Inductances can be found with using “Integral calculator”. To find the inductance you should use the flux linkage or stored energy of the magnetic field. The results obtained in these two ways should be compared. Also “Integral calculator” allows us to find mutual inductance of the coils if we use formula (1).

You can find the mecanical force, if you click the "force" item in the menu of "Integral values". To use this item you should previously surround the force object with an outline located close to the object. For example, in Fig.8a the contour *cdef* is necessary for calculating the force acting on the left coil.

Software ***Qfield*** allows to investigate in detail the influence of various factors acting on electromagnetic forces such as properties of materials of coils and discs, their geometric dimensions and source frequency.

The amount of calculations sets the teacher.

Questions for Self-Examination

1. How does the electromagnetic force change if the current in the coils, connecting in series, doubles?

2. What factors does the force of interaction between the coils depend on?

3. How could you explain the emergence of the interaction between the coil with DC and the ferromagnetic disk near the coil?

Supplement 1.

The Protocol of the Laboratory Work

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The Department of Theoretical Electroengineering and Electromechanics

The Laboratory of Electromagnetic Field Theory

The Protocol of the Laboratory Work

« INVESTIGATION OF MECHANICAL INTERACTIONS IN THE CIRCUITS SYSTEM WITH ELECTRIC CURRENTS»

____.____.201_

Fulfilled by students of gr. ___________, team №_______

________________________ ____________________________ ________________________

(surname) . (surname) (surname)

Checked by ______________________

1. The force of interaction at series connection of the coils

1a. aiding connection. ***I*** = ……A. (DC)

z,cm													
P, gr													
P_0 gr													
P-P_0													

1b. opposing connection. ***I*** = ……A. (DC)

z,cm													
P, gr													
P_0 gr													
P-P_0													

1c. aiding connection. ***I*** = ……A. (DC)

z,cm													
P, gr													
P_0 gr													
P-P_0													

1d. opposing connection. ***I*** = ……A. (DC)

z,cm													
P, gr													
P_0 gr													
P-P_0													

1e. opposing/ aiding connection. ***I*** = ……A. (AC)

z,cm													
P, gr													
P_0 gr													
P-P_0													

2. Mutual inductance sign determination. *z* =…….cm. (AC)

aiding connection. opposing connection

U', V	*I*', A	*P*', W		*U*'',V	*I*'', A	*P*'', W

3. Determination of the 2nd coil parameters (R_2, L_2)

U_2, V	I_2, A	P_2, W

4. *M*(*z*) determination. . ***I*** = …A, *f* = …. Hz.

z, cm											
U, V											

5. The force of interaction when the 2nd coil is short circuit, $\boldsymbol{I_1}$ = …..A, (AC)

z,cm													
P, gr													
P_0 gr													
P-P_0													

6. The force, acting on the coil in the presence of ferromagnetic disk. $\boldsymbol{I}$ = ……A, (DC)

z,cm													
P, gr													
P_0 gr													
P-P_0													

7. The force, acting on the coil in the presence of ferromagnetic disk. $\boldsymbol{I}$ = ……A, (AC)

z,cm													
P, gr													
P_0 gr													
P-P_0													

8. The force, acting on the coil in the presence of aluminium disk. $\boldsymbol{I}$ = ……A, (AC)

z,cm													
P, gr													
P_0 gr													
P-P_0													

Supplement 2.

Glossary of Terms.

постоянный и переменный синусоидальный ток (напряжение)-
direct current (voltage) - DC and alternating sinusoidal current (voltage) - AC
действующее значение переменного тока – RMS (root-mean-square) of the AC
частота - frequency
угловая частота - angular frequency
электромагнитная сила - electromagnetic force
знак силы- the sign of the force
отталкивающая сила- repulsive force
сила притяжения- attractive force
вихревые токи -eddy currents
энергия магнитного поля-magnetic field energy
производная от энергии магнитного поля - derivative of the magnetic field energy
тело-body
ферромагнитное - ferromagnetic
проводящее- conductive
диск-disk
алюминиевый- aluminum
соосные элементы -coaxial elements
катушка- coil
круглая - round
коаксиальная- coaxial
идентичные (катушки) - identical
способ соединения катушек - method of the coils connection
согласное (соединение)-adding connection
встречное - opposite connection
параметры катушек - parameters of coils
индуктивность - inductance
взаимная индуктивность– mutual inductance
активное сопротивление- active resistance
лабораторные весы –laboratory scales
взвешивание - weighing, weighting
разность- difference
стальная штанга- steel rod
измерительная схема- measuring circuit
реостат - rheostat
амперметр - ammeter
вольтметр - voltmeter
ваттметр – wattmeter

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