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DETERMINATION OF THE INDUCTIVENESS OF A PHYSICAL MODEL OF TRACK COILS FOR HIGH-SPEED TRANSPORT

The object of research is the parameters and characteristics of track coils with different design parameters for a physical model of high-speed maglev transport. The problem that arises in such a system is the untimely switching on of the track coils, which leads to a malfunction due to a short-term disappearance of the traction force. Solving this problem will allow the vehicle to improve the conditions of movement of the high-speed maglev transport. This will make it possible to make a reasonable choice of the parameters of the track coil of a physical model of high-speed transport, which would have the required inductance value at different switching modes.

The required switching frequency will depend on the desired speed of movement of the vehicle and the parameters of the track coils. An important task within the framework of research on maglev transport is the development and creation of a fundamentally new control system. Such a system would have a track structure with traction coils of a rational shape and parameters that would implement certain control processes of the experimental unit. The task of the research is to create a physical model of track coils of high-speed transport and to conduct an experimental determination of the dependence of electrical parameters (inductance) on the frequency of a sinusoidal signal for different winding parameters of track coils. To implement the technical solution, a physical model of the track coil was created, which takes into account the necessary requirements for the study. The search for more favorable technological solutions requires conducting research on electrical processes in the track structure circuit of the physical model of the track coil. This will allow to substantiate the prerequisites for the creation, accumulation and transfer of the necessary energy to the track coils in physical models that will simulate the principles of movement and control of magnetic levitation transport.

During the research, the results were obtained by applying mathematical statistics methods and the development of a track coil with optimal parameters for a physical model of a high-speed transport experimental unit was carried out.

The results obtained with the correct selection of the track coil parameters can create prerequisites for the further development of an experimental switching system for physical model of high-speed transport. In this case, the operating reserve can be determined by the required reserve of effective operation of the track coils to implement the necessary laws of rolling stock control.

Keywords: *magnetic levitation transport, track coils, physical model, experiment, inductance, transient processes, control system.*

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1. Introduction

High-speed magnetic levitation transport (maglev) is a high-tech vehicle that uses the power of electromagnetic interaction between superconducting magnets on vehicle and coils on the track structure. This interaction is necessary for levitation, movement and stabilization of the train without mechanical contact with the rails. The high manufacturability of this type of transport is determined by the complexity of the design, the need for high accuracy of interaction between all components of ground controls and the vehicle, which directly moves within the track structure.

The key element of the track structure of a maglev system is the track coils, which create a magnetic field for lifting the vehicle and achieving its stable position within the track structure [1]. The main parameters of the track coils are their resistance and inductance at specified parameters, which include geometric dimensions, number of turns, diameter of the winding wire, etc. The dynamic parameters of the track coil include the switch-on time. The value of the switch-on time is limited by the moment when the maximum electromagnetic force is reached (saturation mode).

Currently, there are many research works that allow solving the problems that arise in a high-speed vehicle. For example, work [2] shows the influence of coil parameters on the overall energy efficiency of maglev systems. The focus of this paper is on systems with superconducting excitation and energy saving, rather than a detailed analysis of the inductive parameters of conventional track coils. The modeling part focuses on the theoretical argumentation of the energy advantages, while in this study the empirical measurement of inductance in the laboratory is of key importance.

Article [3] analyzes the methods and equations for calculating inductance that can be used in the experimental determination of the parameters of track coils. Methods related to the creation of experimental full-scale models can improve the accuracy of measurements and ensure the correctness of the results obtained. The disadvantage of this work is that it doesn't take into account the modern features of high-speed transportation systems, in particular the specifics of frequency and temperature effects in maglev systems. The focus is on general methods for calculating inductance, but without reference to the interaction of coils with a moving object or complex switching dynamics.

In systems based on the principle of electrodynamic suspension (SCMaglev), thousands of coils can be installed along the track structure, which must be switched on and off synchronously depending on the location of the vehicle (rolling stock). This determines the requirement for high accuracy and speed of the control system. The results of study [4] show the dependence of the track structure design on the parameters of coils in maglev systems. Taking into account the influence of reactive elements and surface current effects reveals directions and ways that can improve the accuracy of measurements of inductance and other coil parameters [5]. The set of shortcomings of these publications is the lack of an explanation of the effect of the power supply frequency on the inductance and statistical analysis of the measured parameters.

The determination of the parameters and characteristics of the track coils required for the operation of maglev transport is shown in [6]. The article discusses methods for improving energy efficiency, which is important for future modernization of maglev systems, in particular in terms of reducing losses in track elements such as coils. This article analyzes efficiency in a broad sense, but doesn't address the issue of synchronous switching on and off of coils and the associated time delays.

The results of the studies presented in [7, 8] partially address the issue of the properties of coil models at different frequencies of a given signal.

A general overview of maglev technologies shown in [9, 10] gives an understanding of the relevance and prospects for further development of this mode of transportation.

Therefore, the peculiarities of known studies and identified problems that affect the speed of rolling stock increase the relevance of maglev technologies. This contributes to the expansion of research aimed at the experimental determination of the parameters of track coils.

Further increase in speed is possible by optimizing traction and levitation forces, reducing energy consumption, and ensuring stable dynamics of interaction between magnetic suspension elements and structural elements of the transport system.

Research aimed at the experimental determination of the parameters of track coils is timely and necessary.

One of the main challenges affecting high-speed vehicle movement is ensuring stable and efficient interaction between the magnetic suspension and the traction system. During high-speed movement, precise control of electromagnetic fields becomes critical to maintain the required value of levitation, traction, and lateral stabilization.

To research maglev transport, it's necessary to develop and create a physical model of high-speed transport. Since this task is complex, it can be divided into different components: a traction system and a control system. The traction system consists of track coils (stationary part) and a vehicle (moving part). The problem that arises in the process of developing a traction system is the reasonable choice of winding parameters of a physical model of a track coil for high-speed transportation. The basis for the choice is the required inductance value at different switching modes in order to ensure the movement of the vehicle through the interaction of magnetic fields. If the coil doesn't turn on in time, the vehicle will experience a malfunction in the form of a short-term loss of traction. This will affect the general conditions of movement of the moving part (vehicle) of high-speed maglev transport.

An important task is to develop a physical model system within the framework of maglev transport studies. Such a model would have a track structure with traction coils of a rational shape and parameters that would implement certain control processes of the experimental unit. In this case, it's assumed that the switching frequency will depend on the desired vehicle speed and the parameters of the track coils.

The development and creation of a physical model allows to investigate various parameters of the track coils and implement certain control processes of the experimental unit.

The track coils are important elements in magnetic levitation systems, as they create the alternating magnetic field necessary for movement and achievement of a stable position within the track structure. One of the main parameters of the coil is the inductance L, which characterizes the ability to accumulate magnetic energy when electric current flows.

Since the track coils considered in this article are created for the first time, the task of changing the inductance L in their experimental studies arises.

Thus, *the aim of research* is to experimentally determine the dependence of the inductance L on different values of the frequency f of a sinusoidal signal of path coils with different parameters and characteristics and to further analyze the results obtained by applying mathematical statistics.

2. Materials and Methods

The object of research is the processes, parameters, and characteristics of track coils with different design parameters for a physical model of high-speed maglev transport.

Using the features of electrical circuits with inductive elements, it was investigated an electrical circuit with a coil to which a sinusoidal signal from the signal generator G3-33 is applied. The effective values of voltage and current in the track coils with different winding parameters were determined using a RIGOL DS1104B oscilloscope (China). The parameters of the coil's electrical circuit were studied with a different frequency range (from 1 kHz to 200 kHz). The obtained results of measurements and parameter calculations are evaluated by methods of mathematical statistics and presented in the form of graphical images.

3. Results and Discussion

A physical model has been developed that allows investigating the value of the dependence of the inductance L on the geometric parameters of the maglev transport path coil. The dimensions of the coil used in the study are shown in Fig. 1.

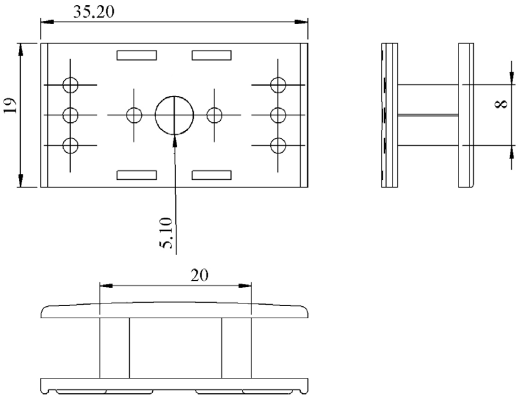


Fig. 1. Dimensions of a physical model of a track coil

The scheme for the experimental determination of the inductance L (Fig. 2) consists of a sinusoidal signal generator G (G3-33), a resistor R, and an inductance coil L. An oscilloscope (RIGOL DS1104B) is used to measure the effective voltage value.

An experimental setup was used to measure the parameters of a physical model of high-speed transport track coils (Fig. 3).

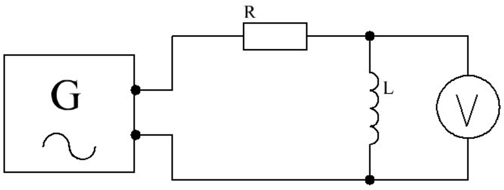


Fig. 2. Scheme of the experiment

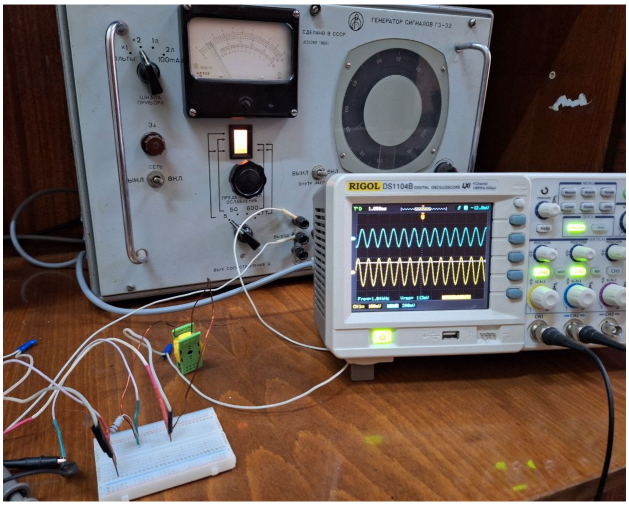


Fig. 3. Experimental unit for determination of electrical parameters of a physical model of track coils for high-speed transport

The parameters were studied for five coils with different parameters (wire diameter, number of turns). The design and dimensions of the coil remained unchanged due to the geometry of the test stand (Fig. 1). The parameters of the tested coils are given in Table 1.

Table 1

Winding parameters of the studied coils

Coil	Wire diameter *d*, mm	Turns *w*, number	Coil resistance *R*, Ohm
A	0.6	35	0.6
B	0.45	112	1.4
C	0.36	272	4.5
D	0.2675	550	18.1
E	0.24	720	26.3

To reduce the error, 15 measurements were made at the current value of each coil and a resistance of $R=0.4$ Ohm. The resistor in the measuring circuit makes it possible to more accurately determine the inductance *L* of the track coils, especially at different frequencies and load conditions. It also improves the reliability of the experimental data.

The measurements were performed at a signal frequency of 1 kHz (Table 2).

Measurements for other values of the signal frequency *f* were performed in a similar way. The measurement results (mean value U_{RMS}) are presented in Table 3.

The obtained results are presented by the method of statistical distribution of values (Fig. 4).

The parameters were calculated analytically, without the use of software.

Effective value of the current flowing in the circuit

$$I_{RMS}=\frac{U_{RMS}}{R}, \text{A}, \tag{1}$$

where U_{RMS} – the effective voltage value, V; R – the resistance, Ohm.

The value of the total impedance of a circuit in the general case, expressed in terms of Ohm's law

$$Z=\frac{U_{RMS}}{I_{RMS}}, \text{Ohm}, \tag{2}$$

where I_{RMS} – the effective current value, A.

An equation for determining inductive resistance

$$X_L=2\cdot\pi\cdot f\cdot L, \text{Ohm}. \tag{3}$$

The value of inductance *L* from the equation (3)

$$L=\frac{X_L}{2\pi f}, \text{H}. \tag{4}$$

Total resistance (impedance) in a series circuit with active resistance *R* and inductive resistance X_L

$$Z=\sqrt{R^2+X_L{}^2}, \text{Ohm}. \tag{5}$$

The final expression for determining the inductance based on (3)–(5)

$$L=\frac{\sqrt{Z^2-R^2}}{2\pi f}, \text{H}. \tag{6}$$

The results of the calculations are summarized in Table 4.

Table 2

Measuring the effective voltage value at a signal frequency of $f=1$ kHz

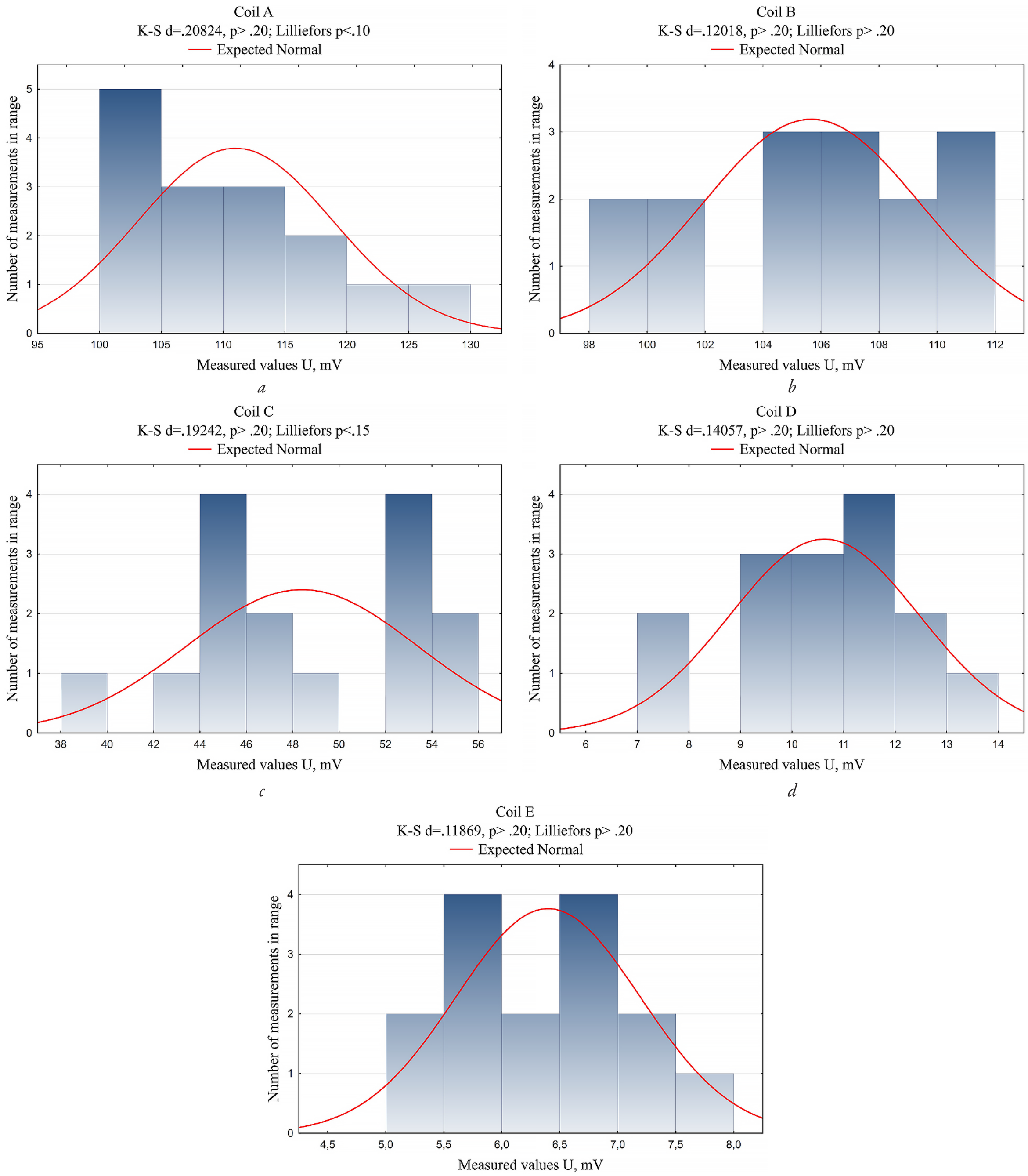
Measurement number	Coil A	Coil B	Coil C	Coil D	Coil E
	U_{RMS}, mV	U_{RMS}, mV	U_{RMS}, mV	U_{RMS}, mV	U_{RMS}, mV
1	119.46	99.94	43.06	10.27	5.15
2	107.41	110.25	44.21	9.86	6.32
3	112.75	101.82	52.7	11.97	5.26
4	115.19	105.86	55.93	10.35	5.73
5	107.24	106.86	52.96	9.31	7.98
6	103.36	100.91	52.37	12.03	5.82
7	126.3	107.02	39.92	7.13	5.97
8	124.39	104.33	49.95	7.35	6.83
9	107.42	99.64	46.28	12.55	6.2
10	101.73	106.15	46.36	13.7	6.85
11	103.12	109.12	52.73	9.44	6.98
12	104	110.64	44.45	11.89	7.21
13	114.01	104.29	45.67	10.37	7.19
14	114.62	110.16	55.24	11.77	6.71
15	103.99	108.06	44.19	11.46	5.79
Average value	111	105.67	48.4	10.63	6.4

Table 3

Effective voltage value for different frequencies *f*

Signal frequency *f*, kHz	Coil A	Coil B	Coil C	Coil D	Coil E
	U_{RMS}, mV	U_{RMS}, mV	U_{RMS}, mV	U_{RMS}, mV	U_{RMS}, mV
50	3.12	2.95	1.15	0.577	0.689
100	1.95	1.68	0.729	0.575	0.753
200	1.25	1.02	1.39	0.662	716.3

According to the obtained values (Table 4), graphs of the dependence of the inductance *L* on the frequency of the sinusoidal signal *f* are plotted (Fig. 5).


Coil A
K-S d=.20824, p> .20; Lilliefors p<.10

Coil B
K-S d=.12018, p> .20; Lilliefors p> .20

Coil C
K-S d=.19242, p> .20; Lilliefors p<.15

Coil D
K-S d=.14057, p> .20; Lilliefors p> .20

Coil E
K-S d=.11869, p> .20; Lilliefors p> .20

a *b* *c* *d* *e*

Fig. 4. Statistical distribution of measured values of coil voltages: *a* – coil A, *b* – coil B, *c* – coil C, *d* – coil D, *e* – coil E

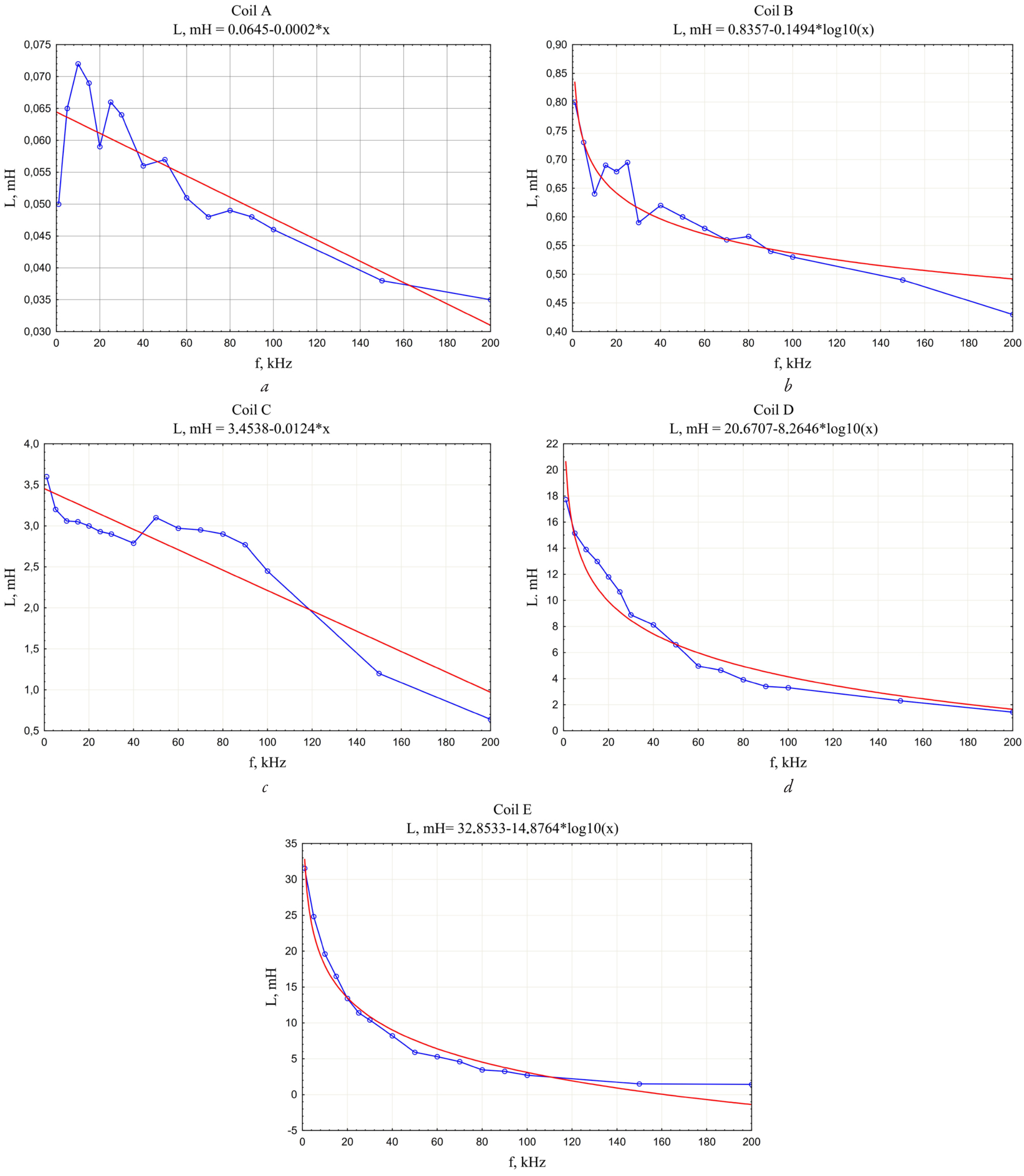
Table 4

Determination of coil parameters

Coil	U_{RMS}, V	I_{RMS}, mA	Z, Ohm	X_L, Ohm	L, mH
1	2	3	4	5	6
f = 1 kHz					
A	0.14	280	0.5	0.335	0.05
B	1.4	264	5.3	5.111	0.8
C	2.8	121	23.14	22.69	3.6
D	3	26.575	112.88	111.428	17.73
E	3.2	16	200	198.26	31.56
f = 50 kHz					
A	0.14	7.8	17.95	17.93	0.057
B	1.4	7.375	189.8	189.825	0.6
C	2.8	2.875	973.9	973.9	3.1
D	3	1.44	2078.6	2078.6	6.6
E	3.2	1.72	1856.95	1856.8	5.9

Continuation of Table 4

1	2	3	4	5	6
f = 100 kHz					
A	0.14	4.875	28.72	28.712	0.046
B	1.4	4.2	333.3	333.3	0.53
C	2.8	1.82	1536.4	1536.4	2.45
D	3	1.44	2085.86	2085.8	3.3
E	3.2	1.88	1698.4	1698.2	2.7
f = 200 kHz					
A	0.14	3.18	44.094	44.09	0.035
B	1.4	2.55	549.01	549.02	0.43
C	2.8	3.475	805.76	805.74	0.64
D	3	1.657	1810.8	1810.68	1.44
E	3.2	1.79	1786.96	1786.77	1.42



a *b* *c* *d* *e*

Fig. 5. Dependence of the inductance *L* of the track coils with different parameters on the frequency of the sinusoidal signal *f*

From the obtained values, it can be concluded that inductance decreases in the track coils with different parameters as the frequency of the sinusoidal signal increases. It's assumed that the decrease is due to the skin effect, when at high frequencies the current in the conductor shifts closer to its surface, which reduces the effective cross-sectional area of the wire. This increases the active resistance of the conductor and can change the effective current value, which affects the magnetic field and inductance.

The practical significance of the results obtained is the creation of an experimental track coil for high-speed transport models. This will make it possible to obtain an array of data on the operation of the underlying control principles and the response of track elements (coils). The results of the study contribute to the further use of experimental physical models of high-speed transport based on the principle of electrodynamic traction. In particular, the research and results obtained will allow the creation of a combined control system for high-speed transport.

The limitation of the study is that the created track coil of the corresponding model had one typical size and its parameters (number of turns, wire diameter) were variable. Since changing these parameters will change the value of its inductance, it is necessary to calculate the electrical parameters in accordance with the size of the physical models for the study of high-speed transport when building physical models.

A perspective direction for further research is to determine the dynamic performance of track coils. Important factors in the creation of experimental physical models are the determination of thermal modes of operation, as well as the coordination and synchronization of the switching on of coils combined into sections.

4. Conclusions

As a result of an experimental study, the dependence of the inductance of a physical model of high-speed transport track coils on the frequency of a sinusoidal signal was determined. In particular, it was found that the inductance decreases with increasing frequency, which is explained by the influence of the skin effect. This decrease in the effective cross-sectional area of the conductor increases the active resistance and reduces the magnetic permeability, which directly affects the inductance value.

The research results detail the influence of winding parameters and frequency regime on the electromagnetic properties of the system, which makes it possible to reasonably select the parameters of coils for controlled movement of maglev transport.

The practical significance of the results is to determine the experimental data for the construction of a system for switching and controlling track coils in experimental setups.

Expected successes from the implementation of the results include increasing the efficiency of physical modeling and control of maglev transport, reducing the probability of failures due to untimely coil switching on, and improving future technical solutions in the field of high-speed maglev transport.

Quantitative characteristics were obtained, in particular, inductance for each coil in the frequency range from 1 to 200 kHz (for example, for coil E: $L = 31.56$ mH at 1 kHz, $L = 1.42$ mH at 200 kHz), can be used in the development of control schemes to provide traction and synchronous control of the coils. The research results don't contradict the general laws of electrical engineering in inductive circuits and the processes of current change at different signal frequency values.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other, which could affect the research and its results presented in this article.

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The manuscript has no linked data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in the creation of the current work.

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