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Calculation of the parameters of the electromechanical shock absorber of the high-speed electric train

The article examines the issue of the chassis system of a high-speed electric train with body inclination and a vibration recovery system. The advantages of using an electromechanical shock absorber over hydraulic, pneumatic and similar systems are described. The authors considered the main characteristics of the DC electromechanical shock absorber. The main overall parameters of the shock absorber were presented. Attention is paid to the relevance of using an electromechanical shock absorber of a linear type, in comparison with analogues, including the ability to recover energy. Attention is drawn to the structure of the DC electromechanical shock absorber. The functional control scheme of the electromechanical shock absorber is considered and the control algorithm is described. The calculation areas of the parameters of the electromechanical shock absorber are determined. A 3D model of an electromechanical shock absorber in the Ansys Electronics software environment is presented. A finite-element mesh was built for further calculations of the magnetic field and inductance. In the article, attention is paid to the calculation of the magnetic field in the most intense mode. A picture of the shock absorber's magnetic field at the maximum working clearance was obtained and interim results were discussed. The results of calculating the inductance depending on the operating gap of the shock absorber are presented. Conclusions were made based on the results of calculations of magnetic and electrical parameters of an electromechanical shock absorber based on a linear direct current motor.

Keywords: *electromechanical shock absorber, recuperation, body tilt, electric rolling stock, oscillations.*

Introduction. Modern railway transport is a complex logistics system that requires solving issues related to traffic safety and the speed of electric rolling stock, which is primarily determined by its driving performance [1]. These indicators depend on many factors: the traction system, which over time has undergone many improvements in the control system, the traction motor and the undercarriage system (suspension) [2, 3].

One of the ways to increase the speed of rail transport is the use of electric rolling stock with body tilting mechanisms. This technology allows you to significantly increase the speed of trains when passing curved sections of the path, which is an alternative to creating a new infrastructure for high-speed railways. The prospect of applying body tilting technology for high-speed traffic is confirmed by the successful operation in 15 countries of the world of more than 60 types of trains, which are created by the world's leading manufacturers of railway electric rolling stock.

The application of the technology of tilting car bodies in railway rolling stock has a history of more than 50 years. The first studies and experiments on reducing the centrifugal force affecting passengers and increasing the speeds of movement in curves were carried out from the end of the 1930s by the companies Deischl and Van Dorn & Beemer. In 1938, the Pullman Palace Car Company built an experimental car with a tilting body, but the lack of vibration damping provoked the appearance of symptoms of "seasickness" in passengers. In 1956, the Pullman Palace Car Company built two Train-X trains, the first tilting trains in commercial operation. These trains were equipped with a passive body tilt drive and were withdrawn from service after a short period of time due to unsatisfactory running qualities [4].

Analysis of recent research and problem statement. In high-speed trains, pneumatic, hydraulic, and electromechanical systems are used as body tilt drives, which have few advantages and disadvantages [5]. The hydraulic system has a large number of lines and devices that work under high pressure, which reduces the overall reliability of the system and increases the likelihood of leaks of the working fluid. The pneumatic system, the device of which, in fact, is similar to the hydraulic one, has an increased activation time due to the low density of the working medium - air. However, its elements are directly present in every type of pneumatic spring suspension without which it is already impossible to imagine modern high-speed electric trains. The electromechanical system used on modern trains does not provide the ability to independently return the body to its original position in the event of a power outage or other emergency situations, which directly affects traffic safety. Also, a large amount of energy is required for the operation of the described body tilting systems [6].

Currently, there are many energy accumulators in trains, which can be additionally fed with the energy that occurs when damping oscillations with an electromechanical shock absorber [7, 8].

Thanks to the installation of an electromechanical system of tilting the body and recovery of oscillations in the undercarriage of electric locomotives, it is possible to increase the carrying capacity of the railway, thereby solving the problem of long-term passenger transportation in Ukraine. When using this system together with the pneumatic system, it is possible to cover the entire frequency range of oscillations and stabilize the oscillatory characteristics of the body, which will increase the comfort for passenger transportation [9].

It was previously determined that the use of a direct current electromechanical shock absorber can provide several functions: tilting of the body when turning with rolling stock, and recuperation of oscillations, which will ensure the accumulation of energy for its own needs [10]. At the same time, the system requires less maintenance than pneumatic or hydraulic systems, and is less complicated to operate.

The electromechanical shock absorber control system can be based on a microcontroller that can monitor the angle of the body relative to the horizon in real time, and perform its work both on the basis of algorithms and on the basis of artificial intelligence [11].

The purpose and tasks of the research. Presentation of the main weight and size characteristics of an electromechanical shock absorber. Construction of a 3D model of an electromechanical shock absorber in the Ansys Electronics software environment for calculating the inductance of the stator windings at a different set angle of inclination of the body (working gap of a linear motor) [12]. Obtaining a picture of the magnetic field of an electromechanical shock absorber in the working range.

Research materials and methods. The electromechanical drive, which is installed in the suspension system of moving vehicles (usually automotive equipment [13]) is a combination of a stepping electric motor, a reducer and a screw pair that ensures linear movement of the rod. The presence of a screw pair in this type of drive eliminates self-return of the body to its initial position due to its jamming when the power is turned off. However, this type of power drive has balanced weight and size indicators, high speed, low maintenance, and a wide range of adjustment. This led to the use of an electromechanical drive on most trains with tilting bodies currently produced.

Air-spring suspension meets the requirements of electric rolling stock, but requires additional equipment and its maintenance, therefore, an electromechanical shock absorber can be part of the chassis of a high-speed electric train together with air-spring suspension, which will allow covering the entire range of oscillations [14, 15]. The most effective application of an electromechanical shock absorber is when damping frequencies in the range of 1-500 Hz. A comparison of a synchronous type linear motor and a direct current linear motor was considered, where the advantages of a linear motor were described. First of all, it is ease of management and maintenance.

Thus, let's focus on the design shown in fig. 1.

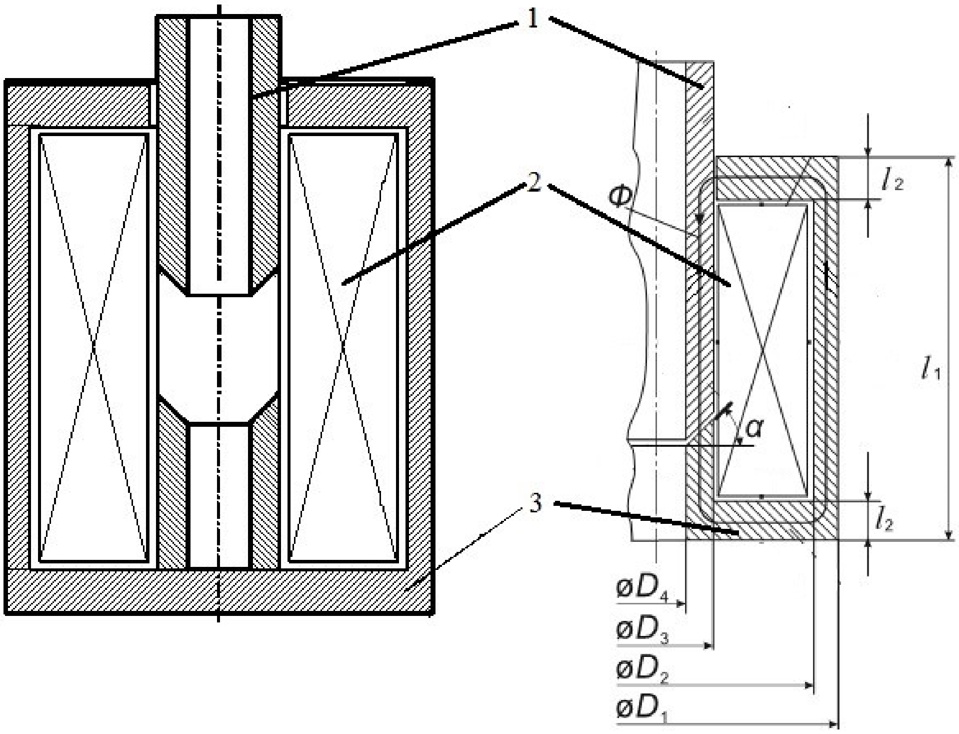

Fig. 1. **DC electromechanical shock absorber: 1 – anchor; 2 – stator winding; 3 – stator**

Table 1 shows the main overall characteristics of the electromechanical shock absorber.

Table 1. **The main overall characteristics of the electromechanical shock absorber**

Parameter	Value	Notes
D_1	450 mm	The diameter of the electromechanical shock absorber
D_2	400 mm	The diameter to the end of the stator winding
D_3	292 mm	The diameter of the anchor assembly
D_4	110 mm	The diameter of the anchor pipe
l_1	510 mm	The length of the electromechanical shock absorber
l_2	56 mm	The length to the stator winding
α	5°	The angle of inclination of the tip of the anchor

This type of motor is distinguished by its simple design, the stator winding has one phase.

The functional diagram of the control system for two linear direct current motors is shown in figure 2. The motors are controlled as follows: a AC voltage to the diode rectifier (block 1), after which a direct current voltage is obtained at the output of the block and passes to the direct current (DC) link (DCL - block 2). The DCL includes a passive filter, namely: a capacitor and an inductor. The DCL is connected to the thyristor blocks (block 4, 5), which supply voltage to the linear motors (block 6, 7). Thyristors are controlled by a microcontroller block (MC - block 3), while the optimal pulse width modulation (PWM) frequency is 1-3 kHz [16, 17]. Measuring the angle of inclination relative to the horizon can be done using an accelerometer, which can provide initial position information, and a gyroscope, which measures angular velocity.

The control scheme is similar to the control scheme of a synchronous linear motor, but differs in the absence of transistors and the presence of thyristors, which reduces the cost of the control system. At the same time, the force is practically not affected by the position of the anchor relative to the frame, which ensures the stability of the damping forces in the case of gaps between the body and the trolley.

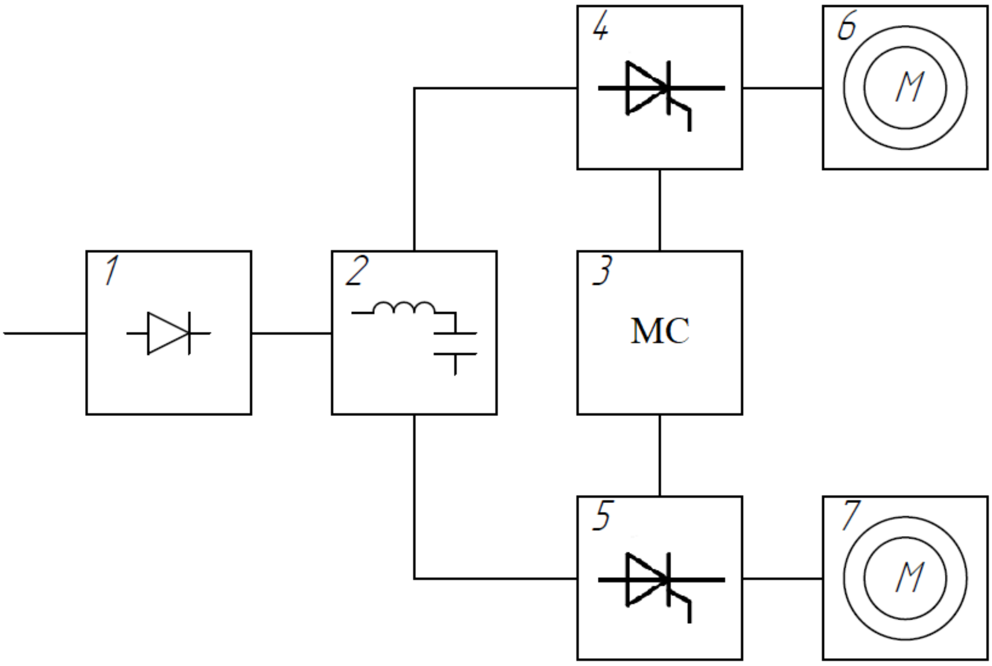

Fig. 2. **Functional control scheme of a direct current linear motor**

The calculated range of electromechanical shock absorber parameters consists of the following parts:

– subarea of the stator of the electric motor (Fig. 5): material – electrical steel 2211;

– subarea of the electric motor armature (Fig. 5): material – electrotechnical steel 2211;

– subarea of the armature winding of the electric motor (Fig. 5): the material is copper, while the magnetomotive force (MMF) of the armature is 70,000 A (working gap 70 mm), with the number of turns 175;

– subarea of the air (Fig. 5): material – air;

– an additional subarea of the working gap of the electric motor (Fig. 5): the material is air, which is necessary for the correct calculation of the magnetic field in the air gap.

At the same time, the steel filling ratio is 0.95; the sheet thickness is 0.5 mm for both the stator and the armature.

The calculation of the magnetic field by the finite element method was carried out using the Ansys Electronics software complex.

Based on the maximum angle of inclination of the high-speed electric train body; and the traction and loading characteristics of the electromechanical shock absorber, which is presented in Figure 3 (where x is the working clearance of the linear shock absorber), it is rational to obtain a picture of the magnetic field in the most intense mode of operation of the tilt drive - critical and modes close to it at a maximum tilt angle of 7°, which is equal to the working gap of 70 mm. At the same time, for further simulations of the slope and recovery of oscillations in the MATLAB Simulink software environment, and the obtained polynomial, the inductance calculation must be performed over the entire operating range of the electromechanical shock absorber, which corresponds to the value from 0 to 70 mm, with an optimal step of 5 mm.

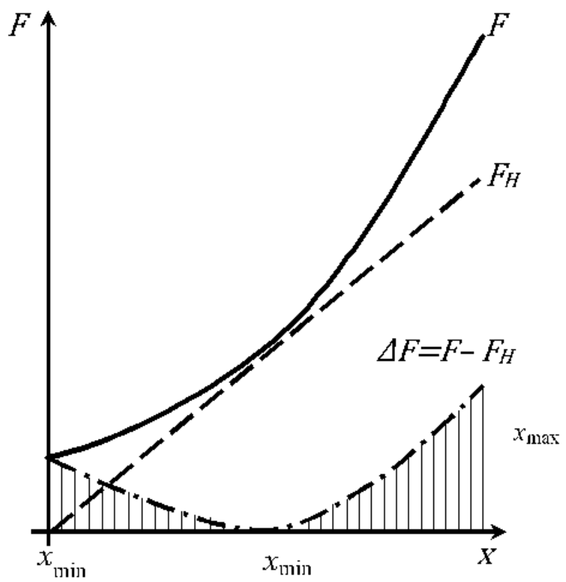

Fig. 3. **Traction and loading characteristics of an electromechanical shock absorber**

A 3D model of an electromechanical shock absorber was built in the Ansys Electronics software environment, which is presented in Figure 3.

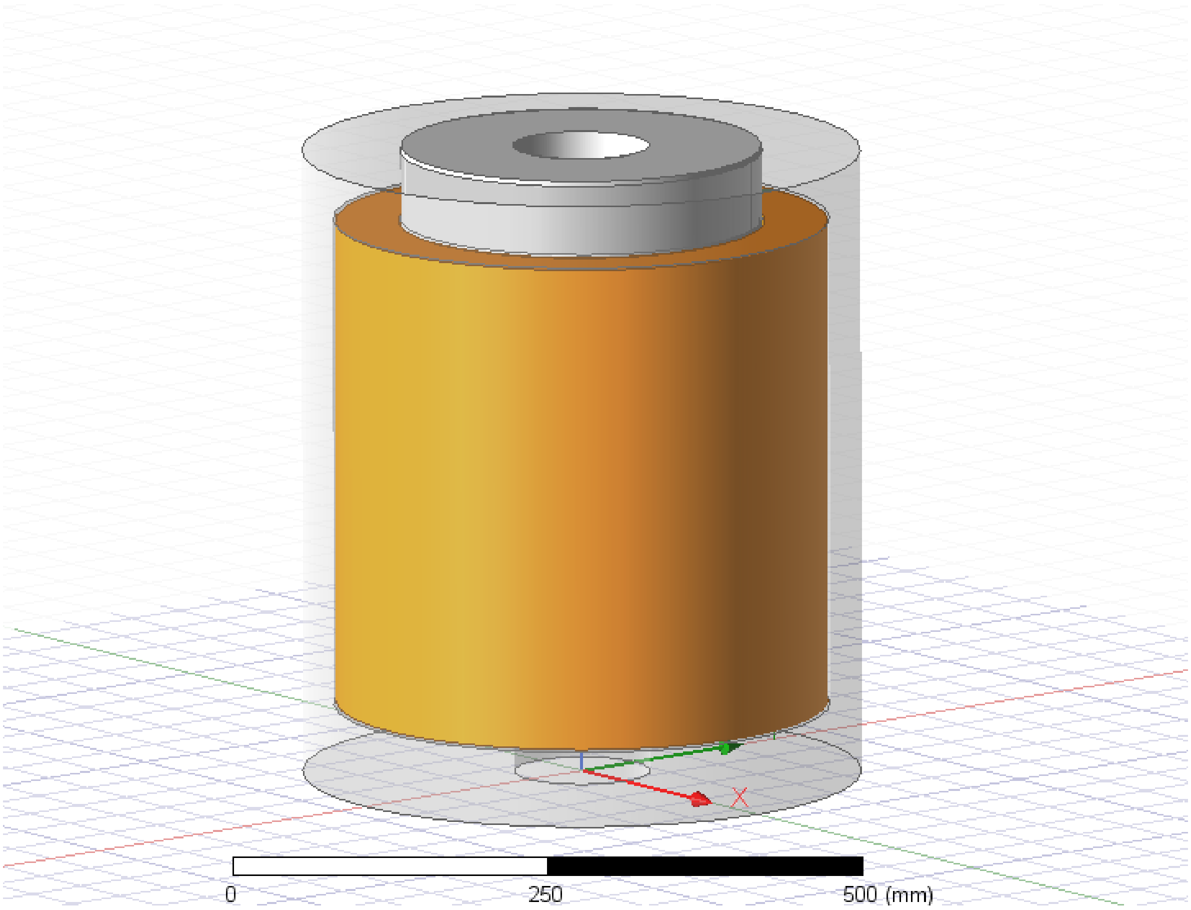

Fig. 4. **3D model of an electromechanical shock absorber (working gap 0 mm)**

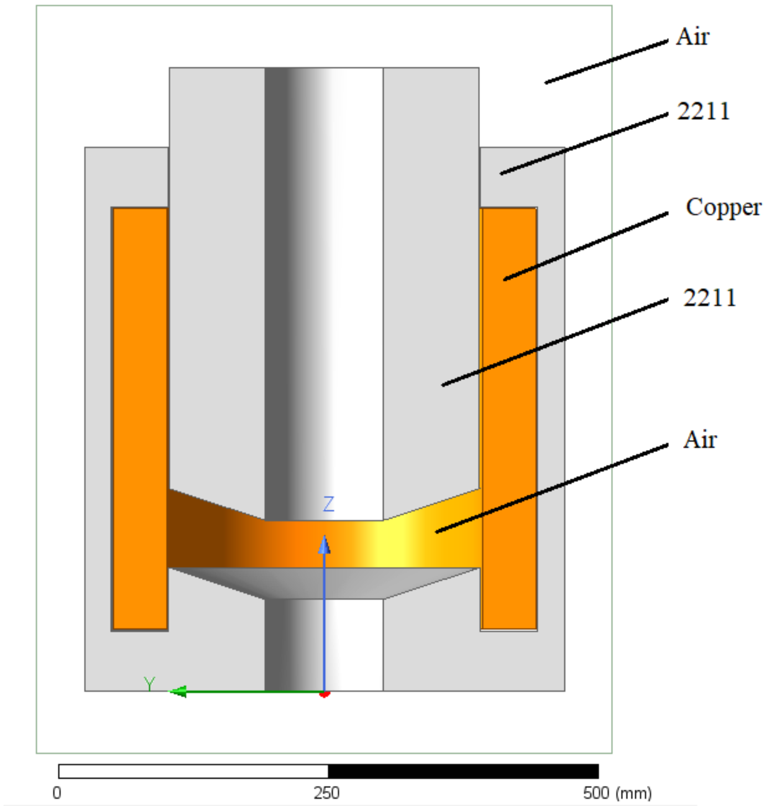

Fig. 5. **Cross-sectional model of an electromechanical shock absorber (working clearance 70 mm)**

In fig. 5 shows the resolution of the problem of calculating the magnetic field using the finite element method in an axially symmetric form. To limit the calculation area, an additional surface is introduced, which when setting the problem is Region (Fig. 3).

To correctly calculate the electromagnetic force, it is necessary to calculate the magnetic field in the air gap. The following mesh generation parameters are set: for the sub-region of the working gap, the initial radius of the mesh generation is 0.5 mm, and for other sub-regions, it is set to adaptive (Fig. 7).

Electrical steel 2211 has a magnetization curve, which is presented in the figure 6.

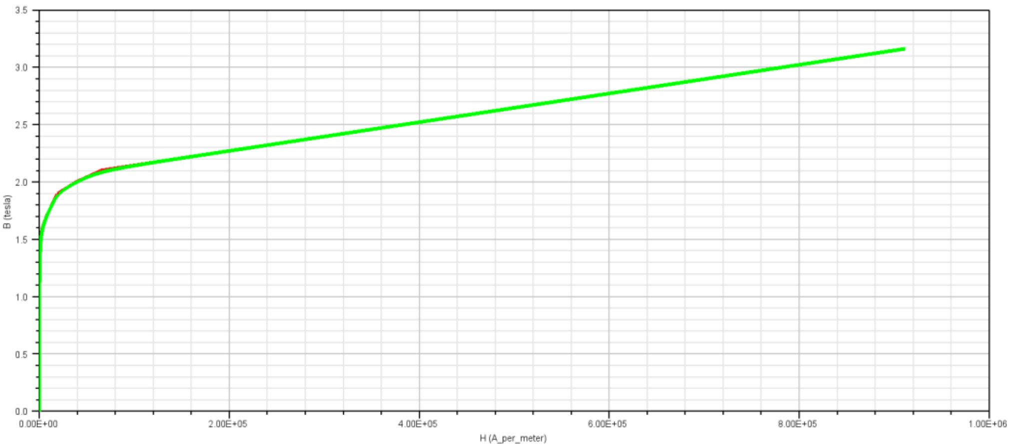

Fig. 6. **The main magnetization curve of electrical steel 2211**

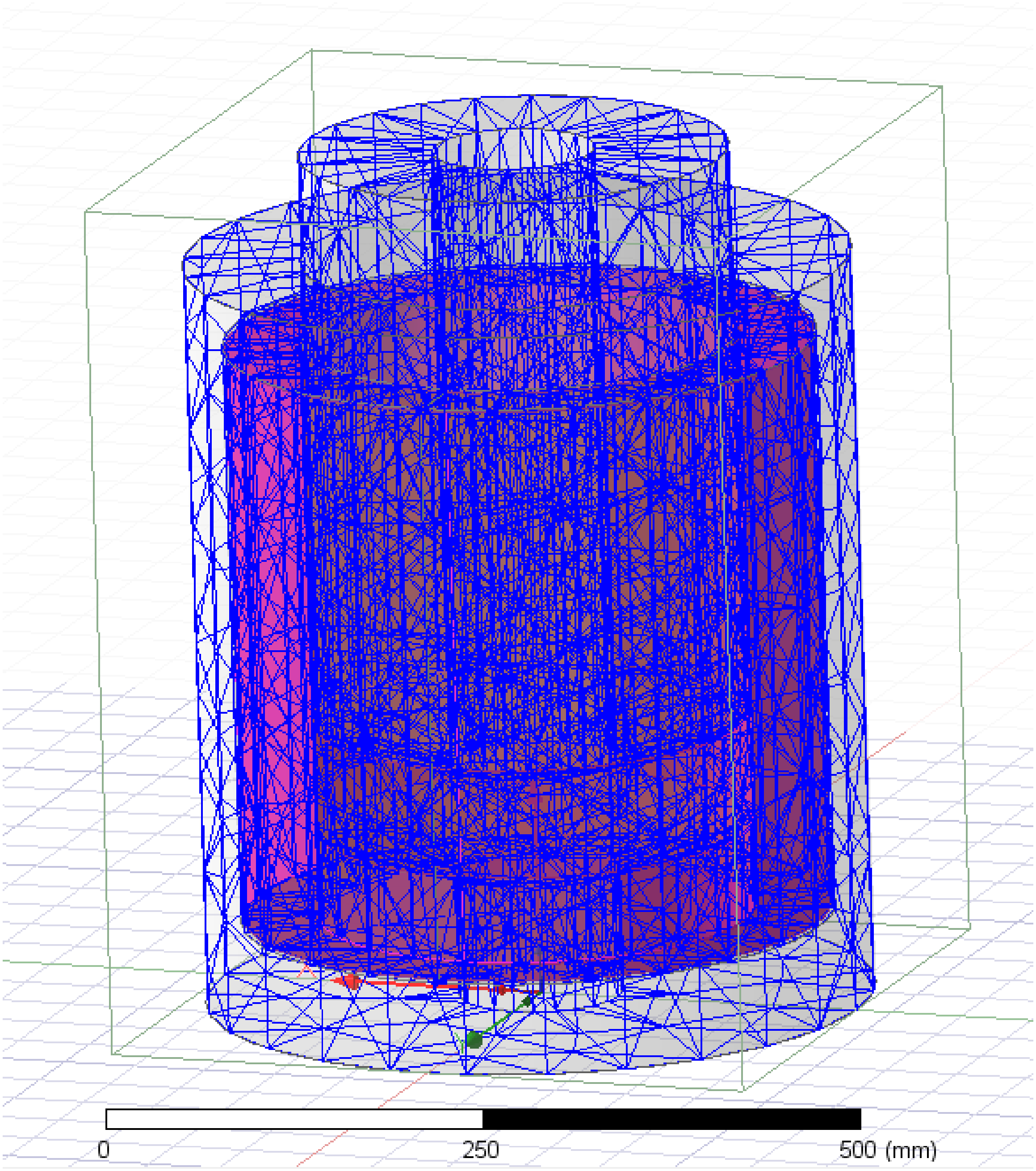

Fig. 7. **Finite element mesh**

Maxwell's stress tensor determines the force on a unit area due to the magnetic field on the surface. The differential force is calculated according to the formula 1.

$$dF = \frac{1}{2}[H_m \cdot (B \cdot n) + B \cdot (H_m \cdot n) - (H_m \cdot B) \cdot n_m]\,, \quad (1)$$

where n means the normal state of the direction to the surface at the calculated point, B, Hm – magnetic field induction and stress at the calculated point.

Further, in the paper, calculations of the magnetic field for an air gap of 70 mm were carried out using the finite element method. Pictures of magnetic fields are given in the figure 8.

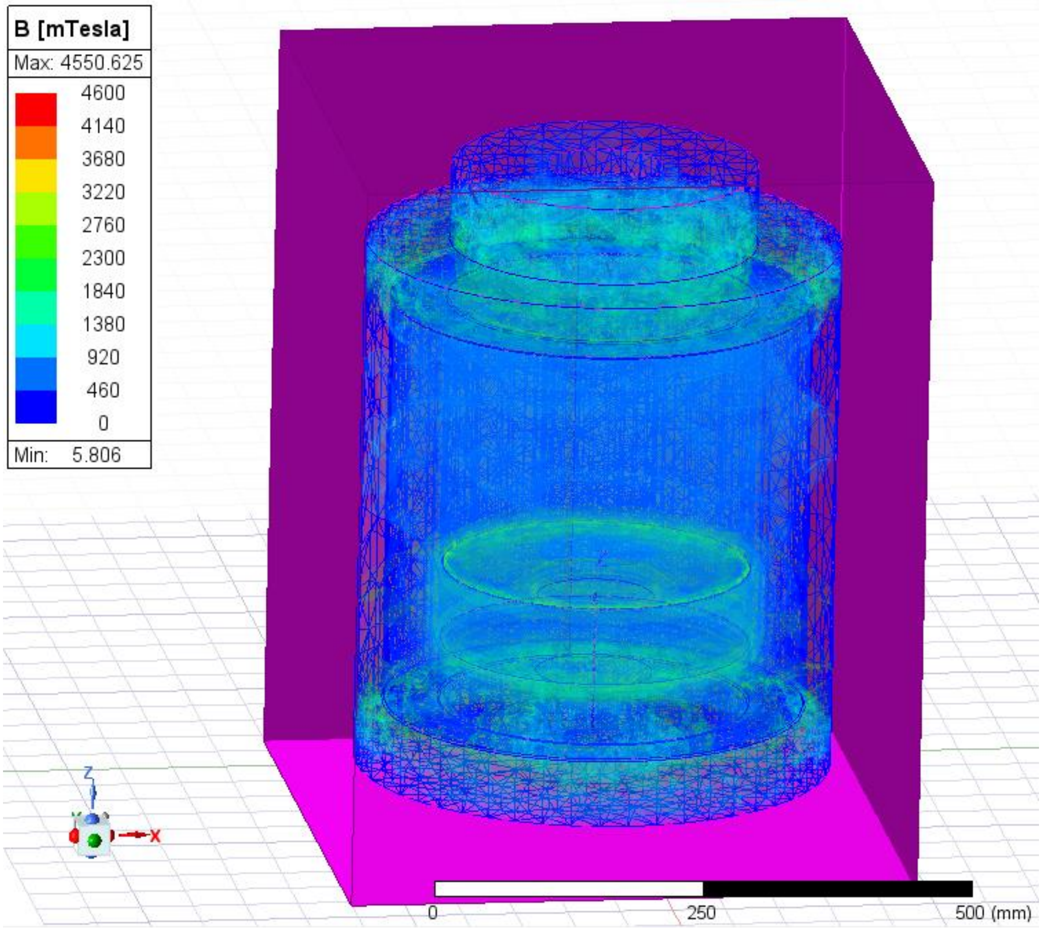

Fig. 8. **The model of the coaxial linear direct current electromagnetic type motor and the results of the calculation of the magnetic field at a maximum working gap of 70 mm**

Based on the obtained result of the calculation of the magnetic field of the electromechanical shock absorber with a maximum working gap of 70 mm, and the data from Figure 6, namely, the main magnetization curve of electrical steel 2211, we can fully conclude that in the most critical mode of operation from body inclination and vibration recovery (the angle of inclination is 7°), the magnetic wire does not enter the saturation mode, which will provide us with the predicted operation of the shock absorber as part of the suspension system of the high-speed electric train.

Further, in the work, the inductance of the linear type electromechanical shock absorber was calculated depending on the working gap of the shock absorber in the Ansys Electronics (Magnetostatic) software environment:

- the range of the working gap of the shock absorber 0 mm-70 mm;
- the step of the working gap is 5 mm.

The result of calculating the inductance with a maximum working gap of 70 mm is presented in Figure 8. The results of calculating the inductance in the entire given range are presented in Table 2.

	$move	Matrix1.L(Winding1,Winding1) [mH] Setup1 : LastAdaptive
1	0.000000	32.066860

Fig. 8. **The result of calculating the inductance of the shock absorber with a maximum working gap of 70 mm**

Table 2. **The result of the calculation of the inductance of the electromechanical shock absorber depending on the working gap (range of the working gap 0 mm-70 mm)**

№	Working gap of the shock absorber, mm	Inductance, mH
1	0	40,6
2	5	39,8
3	10	39,1
4	15	38,9
5	20	37,7
6	25	37,2
7	30	36,7
8	35	35,9
9	40	35,4
10	45	34,8
11	50	34,4
12	55	33,6
13	60	33,3
14	65	32,6
15	70	32,1

Conclusions.

1. An alternative system of the undercarriage of a high-speed electric train is presented, which will allow performing the work of tilting the body and recuperating vibrations, and at the same time have a number of advantages over hydraulic and pneumatic systems, including in terms of speed and ease of maintenance.
2. A 3D model of an electromechanical DC shock absorber was built in the Ansys Electronics software environment. The criteria of the finite-element mesh, calculation zones, etc. are defined.
3. The results of the calculation of the magnetic field at the maximum operating gap of the electromechanical shock absorber of 70 mm are presented, showing the maximum value of induction in the steel of the shock absorber of 2.2 T, i.e., it does not enter the saturation mode, which ensures the predicted operation of the shock absorber.
4. Calculations of the inductance of the electromechanical shock absorber depending on the angle of tilt of the body in the range from 0° to 7° (the working gap of the electromechanical shock absorber in the range from 0 mm to 70 mm) are presented, from which a polynomial will be obtained in the future and synthesized into a mathematical model of a high-speed electric train in the software MATLAB Simulink environment.

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Розрахунок параметрів електромеханічного амортизатора швидкісного електропоїзда

Стаття розглядає питання системи ходової частини швидкісного електропоїзду з нахилом кузова та системою рекуперації коливань. Описано переваги використання електромеханічного амортизатора перед гідравлічною системою, пневматичною та аналогічними. Авторами було розглянуто основні характеристики електромеханічного амортизатора постійного струму. Було представлено основні габаритні параметри амортизатора. Приділяється увага актуальності використання електромеханічного амортизатора лінійного типу, у порівнянні з аналогами у тому числі й у можливості рекуперувати енергію. Звертається увага на структуру електромеханічного амортизатора постійного струму. Розглянута функціональна схема керування електромеханічним амортизатором та описано алгоритм керування. Визначені розрахункові області параметрів електромеханічного амортизатора. Представлена 3D модель електромеханічного амортизатора у програмному середовищі Ansys Electronics. Побудована кінцево-елементна сітка для подальших розрахунків магнітного поля та індуктивності. У статі приділяється увага розрахунку магнітного поля у найбільш напруженому режимі. Отримано картину магнітного поля амортизатора при максимальному робочому зазорі та обговорено *проміжкові підсумки. Представлені результати розрахунку індуктивності в залежності від робочого зазору амортизатора. Зроблено висновки за результатом розрахунків магнітних та електричних параметрів електромеханічного амортизатора на базі лінійного двигуна постійного струму.*

Ключові слова: *електромеханічний амортизатор, рекуперація, нахил кузова, електрорухомий склад, коливання.*