Для запропонованої конструкції електромеханічного амортизатору розроблено методика визначення основних розрахункових параметрів. Методика основана на спрощеній математичній моделі по визначенню електромагнітної та електрорушійної сили електромеханічного амортизатору. Особливістю моделі є урахування режимів роботи постійного магніту на основі розрахунку магнітного кола. Створення модель дозволяє проводити приблизний розрахунок режимів роботи амортизатора та може бути використана у вирішенні задачі оптимізації параметрів електроамортизатору. Проведено перевірка адекватності розробленої спрощеної математичної моделі шляхом порівняння результатів розрахунку механічної характеристики амортизатора за спрощеною методикою та методом кінцевих елементів в аксіально-симетричній постановці задачі. Отримано наявне добре співпадіння результатів розрахунків за спрощеною методикою та шляхом моделювання магнітного поля за методом скінченних елементів. Визначенні геометричні співвідношення між елементами конструкції, які забезпечують оптимальне рівномірне магнітне навантаження в елементах магнітопроводу. Проведена постановка задачі умовної двокритеріальної оптимізації параметрів електромеханічного амортизатору. Обрані обмеження, що поділено на три наступні категорії. Обмеження за розмагніченням постійного магніту, що дозволяють зберегти працездатність постійного магніту. Обмеження за щільністю струму, яке забезпечує теплові режими роботи амортизатору. Компоновочні обмеження та обмеження на параметри задачі оптимізації, що забезпечують розміщення конструкції у ходовій частині візка. Запропоновано у якості критеріїв обрати приведений об'єм амортизатору, що обумовлює затрати на створення амортизатору та його ККД, який обумовлює рекуперовану енергію коливань. Проведено згортку параметрів до єдиної цільової функції затрат та обрані вагові коефіцієнти. У якості метода оптимізації обрано комбінований метод, що включає в себе генетичний алгоритм, на попередньому етапі пошуку. На завершальному етапі оптимізаційної процедури уточнення оптимуму здійснюється методом Нелдера-Міда. За результатами вирішення задачі оптимізації параметрів амортизатору визначені оптимальні геометричні розміри та кількість витків обмотки електромеханічного амортизатору

Ключові слова: електромеханічний амортизатор, метровагон, магніт, згортка параметрів, генетичний алгоритм, метод Нелдера-Міда

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DEVISING A PROCEDURE TO CHOOSE OPTIMAL PARAMETERS FOR THE ELECTROMECHANICAL SHOCK ABSORBER FOR A SUBWAY CAR

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1. Introduction

Running parts of wagons are intended to guide the movement of a carriage by transferring loads from the body onto the rail. The location of carriages in a running part affect their design features and operating conditions.

The main and integral element of cars' carriages is a system of spring suspension of the running part. Effectiveness of its operation depends on a railroad irregularity, external influences exerted on the carriage part of rolling stock, as well as on reducing the oscillations from a running part, which affect the elements of the rolling stock and rail tracks.

Traffic safety and the speed of electric rolling stock in urban and main line rail transport are primarily defined by the operational indicators for its running part. Smooth motion and dynamic indicators of rolling stock are affected primarily by the type and design of an oscillation damper – the shock absorber. The best indicators in terms of smooth movement are demonstrated by pneumatic shock absorbers [1], however, their application requires an additional system of pneumatic power – compressors that bring down the total energy efficiency of electric rolling stock.

An alternative approach to improving the dynamic indicators for rolling stock running parts is the use of electromechanical shock absorbers. Such shock absorbers are able to recover a share of the energy of oscillations into electrical energy with the possibility of its further utilization by rolling stock.

Based on the world experience, a promising solution is to use electromechanical shock absorbers in running parts of the rolling stock. A given scientific and technical solution improves the operational efficiency of running parts in rolling stock by adjusting the damping force. In this case, there is a possibility to recover electrical energy into the grid, which is not possible when using other types of shock absorbers.

2. Literature review and problem statement

Electromechanical shock absorbers have been widely used in automobile transportation means. Of great interest is the electrical suspension Bose Suspension System (made by Bose Corporation, United States), which was investigated in papers [2, 3]. In the structure on the base of the sedan Lexus LS400 (Toyota Motor Corporation, Japan) a spring suspension was replaced with torsion, and shock absorbers – with linear electric motors, managed through powerful amplifiers by a computer unit. The information it receives is sent from each wheel's running sensors. Such a solution greatly complicates the design and makes it impossible to generate a process of energy recuperation. Patent [4] suggests the structure of an electric shock absorber that includes a twisted element whose outer part is made of a conductive material. The magnetic element consists of a rod whose central axis hosts magnets. The outer part is made such that at vertical displacements of a wheel the rod with magnets could enter it. A current arising in the winding depends on the travel of the wheel. The presence of some magnet increases the working frequency of the shock absorber and losses in steel, which significantly compromises its effectiveness to recover energy. Paper [5] proposed to use, as part of the shock absorber, a rotational electric generator that has a rack and pinion-gear mechanism, which converts the linear motion of the piston into the rotational movement of the rotor. The rotor' s unilateral rotation at different directions of the wheel motion is ensured by two conical gears and two advance couplings. Such a scheme complicates the design while impact loads in a suspension lead to a substantial reduction in the resource of advance couplings. Study [6] considers a method to control operational modes of running parts by using controlled electromechanical shock absorbers, activated with the help of energy generators without using an external power source. It was experimentally proven that when driving on a bumpy, wave road the suspension parameters could be controlled by activating the electromechanical shock absorbers with a regenerated voltage of a certain magnitude. Papers [7, 8] propose converting kinetic energy without spring masses that have backward-onward displacements when a machine moves over irregularities [7] into the rotary motion of the collector's shaft [8]. A mechanical, pneumatic energy collector, or an electric energy collector (recharged battery), could act as a collector. The cited studies give grounds to argue about a possibility to recuperate the energy of oscillations into electrical energy. Papers [9] proposed a technical solution that ensures, at a change in the direction of motion speed, the rotation of the collector's drive in one direction. When using an electric machine, applying a device of the rotary (rotative) type appears attractive, but complexity of the structure of the mechanical part increases its mass and raises cost. An alternative to rotative electromechanical transducers is the linear converters. Previous calculations and estimation of indicators of the electromechanical shock absorber, reported in work [10], showed that geometric constraints significantly reduce its capabilities; it is advisable to increase the size to a maximum given the conditions for a suspension assembly.

When choosing the type of electromechanical transducer for a shock absorber, we note that among known types – asynchronous, synchronous, electromagnetic, and DC – the most suitable variant turns out to be the latter [11, 12]. For the first two types, ensuring relatively small displacements requires using complex semiconductor converters. These converters must change voltage and frequency to units of Hertz at the output. In addition, these types of engines are characterized by low loading capacity. A third one is characterized by quite an uneven characteristic of thrust force due to movement, which is close to hyperbolic. The electromechanical shock absorber needs a constant traction [10] (mechanical) characteristic that varies only due to the speed of the armature's motion.

Thus, we shall focus on the structure shown in Fig. 1.

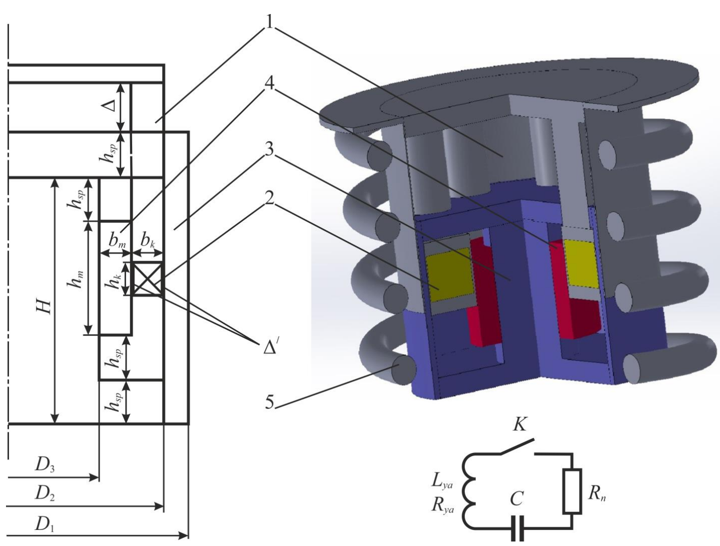

Fig. 1. Mechanical shock absorber of direct current: 1 – armature; 2 – armature winding; 3 – bed; 4 – permanent magnet; 5 – spring

The operating principle of shock absorber implies the following. Permanent magnet 4 (Fig. 1) is radially magnetized. Power magnetic lines of excitation flux are closed along the circle: air gap with armature 1 (Fig. 1) and armature winding 2 (Fig. 1), the bed's backrest, bed 3 (Fig. 1), a permanent magnet. The excitation flux is coupled to the armature winding located on the non-magnetic armature. When the armature moves (upwards or downwards), caused by external dynamic forces of oscillation of the body and the trolley, the armature moves. The electromotive force (EMF) occurs in the winding of the armature. When the armature winding is circuited for load, the current of armature appears. In conductors at the armature winding with a current there emerges a force directed against the dynamic forces that leads to damping the body's oscillations. The excitation flux is affected by the flux of armature's reaction that demagnetizes one of the halves of the bed's magnetic circle (upper or bottom). This process proceeds depending on the direction of armature motion (downwards or upwards). It magnetizes another (opposite), which may lead to the saturation of a magnetic circle and reduction in the electromagnetic force. All these processes are quite similar to processes in a unipolar electric motor of direct current.

As noted in [13], the spring suspension at cars' carriages E, Ezh their modifications, and 81-717, 81-714, is composed of the journal and central. The latter serves to transmit a tractive effort from a carriage of the car's body, a load from the weight of a body, to the frame of the body, it also springs the body relative to carriages, thereby softening the bumps and impacts arising from uneven tracks and when fitting the curved sections during the movement of rolling stock. To reduce friction forces that negatively affect the spring structures when transmitting tough impacts, the central suspension, as well as journal suspension, at carriages employ the double-row cylindrical springs. In terms of their design, as well as fabrication technology and repair, they are much simpler than the sheet elliptic springs. A suspension produced using cylindrical springs is more than one and a half times lighter than the equivalent in terms of the static deflection of a spring suspension with elliptical springs. To damp oscillations that occur during movement of rolling stock, the central suspension of carriages employs hydraulic shock absorbers.

Paper [14] considered promising systems of spring suspension used for cars in urban electric transport. The authors analyzed the present status of structures for spring suspensions at urban rail electric rolling stock and identified promising directions for their improvement. It was noted that as regards the designs of carriages and spring suspensions for urban electric transport, the following is true: the carriages for tram and subway cars most often employ, to dampen oscillations, the friction oscillation dampers, installed in the central suspension; to improve the smoothness of ride they are complemented with hydraulic dampers; in the latest designs, both in tram cars and metro cars, oscillations have been dampened by a pneumatic adjustable suspension that is installed instead of the friction damper in the second stage at a spring suspension. Friction and hydraulic dampers make it possible to dampen oscillations generated during movement of urban electric transport, however, it is impossible to adjust their parameters at different loads on cars; application of pneumatic springs enables the adjustment of parameters for damping depending on the load on a car and the magnitude of external influences, however, pneumatic suspension requires additional energy costs and capacity of the pneumatic system.

Cars from the E-KM series [15], built by upgrading the cars Ezh at PAT Kriukiv Railway Car Manufacturing Plant (Kremenchuk, Ukraine), are equipped with new carriages, model 68-7054, with a central pneumatic spring suspension that is supplemented with hydraulic shock absorbers.

Paper [1, 13] considers operation of the pneumatic spring suspension mounted in the second stage at carriages of the subway car 81-558 "Neva" (ZAO "Vagonmash", Russia). As noted in [13], using pneumatic suspension significantly improves the smoothness of ride of a subway car but it requires extra energy for compressor operation and reduces the overall efficiency of a transportation means. To eliminate the latter drawback, it is planned to install, in a subway car, in place of the pneumatic springs, the electromechanical shock absorbers whose basic characteristics are given in Table 1. It is planned to install, as electrical load R_n (Fig. 1) on an electromechanical shock absorber, a semiconductor voltage transducer, which would stabilize the voltage and supply it to the subway car's network. The output voltage for the shock absorber is chosen to be close to the voltage of onboard network of 80±10 V to simplify the circuitry of the transducer.

Table 1

Basic characteristics of electromechanical shock absorber

Parameter	Magnitude	Notes
F_{dem}	2,000 N	Rated electromagnetic force at the armature of shock absorber
V_{dem}	0.08 m/s	Rated speed of the armature of shock absorber
Δ	0.08 m	Maximum travel of shock absorber, according to Fig. 1
H_c	9.5 10^5 A/m	Coercive force of permanent magnet
B_{ost}	1.05 Tl	Residual induction of permanent magnet
$H_{\max}$	0.3 m	Maximum height of the yoke of shock absorber, according to Fig. 1
$D_{1\max}$	0.5 m	Maximum outer diameter of shock absorber, according to Fig. 1

The operation principle shows that electromagnetic force depends, primarily, on current in the winding of an armature. The force is almost not affected by the position of an armature relative to the bed, providing stability of the damping forces at gaps between the body and the carriage. The main issue in the design of electromechanical shock absorbers of the examined type is the absence of procedures for selecting basic geometric rotameters. Thus, they may be chosen based on solving the problem of optimal design taking into consideration the constraints for assembly in a running part. All this gives grounds to assert that it is expedient to conduct a study aimed to devise a procedure for optimal design of parameters for the electromechanical shock absorber.

3. The aim and objectives of the study

The aim of this study is to devise a procedure for determining the optimal geometric parameters and data on windings for the electromechanical shock absorber for a subway car.

To accomplish the aim, the following tasks have been set:

– to suggest a simplified mathematical model to determine the electromagnetic force and EMF of the electric shock absorber;

– to define geometric ratios in the elements of a shock absorber's structure;

– to state the optimization problem on parameters of electromechanical shock absorber for a subway car;

– to analyze the results from synthesis of the electromechanical shock absorber for a subway car.

4. Basic provisions for the procedure to define optimal parameters for the electromechanical shock absorber for a subway car

Based on the preliminary conducted analysis, the basic method underlying the proposed procedure is a method of optimal design [10]. According to it, in order to state a problem on analysis, we shall construct a mathematical model of the electromechanical shock absorber.

4. 1. Mathematical model for determining the electromechanical and electromotive force of electromagnetic shock absorber

The electromagnetic force acting on the winding of an armature with m.m.f. IW and EMF can be computed from expression [22]:

$$F_{dem} = B_\delta (IW) l_{sr},$$

$$E_{dem} = B_\delta V_{dem} l_{sr}, \tag{1}$$

where B_δ is the induction of a magnetic field in the air gap, l_{sr} is the average length of the turn that can be computed from the geometric parameters of a shock absorber in line with expression

$$l_{sr} = \pi (D_3 + 2b_m + 2\Delta' + b_k). \tag{2}$$

To determine induction of the magnetic field in the air gap, we shall consider the operational mode of a permanent magnet at a shock absorber. Lately, among the materials for permanent magnets the most common are the alloys of NdFeB. A demagnetization curve (Fig. 2) is of an approximately linear shape. The main resistance against a magnetic flux is due to the air gap between the permanent magnet and a bed. Resistance is composed of thickness of the winding and two technological gaps (b_k+2Δ′). We accepted the following assumptions:

– the resistance against a magnetic flux is composed of the resistance of the air gap;

– the influence of the flow of current from the armature on the operational mode of a permanent magnet is negligible.

It is possible to determine induction in a permanent magnet, which is equal to the induction in the air gap, from geometric ratios in Fig. 2.

M.m.f. at working point A can be determined from expression:

$$I_m = H_\delta (b_k + 2\Delta') = \frac{B_\delta}{\mu_0}(b_k + 2\Delta'), \tag{3}$$

where H_δ is the intensity of field in the air gap, μ_0 is the air magnetic permeability.

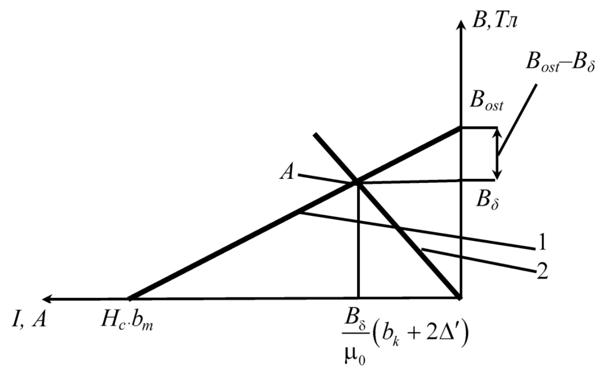

Fig. 2. Determining the induction of a magnetic field in the air gap: 1 — magnetic characteristic of permanent magnet; 2 — magnetic characteristic of air gap

According to the similarities of triangles in Fig. 2

$$\frac{B_{ost} - B_\delta}{B_{ost}} = \frac{\frac{B_\delta}{\mu_0}(b_k + 2\Delta')}{H_c b_m}. \tag{4}$$

We obtain from expression (4):

$$B_\delta = \frac{1}{\frac{1}{B_{ost}} + \frac{(b_k + 2\Delta')}{\mu_0 H_c b_m}}. \tag{5}$$

By substituting expressions (2) and (5) in (1), we obtain:

$$F_{dem} = \pi \frac{D_3 + 2b_m + 2\Delta' + b_k}{\frac{1}{B_{ost}} + \frac{(b_k + 2\Delta')}{\mu_0 H_c b_m}} IW, \tag{6}$$

$$E_{dem} = \pi \frac{D_3 + 2b_m + 2\Delta' + b_k}{\frac{1}{B_{ost}} + \frac{(b_k + 2\Delta')}{\mu_0 H_c b_m}} V_{dem}. \tag{7}$$

Expressions (6) and (7) represent the simplified mathematical model for determining the electromagnetic force and the electric shock absorber's EMF.

4. 2. Checking the adequacy of a mathematical model

To test the adequacy of model (6) and (7), we shall conduct a series of digital experiments on calculating the mechanical characteristic of a shock absorber for a subway car by the method of finite elements, employing the programming environment FEMM [16–18].

Fig. 3 shows the statement of the problem on calculating a magnetic field by the finite element method in the axial-symmetrical form. This is possible because a shock absorber has an axis of symmetry that coincides with the axis of the armature. To limit the estimated zone, we have introduced an additional spherical surface, which is represented in the problem statement by semicircle A (Fig. 3).

The estimated area consists of the following parts.

– The sub-field of bed shock absorber (Fig. 3, position 1): material – electrotechnical steel.

– The sub-field of a winding of the electric shock absorber's armature (Fig. 3, position 2): material – copper. The sub-field of a permanent magnet (Fig. 3, position 3): material –

a permanent magnet with a coercive force (H_c) of $9.5 \cdot 10^5$ A/m and a residual induction (B_{ost}) of 1.05 Tl.

– The sub-field of air (Fig. 3, position 4): material – air.

– An additional sub-field of the shock absorber's working gap (Fig. 3, position 5): material – air, necessary for the correct calculation of magnetic field in the air gap.

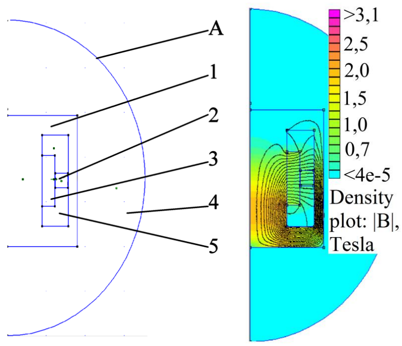

Fig. 3. Calculation of the magnetic field of a shock absorber using the method of finite elements at working travel Δ=40 mm: *a* — estimated area; *b* — results from calculating a magnetic field

Next, we calculated a magnetic field for working travels Δ in the range from 0 to 80 mm. The pattern of the magnetic field at Δ=40 mm is shown in Fig. 3. By using a procedure from [16] we calculated electromagnetic forces, whose dependences on the armature's motion are shown in Fig. 4.

For a comparative analysis, Fig. 4 shows the mechanical characteristics determined by using the simplified mathematical model (6), (7) and by using the finite element method.

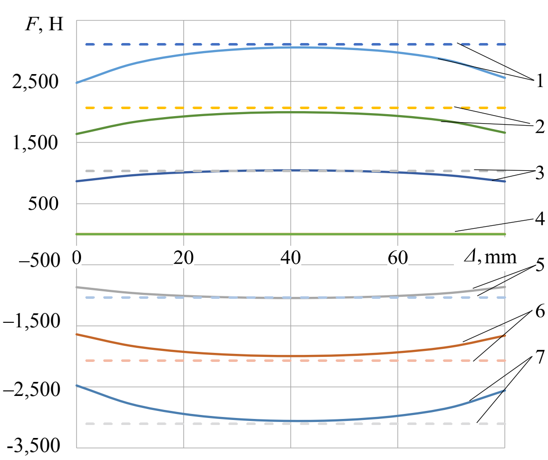

Fig. 4. Mechanical characteristics of shock absorber at the winding m.m.f.: 1 — 7,780 A; 2 — 5,120 A; 3 — 2,590 A; 4 — 0 A; 5 — –2,580 A; 6 — –5,120; 7 — –7,780 A, dotted line indicates values derived in line with (6)

Fig. 4 shows a good match between the results from calculations using the simplified procedure and when modeling the magnetic field of an electric shock absorber by the method of finite elements. The maximum deviation of the simplified (at travels from 10 mm to 70 mm) model is 11.8 %. At travels from 20 mm to 60 mm the maximum deviation is 5.6 %. Such a result corresponds to the considered class of estimations and confirms the adequacy of the constructed model. At travels from 0 to 10 mm and from 70 to 80 mm the maximum deviation does not exceed 25.3 %, predetermined by the significant saturation of elements in the magnetic circuit and by increasing scattering fluxes. Thus, at shock absorber operation with the minimum and maximum travels it is necessary to consider a decrease in the electromagnetic force, which could be compensated for by increasing current in the winding.

Therefore, the proposed procedure and the simplified mathematical model are acceptable and could be used in further research.

4. 3. Deriving geometric ratios for a shock absorber

To solve the optimization problem, we give the geometric ratios predetermined by the selected design of shock absorber.

Magnetic fluxes in the elements of the magnetic circuit of the outer and inner back of the stator, permanent magnet, the upper and lower back of the stator at the most loaded place – connecting to the inner back and permanent magnet – can be determined from expressions (8) to (11)

$$\Phi_1 = \frac{\pi}{4} \cdot \left(D_1^2 - D_2^2\right) \mathrm{B}_1, \tag{8}$$

$$\Phi_4 = \frac{\pi \cdot D_3^2}{4} B_1, \tag{9}$$

$$\Phi_3 = \Phi_3 = \pi D_3 h_{sp} B_1, \tag{10}$$

$$\Phi_m = \pi D_3 h_m B_\delta, \tag{11}$$

where B_1 is the induction at steel elements of the magnetic circuit under a rated mode. The cross-sectional area of copper in the winding considering a filling factor $k_z S_W = k_z b_k h_k$.

Considering that magnetic fluxes in the upper and lower backsides of the stator are the same and equal to half the flux of the permanent magnet, it is only fair when calculating the size of the cores that the best ratio of geometric parameters for an electric shock absorber is

$$\begin{gathered} D_2 = D_3 + 2\left(b_m + b_k + 2\Delta'\right), \quad D_1 = \sqrt{D_3^2 + D_2^2}, \\ h_m = \frac{D_3 B_1}{2 B_\delta}, \quad h_{sp} = \frac{D_3}{4}, \\ h_k = h_m - 2\Delta, \quad H = h_m - 4 h_{sp}. \end{gathered} \tag{12}$$

Thus, we have given the geometric parameters for a shock absorber of the selected structure and derived their optimal ratio.

4. 4. Statement of the optimization problem

A prerequisite to solve the optimization problem is determining its parameters and constraints.

It is rational to choose, as parameters to solve the optimization problem, the geometric parameters H, D_1, D_2, D_3, h_m, b_m, h_k, b_k, h_{sp}. However, (12) shows that H, D_1, D_2, h_m, h_k are linearly dependent on other parameters. Therefore, they must be attributed to functions for other optimization parameters. Finally, the selected parameters for the problem are the thickness of the permanent magnet and winding, the diameter of an inner core and the number of turns in the winding of an armature: D_3, b_m, b_k, W.

Constraints could be divided into three categories.

1) Constraints for a permanent magnet's demagnetization.

Operational modes of the permanent magnet are limited by the minimal induction along a linear section of the demagnetization curve. If the induction drops below this mark, a partial magnet demagnetization may follow. For a permanent magnet made from the alloy NdFeB the minimum induction along the linear section of the demagnetization curve is 0.1 Tl, so $B_\delta > 0{,}1$.

2) Constraints for a current density.

An important parameter that limits operational efficiency is the density of a current in the winding of an armature. It may be calculated based on expression (7) from ratio

$$J_W = \frac{I}{S_W} = \frac{F_{dem}\left(\dfrac{1}{B_{ost}} + \dfrac{(b_k + 2\Delta')}{\mu_0 H_c b_m}\right)}{\pi W k_z b_k h_k (D_3 + 2b_m + 2\Delta' + b_k)}. \qquad (13)$$

3) Constraints that are imposed on the shock absorber due to its location in the running part of a subway car (assembly constraints).

The above constraints are predetermined by the requirement to arrange the shock absorber in the assembly volume of the running part, as well as by the structure of the shock absorber itself [18] D_1<0.5 m, H<0.3 m.

4) Constraints that are imposed on parameters for the optimization problem. The geometric dimensions of the elements of design, which are parameters for the optimization problem are imposed with constraints predetermined by the fabrication technology. In addition, the number of turns in the winding should be an integer and cannot exceed 10,000 while it cannot be less than 1:

$$0{,}01 \text{ m} < D_3 < 0{,}5 \text{ m};$$

$$0{,}01 \text{ m} < b_m < 0{,}5 \text{ m};$$

$$0{,}01\text{m} < b_k < 0{,}5 \text{ m};$$

$$1 < W < 10000. \qquad (14)$$

It is possible to choose the following as objective functions to solve the problem:

– cost of constructing a shock absorber;

– energy that could be recovered by a shock absorber during its operation.

In this case, a first criterion must be minimized while a second one – maximized. Consider both objective functions.

1) Objective cost function. Expenses for designing the structure of a shock absorber are proportional to the cost of materials that are needed to construct it. Such an approach to selecting objective functions was applied in papers [18, 20, 21]. Cost of materials may be determined from expression:

$$C = C_{st} + C_c + C_{pm}, \qquad (15)$$

where C_{st}, C_c, C_{pm} are the expenses for materials made of steel, materials for a copper winding and a permanent magnet, respectively.

To be able to use the procedure for different market prices for materials, we suggest using the reduced amounts of materials

$$V = \frac{C}{Z_{st}} = \frac{C_{st}}{Z_{st}} + \frac{C_c}{Z_{st}} + \frac{C_{pm}}{Z_{st}} = V_{st} + V_c k_c + V_{pm} k_{pm}, \qquad (16)$$

where Z_{st} is the price for 1 m^3 of steel used in the structure of a shock absorber; V_{st}, V_c, V_{pm} are the volumes of steel, winding copper, and a permanent magnet for the shock absorber, respectively; k_c, k_{pm} are the coefficients of copper and a permanent magnet calculated from ratios:

$$k_c = \frac{\rho_c Z_{c1}}{\rho_{st} Z_{st1}},$$

$$k_{pm} = \frac{\rho_{pm} Z_{pm1}}{\rho_{st} Z_{st1}}, \qquad (17)$$

where $\rho_c, \rho_{st}, \rho_{pm}$ is the density of copper, steel, and a permanent magnet, respectively, and Z_{c1}, Z_{st1}, Z_{pm1} is the cost of 1 kg of copper, steel, and a permanent magnet, respectively. Given the current state of the economy, they are equal to k_c=5.64, k_{pm}=47 r.u.

The reduced volume of the materials has relatively small fluctuations relative to the currency exchange rate, indicating the versatility of the devised approach.

The volume of steel, copper, and a permanent magnet for a shock absorber is determined from expressions (18) to (20), respectively,

$$V_{st} = \frac{\pi}{4} H\left(D_3^2 + D_1^2 - D_2^2\right) + \frac{\pi}{2} h_{sp}\left(D_2^2 - D_3^2\right). \qquad (18)$$

$$V_c = \pi\left(D_3 + 2b_m + 2\Delta' + b_k\right) b_k h_k. \qquad (19)$$

$$V_{pm} = \pi\left(D_3 + b_m\right) b_m h_m. \qquad (20)$$

Thus, expression (16), considering expressions (17) to (20), is the first criterion chosen to solve the problem on determining the optimal parameters for an electromechanical shock absorber.

2) The criterion that defines the energy recovered by a shock absorber over its operation time

$$W = P_{msr} T_\Sigma \eta, \qquad (21)$$

where P_{msr} is the average power of mechanical oscillations of the car's body; T_y is the service life of a shock absorber; η is the efficiency of a shock absorber. The first two components P_{msr}, T_y are defined by external factors and depend on the design of the running part of EMF. Efficiency of a shock absorber is defined in turn by the losses in its structure and depends on it. Therefore, efficiency of the shock absorber defines the energy that could be recovered by the device, and can be chosen as a second criterion.

Losses in a shock absorber consist of losses in the copper of a winding, steel in a magnetic circuit, and mechanical losses. Determining the two latter components of losses at the preliminary stage of calculations is a very complicated task. In addition, values for losses in steel are minor because the alternating magnetic flux passes only the upper and lower backside of the stator, and its frequency is 0.5...10 Hz. This is significantly below the indicators for common electrical machines.

Efficiency of the shock absorber is

$$\eta = 1 - \frac{p_\Sigma}{P_1} = 1 - \frac{R_{ya}}{R_{ya} + R_n} = 1 - \frac{R_{ya}}{R_\Sigma}, \qquad (22)$$

where R_{ya}, R_n, R_Σ is the resistance of the armature, the load, and the total resistance of the armature's winding circle that can be derived from expression

$$R_\Sigma = \frac{E_{dem}}{I}.$$

To determine E_{dem} and I, it is possible to apply the simplified mathematical model (6) and (7)

$$E_{dem} = \pi \frac{D_3 + 2b_m + 2\Delta' + b_k}{\dfrac{1}{B_{ost}} + \dfrac{(b_k + 2\Delta')}{\mu_0 H_c b_m}} V_{dem}, \qquad (23)$$

$$I = \frac{F_{dem}\left(\dfrac{1}{B_{ost}} + \dfrac{(b_k + 2\Delta')}{\mu_0 H_c b_m}\right)}{\pi W \left(D_3 + 2b_m + 2\Delta' + b_k\right)}. \qquad (24)$$

Resistance of the shock absorber's loading is determined considering the average length of a turn, its plane, and specific resistance of copper

$$R_{ya} = 1{,}72 \cdot 10^{-8} \pi \frac{\left(D_3 + 2b_m + 2\Delta' + b_k\right)}{b_k h_k k_z} W^2. \qquad (25)$$

Thus, expression (22), considering expressions (23) to (25), is a second criterion, chosen to solve the problem on determining the optimal parameters for an electromechanical shock absorber.

3) Convolution of parameters.

The examined optimization problem refers to the group of multi-criteria optimization problems. We have chosen two criteria, equal in terms of benefit, as the criteria: the reduced volume of materials (V) and the shock absorber's efficiency (η). For problems of this type, in accordance with [20, 22], one must carry out the convolution of parameters by establishing a common criterion:

$$F' = k_1 V - k_2 \eta \to \min, \qquad (26)$$

where k_1, k_2 are the weight coefficients for the convolution of parameters. Sign «–» in the expression is needed to account for the fact that the second factor requires maximization.

The physically weighting factors must convert the reduced volume of materials and efficiency to the values for financial costs. Thus, given today's price for electrotechnical steel and the price for electricity, as well as a 10-year term for using a shock absorber, the weight coefficients are equal to: k_1=3.1 10^2 c.u./m^3, and k_2=71.1 c.u.

4. 5. Choosing a method to solve the optimization problem

Solving test tasks using a widely used method of the deformed polyhedron [20] has shown that the solving result strongly depends on a starting point. Achieving the desired magnitude of force for an electric shock absorber is possible at various combinations of geometric dimensions. There is a possibility that a solution may not be found at all. This testifies to a set of local minima, that is, to that the objective function is multi-extreme. Therefore, the operators in an optimization procedure must contain, together with deterministic, stochastic components as well, which can revive the search process if it gets stuck it at the local minima of the objective function's relief. One of such optimization methods is the method that employs genetic algorithms [21, 23, 24].

Genetic algorithms are characterized by a certain drawback. The optimal solution is determined with a low precision. To exclude this drawback, paper [12] proposed a combined genetic algorithm, which at the final stage of the search applies local optimization methods, specifically the Nelder-Mead method [22]. Such an approach improves search efficiency and refines a global minimum.

4. 6. Results from solving the optimization problem

According to the set optimization problem, and by using a method of genetic algorithm, we derived preliminary data on solving the problem of conditional optimization. The path to solve the problem is given in coordinates b_k, b_m, D_3 in Fig. 5, in coordinates b_k, b_m, W in Fig. 6. Fig. 5, 6 show only the best points. The initial search point is marked with a circle, and the resulting – with a diamond.

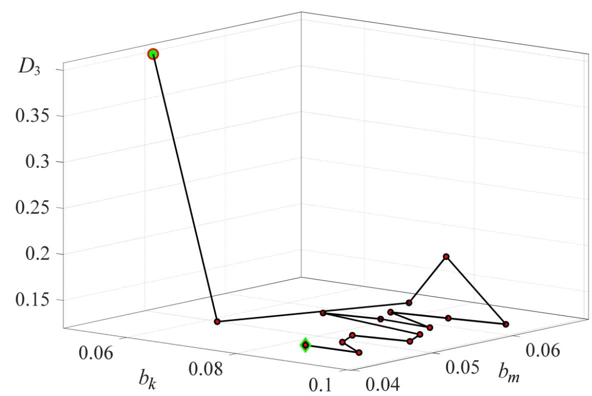

Fig. 5. Path to solve the optimization problem for the parameters of an electromechanical shock absorber using the method of genetic algorithm in coordinates b_k, b_m, D_3°

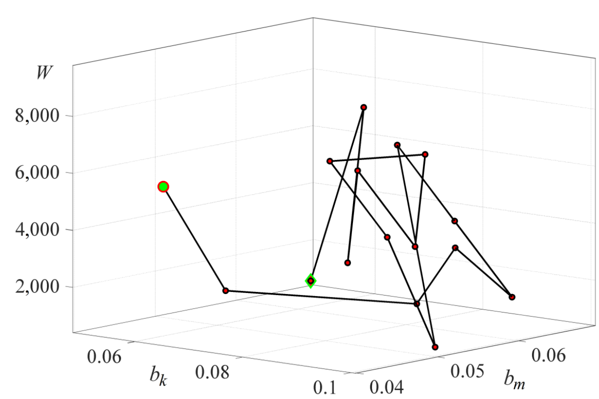

Fig. 6. Path to solve the optimization problem for the parameters of an electromechanical shock absorber using the method of genetic algorithm in coordinates b_k, b_m, W°

Fig. 5, 6 show that when solving a problem with many extrema, the search for solution involved the entire set of possible solutions. Therefore, the resulting solution is in the region close to the global minimum.

The path to solve the problem at the final stage using the Nelder-Mead method in coordinates b_k, b_m, D_3 is shown in Fig. 7, in coordinates b_k, b_m, W – in Fig. 8.

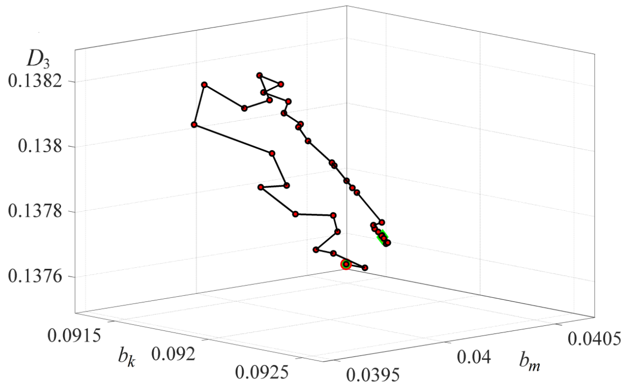

Fig. 7. Path to solve the optimization problem for the parameters of an electromechanical shock absorber using the Nelder-Mead method in coordinates b_k, b_m, D_3°

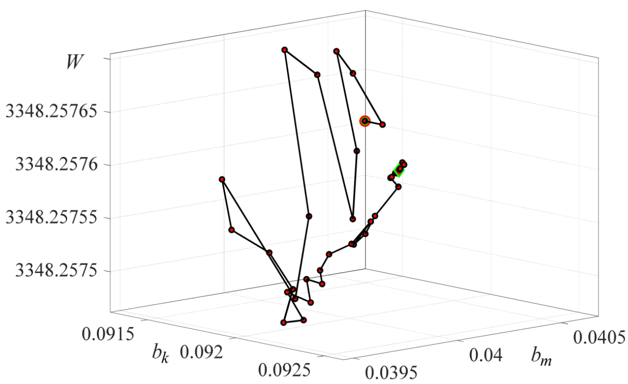

Fig. 8. Path to solve the optimization problem for the parameters of an electromechanical shock absorber using the Nelder-Mead method in coordinates b_k, b_m, W°

Fig. 7, 8 show that this algorithm makes it possible to improve the accuracy of determining a global minimum, excluding values at local minima. Numeric values of final results are given in Table 2.

Table 2

Results from the final calculation of parameters for the shock absorber using the Nelder-Mead method

Parameter	Magnitude	Parameter	Magnitude
b_k	0.093 m	b_m	0.04 m
D_3	0.138 m	W	3348 m
D_1	0.429 m	D_2	0.407 m
h_m	0.161 m	$h_к$	0. 081 m
h_{sp}	0.035 m	H	0.299 m
R_{ya}	31.45 Ohm	R_Σ	40.32 Ohm
E	89.8 V	I	2.227 A
V_{st}	0.0168 m^3	V_c	0.0074 m^3
V_{pm}	0.0036 m^3	V	0.226 m^3
η	0.22	F	54.16 c.u.

Table 1 and Fig. 7, 8 show that the results of using the final calculation of the optimal value for the shock absorber parameters insignificantly changed the value for the size of a permanent magnet and the armature's winding. The number of turns remained unchanged. The value for the objective cost function decreased by 0.1 %.

5. Discussion of results from synthesizing an electromechanical shock absorber for a subway car

Our proposed design of the electromechanical shock absorber consists of the stator with a coaxial permanent magnet and the armature with a winding placed in a magnetic field. Note that the design of the shock absorber ensures a stable value for the electromagnetic force at any position of the armature, and its value is defined primarily by EMF of the armature's winding, which depends on the motion speed of the armature and the load parameters. This result is due to the stability of the constant flow, which is coupled with the winding of the armature, throughout the entire movement lengthwise the magnet.

Based on the results from calculations using the proposed procedure, it was determined that the optimum height of the shock absorber is close to maximum (0.299 m, Table 2) and the outer diameter – 86 % of the maximum value (0.427 m, Table 2). The cross section of the armature's winding approaches square (0.093×0.081 m, Table 2 and Fig. 7). The thickness of a permanent magnet (0.04 m, Fig. 8 and Table 2) represents 43 % of the thickness of the winding (0.093 m, Fig. 8 and Table 2) and the height (0.0161 m, Table 2) exceeds the height of the winding (0.081 m, Table 2) by approximately 2 times. The optimal value for efficiency is within 21...22 % (Table 2). The result obtained is due to the fact that a further increase in efficiency leads to excessive costs of active materials and, therefore, it is impractical.

Based on the results from calculations in line with expressions (23) and (24), the designed shock absorber has a rated EMF of the winding of 89.8 V, a current of 2.227 A, which makes it possible to use non-expensive electronic keys as keys.

Thus, the current paper has proposed a procedure for designing electromechanical shock absorbers for subway cars, formed on the basis of a two-criteria synthesis of parameters. The constructed simplified mathematical model (6) and (7) that underlies the procedure makes it possible to reduce its order without simplifying the defining factors, which was confirmed by a comparative analysis of results from calculating an electromagnetic force using a given procedure and applying the method of finite elements (Fig. 4). When stating the optimization problem for the parameters of an electric shock absorber, we introduced constraints that make it possible to account for the design of the running part of a subway car (carriages and a body).

The devised procedure could be applied to design electromechanical shock absorbers for railroad vehicles, installed at the second of spring suspension. It is possible to use, as a material for the permanent magnet, only highly coercive permanent magnets with a demagnetization curve close to linear.

Further advancement of the devised procedure on determining optimal parameters for the electromechanical shock absorber could involve the consideration of the load parameters; that, however, could complicate the process of determining the objective function.

6. Conclusions

1. We have constructed a simplified mathematical model to determine the electromagnetic force and EMF for electromechanical shock absorber. Feature of the model is taking into consideration the operational modes of the permanent magnet based on the calculation of a magnetic circle. The devised model makes it possible to perform an approximate calculation of the operational modes of a shock absorber and could be used for solving a problem on the optimization of parameters for the electric shock absorber.

We have verified adequacy of the constructed simplified mathematical model by comparing the results from calculating a mechanical characteristic for the shock absorber using the simplified procedure and by a finite element method in the axial-symmetrical statement of the problem. We have obtained matching results from calculations using the simplified procedure and by modeling a magnetic field of the electric shock absorber applying a finite element method – divergence does not exceed 11.8 % at shock absorber travels from 10 mm to 70 mm.

2. Analysis of geometric ratios in the design of an electromechanical shock absorber has been performed. We have determined the geometric ratios between elements of the structure (12), which ensure a uniform magnetic load in the elements at a magnetic circuit and make it possible to reduce the number of parameters when stating an optimization problem from 10 (H, D_1, D_2, D_3, h_m, b_m, h_k, b_k, h_{sp}, W) to 4 (D_3, b_m, b_k,W).

3. We have stated the problem on a conditional two-criteria optimization of parameters for the electromechanical shock absorber.

The chosen constraints are divided into three categories:

– constraints for a permanent magnet demagnetization that make it possible to maintain the operability of a permanent magnet;

– constraints for the density of the current, which ensures the thermal modes of shock absorber operation;

– constraints that are imposed on the shock absorber due to its location in the running part of a subway car (assembly constraints), and constraints for the parameters of the optimization problem that ensure the arrangement of the structure in the running part of the carriage.

It has been proposed to choose as criteria the reduced volume of a shock absorber, which predetermines the cost to construct the shock absorber and its efficiency, which predetermines the recuperated energy of oscillations. The convolution of parameters has been carried out to obtain a single objective cost function; the weights have been defined. That makes it possible to determine the optimal parameters for the electric shock absorber based on two equivalent criteria – the reduced volume of materials and efficiency.

We have selected a combined method as the optimization method that includes a genetic algorithm at the preliminary stage of the search. At the final stage of the optimization procedure the optimum is refined using the Nelder-Mead method.

4. The results from solving the problem on optimizing the parameters for a shock absorber were applied to establish the optimal geometric dimensions and the number of turns (3.348) in the winding of the electromechanical shock absorber. The path to solve the problem underlies the procedure to determine parameters for the electromechanical shock absorbers for subway cars.

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