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Increasing the damping properties of the magnetorheological actuator of the vehicle suspension control system

Introduction. *In accordance with one of the ways of solving the problem of increasing the smoothness of the vehicles, a controlled suspension is proposed, which is created on the basis of the use of «smart» materials – magnetorheological elastomers, the mechanical properties of which, in particular, damping, can be changed with the help of a controlling magnetic field. This is implemented with the help of the magnetorheological actuator of the suspension control system, which has the form of an elastic bushing of the suspension arm, consisting of several electrically connected in series toroid-like coils (with a core of magnetorheological elastomer). The device is powered by current, the value of which is controlled by the operator, or automatically, depending on the road profile and driving mode. Magnetorheological actuators (elastic bushings) are placed in the holes of the suspension levers instead of standard rubber ones and combined with a controlled current source. Thus, the suspension becomes controllable, which makes it possible to set the necessary vibration damping of the vehicle body to increase its smoothness.* ***Problem****. The disadvantage of the previous designs of the magnetorheological actuator is the insufficient amount of the magnetic flux density and the unevenness of its distribution within the elastic bushings. As a result, the damping properties of such controlled suspensions become insufficiently effective, which reduces the possibility of increasing the smoothness of the vehicles.* ***The purpose*** *of the work is to increase the damping properties of the magnetorheological actuator of the vehicle suspension control system, which will increase the control efficiency.* ***The task*** *is to improve the design of the performing magnetorheological device, to carry out calculations and develop a calculation scheme of the study, to determine the average magnetic flux density value and its distribution across the cross-section of the device, to calculate the dependence of the device damping indicator on the magnetic flux density, to compare the damping indicators of the improved device with previously known ones.* ***Methodology.*** *Research tasks were solved on the basis of magnetic field analysis using methods of magnetic field theory and SOLIDWORKS® and FEMM software packages, as well as analysis of the dependence of the damping properties of bushings from magnetorheological elastomers on magnetic flux density. A description of the design and principle of operation of the magnetorheological actuator of the vehicle suspension characteristics control system is given, based on which the calculation scheme was developed.* ***Results.*** *The results of research calculations showed that the average value of magnetic flux density in the proposed design of the device reached 0.85 T, its distribution became fairly uniform, and there were no zones where it was abnormally small. For the first time, the dependence of the damping index on the magnetic flux density of the controlling magnetic field has signs of scientific novelty. It was found that this indicator for the proposed design of the device increased by 22 % compared to previous other designs, which will increase the efficiency of the control system and the smoothness of the vehicle. A positive result was achieved due to the following features of the proposed design of the suspension actuator: the elastic sleeve consists of several coaxially located actuators made of anisotropic magnetorheological elastomer, in which the conglomerates of the ferromagnetic filler during the manufacturing process are located collinear to the direction of the angular deformations of the sleeve and the control magnetic field flux density vector, and the devices have control coils located on their surfaces, which are made of conductive elastic elastomer and electrically connected in a series circuit.* ***Originality****. The control method, previous designs and construction of this controlled suspension are protected by patents of Ukraine.* ***Practical value****. The direction of further research is to optimize the parameters of the control coils in order to reduce the energy consumption for them and to protect them from overheating.* References 20, figures 10.

Key words: **magnetic field, magnetorheological actuator, anisotropic magnetorheological elastomer, control system, vehicle suspension, damping.**

Проблема. *Відповідно до одного із напрямків вирішення проблеми підвищення плавності ходу транспортних засобів, запропоновано керовану підвіску, яку створено на базі застосування «інтелектуальних» матеріалів – магнітореологічних еластомерів, механічні властивості яких, зокрема демпфування, можна змінювати за допомогою керуючого магнітного поля. Це реалізовано за допомогою виконавчого магнітореологічного пристрою системи керування підвіски, який має вигляд пружної втулки важеля підвіски, що складається із декількох електрично поєднаних у послідовне коло тороподібних котушок (з осереддям із магнітореологічного еластоміру). Пристрій живиться електричним струмом, величина якого керується оператором, або автоматично, в залежності від дорожнього профілю та режиму руху. Виконавчі магнітореологічні пристрої (пружні втулки) розміщують у важелях підвіски замість штатних гумових і поєднують із керованим джерелом струму. Таким чином, підвіска стає керованою, що надає можливість встановлювати необхідне демпфування коливань корпусу транспортного засобу для підвищення його плавності ходу. Недоліком попередніх конструкцій виконавчого магіторереологічного пристрою є недостатня величина індукції та нерівномірність її розподілу в межах пружних втулок. Внаслідок цього демпфуючі властивості таких керованих підвісок недостатньо ефективні, що знижує можливості підвищення плавності ходу транспортних засобів.* ***Метою*** *роботи є підвищення демпфуючих властивостей виконавчого магнітореологічного пристрою системи керування підвіски транспортного засобу, що збільшить ефективність керування.* ***Завдання.*** *Удосконалити конструкцію виконавчого магнітореологічного пристрою, провести розрахунки середньої по перерізу пристрою величину індукції магнітного поля та її розподілу, скласти залежність показника демпфування пристрою від індукції магнітного поля, порівняти показники демпфування удосконаленого пристрою з попередніми.* ***Методологія****. Задачі дослідження вирішувалися з використанням методів теорії магнітного поля та програмних пакетів SOLIDWORKS® і FEMM, а також аналізу залежності демпфуючих властивостей втулок з магнітореологічних еластомірів від індукції магнітного поля. Наведено опис конструкції та принцип дії виконавчого магнітореологічного пристрою системи керування підвіски транспортного засобу, на основі чого розроблено розрахункову схему.* ***Результати*** *розрахунків показали, що середня величина індукції магнітного поля у запропонованій конструкції пристрою досягла 0,85 Т, її розподіл став достатньо рівномірний, а зони, де вона аномально мала, відсутні. Складена вперше залежність показника демпфування від індукції керуючого магнітного поля має ознаки наукової новизни. Отримано, що даний показник для запропонованої конструкції пристрою збільшився на 22 % порівняно з попередніми*

конструкціями, що підвищить ефективність системи керування та плавність ходу транспортного засобу. Позитивний результат досягнуто завдяки наступним особливостям запропонованої конструкції виконавчого пристрою: пружна втулка складається із декількох, розташованих співвісно, виконуючих пристроїв з анізотропного магніторелогічного еластоміру, у якого конгломерати феромагнітного наповнювача в процесі виготовлення розташовано колінеарно до напрямку кутових деформацій втулки та вектору індукції керуючого магнітного поля, а котушки керування виконано із струмопровідного пружного еластоміру. Спосіб керування, попередні конструкції та конструкцію даної керованої підвіски захищено патентами України. Напрямки подальших досліджень полягають у оптимізації параметрів котушок керування з метою зниження енергоспоживання та їх захисту від перегріву. Бібл. 20, рис. 10.
Ключові слова: **магнітне поле, виконавчий магніторелогічний пристрій, анізотропний магніторелогічний еластомір, система керування, підвіска транспортного засобу, демпфірування.**

Introduction. The use of controlled suspensions (CSs) is considered a promising way to solve the problem of improving the smoothness of the vehicles. This is especially relevant for military vehicles, as they move at relatively high speeds on dirt roads and rough terrain. However, known technical solutions of CSs are characterized by complexity, high cost and low reliability. Eliminating these shortcomings is a complex scientific and applied problem, the solution of which is being worked on by experts from all developed countries. One of the variants of the actuator of the CS is a hydro damper filled with a magnetorheological («smart») liquid, the properties of which, in particular, density, change under the influence of the magnetic field. This allows to control its damping properties and influence the smoothness of the vehicle's movement when driving off-road. But the wide distribution of such CSs is restrained by the problem caused by the abrasive action of magnetic particles on the interacting parts of the actuator, which reduces durability, and the instability of the characteristics of the magnetic fluid, which is caused by the sedimentation of the magnetic particles, which reduces the control efficiency and the smoothness of the vehicle's movement. The problem can be solved by using actuator, where the liquid is replaced by a magnetorheological elastomer (MRE), which is devoid of these disadvantages. The use of MRE in the vehicles' CSs was proposed by the authors for the first time – a method and design, confirmed by patents of Ukraine. This work is devoted to the improvement of the magnetorheological actuator (MRA) in order to increase its efficiency. It is intended for military wheeled vehicles, but is also suitable for other vehicles, for example, for electric vehicles with powerful current sources. It is connected to operate for a short time, in addition to the main elastic elements and damping devices of the suspension in case of the need to increase damping when overcoming sections with a difficult road profile on resonant driving modes. This allows to maintain the necessary smoothness of movement, without reducing the speed of movement. In the event of failure of this CS, the vehicle will remain with the usual suspension and will not lose traction. In this way, the urgent tasks of ensuring high reliability of vehicles are also solved.

MREs are a mixture of an elastic matrix (rubber or elastomer) and a ferromagnetic filler, for example, carbonyl iron powder, with a particle size of about 5 μm. The mixture is polymerized and MRE is obtained with a uniform (isotropic) distribution of particles in the matrix, or with an anisotropic one, if the polymerization process is carried out in a magnetic field. At the same time, filler particles form conglomerates in the form of columns, which are located along the lines of the magnetic flux density.

It is known that anisotropic MREs change their elastic and damping properties to a greater extent under the influence of a controlling magnetic field than isotropic ones. This affects the frequency response of the vibrations of the sprung body of the vehicle. An increase in damping causes a decrease in the amplitudes of oscillations and accelerations and, accordingly, in the height of the resonance maximum of the frequency response. An increase in the stiffness of the suspension increases the natural frequency of oscillations of the sprung body on it. This violates its coincidence with the frequency of excitations from unevenness of the road profile and protects against the occurrence of resonant oscillations. Meanwhile, certain problems arise when using MRE, due to the difficulty of obtaining the necessary magnetic flux density of the controlling magnetic field and its uniform distribution within the MRA. A large number of publications, patents and examples of practical application prove the promising direction of solving the problem of increasing the smoothness of the vehicle's movement by using the CS. In this regard, scientific and practical works aimed at improving CSs, in particular, by using MRA in them, improving the damping properties of which this work is aimed at, are relevant.

Analysis of previous studies. In work [1] it is stated that the further improvement of the quality indicators of vehicles due to the improvement of suspension systems requires the application of control of the characteristics of their elastic and damping devices. But traditional materials (metals, composite materials, rubber, elastomers, gases, liquids, etc.) used in these units have exhausted their capabilities to ensure the necessary control of the characteristics of suspension systems. This is due to the immutability of the physical properties and characteristics of these materials, which leads to complex, high-cost and unreliable technical solutions and hinders the introduction of CSs on vehicles.

The authors propose to solve this urgent problem by using alternative materials in the CSs, known in the world as *smart materials*. This will simplify the technology of production of CSs, and will contribute to their implementation on vehicles. At the time, there was a certain spread of CSs, in which the working element is a magnetorheological fluid (MF). Meanwhile, it has significant disadvantages, one of which is the sedimentation of magnetic particles in the liquid. The authors consider several measures to optimize MF deposition from the point of view of the viscosity of the dispersion medium, the suspension strength of the dispersed phase, and innovations in additives. The proposed active mechanism for solving the sedimentation problem promises to improve the performance of MF dampers, even if the sediment persists. But deposition of MF can be reduced only to a certain extent [2].

Another shortcoming of hydro shock absorbers with MF is considered in work [3], which is related to the sensitivity to pulse loads, which is undesirable for impact protection. This causes large damping forces that are transmitted to the vehicle body and pose a serious threat to passengers and mechanical structures. It is reported on the development of a MF hydro shock absorber with low sensitivity to pulse loads. Analytical and experimental studies proved that its sensitivity to impact has decreased.

The work [4] is devoted to testing and modeling the properties of isotropic MRE under the action of static-dynamic compressive loads. On the basis of silicone elastomer, isotropic MREs with different contents of magnetic particles were made. To apply a controlled magnetic field to the MRE during dynamic tests, an electromagnet with magnetic flux density of up to 0.9 T was developed. The «stress-strain» hysteresis loops of manufactured MREs were experimentally obtained under the action of dynamic compressive loads in combination with various static pre-strains. The effect of particle content, strain amplitude, static pre-strain and load frequency on the storage and loss modules of MREs was investigated. The results showed that regardless of the applied magnetic field, the deformation behavior of MREs was in an approximate linear viscoelastic state if the deformation amplitude was less than 7.5 %. Both the absolute and relative effects of MREs increase with increasing particle content and decrease with increasing strain amplitude. Changing the load frequency has almost no effect on MREs. Empirical models are proposed for predicting MRE storage and loss modules as functions of magnetic flux density, magnetic particle content, strain amplitude, frequency, pre-strain, and load. The models can provide effective predictions of storage modules and losses of MREs for the load conditions used in this work.

The work [5] considers the compression characteristics of MRE based on silicon. The developed electromagnet allows for dynamic compression tests up to 300 Hz of samples 40 × 40 × 8 mm in size. Magnetic flux density of about 1 T was achieved, and the predicted increase in the dynamic stiffness of the MRE was obtained. An electromagnet can be used to manufacture and solidify anisotropic MREs.

In work [6], it was noted that MREs have wide possibilities for use in transport as suspension shock absorbers, due to the relatively lower complexity and cost of the structures of absorbing devices based on them, environmental perfection and the absence of disadvantages inherent in MREs. But the authors do not provide the characteristics of MREs and the results of their use.

The work [7] is devoted to obtaining the dependence of the relative magnetic permeability on the concentration of the MRE filler. Its maximum value (6.6) was obtained for 50 % volume concentration of particles. There is no explanation for the increase in magnetic permeability in the work.

The assessment of the influence of the controlling magnetic field on the vibration-isolating properties of MREs was studied in [8] and numerous other works. A significant improvement in the damping properties of MREs under the influence of a magnetic field was revealed.

In [9], it was noted that the known method of producing MRE takes more than a day, since matrices made of natural rubber or silicone rubber require a long time for polymerization. It is proposed to use (poly)dimethylsiloxane as a matrix with its polymerization at a high temperature. This reduces the production time of MRE to 90 minutes. The study of the dynamic properties of MRE produced by the new method gave positive results.

The effect of changing the Young modulus (0.14 – 14.6 MPa) on the physical characteristics of MRE was studied in [10]. The dependence of the damping properties of the composites on the content of particles (7, 10, 14, 21, 31 vol. %) and on the mechanical properties of MRE was also investigated. An increase in damping properties occurs in a certain proportion of magnetic particles, which can be explained by the magnetic exchange between them. Damping properties (hysteresis) are worse in MRE with a higher Young modulus. Irregular participation of MRE magnetic particles in hysteresis was revealed.

In [11], a linear magneto-viscoelastic model for anisotropic MRE is proposed, which allows determining the influence of the magnetic field on the dynamic shear modulus depending on the strength and frequency of the magnetic field. Errors between experimental values and calculations obtained by simulation do not exceed 10 %.

In [12], a method of calculating elastomeric structures that takes into account their features is proposed. In the calculation process, a vector of nodal displacements is found, on the basis of which the fields of deformations and stresses and their values are determined.

Studies of a conical vibration isolator with MRE have proven its effectiveness: it provides reliable vibration isolation due to an increase in the frequency of oscillations by 46.29 % during the control process and control forces up to 75 N. It is noted that vibration isolators with MRE have high energy consumption and unprofitable production [13].

The work [14] presents the results of research on the strain sensor, which was created on the basis of a wire MRE containing a polyurethane sponge with silver nanowires (AgNW), and particles of carbonyl iron and polydimethylsiloxane. The research revealed that the relative change in its resistance reached 91.8 % at a deformation of 20 % when a control magnetic field of 0.428 T was added. There is a prospect of using this material in smart devices, composite electrodes and soft sensors.

The work [15] gives the results of the research of the sensor in the form of a disk (ferromagnetic marker), which is built into a cylindrical MRE. Its 3D displacement is estimated by monitoring the inductance changes of the four inductance coils. Studies of inductance coils revealed its monotonic change and linearity with respect to the applied normal force and shear force. A conclusion was made about the effectiveness of using MRE in sensors.

The results of research on the magnetic field sensor created on the basis of MRE are given in [16]. The sensor can be used to measure uniform magnetic field. The sensor demonstrates a fast response (20 ms) and good magnetic field detection characteristics in the range from 40 to 100 mT.

The work [17] gives the results of research on adaptive absorbers, in which the resonance shift property was used by using MRE. It is known that passive nonlinear absorbers have a wider effective frequency band. The authors combined these two characteristics in a hybrid MRE absorber, which at the same time can shift its own frequency and has a wider absorption band. The results of the research proved that the adaptability of the hybrid absorber is ensured thanks to the MRE.

The analysis of the above studies showed that the dependence of the damping properties of the MRA on the direction of the filler conglomerates on its deformations and on the magnetic flux density vector of the controlling magnetic field is not sufficiently revealed.

In this regard, complex studies were carried out: calculation – by means of computer modelling of the distribution of the magnetic field in the MRA of the suspension of the vehicle, and full-scale – elastic samples from MRE (for comparison of rubber) on a dynamic stand. The samples had a diameter of 20 mm, a central hole with a diameter of 8 mm and a thickness of 10 mm; the content of carbonyl iron (by volume) was 40 %. The frequency of natural oscillations of the mass on these elastic samples was about 2 Hz. Based on the experience presented in [11], the samples were made of MRE with an anisotropic structure: they were polymerized in a magnetic field. The direction of the vector of this field in one part of the samples was orthogonal, and in the other – collinear to the direction of the controlling magnetic field. The damping properties of the samples were evaluated by the averaged relative damping index D

$$D = [\ln(A_1 / A_2)] / 2\pi, \quad (1)$$

where A_1 and A_2 are the successive amplitudes on oscillograms of natural oscillations.

It was found that with orthogonal direction of the control magnetic field vector (0.6 T) to the direction of sample filler conglomerates, the relative damping index was 0.04 – 0.05, and with collinear 0.071 – 0.083, i.e. much more.

The development and computer modelling of the designs of suspensions of vehicles with MRA was also carried out [18, 19].

Figure 1 shows the visualization of the controlling magnetic field in the form of magnetic lines of force on cross-sections according to the first (*a*) and second (*b*) variants of the elastic suspension hinge with MRA. The controlling magnetic field was created by the current of the control coil *3*, which is located on the outer surface of the MRA. This made it possible to place it in the dimensions of serial hinge *4*, which simplified the replacement of the element from rubber to MRA.

It was found that the flux density of the controlling magnetic field within the MRA (position *2*) is irregularly distributed – it is less than 0.1 T on a large area in the middle, and reaches 0.6 T near the end parts.

This means that about 20 % of the volume of the MRA does not participate in the creation of the damping force, which accordingly reduces the efficiency of the suspension control [10]. Splitting the control coil into two parts in option (*b*) did not significantly change the picture.

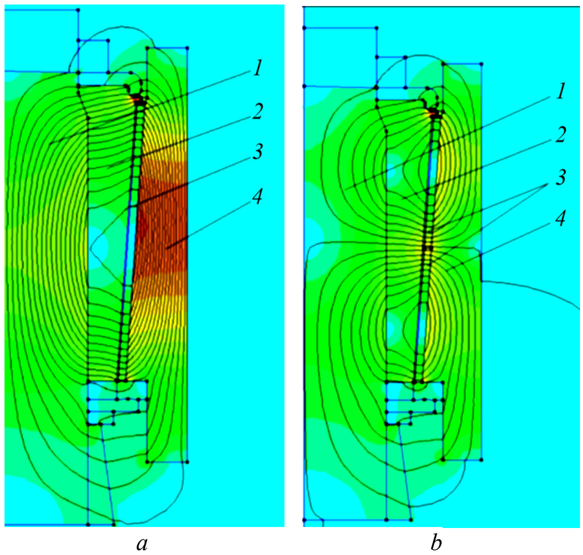

Fig. 1. Visualization of the controlling magnetic field in sections of the MRA according to the first (*a*) and second (*b*) variants of the hinge design: *1* – axis of the hinge; *2* – MRA; *3* – control coil; *4* – hinge

The average magnetic flux density in both variants was about 0.25 T, i.e. significantly less than the magnetic flux density at which the magnetic saturation of the particles of the MRA filler begins. In both variants, it was not possible to direct the magnetic flux density vector of the controlling magnetic field collinearly to the direction of deformations of the MRA: they are orthogonal.

The emergence of «magnetic bridges» from the end parts of the elastic hinge was revealed, where the magnetic flux density exceeded 1 T. Therefore, the adjacent parts of the magnetic circuit reached saturation, which prevented the increase in the magnetic flux density of the controlling magnetic field.

In the third version of the design, the control coil was located from the end of the MRA, which made it possible to increase the number of wire turns in it and, accordingly, the magnetomotive force (MMF) (Fig. 2).

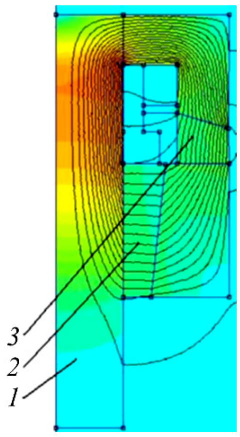

Fig. 2. Visualization of the controlling magnetic field on the MRA according to the third variant of its design: *1* – axis of the hinge; *2* – cylindrical part of the MRA; *3* – end part of the MRA

The MRA is divided into two parts: the first (end) one – in the form of a conical ring, and the second one –

in the form of a conical cylinder on the axis of rotation of the hinge. Collinearity of the vector of the controlling magnetic field and the direction of the conglomerates of magnetic particles has been achieved. This should increase the vibration damping factor to 21 % compared to the isotropic MRA [9, 11].

The study revealed that this MRA excludes parts where the flux density of the controlling magnetic field is too small. Thanks to this, a higher average value (0.6 T) was achieved. But at the same time, it was not possible to achieve collinearity of the flux density vector of the controlling magnetic field, which is tangent to the magnetic field lines, with the direction of deformation of the MRA, which is orthogonal to them.

In all variants, «magnetic bridges» appear on the end parts, which prevents increasing the flux density of the controlling magnetic field. All this required prolonging the search for a more perfect design of the MRA.

Figure 3 shows a scheme of a vehicle suspension with MRA.

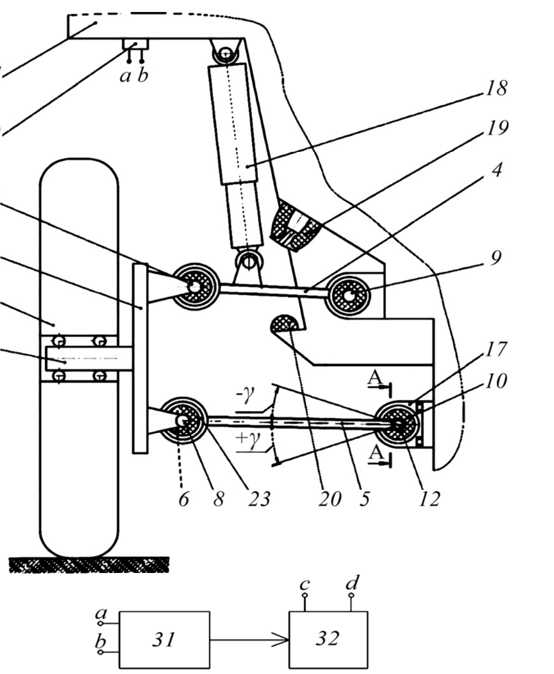

Fig. 3. Scheme of the suspension of the vehicle with MRA: *1* – axle; *2* – wheel; *3* – rotary fist; *4* – upper lever; *5* – lower lever; *6* – MRA; *7* – *10* – axes; *11* – spring-loaded housing; *12* – torsion shaft; *17* – bracket; *18* – hydraulic shock absorber (HA); *19*, *20* – stops; *23* – MRA of the CS; *30* – sensor unit; *31* – control unit; *32* – current source

The goal of the work is to improve the damping properties of the MRA of the vehicle suspension control system by improving its design.

To achieve the goal, the tasks are set:

- to analyze and compare known MRAs and develop a new, improved design;
- to determine the average value and distribution of the flux density of the controlling magnetic field across the MRA cross-section;
- to build the dependence of the MRA damping index on the flux density of the controlling magnetic field;
- to compare the damping indicators of the developed MRA with known structures.

The research methodology consisted in the numerical calculation of the magnetic field arising in the MRE device of the vehicle suspension control system, using the SOLIDWORKS® and FEMM software packages, and the determination of the damping properties of the suspension based on the dependence of the damping index on the flux density of the controlling magnetic field revealed in previous works.

The object of research is an improved MRA, which consists of a coil in the form of a toroid, the core of which is made of anisotropic MRE, and the coil receives current from the power supply unit, while the current value is set by the control unit. This design is protected by a patent of Ukraine [20]. The MRA *23* (Fig. 3) can be installed on axes *7* – *10*.

It should be noted that it is impossible to reproduce an anisotropic MRA with the directions of the filler conglomerates, which coincide simultaneously with all the various deformations of the elastic sleeve during the movement of the vehicle. Therefore, a MRA was created, the direction of the filler conglomerates of which coincides only with the direction of the angular deformations of the elastic sleeves.

Let's consider the operation of the MRA in the CS. The stiffness of the CS is defined as the sum of the stiffnesses of the torsion shaft *12* and MRA *6* brought to the wheel, which can be installed in all (or a certain part) of the hinges of the levers. Damping forces of the HA *18* and MRA *6* are brought to the wheel axis and add up. The controlling magnetic field is created by the current *I* in the control coils *24*, which are electrically connected in a series circuit (Fig. 4–6).

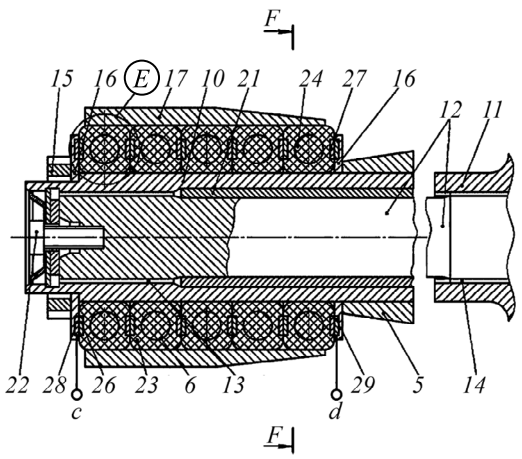

Fig. 4. Section *A-A* (according to Fig. 3): *6* – elastic sleeve from five MRAs; *10* – axis; *11* – spring-loaded housing; *12* – torsion shaft; *13*, *14* – slotted connections; *15* – nut; *16* – washer; *17* – bracket; *21* – sleeve; *22* – bolt fastening; *23* – MRA in the form of a toroid; *24* – control coils; *26* – *29* – contact rings

This field magnetizes the ferromagnetic particles of the MRA filler and they begin to interact with each other, compressing the porous matrix that is located between them. This causes an increase in the frictional forces between the molecular structures in the matrix and, accordingly, the damping forces in the suspension, in proportion to the current *I*.

The process of adjusting the vibrations of the sprung body is as follows. The most dangerous are periodic irregularities that cause resonant oscillations at the corresponding speed of movement. At the same time, wheel *2* moves vertically with a frequency of unevenness and transmits the movement through axis *1* to the fist *3*, upper *4* and lower *5* levers, which rotate relative to axes *7 – 10*, and cause angular deformations $\pm\gamma$ of the MRA *6* on these axes (Fig. 3).

The use of anisotropic MRE, in which conglomerates of ferromagnetic filler during the manufacturing process are located collinear to the direction of angular deformations of MRA *6* and the vector of the flux density of the controlling magnetic field, provides the greatest influence on their damping properties (Fig. 6).

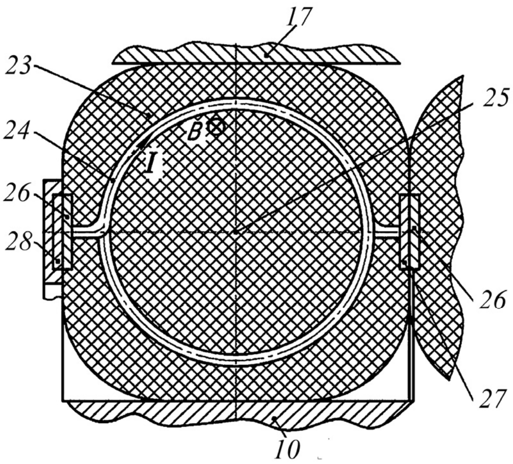

Fig. 5. Unit *E* (according to Fig. 4): arrow *I* indicates the direction of the current in the control coil *24*; ***B*** – magnetic flux density vector; *10* – axis; *17* – bracket; *23* – MRA; *25* – central axis of symmetry of the section of the control coil *24*; *26* – *28* – contact rings

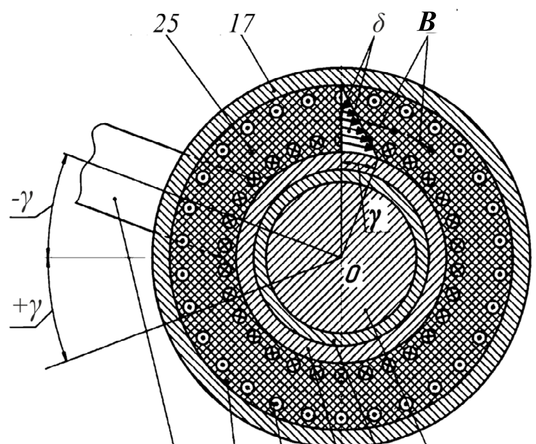

Fig. 6. Section *F-F* (according to Fig. 4): *12* – torsion shaft when it is turned together with the lower lever *5* to the angle *γ*; *δ* – direction of shear deformation; ***B*** – magnetic flux density vector of the controlling magnetic field; *5* – lower lever; *6* – MRA; *10* – axis; *12* – torsion shaft; *17* – bracket; *21* – sleeve; *24* – control coil; *25* – central axis of symmetry of the section of the control coil *24*

The execution of the control coil *24* (Fig. 4, 5) from an elastic current conductor, for example, of polyacetylene, the modulus of elasticity of which is close to the modulus of elasticity of MRE, excludes mutual movement and friction of the contacting surfaces of the control coil *24* with MRE, which will increase the reliability of the device. When the current in the control coils *24* increases, their magnetic field will increase, accordingly, the rigidity and damping of the MRA *6* will increase, which will cause a slight increase in the frequency of the self-oscillations of the sprung body. This frequency will differ from the frequency of following irregularities in the road profile (excitation), as a result of which the amplitudes of resonant oscillations of the sprung body will decrease. Thanks to the control, the damping force in the MRA will also increase, which will be added to the damping force of the HA. This will lead to an improvement in the smoothness of the vehicle.

Research results. To achieve the tasks set, a hypothesis was formulated: *since it is known that coils in the form of toroids concentrate the electromagnetic field in their cores, it can be expected that the toroidal MRA will increase the flux density of the controlling magnetic field, ensure its uniform distribution over the volume and exclude «magnetic bridges».*

The initial data for the research were the drawings of the MRA (Fig. 6), the magnetic characteristics of the hinge steel and MRE filler, the current and the number of turns of the control coil and its geometric parameters:

- the average diameter varied within 70 – 100 mm;
- the diameter of the radial section is 15 mm;
- the diameter of the concentric hole is 8 mm;
- the matrix material – silicone rubber;
- the size of the filler particles is 5 – 10 μm;
- the filler content by volume is 40 %;
- the filler material – carbonyl iron;
- the relative magnetic permeability of the MRA varied within 6 – 8.9.

The operating time of the MRA (time of supplying current to the control coil) was taken to be 10 s, which helped to prevent their overheating. This time is justified by the following. It is known that, according to statistics, a road profile that is difficult from the point of view of smoothness of movement is found on the terrain only periodically, and has 4-6 peaks and depressions in a section 30-50 m long. When hitting the third bump, there is often a breakdown of the suspension and a significant excess of the permissible ergonomic norms of vertical accelerations. As a result, the vehicle's driver is forced to reduce speed sharply. To prevent this, the proposed MRAs of the CS are connected (better automatically, for example, with the help of a sensor of vertical accelerations of the sprung body) only when overcoming a difficult section. At a speed of 8-11 m/s, it will be about 5-7 s. So, the operating time of the MRA with a small margin can be taken as 10 s. This will help to maintain the necessary smoothness of movement without reducing the speed of movement. In case of MRA failure, the vehicle will remain with standard suspension, which will ensure its reliability.

The finite element mesh was created by the FEMM software package in automatic mode with the possibility of its adjustment to clarify the research results. With the use of the SOLIDWORKS® code, the calculation scheme and the problem definition of calculating the magnetic field of the MRA were drawn up (Fig. 7). After setting the parameters, construction materials, as well as forming the winding of the control coil, the FEMM code visualized the magnetic field in the form of lines of force. Examples of calculation results are shown in Fig. 7, 8.

The calculation of the magnetic field was carried out on the cross-section of the generating circle of the toroid, which determines the design of the MRA. It is assumed that the part of the circle of rotation of the toroid according to the thickness of the calculation area is a straight line. Thus, the calculation area becomes cylindrical in shape, the radius of which is determined by the radius of the generating circle of the toroid. Taking into account the assumption, the magnetic field of the toroid can be determined with an axially symmetric formulation of the problem. The axis of symmetry will be tangent to the circle of rotation of the toroid.

Boundary conditions: the magnetic vector potential is zero at the boundary *A*, and periodic boundary conditions are adopted at the boundaries *B* and *C*. In the calculation area, *1* – MRA material, *2* – polyacetylene, which is a winding with a control current, *3* – steel.

Figure 8 shows the calculation area of the MRA. The study revealed that with a current in the winding of 7.18 A, MMF F = 17232 A, current density J = 42 A/mm^2, the distribution of magnetic flux density in the MRA is close to uniform – on average 0.85 T, i.e. the largest among other design variants. Zones where the magnetic flux density does not exceed 0.1 T (which is 2.5 times less than its average value) and «magnetic bridges» (where the magnetic flux density is greater than 1 T and the particles of the filler have reached magnetic saturation) are absent. The current density at the contacts (Fig. 5, items *26* – *28*) is low and amounts to 2.4 A/mm^2, because the contact area is much larger than the cross-sectional area of the winding.

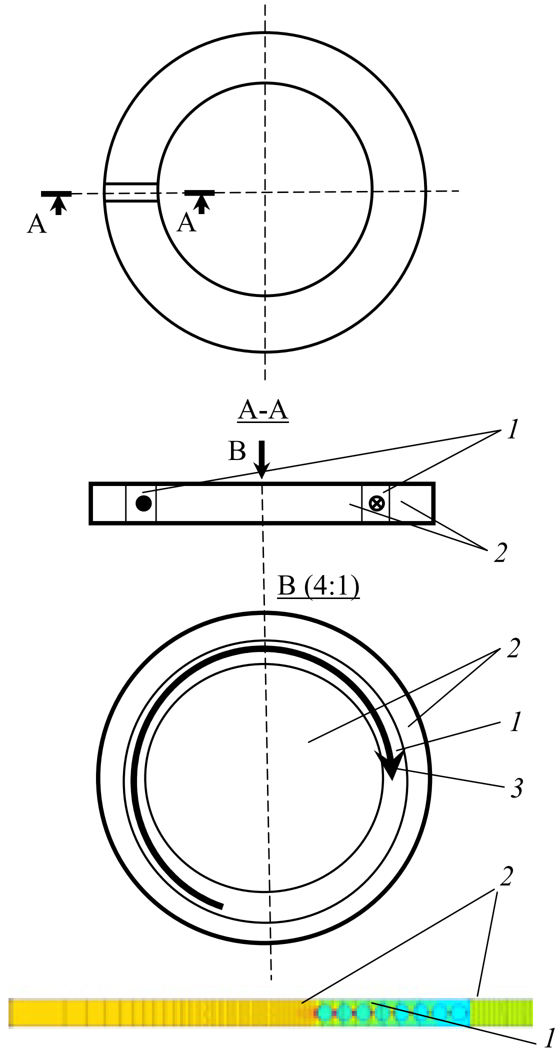

Fig. 7. On the formulation of the problem of calculating the magnetic field: *1* – area with current; *2* – MRA; *3* – current

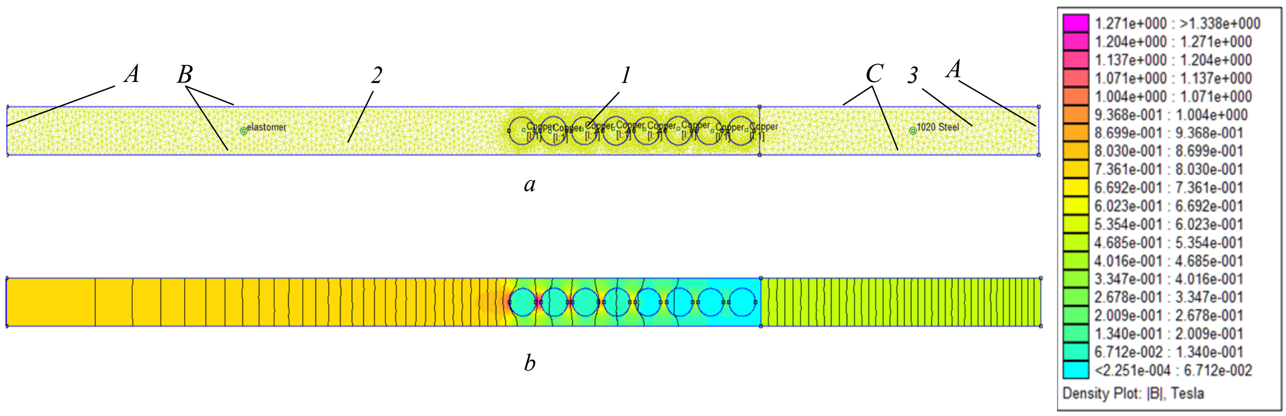

Fig. 8. Formulation (*a*) and results of solving (*b*) the problem of calculating the magnetic field of the MRA

The MRA coil is fed by current in pulse mode with effective cooling – the role of a radiator is performed by the surface of the components of the undercarriage of the vehicle, which is blown by air. Calculations of overheating of the MRA proved that its temperature does not exceed 45-47 °C during the operating cycle.

The results of the study by means of computer modelling of the dependence of the average flux density of the controlling magnetic field on the average diameter and relative magnetic permeability of the improved MRA are shown in Fig. 9.

As can be seen from Fig. 9, a decrease in the average diameter of the MRA toroid contributes to an increase in the flux density of the controlling magnetic field, and an increase, on the contrary, slightly decreases it. An increase in the relative magnetic permeability is desirable because it proportionally increases the flux density of the controlling magnetic field of the MRA.

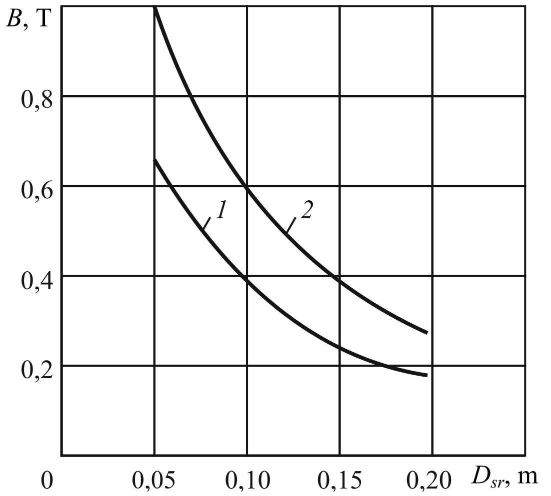

Fig. 9. Dependence of the average flux density of the controlling magnetic field on the average diameter of the MRA and its relative magnetic permeability: *1* – μ = 6; *2* – μ = 8.9

As the MRA filler approaches the state of magnetic saturation, the relative magnetic permeability begins to decrease, which, accordingly, affects the flux density of the controlling magnetic field and the damping properties of the MRA. Therefore, appropriate restrictions are imposed on the MMF and control electric current values.

To evaluate the damping properties of the improved MRA in the form of a toroid, the results of the research presented in [18] were used, where 10 mm thick samples of anisotropic MRE containing 40 % (by volume) filler (carbonyl iron) were experimentally investigated. The direction of the conglomerates in the MRE coincided with the direction of deformation of the samples and the vector of the controlling magnetic field. Since this coincides with the features of the improved MRA, it can be assumed that their damping properties will be sufficiently close to each other.

Taking this into account, the dependencies of the damping index on the flux density of the controlling magnetic field were compiled for the magnetization curves of MRE that are close to the linear parts, when the filler particles have not yet reached magnetic saturation:

$$D = 0{,}038 + 0{,}075B. \quad (2)$$

Therefore, when the flux density of the controlling magnetic field increases to 0.6 T, the relative damping index increases according to the linear law from 0.038 to 0.083, that is, by 2.2 times. At the same time, the amplitudes of mass fluctuations on samples with MRE decreased by half [18].

Using dependence (2), the relative damping index of the MRA D_V in the form of a torus was calculated with the flux density of the controllimg magnetic field B = 0.85 T, which was achieved in it (Fig. 7, 8):

$$D_V = 0{,}102; \quad (3)$$

$$\Delta D_V = 0{,}102 / 0{,}038 = 2{,}68. \quad (4)$$

Thus, the damping factor increased by 2,68 times compared to the case when the controlling magnetic field is absent. This is 22 % more than what was achieved in previous MRA designs (Fig. 1, 2).

Evaluation of the effectiveness of the improved MRA in the form of a torus was carried out by comparing the relative damping index and the force of non-elastic resistance ((N/(m/s) or kg/s)) of two vehicles. The first of them is equipped with a suspension containing elastic hinges made of rubber, and the second one elastic hinges with MRA in the form of a torus.

The damping properties of rubber are not affected by the magnetic field, therefore its relative damping index D_r, obtained during bench tests, is constant and equal to

$$D_r = 0{,}035. \quad (5)$$

The experimentally obtained force of non-elastic resistance of the HA of the standard suspension of one of the vehicles is equal to:

$$\beta_a = 4000 \text{ kg/s}. \quad (6)$$

To determine the force of the non-elastic resistance of the suspension with MRA, we will use the known dependence for the critical resistance coefficient β_k of the oscillating system [kg/s]:

$$\beta_k = 2\cdot(C\cdot m)^{0,5}, \quad (7)$$

where m is the mass involved in oscillations; C is the suspension stiffness.

With the mass m = 2000 kg of the part of the body, which is on one wheel of the vehicle, and the stiffness of the elastic suspension C = 117800 N/m, the critical force of the non-elastic resistance of the suspension with improved MRA β_{kv} will be

$$\beta_{kv} = 2\cdot(117800\cdot2000)^{0,5} = 30699 \text{ kg/s}. \quad (8)$$

The force of the non-elastic resistance of a vehicle suspension with M without HA β_v

$$\beta_v = 0{,}102\cdot30699 = 3099 \text{ kg/s}. \quad (9)$$

The force of the non-elastic resistance of the suspension of a vehicle with HA and elastic hinges of levers with MRA β_{av}

$$\beta_{av} = 4000 + 3099 = 7099 \text{ kg/s}. \quad (10)$$

The force of the non-elastic resistance of the suspension of a vehicle with rubber hinges without HA β_r

$$\beta_r = 0{,}035\cdot30699 = 1074 \text{ kg/s}. \quad (11)$$

The force of the non-elastic resistance of the suspension of a vehicle with HA and elastic hinges of levers made of rubber β_{ar}

$$\beta_{ar} = 4000 + 1074 = 5074 \text{ kg/s}. \quad (12)$$

The relative damping index of the suspension of the vehicle with HA and elastic hinges of levers made of rubber is

$$D_{ar} = (\beta_a + \beta_r) / \beta_k; \quad (13)$$

$$D_{ar} = (4000 + 1074) / 30699 = 0{,}165. \quad (14)$$

The relative damping index of the suspension of the vehicle with HA and elastic hinges of the levers with improved MRA is

$$D_{ar} = (\beta_a + \beta_v) / \beta_k; \quad (15)$$

$$D_{ar} = (4000 + 3099) / 30699 = 0{,}231. \quad (16)$$

Obviously, thanks to the increase of 7099/5074 = 1.4 times the force of the non-elastic resistance of the suspension when it is equipped with an improved MRA, the damping qualities and smoothness of the vehicle are significantly improved.

To evaluate the effectiveness of the control of damping of the suspension of the vehicle, Fig. 10 shows the dependence of the relative damping index on the flux density of the controlling magnetic field for variants of the MEA designs and the standard suspension of the wheeled vehicle.

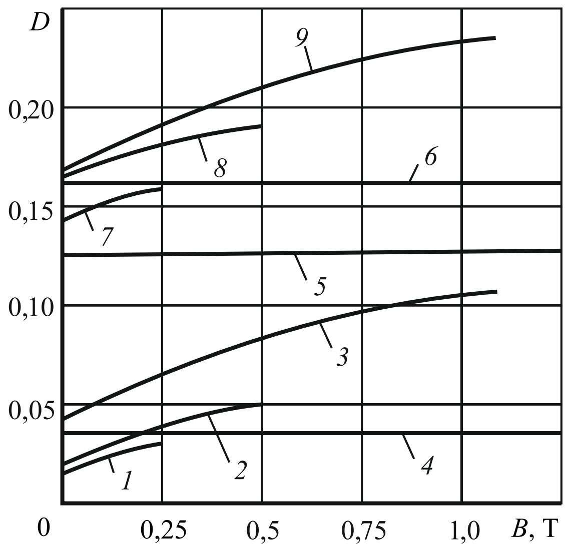

Fig. 10. Dependencies of the relative damping index of the suspension oscillations on the flux density of the controlling magnetic field of the MRA. *Experimental*: *1* – the first and second variants of MRA; *2* – the third variant of the MRA; *3* – improved MRA; *4* – elastic rubber hinges; *5* – HA; *6* – standard suspension with HA and rubber elastic hinges. *Calculated*: suspension with HA and elastic hinges: *7* – according to the first and second variants of the MRA; *8* – according to the third variant of the MRA; *9* – with improved MRA

Graphs in Fig. 10 allow to compare the efficiency of a few vehicles' suspensions. Graph *1* proves that the MRA according to the first and second variants of designs has a relative vibration damping index of no more than 0.03. When installing it to the suspension together with the regular HA (*5*), a relative vibration damping index is no more than 0.16 (*7*) is realized, i.e. at the minimum level of the recommended (0.15 – 0.25) for vehicles. The reasons for this are related to the presence in the MRA of a volume with too little flux density of the controlling magnetic field, «magnetic bridges» on the end parts of the magnetic circuit of the elastic hinge, and the lack of collinearity of the flux density vector of the controlling magnetic field with the directions of the filler conglomerates and deformations of the MRA.

Graph *2* proves that the MRA according to the third variant of the design has a relative vibration damping index of 0.05. When installing it to the suspension together with the standard HA (*5*), a relative vibration damping index of 0.18 (8) is realized, i.e. at the minimum level, The reason for this is the appearance of «magnetic bridges» and the lack of collinearity of the flux density vector of the controlling magnetic field with the directions of deformations and filler conglomerates.

Graph *4* proves that standard rubber elastic hinges reproduce the relative vibration damping index at the level of 0.035. When installing them to the suspension together with the standard HA (*5*), the relative vibration damping index (*6*) is realized at the level of 0.165, that is, almost the minimum recommended. This is confirmed by experimental studies of the movement of vehicles on roads with a heavy profile, in the process of which it was found that there is not enough damping on such roads, and standard HAs overheat [1].

Graph 3 proves that the suspension equipment of the vehicle with an improved variant of the MRA design reproduces the relative vibration damping index at the level of 0.102. When installing the MRA to the suspension together with the standard HA (*5*), a relative vibration damping index of 0.231 (*9*) is realized, which is close to its maximum recommended value (0.25). The reason for this is as follows: collinearity of the flux density vector of the controlling magnetic field with the directions of deformations and conglomerates of the MRA filler is ensured, the controlling magnetic field is concentrated only in the toroid and is regularly distributed throughout its volume, and there are no «magnetic bridges».

An increase in the relative vibration damping index from 0.165 to 0.231 (that is, by 1.4 times) during suspension control should significantly improve the smoothness of the vehicle.

Conclusions.

1. Analysis of the sources revealed that magnetorheological elastomers have certain prospects for use in technical devices. Known designs of magnetorheological actuators (MRAs) of controlled suspensions (CSs) of vehicles have inherent disadvantages: it is impossible to achieve the required value of the flux density of the controlling magnetic field, to direct it along conglomerates of ferromagnetic filler and deformations, and the presence of zones where it is too small, which reduces the efficiency of control of CS.

2. The design of the MRA, which is devoid of the mentioned shortcomings, has been improved and patented, and is made in the form of toroids with control coils made of conductive elastic polymer.

3. It was found that the average value of the flux density of the controlling magnetic field of the improved MRA reaches 0.85 T (that is, the limit where the ferromagnetic filler is just beginning to be magnetically saturated, and the magnetization graph is close to linear, and its relative magnetic permeability is the largest and almost constant), and the zones where the magnetic flux density is too small – absent.

4The dependence of the damping index of MRE samples on the flux density of the controlling magnetic field is built, which allows to predict its damping qualities at the design stage of the CS.

5. The efficiency of suspensions with an improved MRA and with a regular suspension containing elastic hinges made of rubber was compared in terms of the relative damping index. The relative vibration damping index of the vehicle suspension with standard hydraulic shock absorber and elastic lever hinged with improved MRA at the largest control current is 0.231, which is 1.4 times more than that of the standard suspension, which will positively affect the smoothness of the vehicle.

6. The direction of further research is to optimize the parameters of the control coils to ensure their protection against overheating.

Conflict of interest. The authors of the article declare no conflict of interest.

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