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DETERMINING THE DYNAMIC INDICATORS OF THE PNEUMATIC SPRING FOR HIGH-SPEED ROLLING STOCK IN THE ZONE OF A RAIL JOINT ALONG A RAILROAD TRACK

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The object of this study is the pneumatic spring of the high-speed railroad rolling stock that moves over the rail joint of a railroad track with a vertical ledge.

The task solved was establishing the dynamic behavior of the rubber cord shell of the pneumatic spring of the high-speed railroad rolling stock, taking into account the design features of the railroad track, namely the rail joint.

The methodology for experimental testing of the pneumatic spring of the high-speed railroad rolling stock using the proposed dynamic test installation is given. Experimental tests of the pneumatic spring were carried out within the rail joint of the railroad track, which has a vertical ledge of 7.0 mm. It was established that the maximum value of the accelerations of the rubber cord shell of the pneumatic spring occurs in the vertical plane. The maximum vertical accelerations of the rubber cord shell of the pneumatic spring were 2.4 m/s^2, horizontal transverse accelerations – 0.85 m/s^2, and horizontal longitudinal accelerations – 0.9 m/s^2.

It was determined that the deformations of the pneumatic spring in the vertical plane are higher than the deformations in the horizontal plane. The value of the maximum vertical deformations of the pneumatic spring was 4.1 mm, while the maximum value of horizontal deformations was 1.2 mm.

The natural frequencies and logarithmic decrements of oscillations damping were determined based on the obtained records of the free oscillations of the rubber cord shell of the pneumatic spring. It was established that the value of the first natural frequency of oscillations of the pneumatic spring is 3.21 Hz.

The logarithmic decrement of oscillation damping of the rubber cord shell of the pneumatic spring was determined based on the constructed graph of oscillation damping with an approximating exponent. It is 0.2147.

The obtained values of the dynamic indicators of the new pneumatic spring could be used in the future to control changes in the physical and mechanical properties of the rubber cord shell of the pneumatic spring under the operational conditions of the railroad track. In practice, engineers and scientists will be able to take into account the obtained dynamic parameters of the spring when designing and improving the pneumatic spring for high-speed train movement

Keywords: joint of railroad rails, pneumatic spring, high-speed rolling stock, acceleration of the rubber cord shell, deformations of the spring, natural frequency of spring oscillations

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1. Introduction

The introduction of high-speed rolling stock in railroad transport makes it possible to solve the task to improve the capacity of railroads. However, a significant increase in operational speeds of rolling stock implies the need to control its dynamic indicators and traffic safety indicators [1, 2]. In addition, an increase in the speed of rolling stock leads to structural changes in its mechanical part. Therefore, on high-speed trains, a pneumatic system of spring suspension is used in the second stage of spring suspension [3]. The main structural element of the system is a pneumatic spring of the diaphragm type, which can work in both vertical and horizontal longitudinal and transverse directions (Fig. 1).

The pneumatic spring for high-speed rolling stock is a rubber cord shell that deforms during dynamic operation. The use of a pneumatic spring suspension system makes it possible to increase the static deflection of the system, improve anti-vibration properties, and increase the comfort of passenger transportation.

During rolling stock operation, there is a force interaction between the wheelset and the rail track [4]. Features of the force interaction are the joints; when traveling over them, a dynamic addition of forces occurs between the structural elements of the rolling stock, which causes oscillations and deformations of the pneumatic spring. The forces lead to the deformation of the pneumatic spring, and the fluctuations also affect the criteria of driving comfort. The magnitude of the forces, deformations, and accelerations of the pneumatic spring mainly depends on its dynamic characteristics. All this mainly forms the general level of dynamic indicators and safety indicators for the rolling stock motion during its high-speed movement.

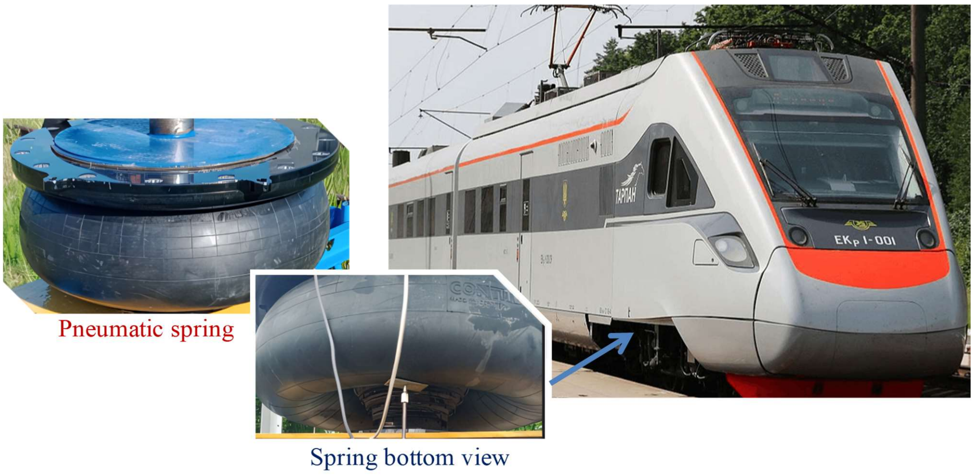

Fig. 1. Pneumatic spring for high-speed rolling stock

Taking into account the peculiarities of force interaction between the rolling stock and the rail track, investigating the spatial deformations and accelerations of the pneumatic spring that occur when traveling over the rail track junction is an urgent task of scientific research. This will make it possible, in the future, even at the stage of designing high-speed rolling stock, to determine its dynamic indicators and traffic safety indicators under various operating conditions of the railroad. From a practical point of view, the use of reference values of accelerations, deformations, and natural frequencies of oscillations of the pneumatic spring will make it possible to monitor its technical condition throughout the entire service life of the rolling stock.

2. Literature review and problem statement

Much attention has been paid to investigating the dynamic operation of the pneumatic spring of the high-speed rolling stock and determining its dynamic characteristics under different operating conditions. Namely, in work [5], the influence of the pneumatic system of spring suspension on the comfort of movement of high-speed rolling stock was investigated. Using the test setup, the influence of the deformation amplitude and internal pressure on the transverse stiffness of the pneumatic spring was analyzed. The vertical stiffness was found at different amplitudes and frequencies of disturbances, volumes of the additional tank, and diameters of the connecting pipeline. However, the studies were conducted under laboratory conditions by applying a sinusoidal disturbance. This does not make it possible to investigate the random nature of the disturbance that occurs under the rolling stock operating conditions, especially in the zone of the rail joint of the railroad track.

In [6], a mathematical model of the vertical stiffness of a pneumatic spring was built. To this end, the equations of thermodynamics and hydrodynamics were used, and the geometric parameters were found by an approximate analytical method. To check the accuracy and reliability of the mathematical model, experimental tests were carried out at a disturbance frequency of up to 20 Hz with an amplitude from 2 mm to 10 mm. However, the work did not investigate the accelerations of the pneumatic spring and its deformations taking into account the vertical ledge at the rail joint of the railroad track.

In [7], the effect of the geometric parameters of the connecting pipeline and the volume of the additional tank on the dynamic characteristics of the pneumatic spring suspension system was investigated. Research was conducted in the frequency range 0 20 Hz, in accordance with the EN13597 standard. The proposed mathematical model and the conducted experimental studies do not give a complete picture of the dynamic operation of the pneumatic spring since they do not take into account the peculiarities of the interaction of the rolling stock with the rail track in the area of the rail joint.

In work [8], the authors reported a study into the influence of parameters for the pneumatic spring suspension system on its dynamic characteristics, and then these parameters were adjusted to minimize the Sperling comfort index during rolling stock operation. It was established that by modifying the parameters of the pneumatic spring suspension system, passenger comfort improves. In this case, the ride comfort index decreases by approximately 10 %. A sinusoidal motion with a frequency from 0.5 Hz to 10 Hz and an amplitude of ±10 mm was used as a disturbance. At the same time, the research does not take into account the accelerations that occur on the pneumatic spring when traveling over a rail track joint.

In addition, work [9] considered a complete four-axle rolling stock model with 70 degrees of freedom, which included a body, two bogies, and four axles of wheelsets. In order to take into account the influence of rail track irregularities, a simplified model of the railroad track is proposed [10, 11]. The basis of the conducted research was the optimization of parameters for the pneumatic spring suspension system based on the use of the Genetic Algorithm optimization method. However, the model of the railroad track does not take into account joint irregularities, which are often a disturbing factor in the operation of rolling stock. As a result, such studies need to be continued.

Theoretical modeling and experimental analysis of the vertical stiffness of a pneumatic spring were carried out in [12]. The new air spring model includes structural parameters including effective area, rate of change of effective area, effective volume, rate of change of effective volume, and stiffness of the rubber cord shell. An experimental setup was designed for identification of structural parameters and verification of vertical static and dynamic stiffness. The tests showed that the stiffness of the rubber cord shell has amplitude-dependent and frequency-dependent characteristics. However, the disturbances created by the experimental setup are standard and do not reflect the real operating conditions of the rolling stock during its interaction with the rail track and in the area of the rail joint. In addition, the main attention was paid to the vertical stiffness while other dynamic parameters of the pneumatic spring were not investigated.

In [13], the authors investigated the impact of the dynamic operation of the pneumatic spring suspension system on the safety and comfort of rolling stock. To this end, quasi-static and dynamic tests of the pneumatic spring were carried out using the test installation. It was established that neglecting the effects of the connection between shear and roll deformation in the pneumatic spring could lead to an underestimation of the maximum load on the track in the vertical direction, which is associated with the passage of a curved section of the track. However, in the work, comfort was analyzed only in the vertical direction and only with a cosine disturbance. It should be noted that this research approach does not take into account the influence of a rail joint in the railroad track on the dynamic parameters of the pneumatic spring in the high-speed rolling stock.

In [14], the influence of different types of connection between the pneumatic spring and the additional tank on the dynamic characteristics of the pneumatic spring suspension system was investigated. It has been established experimentally that it is recommended to use a pneumatic system of the "bellow-orifice-pipe-reservoir" type to suppress low-frequency disturbances. For damping high-frequency disturbances, it is recommended to use a pneumatic system of the "bellow-orifice-reservoir" type.

In [15], the vertical stiffness of a pneumatic spring was investigated, taking into account the rate of change of its effective area. Four different experimental methods were used to study the static and quasi-static vertical stiffness of the pneumatic spring. The influence of its geometric parameters on the vertical stiffness of the pneumatic spring has been established. In addition, the authors of paper [16] verified the results obtained using the finite element method by the ABAQUS software. It is noted that the results obtained by FEM are much closer to the experimental results.

However, works [14–16] did not take into account the influence of the joint irregularities of the railroad track on the dynamic behavior of the pneumatic spring suspension system and did not determine the vertical and horizontal accelerations that occur in this case.

The importance of modeling the operation of the main components in the pneumatic spring suspension system when performing dynamic modeling of rolling stock is considered in [17]. Experimental tests were carried out in the vertical direction due to the great influence it has, in particular, on the comfort of movement, the safety of movement and the dynamic interaction of the rolling stock with the rail track. It was found that the dynamic behavior of the pneumatic spring largely depends on the amplitude and frequency of the disturbance. However, such studies need to be improved in order to take into account the influence of a rail joint on change in the dynamic parameters of the spring.

In [18], the authors investigated the operation of the pneumatic spring suspension system, taking into account the non-linear operation of the height control valves, and the pressure drop between the pneumatic springs. The influence of the flow characteristics of the height control valve on the imbalance of the wheel load during the movement of the rolling stock along the curved section of the track is considered. The results indicate the importance of such modeling for evaluating the safety of rolling stock movement at low speeds and along curved sections of the railroad track. The effect of the angle of the lever of the height adjustment valve of the pneumatic spring on the imbalance of the load on wheels when passing curved sections of the track of a small radius was studied in [19]. However, the authors did not consider the dynamic behavior of the pneumatic spring in the case of traveling over the joint unevenness of a rail track.

In work [20], the stiffness and damping of the pneumatic spring suspension system were determined through experimental research. It is shown that the dynamic behavior of the pneumatic spring suspension system can be made more universal by conveniently choosing the sizes of its elements, in particular, the volumes of the pneumatic spring and the additional tank. On the one hand, reducing the volume of the air spring increases the stiffness and therefore also the highest natural frequency. On the other hand, increasing the tank volume decreases the stiffness and therefore the lowest natural frequency.

In [21], the authors investigated the effect of volume of the additional tank and the initial pressure in the spring on the dynamic parameters of a pneumatic spring suspension system. It was established that the change in the volume of the additional tank has a slight effect on the amount of deformation of the pneumatic spring at different speeds of the high-speed rolling stock. In addition, it was noted that the increase in the volume of the additional tank and the initial pressure in the pneumatic spring leads to an increase in energy loss during the operation cycle of the pneumatic system.

In [22], the authors conducted a study on the influence of the diameter and length of the connecting pipeline of the pneumatic spring suspension system on the energy loss and damping coefficient during its operation cycle and the stiffness of the pneumatic spring.

The studies reported in works [21, 22] have certain limitations. The dynamic parameters (stiffness and damping coefficient) of the pneumatic spring suspension system were derived with the parameters of only one unevenness on the rail track. At the same time, this unevenness does not correspond to the unevenness that occurs when the rolling stock wheel rolls along the rail joint of a railroad track.

In [23], to check the adequacy of the developed analytical model, bench tests of the pneumatic spring suspension system were conducted. The generalized analytical model built is used to predict the amplitude- and frequency-dependent behavior of the pneumatic spring taking into account pneumatic thermodynamics, effective friction, and viscoelastic damping. However, the bench tests involved the setting of harmonic disturbances of the pneumatic spring with different amplitudes and frequencies, which does not reflect the real conditions of operation of rolling stock on a rail track. This is due to the design of the bench test equipment.

In [24], the authors experimentally determined the dynamic stiffness of a pneumatic spring. It was established that when passing a curved section of a railroad track, the lateral and longitudinal stiffness of the pneumatic spring increased due to the lateral displacement of the body relative to the bogie, which reduced the rolling stock's ability to pass the curved section. In addition, it was found that the operation of the height control valve was able to slightly reduce the roll ratio, a phenomenon that cannot be simulated by conventional air spring models. However, the paper did not investigate the effect of contact unevenness on the dynamic stiffness of the pneumatic spring, due to the limited possibilities of the installation.

The lateral stiffness of the pneumatic spring was investigated in [25]. Using a test bench, the authors obtained a complete set of experimental results that can reflect the transverse stiffness and damping characteristics of the air spring system. However, the design of the bench does not make it possible to conduct experiments taking into account the impact of contact unevenness on the lateral stiffness of the pneumatic spring.

So, after reviewing the literature [5–25], it should be noted that the main attention has been paid to the issues of researching the dynamic characteristics of the pneumatic spring suspension system. However, such studies are carried out under laboratory conditions with the assignment of cyclic disturbances, which does not make it possible to take into account the real operating conditions of the rolling stock during its interaction with the rail track. Therefore, the unsolved task is to establish the dynamic behavior of the pneumatic spring of high-speed rolling stock when traveling over a rail junction of a railroad track with a vertical ledge.

3. The aim and objectives of the study

The purpose of our work is to determine the dynamic parameters for the pneumatic spring of high-speed railroad rolling stock in the zone of rail junction of the railroad track with a vertical ledge. This will make it possible to determine the natural frequency of oscillations and the logarithmic decrement of damping of oscillations of the pneumatic spring based on the records of vertical accelerations and deformations of the rubber cord shell of the spring.

To achieve the specified goal, the following tasks must be solved:

– to conduct experimental studies om the impact of a rail joint with the vertical ledge of the railroad track on the acceleration of the pneumatic spring of high-speed rolling stock;

– to determine the horizontal and vertical deformations of the rubber cord shell of the pneumatic spring of high-speed rolling stock when traveling over a rail joint of the railroad track;

– to determine the natural frequency of oscillations and the logarithmic decrement of damping of oscillations of the rubber cord shell of the pneumatic spring in the zone of the rail joint of the railroad track.

4. The study materials and methodology

4. 1. The object and hypothesis of the study

The object of our research is the pneumatic spring of high-speed railroad rolling stock, under the conditions of traveling over a rail joint of the railroad track with a vertical ledge.

The main hypothesis of the research assumes that the dynamic parameters of the pneumatic spring of high-speed rolling stock are determined on the basis of experimental records of vertical values of accelerations and deformations that occur when the test dynamic installation travels over a rail joint of a railroad track with a vertical ledge. This makes it possible to establish the natural frequency of oscillations and the logarithmic decrement of oscillation damping of the pneumatic spring. The structural and logical scheme for determining the dynamic parameters for the pneumatic spring is shown in Fig. 2.

The natural frequencies and logarithmic decrements of damping of vibrations of the rubber cord shell are estimated on the basis of free vertical oscillations based on the records of accelerometers and sensors of linear displacements.

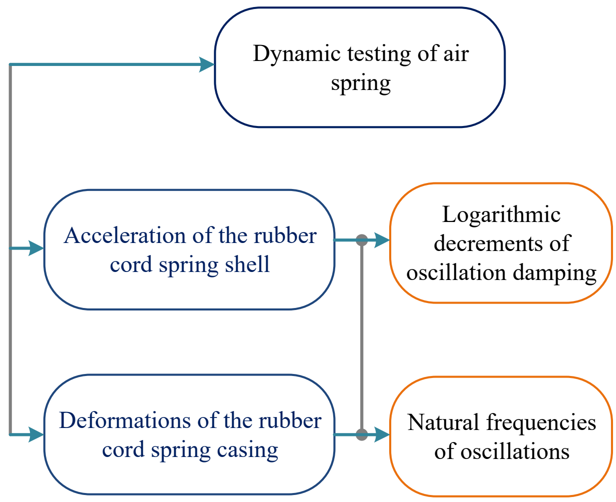

Fig. 2. Structural-logical scheme for determining the dynamic parameters of the pneumatic spring of high-speed rolling stock

4. 2. Methodology for experimental tests of a pneumatic spring

A special dynamic test installation was designed to determine the dynamic parameters for the pneumatic spring of high-speed railroad rolling stock. The dynamic testing installation in working form on the railroad track training ground is shown in Fig. 3.

Fig. 3. Dynamic test installation of a pneumatic spring: 1 – supporting rigid structure of the installation; 2 – pneumatic spring; 3 – loading blocks; 4 – potentiometric sensors of linear movements; 5 – ADXL 335 acceleration sensor; 6 – analog-digital converter; 7 – laptop

The dynamic test installation works as follows. When the installation is set in motion along a rail track with a joint unevenness (Fig. 4), the pneumatic spring, which is fixed on top of the metal frame of the installation, oscillates.

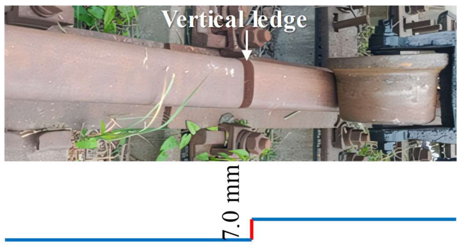

Fig. 4. Rail joint of a railroad track with a vertical ledge of 7.0 mm

The rail joint of a railroad track acts as a source of oscillations for the pneumatic spring. As a result, the rubber cord shell of the pneumatic spring is accelerated and deformed in the vertical and horizontal planes. The acceleration of the rubber cord shell of the pneumatic spring is measured by a high-frequency analog acceleration sensor ADXL 335 along three coordinate axes. Deformations of the spring in the vertical and horizontal directions are measured by analog potentiometric sensors of linear movements.

A programmed analog-to-digital converter connected to a laptop is used to read the measured values of accelerations and deformations of the pneumatic spring. With the help of special software, the measured data is recorded in its memory.

The program of experiments implied the measurement of accelerations and deformations of the pneumatic spring while the dynamic installation travels over a rail joint, which has a vertical ledge of 7.0 mm. In this case, 12 descents of the test installation from the vertical ledge of the rail joint and 12 ascents to the vertical ledge were performed. In this case, the descents and ascents alternated, and the accelerations and deformations of the pneumatic spring were recorded synchronously. The results of our experiments were stored in a separate file on a laptop for further processing and analysis.

4. 3. Theoretical information on determining the natural frequencies and logarithmic decrements of oscillation damping

When traveling over the gap in the joint (Fig. 5), the wheelset receives a shock pulse $S(t)$, which is due to the rupture of the rail thread.

It should be noted that the wheel, when traveling over a gap, changes the momentary center of rotation from point A to point B. In this case, there is an instantaneous change in speed, not in magnitude, but in direction. The vertical component of the velocity vector ΔV appears, which creates the impact.

Taking into account the proportionality of the shock pulse to the speed of movement, its value can be found from the following formula:

$$S(t) = m_{uns}\frac{V}{\Delta t}\cdot\frac{d}{r}, \quad (1)$$

where m_{uns} is the mass of unsprung parts of a wheelset;

V – movement speed;

Δt is the time of travel by a wheelset over a butt gap;

d – the size of the butt gap;

r is the radius of the rolling circle of wheels in a wheelset.

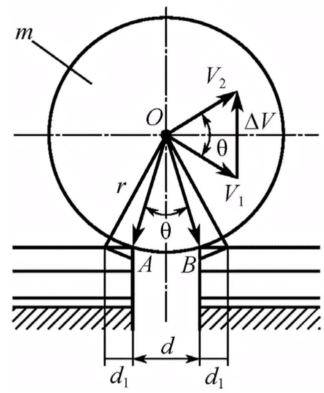

Fig. 5. Movement of a wheelset over a gap in the rail track joint: m is the mass of the wheel; V_1 — speed when leaving the junction of rails; V_2 — speed when hitting the rail junction; ΔV — change in the vertical component of speed V when the wheel travels over a butt gap; r — the radius of the rolling circle of wheels in the wheelset; d — the size of the joint gap in the joint; d_1 — the wear zone of the ends of the joint gap rails at the joint; A, B — instantaneous centers of rotation; θ — angle between the instantaneous centers of rotation A and B

So, formula (1) demonstrates that in order to reduce the value of the impact impulse, it is necessary to reduce the mass of the unsprung parts of the wheelset, as well as to reduce the size of a butt gap.

Oscillations of the over-the-spring structure occur as a result of the shock pulse. Forces arise in the vertical plane: inertial force, elastic force, and dissipative force. In the general case, the equation of oscillations takes the form:

$$m\ddot{z} + \beta\dot{z} + kz = \beta\dot{\eta} + k\eta, \quad (2)$$

where m – mass of the pneumatic spring;

k – stiffness of the rubber cord shell of the pneumatic spring;

z – absolute vertical displacement;

β – damping coefficient;

η – amplitude of the irregularity.

Equation (2) is the equation of vertical oscillations of the model, the left-hand side of which is natural oscillations, and the right-hand side is forced oscillations. The solution to the oscillation equation will make it possible to obtain values of vertical displacements z, velocities $\dot{z}$ and accelerations $\ddot{z}$ of the mass m and to evaluate the dynamic parameters of the model.

The following formula is used to estimate the logarithmic decrement of damping of pneumatic spring oscillations:

$$\lambda = \ln\frac{A(t)}{A(t+T)} = \ln\frac{A_0 e^{-\beta t}}{A_0 e^{-\beta(t+T)}} = \frac{2\pi\beta}{\omega}, \quad (3)$$

where ω is the cyclic frequency of damped oscillations of the system.

It can be seen from (3) that the logarithmic decrement of oscillation attenuation is the ratio of two amplitudes that are separated by a time interval of one period.

The processing of experimental data on free oscillations of the rubber cord shell of the pneumatic spring for high-speed rolling stock was performed according to the methodology given in work [26]. As a result, the natural frequency and logarithmic decrement of damping of oscillations of the pneumatic spring were obtained.

5. Results of determining the dynamic parameters of the pneumatic spring for high-speed railroad rolling stock

5. 1. Experimental studies of accelerations of the pneumatic spring for high-speed rolling stock

Acceleration records of the rubber cord shell of the pneumatic spring were obtained based on the results of the test installation's runs over a rail joint of the railroad track with a vertical ledge. The recordings of spring accelerations in the vertical plane are shown in Fig. 6; the recordings of accelerations in the transverse direction – in Fig. 7; and the recordings of accelerations in the longitudinal direction are shown in Fig. 8.

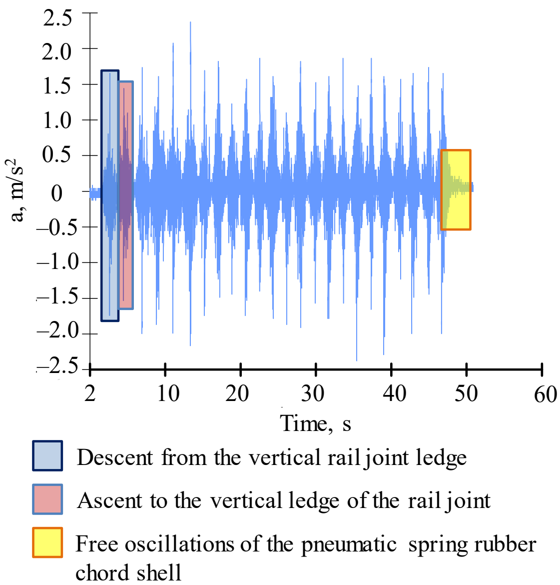

Fig. 6. Recordings of vertical accelerations of the rubber cord shell of the pneumatic spring for high-speed rolling stock

The recordings of vertical accelerations (Fig. 6) demonstrate that the magnitudes of accelerations when the wheel of the dynamic test installation descends from the rail joint and when climbing the vertical ledge are different. From the first two recordings of accelerations, it was established that the values of the accelerations are 1.6 m/s^2 and 1.4 m/s^2, respectively.

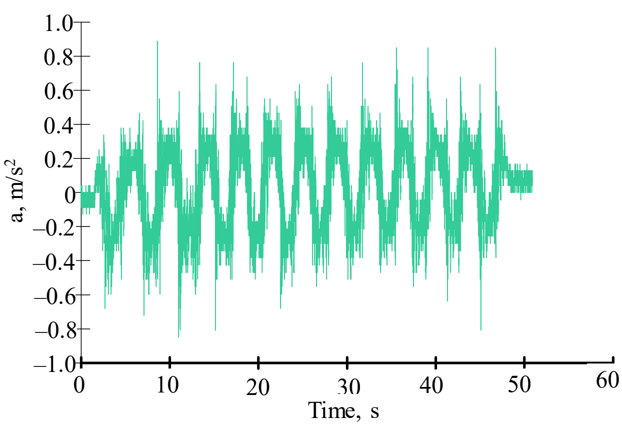

Fig. 7. Recordings of transverse accelerations of the rubber cord shell of the pneumatic spring for high-speed rolling stock

Fig. 7 shows that the horizontal transverse accelerations of the rubber cord shell of the pneumatic spring change synchronously.

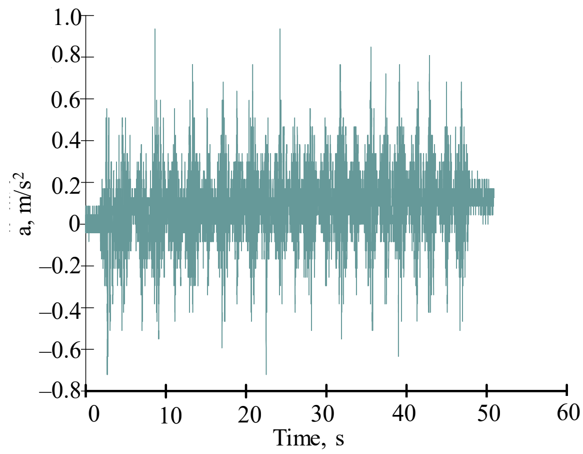

Fig. 8. Recordings of longitudinal accelerations of the rubber cord shell of the pneumatic spring for high-speed rolling stock

Our experimental recordings of accelerations (Fig. 6–8) demonstrate that the values of vertical accelerations are higher than the horizontal transverse and longitudinal accelerations of the rubber cord shell of the pneumatic spring. From the conducted 24 recordings of accelerations, it was established that the values of vertical accelerations are in the range from 1.5 m/s^2 to 2.4 m/s^2, the values of horizontal transverse accelerations are from 0.4 m/s^2 to 0.85 m/s^2, and the values horizontal longitudinal ones – from 0.5 m/s^2 to 0.9 m/s^2.

Therefore, the value of the maximum vertical accelerations of the rubber cord shell of the pneumatic spring for high-speed rolling stock is 2.4 m/s^2, horizontal transverse accelerations – 0.85 m/s^2, and longitudinal accelerations – 0.9 m/s^2. This difference between the vertical and horizontal accelerations of the rubber cord shell of the pneumatic spring is due to the effect of the vertical ledge in the rail joint. When a wheel of a rolling stock comes off the rail joint of a railroad track, the wheel falls, which causes significant vertical oscillations of the spring. When the test installation moves in the reverse direction, a longitudinal impact of the wheel occurs in the vertical ledge of the rail joint.

5. 2. Determining the horizontal and vertical deformations of the pneumatic spring for high-speed rolling stock

The results of recording the vertical and horizontal deformations of the pneumatic spring are shown in Fig. 9, 10. These plots show 12 recordings of deformations of the pneumatic spring when the wheel of the test installation descends from the rail joint with a vertical ledge and 12 recordings of the wheel lifting onto the vertical ledge of the rail joint. Recordings of deformations are alternated, the first being the deformations that occur when the wheel descends from the vertical joint ledge, and the second recording is the ascent to the vertical ledge of the rail joint.

When analyzing the maximum values of vertical deformations of the rubber cord shell of the pneumatic spring along each passage, one can see that the values of vertical deformations are within the range from 2.0 mm to 4.1 mm. The magnitudes of the deformations when the wheel descends from the vertical ledge of the rail joint are higher than when climbing the ledge. This can be seen from the first two recordings of the vertical deformations of the pneumatic spring (descent from a vertical ledge and ascent to a vertical ledge). The maximum value when descending from a vertical ledge is 4.1 mm, and when climbing a ledge – 2.9 mm.

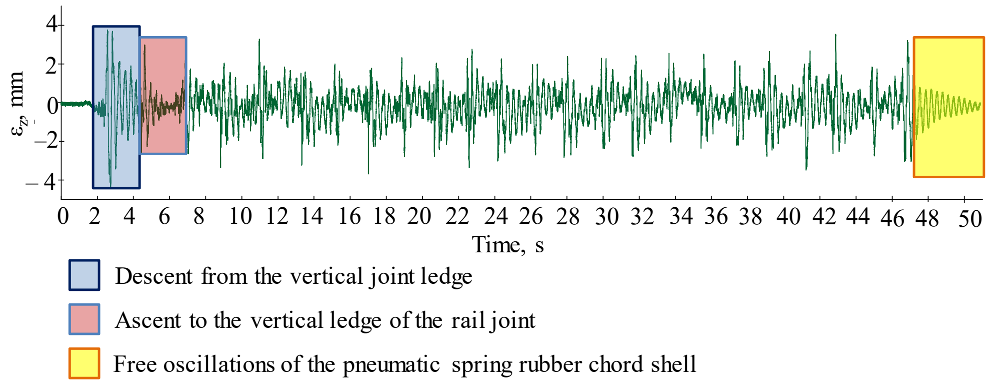

Fig. 9. Recordings of vertical deformations of the pneumatic spring for high-speed rolling stock

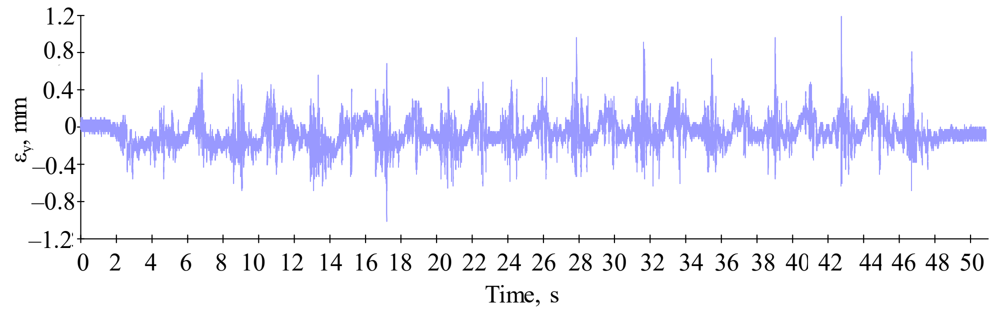

Fig. 10. Recordings of horizontal deformations of the pneumatic spring for high-speed rolling stock when traveling over a rail joint

From the recordings of the horizontal deformations of the rubber cord shell of the pneumatic spring, one can see that the magnitude of the horizontal deformations varies from 0.6 to 1.2 mm.

The deformations of the pneumatic spring in the horizontal direction are smaller than the vertical deformations. The maximum amount of vertical deformations of the spring is 4.1 mm, and horizontal – 1.2 mm.

5. 3. Determining the natural frequency of oscillations and the logarithmic decrement of damping the oscillations of a pneumatic spring

Based on the results of the recordings of vertical accelerations and deformations of the rubber cord shell of the pneumatic spring, we shall determine the natural frequencies and logarithmic decrements of oscillations damping. To this end, on the plots of vertical accelerations (Fig. 6) and vertical deformations (Fig. 9), we highlight the zones of free oscillations of the spring. Selected recordings of free oscillations of the rubber cord shell of the pneumatic spring are shown, respectively, in Fig. 11, 12.

According to the methodology from [26], we shall determine the natural frequencies and decrements of oscillation damping. Plots of the amplitude spectrum of oscillations by accelerations are shown in Fig. 13, and according to the deformations – in Fig. 14. Based on the constructed plots, the first natural frequency of oscillations of the rubber cord shell of the pneumatic spring is determined according to the first peak corresponding to the first natural frequency of oscillations.

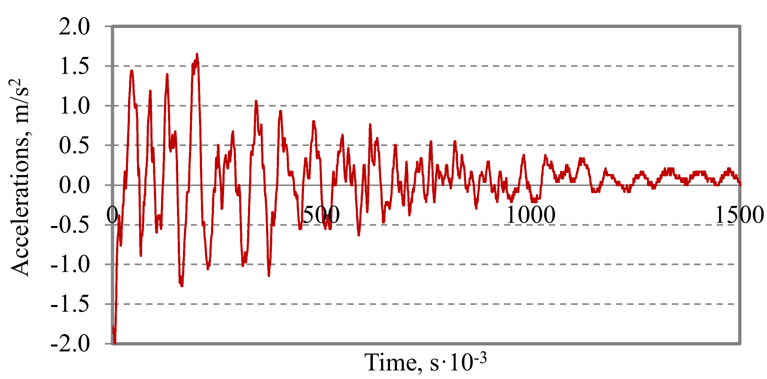

Fig. 11. Recordings of vertical accelerations of free oscillations of the rubber cord shell in a pneumatic spring

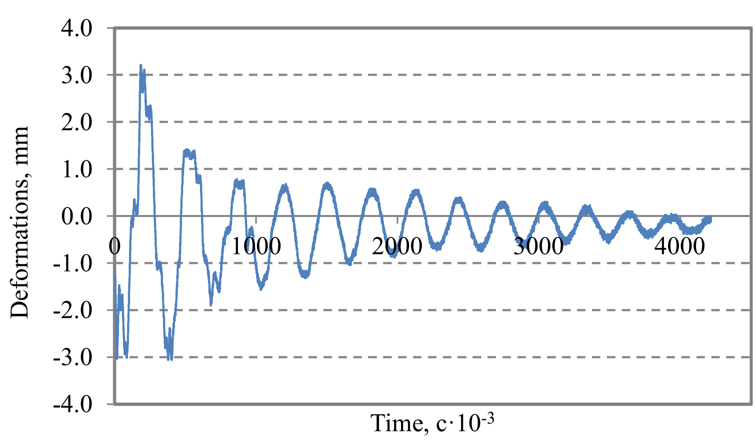

Fig. 12. Recordings of vertical deformations of free oscillations of the rubber cord shell in the pneumatic spring

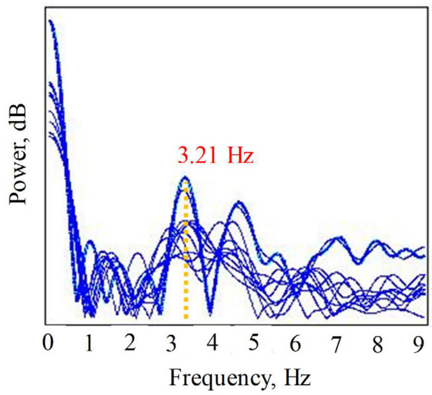

Fig. 13. Amplitude spectrum of free vertical oscillations of the rubber cord shell in the pneumatic spring according to the recordings of vertical accelerations

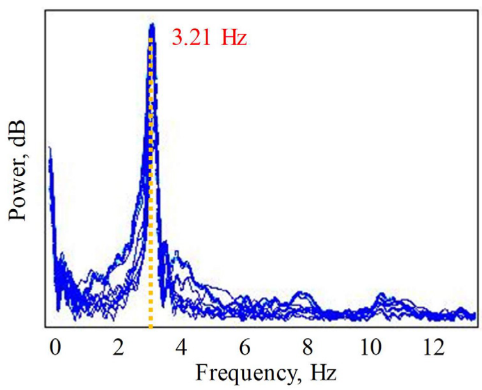

Fig. 14. Amplitude spectrum of free vertical oscillations of the rubber cord shell in a pneumatic spring according to recordings of vertical deformations

The results of processing the measured data of accelerations and deformations of the rubber-cord shell in the pneumatic spring for high-speed rolling stock established that the first natural frequency of oscillation is 3.21 Hz. In this case, the logarithmic decrement of the oscillation damping of the pneumatic spring for high-speed rolling stock is 0.2147.

The obtained values of the natural frequency of oscillations and the logarithmic decrement of damping the oscillations of the new pneumatic spring could be used in the future to control the degradation of the rubber cord shell of the spring under operational conditions.

6. Discussion of results related to the influence of a rail joint of the railroad track on the dynamic parameters of a pneumatic spring for high-speed rolling stock

On the basis of the designed dynamic test setup, experimental studies of the pneumatic spring in the zone of the rail joint of the railroad track were performed. In contrast to existing experimental studies on the pneumatic spring, which were carried out under laboratory conditions [5, 12, 17], this installation allows tests to be carried out under actual operating conditions of the railroad track. As a result of the experiments, recordings of vertical and horizontal accelerations of the rubber cord shell of the pneumatic spring in the area of the rail junction with the vertical ledge were obtained. We also obtained recordings of spring deformation in the vertical and horizontal directions when the test installation traveled over a rail joint.

It should be noted that when the wheel of the dynamic test installation descends from a vertical ledge, the size of which is 7.0 mm, oscillation of the spring occurs in the vertical plane and a slight oscillation in the horizontal plane. As a result, the value of the maximum accelerations of the rubber cord shell of the pneumatic spring (Fig. 6–8) in the vertical plane was 2.4 m/s^2, horizontal transverse accelerations – 0.85 m/s^2, and horizontal longitudinal accelerations – 0.9 m/s^2.

The results of experimental measurements of the deformations of the pneumatic spring showed that their value in the vertical plane of the spring is higher than the horizontal deformations (Fig. 9, 10). The maximum vertical deformation of the pneumatic spring was 4.1 mm, while the maximum horizontal deformation was 1.2 mm.

The difference between vertical and horizontal accelerations and deformations of the rubber cord shell of the pneumatic spring is explained by the effect of the vertical ledge of the rail joint, which causes vertical oscillations of the spring. As a result, this affects the magnitude of vertical accelerations and deformations of the pneumatic spring and slightly affects the magnitude of horizontal accelerations.

It was established that the magnitudes of vertical accelerations and deformations of the pneumatic spring have different values when descending from a vertical ledge and ascending to a vertical ledge of a rail joint of a railroad track. From the first two recordings of accelerations (Fig. 6), it was established that the magnitude of the accelerations when the wheel of the dynamic test installation descends from the rail joint is 1.6 m/s^2, and when it rises to the vertical ledge of the rail joint, it is 1.4 m/s^2. Accordingly, the values of vertical deformations of the rubber cord shell of the pneumatic spring are 4.1 mm and 2.9 mm (Fig. 9). In the case of studies on the dynamic behavior of the pneumatic spring at the cross-piece of the turnout, it was established in [27] that the average value of the vertical deformations of the pneumatic spring in the transverse direction is 3.15 mm. Therefore, it can be stated that the vertical ledge at the junction of the railroad track has a greater influence on the dynamic behavior.

Zones of free oscillations were selected from the recordings of vertical accelerations and deformations of the rubber cord shell of the pneumatic spring (Fig. 11, 12). This made it possible to set the natural frequencies and logarithmic decrements of damping of spring oscillations. It was determined that the first natural frequency of oscillations of the rubber cord shell of the pneumatic spring is 3.21 Hz, and the logarithmic decrement of oscillation damping is 0.2147. The results are confirmed by the research reported in [8], in which it was established that the maximum disturbance of the second stage of the spring suspension occurs in the frequency range from 1.5 to 3 Hz. Differences can be observed due to different types of pneumatic springs and different conditions of the experiment.

The practical significance of our results relates to the possibility of their application by engineers and researchers in the design of pneumatic springs for high-speed rolling stock, taking into account the influence of the rail joint on the dynamic parameters of the pneumatic spring. In addition, the determined natural frequency and logarithmic decrement of damping of vibrations of the rubber cord shell of the new pneumatic spring could be used in the future to control the degradation of the rubber cord shell of the pneumatic spring under the operational conditions of the railroad.

One of the limitations of our research is that the determination of the dynamic parameters of the pneumatic spring for high-speed rolling stock was carried out only within the rail joint of the railroad track with a vertical ledge. The disadvantage of the current study is the lack of manometric air pressure in the pneumatic spring. The further development of this area of research is to conduct studies on the influence of different sizes of contact irregularities, operational and structural parameters of the railroad track and rolling stock on the dynamic parameters of the pneumatic spring for high-speed rolling stock.

7. Conclusions

1. The results of our experimental studies on the effect of a rail joint of the railroad track on the acceleration of a pneumatic spring for high-speed rolling stock showed that the maximum acceleration of the spring occurs in the vertical plane. The magnitude of vertical forces was 2.4 m/s^2, horizontal transverse – 0.85 m/s^2, and horizontal longitudinal – 0.9 m/s^2. In this case, the values of vertical accelerations range from 1.5 m/s^2 to 2.4 m/s^2, horizontal transverse accelerations – from 0.4 m/s^2 to 0.85 m/s^2, and values of horizontal longitudinal accelerations range from 0.5 m/s^2 to 0.9 m/s^2.

The magnitude of accelerations of the rubber cord shell in the pneumatic spring for high-speed rolling stock when the wheel of the dynamic test installation descends from the vertical ledge of the rail joint is 1.6 m/s^2, and when climbing the vertical ledge – 1.4 m/s^2.

2. When traveling over a rail joint of the railroad track, the dynamic test installation established that the maximum value of vertical deformations of the pneumatic spring is 4.1 mm, while the maximum value of horizontal deformations is 1.2 mm.

The magnitudes of vertical deformations of the rubber cord shell in the pneumatic spring for high-speed rolling stock when the wheel of the dynamic test installation descends from the vertical ledge of the rail joint and when it rises to the vertical ledge are different. They are 4.1 mm and 2.9 mm, respectively.

3. Based on the results of free oscillations of the pneumatic spring, it was determined that the first natural frequency of oscillations of the rubber cord shell in the pneumatic spring is 3.21 Hz, and the logarithmic decrement of the oscillation damping is 0.2147.

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, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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