This paper considers issues related to the undercarriage system of a high-speed electric train with body inclination and a vibration recovery system. The main suspension systems of the electric train body, which are currently used, were investigated. The existing shock absorption systems and alternative approaches and solutions for increasing the speed characteristics of electric rolling stock have been highlighted. A basic problem of these suspension systems was put forward, which is the lack of the possibility of recovery of oscillations, as well as the complexity of systems for tilting the body. The main dimensional and power parameters of the proposed promising shock absorber are presented. The characteristics of basic parameters of the electromechanical shock absorber were compared with those of a pneumatic spring shock absorber. A simulation model of a high-speed electric train with an electromechanical shock absorber was built in the MATLAB Simulink environment. The main units of the simulation model were defined and described, owing to which it is possible to simulate the inclination of the body to a given angle and the simulation of vibration energy recovery.

Based on the results of simulating the operation of an electromechanical shock absorber as part of the undercarriage of the electric locomotive, it was determined that the synthesis of this system makes it possible to tilt the body by 5 degrees in 2 seconds. It is also stated that the proposed system makes it possible to reduce the vibrations of the electric train body by 2 times, and to recover 84 W/h of vibration energy. The body tilt results are predetermined by the speed of the mechanism due to the absence of a compressor set used in the pneumatic system.

The scope of application of the vibration damper also includes the automotive field, subject to additional research into the form, amplitude of road surface vibrations and changes in overall parameters in accordance with the requirements

Keywords: electromechanical shock absorber, simulation model, body inclination, vibration damping, undercarriage

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SYNTHESIS OF AN ELECTROMECHANICAL SYSTEM OF BODY TILT AND RECUPERATION OF VIBRATION ENERGY FOR A HIGH-SPEED ELECTRIC TRAIN

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1. Introduction

Modern railroad transport is a complex logistics system that requires solving issues related to traffic safety and the speed of electric rolling stock, which is primarily determined by its driving performance [1]. These indicators depend on many factors: the traction system [2], the control system [3], the traction engine [4], its cooling system [5], and the undercarriage (suspension). In turn, the traction system has undergone many improvements in terms of gear optimization. Modern control algorithms have been introduced into the control system to improve the system's efficiency, which also allows optimizing the temperature regime of the engines. The traction engine underwent changes in design [6], and in some cases it was replaced by a different type of engine.

One of the ways to increase the speed of rail transport is the use of electric rolling stock with body tilting mechanisms. This technology makes it possible to significantly increase the speed of trains when passing curved sections of the path, which is an alternative to creating a new infrastructure for high-speed railroads.

In trains, pneumatic, hydraulic, and electromechanical systems are used as body tilt drives, which have a number of advantages and disadvantages. The hydraulic system has a large number of lines and devices that work under high pressure, which reduces the overall reliability of the system and increases the likelihood of leaks of the working fluid, and also requires proper maintenance by engineers. The pneumatic system, the device of which, in fact, is similar to the hydraulic one, has an increased activation time due to the low density of the working medium – air. The electromechanical system used on modern trains does not provide the possibility of self-return of the body to its initial position in the event of a power outage or other emergencies, which directly affects traffic safety.

To perform the damping function, the basic element of the undercarriage of electric rolling stock is a system of spring, pneumatic-spring suspension, and others [7].

An alternative approach to increase the dynamic characteristics and speeds of electric trains is the use of electromechanical shock absorbers, which can recover part of the oscillations into electrical energy. Such energy can be used on rolling stock and perform the function of tilting the body, simplifying the system. There are many energy accumulators [8] in trains, which can be additionally powered by the energy generated during damping of oscillations by electromechanical shock absorbers. Energy accumulators can be installed both on the transport infrastructure [9] and on the rolling stock of automobile [10] and railroad transport [11]. Therefore, research aimed at improving the running characteristics of an electric locomotive is relevant.

2. Literature review and problem statement

One of the first major series of tilting trains was Japan's 381 series, which entered service between Nagoya and Nagano in 1973 and remained in service for over 20 years. The passive tilting system of trains is based on the body, which rests on the cross beams of the bogies. The springs of the second stage of suspension contribute to tilting through pairs of rollers [12].

A more modern tilting body system was introduced in 1986 with the creation of the ETR450 train. The train contained a hydraulic body tilting system.

More than 5,000 tilting trains are in operation in the world, in Australia, Germany, Finland, France, Switzerland, Sweden, and Japan, Spain, Italy, Canada, China, and a number of other developed countries.

Regarding electromechanical shock absorbers as vibration dampers, used mainly in road transport, they are primarily positioned precisely as vibration dampers [13]. In work [14], a quantitative assessment of the power dissipated in the shock absorber of the car suspension was made, but an effective solution for its accumulation was not proposed. The use of a genetic LQR controller was proposed in [15], while the shock absorber itself is a consumer of energy and there is no way to recover it. A similar algorithm was proposed in [16], but already for use as part of an aircraft chassis. The electric suspension Bose Suspension System (Bose Corporation, USA) is of great interest. In the design based on the Lexus LS400 sedan (Toyota Motor Corporation, Japan), the spring suspension was replaced with a torsion one, and the shock absorbers were replaced with linear electric motors, which are controlled by a computer unit through powerful amplifiers. Information comes to it from sensors of movement of each of the wheels. Such a solution greatly complicates the design and makes it impossible to create an energy recovery process. The patent [17] proposes a design of an electric shock absorber, which includes a twisted element, the outer part of which is made of electrically conductive material. The magnetic element consists of a rod, on the central axis of which magnets are located. The outer part is made in such a way that during vertical movements of the wheel, the rod with magnets can enter it. The current arising in the winding depends on the movement of the wheel. The presence of some magnets increases the operating frequency of the shock absorber and losses in steel, which significantly reduces its efficiency as an energy recuperator.

When choosing the type of electromechanical shock absorber converter, we note that of the known types – asynchronous, synchronous, electromagnetic [18], and direct current – the most suitable option appears to be the latter. To provide relatively small movements in induction and synchronous motors, complex semiconductor converters are required. These converters must change the voltage and frequency to units of hertz at the output. In addition, these types of engines have a low overload capacity. The third is characterized by a rather uneven characteristic of the force of traction from displacement, which is close to hyperbolic. An electromechanical shock absorber requires a constant traction (mechanical) characteristic that varies only with the speed of the armature. A linear motor has a wide range of uses, especially where linear movement is required, and when a rotary motor is used, an additional gearbox is required. A good example is its use to change the direction of train movement [19].

In [20], a comparison of running characteristics of possible types of electromechanical shock absorbers was performed. Also, a comparison was made with existing types, such as air-spring shock absorbers; conclusions were drawn that electromechanical shock absorbers are not inferior to the new generation of shock absorber types in terms of their running characteristics.

In work [21], it is proposed to use a rotary electric generator as part of the shock absorber, which has a rack-and-pinion mechanism that converts the linear movement of the piston into the rotational movement of the rotor. One-way rotation of the rotor in different directions of wheel movement is provided by two bevel gears and two overrunning clutches. Such a scheme complicates the structure while shock loads in the suspension lead to a significant reduction in the resource of overtaking clutches.

A variant of overcoming the complexity of the system and avoiding the transformation of rotary motion into linear movement was studied in [22]. A method for controlling the operating modes of running parts using controlled electromechanical shock absorbers activated by energy generators without the use of an external power source was considered. It has been experimentally proven that when driving on an uneven, undulating road, the suspension parameters can be controlled by activating electromechanical shock absorbers of a certain amount of regenerated voltage. This principle of the damper is most similar to the one proposed in this article, but at the same time, the issue of the tilt of the body has not been resolved.

All this confirms that it is justified to conduct research using a linear mechanism.

3. The aim and objectives of the study

The aim of this study is the synthesis of an electromechanical shock absorber in the undercarriage of a high-speed electric train, which ensures the performance of the tilting of the body and recovery of vibrations and could provide an opportunity to improve the running characteristics of the electric locomotive.

To achieve the goal, the following tasks were set:

– to propose a simulation model of a high-speed electric train with an electromechanical shock absorber;

– to obtain the results of body tilt modeling with an electromechanical car shock absorber;

– to obtain the results of simulation of damping of oscillations by an electromechanical shock absorber in the car.

4. The study materials and methods

The object of scientific research is the process of finding the optimal simulation model of the undercarriage of an electric locomotive with cradle suspension for the synthesis of an electromechanical shock absorber. A hypothesis is proposed, according to which the synthesis of an electromechanical shock absorber will improve the running characteristics of rolling stock.

The following simplifications were adopted in the study. As a source of oscillations, a source of constant sinusoidal oscillations with a frequency of 2 Hz and a constant amplitude was used. The specified frequency is the frequency of oscillations of the body at an average speed of the electric locomotive of 60 km/h. Also, a one-dimensional model of oscillations is used, which means that only one direction of oscillations is considered. This approach makes it possible to simplify the analysis and focus on the main aspects of the influence of fluctuations. This simplification assumes that other possible motions or oscillations that may occur in three-dimensional space are not taken into account or are assumed to be neglected at this stage of the study.

A method of mathematical modeling is the basis of solving the problem of synthesizing an electromechanical shock absorber in the undercarriage. According to the results of mathematical modeling of the electromechanical system, its efficiency of use in the proposed system is determined. Adequacy of the results was confirmed by the use of proven mathematical modeling software package MATLAB Simulink (USA).

5. Results of investigating the electromechanical body tilting system and vibration energy recovery for a high-speed electric train

5. 1. Mathematical model of a high-speed electric train with an electromechanical shock absorber

As the basic design of the shock absorber, an electromechanical DC shock absorber was chosen, the sketch drawing of which is shown in Fig. 1.

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

The principle of operation of the shock absorber can be explained as follows. The shock absorber works on the basis of the principle of using the electromagnetic phenomenon in the context of damping mechanical vibrations. In this device there is a permanent magnet, which is magnetized radially and located on the armature (Fig. 1). This magnet creates a magnetic field, and the magnetic lines of force of this field are collected in a closed circuit together with the air gap between the armature and the stator winding 2 (Fig. 1). When external dynamic forces occur that cause the armature to move up or down, the armature also moves. During this movement, an electromotive force (EMF) is created in the stator winding. This force can be locked into the load and cause an armature current to flow. In the conductors of the stator winding with a current, an electromagnetic force is formed, which opposes the dynamic force that arose as a result of the vibrations of the body. This process helps dampen mechanical vibrations. An important aspect is the influence of the stator reaction flux on the excitation magnetic flux. This flux demagnetizes one of the halves of the magnetic circle of the armature (upper or lower), depending on the direction of movement of the armature (up or down). This phenomenon can lead to saturation of the magnetic circuit and reduction of the effective electromagnetic force. These processes are similar to those observed in unipolar DC electric machines. The direction of the magnetic flux *F* is shown in Fig. 1.

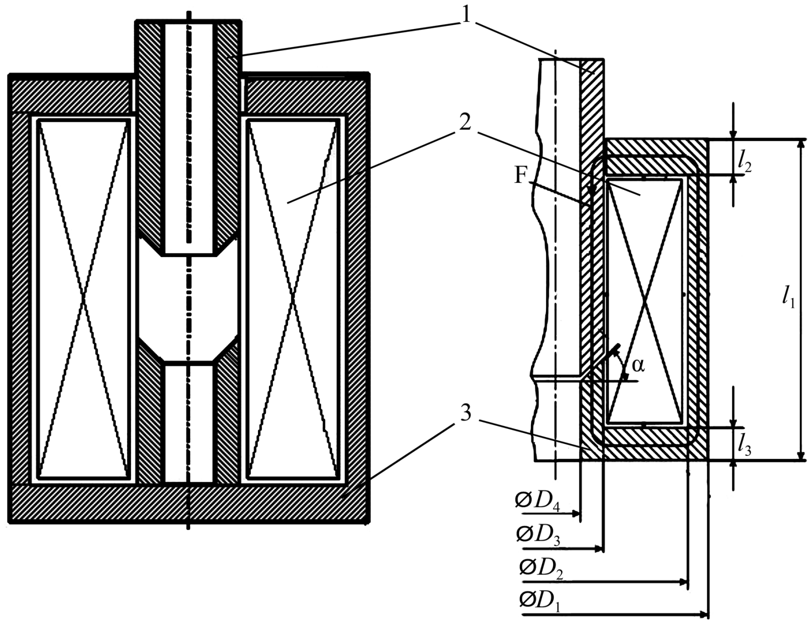

Fig. 1. Sketch drawing of electromechanical DC shock absorber: 1 – armature; 2 – stator winding; 3 – stator

Table 1

The main dimensions of the electromechanical shock absorber

Parameter	Value	Note
D_1	450 mm	Diameter of the electromechanical shock absorber
D_2	400 mm	Diameter to the end of the stator winding
D_3	292 mm	Diameter of the armature assembly
D_4	110 mm	Diameter of the armature pipe
l_1	510 mm	Length of the electromechanical shock absorber
l_2	56 mm	Length to the stator winding
α	5°	Angle of inclination of the tip of the armature

Adjustment of the angle of inclination of the body takes place on the basis of feedback from the inclinometer and is implemented with the help of a PID controller. The regulator automatically adjusts the duty cycle of the pulse-width modulation voltage [23], which is applied to the stator to achieve and maintain the specified angle of inclination. Body roll angle measurement is provided by an inclinometer that can accurately determine the position and roll angle of the body, which minimizes system overshoot.

The main characteristics, according to which it is possible to evaluate the effectiveness of the use of an electromechanical shock absorber, are given in Table 2.

Table 2

Basic parameters of the electromechanical shock absorber

Parameter	Value
Damping coefficient	25 kN*s/m
Operating frequency range	1–500 Hz
Power	2000 N
Specific force	44 N/kg

According to Table 2, it is possible to compare the range of operating frequencies of a pneumatic spring shock absorber, which has operating frequencies of 1–1000 Hz, with the operating frequency parameters of an electromechanical shock absorber. Based on this, the pneumo-spring shock absorber has advantages over the electromechanical one, but according to the previous analysis [24], the oscillation frequency at an average speed of 60 km/h is 2 Hz. That is, the electromechanical shock absorber has a sufficient range of operating frequencies for its use as part of the rolling stock suspension.

Work [25] considered the synthesis of an electromechanical shock absorber in the suspension system of a subway car. It is proposed to use an electromechanical DC shock absorber as part of the undercarriage of a subway car, which makes it possible to recover part of the vibration energy and accumulate it for further use.

To consider the issue of the synthesis of electromechanical shock absorbers, an undercarriage with cradle suspension will be used, the model of which is shown in Fig. 2. The use of this type of undercarriage makes it possible to integrate an electromechanical shock absorber into the suspension system of an electric rolling stock with minimal design modifications.

For a more efficient organization of the research process of an electromechanical shock absorber, excluding from it the stage of building a system of differential equations in the form of a Cauchy problem, the writing of numerical integration procedures should be carried out on the basis of simulation models. Unit modeling approaches make it possible to easily change the structure and configuration of the system without «rewriting» the initial system of differential equations. Mathematical models were solved using simulation modeling in the MATLAB Simulink environment.

The simulation model consists of the following main units: body tilt drive, converter, operation and control modules (Fig. 3). In turn, the converter consists of a power source and two thyristor modules that perform the work of pulse width modulation, which makes it possible to reduce the over-regulation of the system and more correctly maintain the angle of inclination of the body.

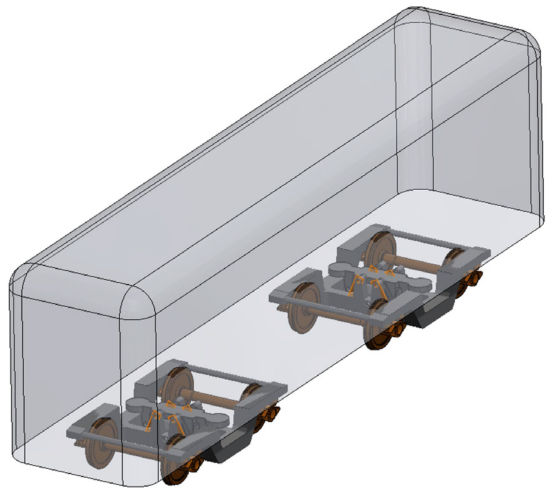

Fig. 2. 3D model of a car with a cradle-type bogie

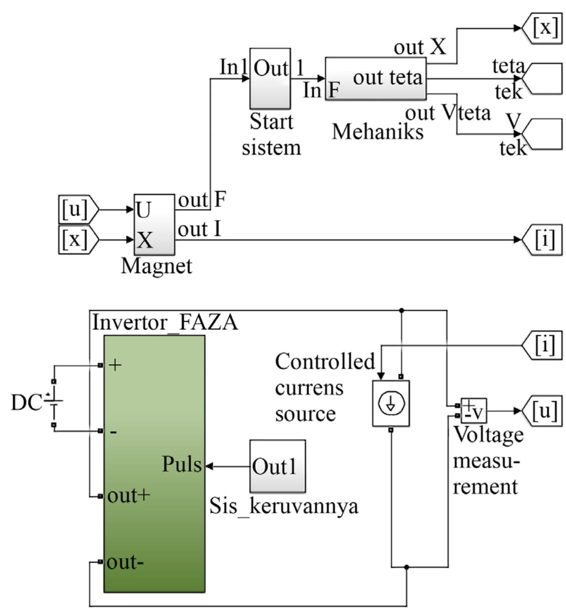

Fig. 3. Block diagram of the tilt mechanism general model

The tilt drive of the body contains the subsystem for modeling the linear electromechanical energy converter «Magnet» (Fig. 5), and the auxiliary subsystem «Mechanics» (Fig. 4), which in turn contains the subsystem for modeling the mechanical part «Mechanism» (Fig. 6).

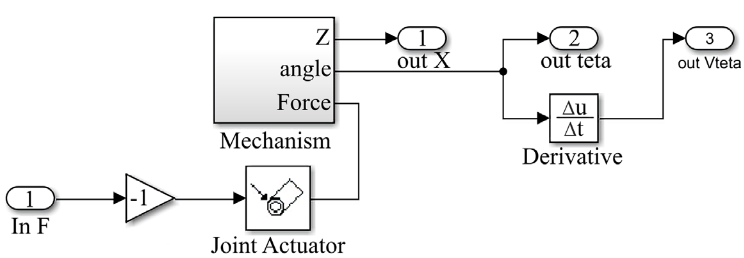

Fig. 4. Block diagram of the «Mechanics» element

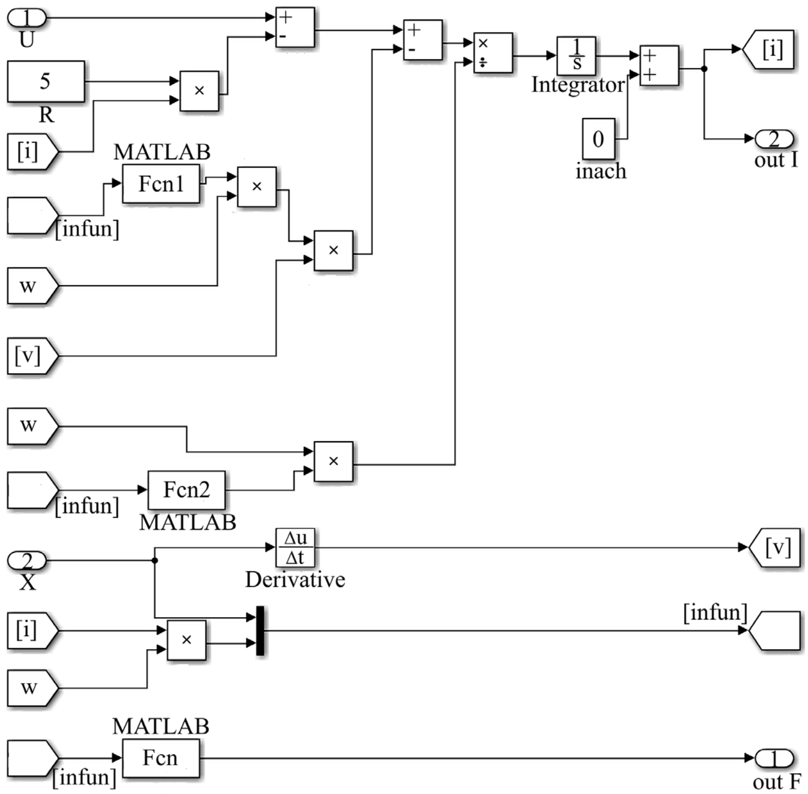

Fig. 5. Block diagram of the «Magnet» element

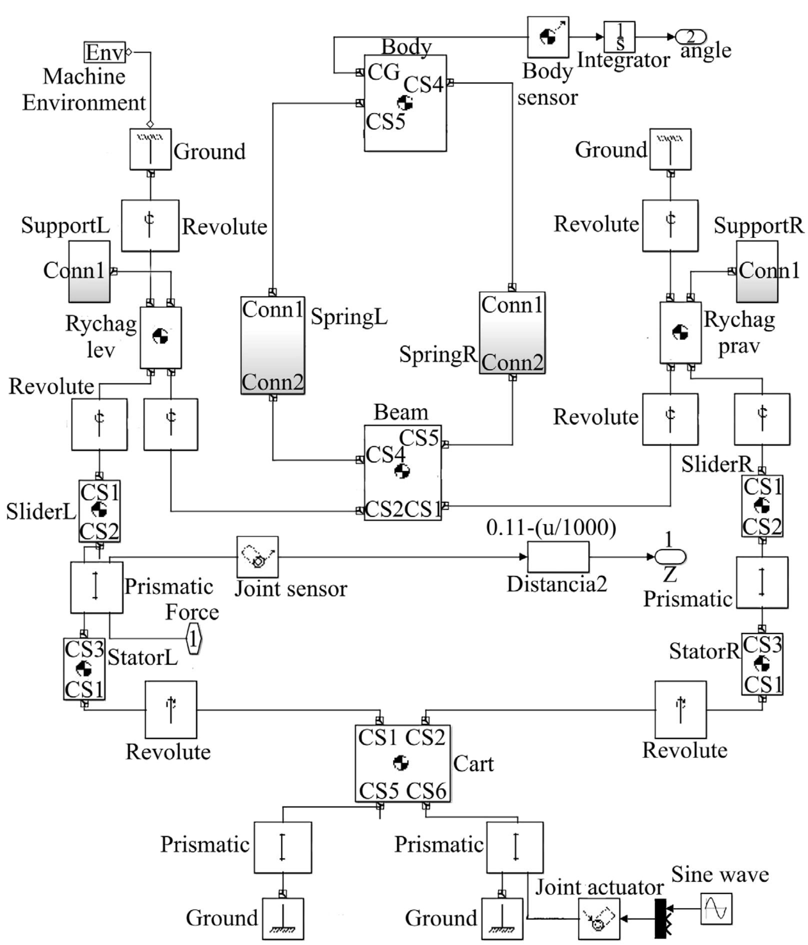

Fig. 6. Block diagram of the «Mechanism» element

The input parameter of this auxiliary subsystem when performing body tilt work is the force realized on the armature, the output parameters are the gap X between the linear motor armature and the stator support, the angle θ of the undercarriage body tilt, and its rate of change. Signal X is fed to the input of the «Magnet» subsystem (Fig. 3), as well as signal U, which is the voltage on the electromagnetic motor obtained from the corresponding output of the converter. The output parameter of the «Magnet» subsystem is the force acting in the working gap of the electromechanical shock absorber (linear motor) of the inclination drive and vibration damping. Also, the current I of the electromagnetic type motor is the output. When switching to the vibration recovery mode, the converter is turned off and a voltage is generated on the output RC filter from the converter, which is generated by the electromechanical shock absorber during the passage of bumps by the electromotive train.

The proposed model of the mechanical part contains a «Body» simulating the body of a high-speed train, which is supported on a tilting beam by means of two pneumatic springs represented by subsystems «SpringL» and «SpringR». The block diagram of the model of the mechanical part is shown in Fig. 6.

The mechanical component of pneumatic springs in this model consists of two objects marked as «DV» and «DN» (Fig. 7). The geometric and physical parameters of these objects correspond to the upper and lower bottoms, respectively. The bottoms are connected by a prismatic hinge that allows a limited degree of freedom – meaning that these objects can only move apart from each other or move closer together.

This hinge is equipped with two sensor-actuated ports. One of these ports is connected to a sensor that is used to measure the distance between the bottoms and the speed of their mutual movement. The second port is connected to the actuator, which is supplied with the value of the pressure force calculated by the mathematical model.

Shock absorbers of this design are electromechanical means of ensuring shock absorption and are used in many systems. They have an armored structure and are connected to other elements of the system using special hinges. Two of these hinges are attached to the shock absorber armatures named «SliderL» and «SliderR» and are connected to the suspension arms, which have their own coordinate systems, which coincide with the coordinate systems of the hinges on the beam suspension. The housings of the electromagnetic motors, designated as «StatorL» and «StatorR», are also connected to the frame of the bogie, called the «Cart», through special joints. These hinges also have actuators that reproduce the friction in the hinges. The armatures of the shock absorbers are connected to the housings through prismatic hinges, which limit the movement to linear movement along the axes. The drive port of the right solenoid motor is used for body tilt or force transmission from vibration damping.

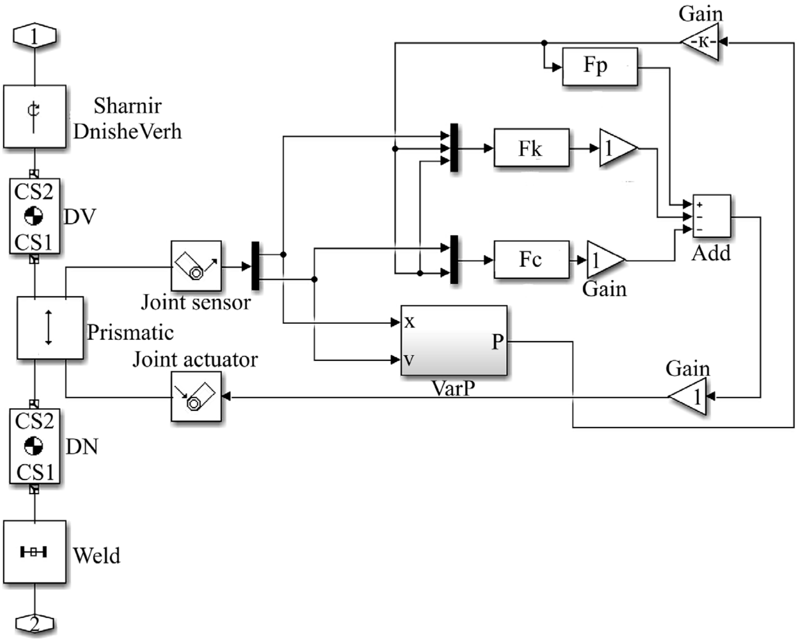

Fig. 7. Block diagram of the «Spring» element

Owing to the «Sine Wave» element, an imitation of oscillations will be set, which in turn will affect the position of the bogie in space, which should move vertically to the left or right, depending on the side of influence.

5. 2. Results of mathematical modeling of the inclination of the car body

Modeling of the body tilt mechanism was carried out under the most intense mode. The maximum angle of inclination of the body was set – 5°, which was determined in work [21] as optimal. The simulation was carried out at a given tilt speed of 2.5°/sec. The tilting process consists of the following stages:

– from second 0 to second 2 – the process of tilting the body to the specified angle is carried out;

– from second 2 up to second 8 – the process of maintaining the angle is underway.

The simulation results are shown in Fig. 8.

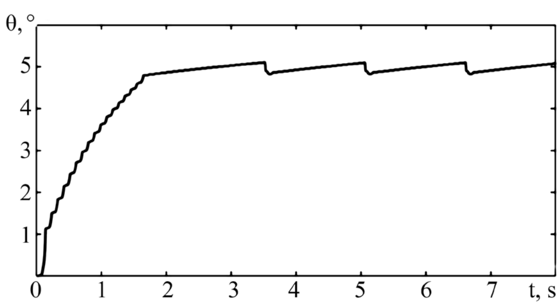

Fig. 8. Oscillogram of body tilt as a function of time

One can see on the oscillogram that reaching the given angle of 5° takes less than 2 seconds. At the same time, the deviation when maintaining the given angle is only ±0.2° (re-adjustment of the system).

The voltage on the armature winding has a pulsating character, which is caused by the action of the control system. The positive part of the pulse, which is limited by the voltage of the power source, is 110 V. The negative part, due to the action of the armature winding, depends on the level of inductance, which increases with the movement of the electromechanical shock absorber during tilting, depending on the position of the magnet, and the duration of the pulse, determined by the excess of the electromagnetic force over the turning force. At the same time, the power supply current is 23 A. The total costs for maintaining the body in an inclined state are 2.5 kW/h. That is, at an average train speed of 60 km/h, 42 W is needed to pass a section of the road with a turn 1 km long.

5. 3. Results of mathematical modeling of vibration damping by electromechanical shock absorber

To simulate oscillations, the movement of the right part of the bogie of a high-speed electric train was set. The displacement amplitude is 50 mm with a frequency of 2 Hz. The frequency of oscillations was based on preliminary analyzes of the road surface at an average speed of electric rolling stock of 60 km/h.

In order to evaluate the operation of the electromechanical shock absorber, a simulation of the operation of the shock absorber without load was carried out.

As a result, the dependence of the voltage on the winding of the electromechanical shock absorber without load (idle mode) on time was built (Fig. 9).

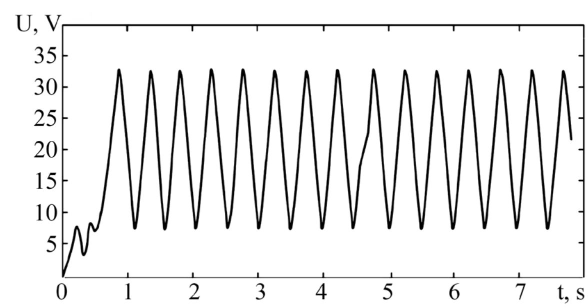

Fig. 9. Oscillogram of the dependence of voltage on the winding of an electromechanical shock absorber without load on time (idle mode)

On the voltage oscillogram of the electromechanical shock absorber (Fig. 10), it can be seen that the voltage produced by the electromechanical shock absorber without load (idle mode) is 33 V in amplitude.

A resistor R, which has a value of 2 ohms, is used as a motor load.

Fig. 10 shows an oscillogram of the operation of an electromechanical shock absorber without connecting a load and with a connected load. The oscillogram of the dependence of voltage on the winding of the electromechanical shock absorber with the load on time is shown in Fig. 11. The oscillogram of the dependence of current in the electric motor-load circuit on time is shown in Fig. 12, and the oscillogram of the dependence of electromagnetic force on the armature of the electromechanical shock absorber in Fig. 13, respectively.

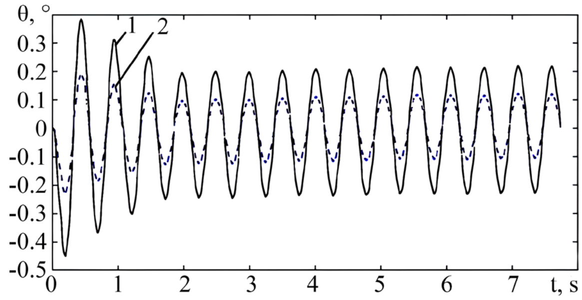

Fig. 10. Oscillogram of the dependence of angle between the bogie and the body on time (electromechanical shock absorber with load): 1 — without connecting the load to the shock absorber windings; 2 — with the load connected to the shock absorber windings

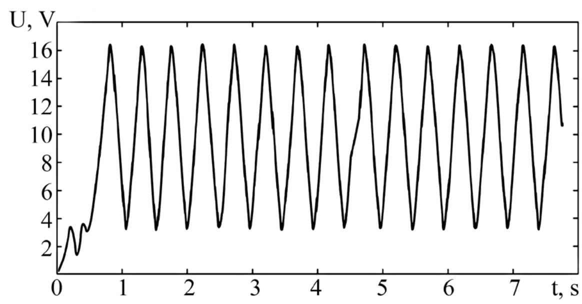

Fig. 11. Oscillogram of the dependence of voltage on the winding of an electromechanical shock absorber with load on time

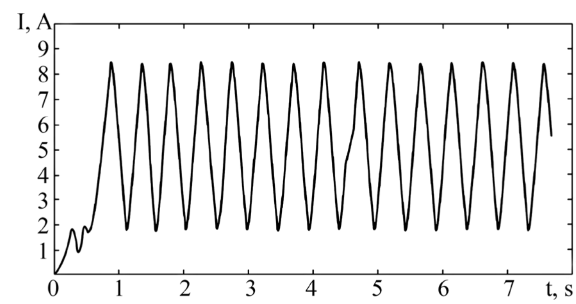

Fig. 12. Oscillogram of the dependence of current in the motor-load electric circuit on time

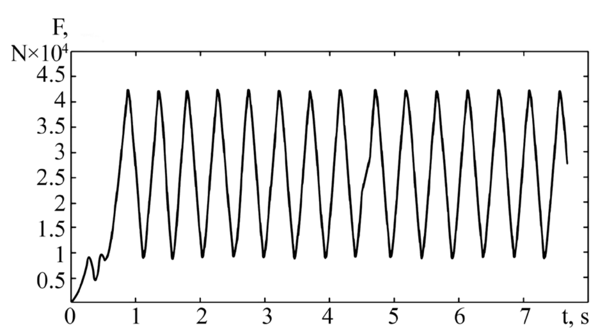

Fig. 13. Oscillogram of the dependence of electromagnetic force on the shock absorber armature on time

It can be seen from the oscillogram of the angle (Fig. 10) that without a load connected to the shock absorber winding (oscillogram 1) at the beginning of operation, the angle changes in the range from –0.45° to +0.38. In 2 seconds, oscillations are damped by a pneumatic spring and the angle range is from –0.2° to +0.2°. When using an electromechanical shock absorber (Fig. 10, oscillogram 2), the result of a 2-fold decrease in the angle between the body and the bogie was obtained, which indicates a corresponding decrease in oscillations. The voltage on the winding of the electromechanical shock absorber when the load is connected is 16.5 V of amplitude value, the current in the motor-load electric circuit is 8.5 A of amplitude value. At the same time, the electromagnetic force acting on the shock absorber armature during vibration damping is 43 kN. Hence, the power that can be produced by the electromechanical shock absorber as a result of vibration damping is 84 W/h.

6. Discussion of results of modeling the operation of an electromechanical shock absorber as part of a high-speed electric train car

The design of an electromechanical shock absorber, consisting of a stator with windings and an armature (slider), is proposed, and a mathematical model of the undercarriage of an electric locomotive is constructed. According to the result of the comparison of the damping characteristics of the air-spring damper and the electromechanical one [21], it is possible to say that the second one is not inferior in the effectiveness of damping oscillations and has a sufficient range of operating frequencies, which is indicated in Table 2.

According to the results of modeling the tilt of the body, it was found that the electromechanical shock absorber takes 2 seconds to reach a given angle of 5°. At the same time, the deviation when maintaining the given angle is only ±0.2° (re-adjustment of the system), which is shown in Fig. 8. The speed of the shock absorber is related to the simplicity of the system and the exclusion of a set of mechanisms for the performance of work, which is also determined by reliability. A hydraulic system and a rotary generator with a rack-and-pinion mechanism [19] cannot ensure reliability due to the previously described complex components and the presence of a complex of additional mechanisms (hydraulic pumps, high-pressure lines, etc.).

According to the simulation results, damping of oscillations and energy recovery by the proposed electromechanical shock absorber is effective, which can be said from the oscillograms in Fig. 9–13. Without operation of the electromechanical shock absorber, the angle between the body and the bogie is in the range from –0.45° to +0.38°. After loading the electromechanical shock absorber, the range of this angle is reduced by 2 times and is from –0.2° to +0.2°. The power recovered by the electromechanical shock absorber is 84 W/h during oscillations with an amplitude of 50 mm and a frequency of 2 Hz, while the electromagnetic force on the shock absorber armature is 43 kN.

That is, the issue of the complexity of body tilting systems is resolved, and two problems (body tilting and vibration recovery) are solved by implementing one system, which gives an advantage over previously proposed solutions [12, 13, 24].

Thus, our work proposes a simulation model of a high-speed electric train, which includes already existing damping systems (pneumo-springs), and promising ones, such as an electromechanical shock absorber, which has a simple design and control system.

A simulation model shown in Fig. 3–7 was built, which can be used as a basis for optimizing the parameters of both the proposed shock absorber and the existing parts of the car (bogie, suspension, body, etc.). The disadvantage of the proposed system may be the difficulty of retrofitting already existing electric locomotives for the synthesis of a system with an electromechanical shock absorber.

The limitation of the proposed simulation model is that the design of the DC electromechanical shock absorber, which is shown in Fig. 1, can be used for tilting the body up to 7 degrees. In order to perform a body tilt with a greater angle, a redesign of the shock absorber structure is required. Also, it should be noted that the research was conducted at oscillations with a constant amplitude and frequency. Therefore, the further development of the model built may involve the simulation of the movement of a high-speed electric train on a section of the road with turns (to simulate the tilt of the body) and irregularities (simulation of oscillations).

7. Conclusions

1. A module-type simulation model of a high-speed electric train car with a cradle-type undercarriage has been proposed and constructed, which makes it possible to easily change the structure and configuration of the system without «rewriting» the initial system of differential equations and scaling it in the future.

2. The results of modeling the tilt of the body of a high-speed electric train were obtained. Achieving the predefined angle of 5 degrees in 2 seconds confirms the effectiveness of using the system to perform work on tilting the body of a high-speed electric locomotive.

3. According to the results of simulation of damping of oscillations with an electromechanical shock absorber, it is shown that the proposed system makes it possible to reduce body oscillations by a factor of 2, while recuperating 84 W/h of energy.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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