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METHODOLOGY FOR EVALUATING THE DYNAMIC PARAMETERS OF THE RUBBER-CORD SHELL OF A HIGH-SPEED ROLLING STOCK PNEUMATIC SPRING IN THE WHEEL-FROG INTERACTION OF A RAILROAD SWITCH

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Abstract:

The object of research is a pneumatic spring of the spring suspension system for high-speed railway rolling stock. A methodology for full-scale dynamic testing of a pneumatic spring of high-speed rolling stock when interacting with a rail track has been developed. The vertical, transverse, and longitudinal accelerations of the rubber-cord shell of the pneumatic spring of the high-speed rolling stock during trailing and facing directions movement along the turnout crossing crossing are determined. It is established that the average values of vertical accelerations in the trailing direction and facing direction movements are higher than the average values of transverse and longitudinal accelerations. It is noted that the values of the average values of vertical and longitudinal accelerations in the trailing direction movement are 24.6% and 13.9% higher than the average values of the accelerations in the facing direction movement. Equality of the values of the average values of transverse accelerations in trailing direction and facing direction movements is noted. Graphs of the amplitude spectrum and logarithmic damping of vibrations of the rubber-cord shell of a pneumatic spring of high-speed rolling stock are obtained. It is established that the average value of the first natural frequency of oscillations of the rubber-cord shell of the pneumatic spring in the vertical, transverse and longitudinal directions during the trailing direction movement along the railroad turnout crossing is 3.17 Hz, 3.7 Hz and 3.49 Hz, and the logarithmic decrement of the oscillation damping is 0.46 , 0.30 and 0.29, respectively. For the facing direction movement, the natural frequency is 3.45 Hz, 3.56 Hz, and 3.47 Hz, and the logarithmic decrement of oscillation damping is 0.35, 0.41, and 0.31, respectively. From a practical point of view, the obtained first frequencies of natural oscillations for the rubber-cord shell of the new pneumatic spring of the high-speed rolling stock are basic, which will allow further monitoring of the change in the dynamic characteristics of the pneumatic spring depending on the operational mileage of the rolling stock.

Keywords: *pneumatic spring, rubber-cord shell, switch frog, acceleration, frequency, logarithmic decrement*

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1. Introduction

Ensuring an acceptable level of dynamic quality indicators of the mechanical part of rolling stock is one of the main tasks in the process of its design, manufacture and operation. Dynamic quality indicators characterize the vibration-proof properties of the mechanical part and traffic safety indicators (Kuzyshyn et al., 2023). Indicators that evaluate the vibration-proof properties of rolling stock include maximum acceleration of the body, maximum movement of the ends of the body, coefficients of vertical and horizontal dynamics. Traffic safety indicators include the stability of the wheel against derailment from the rail, the transverse stability of the crew from tipping over in a curve, and smooth running.

In the second stage of spring suspension, a pneumatic spring suspension system is used, the components of which are a pneumatic spring, an additional reservoir, a connecting pipeline and various valves (Fig. 1). The main advantage of such a system over others is the ability to adjust the deflection of the spring suspension, which occurs due to changes in internal pressure. The system also has better vibration-proof properties due to the use of a rubber-cord shell of a pneumatic spring. As a result, the comfort of passenger transportation improves.

Determination of indicators of dynamic quality of the mechanical part of rolling stock is carried out in the process of its interaction with the rail track. The main factors affecting the values of these indicators are the technical condition of the suspension of rolling stock and rail track. Since there is no jointed track on high-speed traffic lines, the main attention should be paid to the interaction of rolling stock with switches. It is important and relevant to establish the influence of the switch on the maximum acceleration of the pneumatic spring and the body elements in contact with it. This will allow you to assess the overall level of acceleration on the body of high-speed rolling stock during operation and control the criteria for driving comfort.

2. Analysis of literature data and problem statement

Mechanical (Berg, 1999), thermodynamic (Docquier et al., 2007) and finite element models (Li et al., 2013) are used for mathematical modeling of the behavior of the pneumatic spring suspension system. However, in these models, the periodic length inequality of the track is considered as a perturbing factor. Using such a model, it is difficult to assess the effect of passing the turnout crossing on the pneumatic spring suspension system. The paper (Bayraktar et al., 2009) the authors considered several models of pneumatic springs and modeled the second stage of spring suspension of rolling stock. In one case, the link between the body and the trolley was considered as a simple spring damper, and in the other, the linear model Nishimura was used, which separates the volumes of the pneumatic spring and the additional tank, and can also take into account linear viscous damping. Rolling stock was represented by a system with 16 degrees of freedom. The equations of motion were obtained using the Lagrange equation, and the numerical implementation took place in the Simulink/MATLAB environment. The movement and acceleration of the body, trolley and wheelset of rolling stock were studied, and frequency characteristics are obtained. Track irregularities were given in the form of a sinusoid.

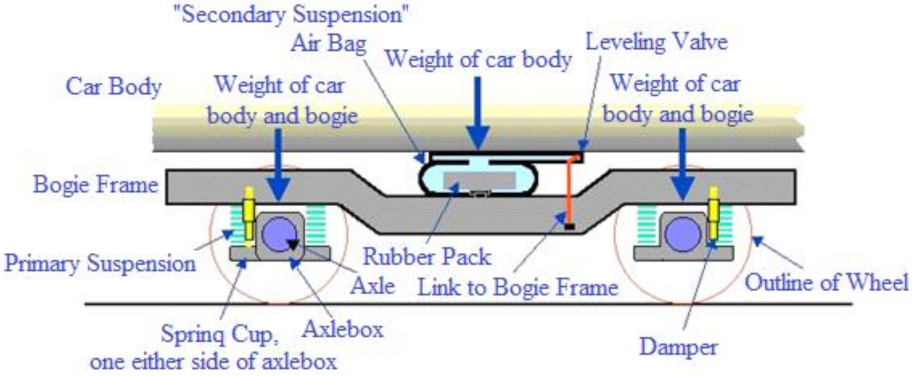


Fig. 1. Mechanical part of rolling stock with pneumatic spring suspension system

The paper (Moheyeldein et al., 2018) an analytical study of the performance indicators of air suspension in comparison with passive suspension, which includes a spring and a hydraulic damper, was conducted. There were two different models of pneumatic springs: classic and dynamic. The results showed that for the dynamic pneumatic spring model, body accelerations were reduced, providing greater comfort at the same time. An analysis of the results obtained in the time and frequency domains was also presented.

The paper (Toyokawa et al., 2020) the authors developed a technology for computer modeling of pneumatic springs of railway vehicle systems, which allows predicting the static and dynamic characteristics of pneumatic springs. Based on the mathematical model, a resonant frequency was obtained at which the transmission of vibrations is maximum. The paper (Facchinetti et al., 2010) it was investigated the effect of air suspension operation on driving comfort in a vehicle. The results of dynamic tests showed that the frequency-dependent behavior of the suspension in the frequency range 0÷20 Hz can be important for assessing the quality of movement. In the calculation process, body flexibility was taken into account using the modal superposition approach, as described in (Diana et al., 2002). The results of modeling traffic on a straight section at a speed of 300 km/h were shown. During the simulation, the path unevenness was determined according to the "low-level" PSD function ERPI. The paper (Shin et al., 2014) it was investigated the effect of a side damper in the secondary suspension on the quality of rolling stock movement. As a result of the tests, it was found that vibration was reduced by about 24% when installing a shock absorber between the trolley and the rolling stock body compared to using a passive damper.

The paper (Mellado et al., 2008) the authors investigated the effect of an active suspension system on the lateral swing of the body and its horizontal accelerations. It was proposed to use pneumatic drives between the body and the trolley, which were connected to the pneumatic springs of the pneumatic spring suspension system. Modeling was performed while driving on a curved section of track. It was found that the maximum horizontal displacements and accelerations in an active system were significantly lower compared to conventional rolling stock.

The paper (Qi et al., 2017) a three-dimensional model of a high-speed electric train compatible with the thermodynamic model of a pneumatic spring was created. The effect of the nonlinear behavior of a pneumatic spring on the dynamic characteristics of rolling stock was analyzed using a dual modeling approach. It was established that the pneumatic spring could improve driving comfort in rolling stock due to its ability to adjust vertical stiffness and damping.

The paper (Tanaka et al., 2019) theoretically and experimentally showed the importance of correctly choosing the initial angle of the leveling valve lever. This made it possible to reduce the imbalance of vertical load on the wheels when passing curved sections of railway track. However, the effect on vertical body accelerations was not studied.

The development of an approach to optimizing the suspension parameters of a rail vehicle based on the kriging virtual prototype model is presented in the paper (Yang et al., 2016). The Sperling index was chosen to assess the quality of movement (Yan et al., 2012).

The dynamic behavior of a pneumatic spring suspension system with a perturbation frequency of up to 400 Hz was studied in the paper (Mendia-Garcia et al., 2023). Based on the results of the conducted experiments, three frequency ranges were identified where different suspension resonances occur: low (up to 30 Hz), intermediate (30-150 Hz) and high (over 150 Hz).

The paper (Mendia-Garcia et al., 2022) the axial and transverse stiffness of the pneumatic spring was analyzed. Experimental tests and simulation results have shown that the pneumatic spring has its own frequency below 100 Hz in the frequency range where vibration is transmitted from the rolling stock structure.

Consideration of the process of gas change inside a pneumatic spring in mathematical modeling of the operation of a pneumatic spring was considered in the work (Wu et al., 2022). This made it possible to consider the exact algorithm of air suspension control systems.

The effect of a transient shock load on a pneumatic spring was studied in the work (Zhou et al., 2022). It is established that the stiffness of the pneumatic spring increases with increasing impact load, and the peak value increases and moves to a high frequency that is close to its own frequency.

The paper (Zheng and Shangguan, 2023) a novel combined model is developed to evaluate the dynamic characteristics of both orifice-type and pipe-type air springs with auxiliary chambers. In addition, the deformations of the pneumatic spring were cyclical (Zheng et al., 2022).

A study of the dynamic behavior of a two-chamber air suspension was conducted in labor (Zhu et al., 2021).

The paper (Kamada and Karaki, 2023) considers ways to reduce vertical vibrations of high-speed rolling stock. Vertical vibration reduction, by controlling the internal pressure of the air spring using μ-synthesis control, is proposed.

A refined stiffness model of rolling lobe air spring with structural parameters and the stiffness characteristics of rubber bellows is developed in the paper (Chen et al., 2021). Prediction models of structural parameters, including effective area and its change rate, effective volume and its change rate, are obtained by geometrical and mechanical analysis. A nonlinear hysteresis model of rubber bellows is also proposed, which is composed of a fractional Kelvin-Voigt model and a smooth friction model in parallel.

The paper (Kandasamy et al., 2021), a pneumatic suspension model with orifice damping was developed and used to evaluate the performance of the air suspension in comparison with the coil-spring suspension in railroad transportation systems. The simulation results show that using air springs reduces the railcar mean vertical acceleration, maximum roll angle, and variations in the wheel/rail contact forces.

The above analysis of works demonstrates a wide range of studies of the operation of a pneumatic spring suspension system, depending on the conditions of interaction of rolling stock with the rail track. Most of these studies correspond to driving conditions in straight and curved sections of the track. However, the passage of the switch by rolling stock and its effect on the operation of the pneumatic system were not studied in any of the considered works. And this is relevant from the point of view of ensuring traffic safety and determining the necessary speed limits.

Therefore, we will analyze the works on the interaction of rolling stock with rail tracks within the switch.

Since the upper surface of the switch rail within the switch varies in width and height in the direction of travel, the contact between the wheel and the rail (Chen et al., 2021) on the left and right sides of the wheelset is asymmetric (Ma et al., 2019). This contact significantly affects the behavior of the wheelset (Fig. 2), including the lateral and vertical forces of wheel-rail interaction (Hao et al., 2023), the stability of rolling stock and the quality of its movement.

Also, the dynamic behavior of pneumatic springs of high-speed rolling stock will be affected by the disruption of the ballast prism of the railway track (Nabochenko et al., 2024a; Nabochenko et al., 2024b; Szabolcs, 2023).

Fig. 2 . Movement of the wheel along the frog of the railroad switch

The paper (Hao et al., 2023) the authors study the nature of changes in the equivalent conicity of the wheel and rail in the switch zone when changing the wheel profile. The model allows you to study the lateral position of the contact points between the wheel and the rail, the lateral movement of the wheelset and the lateral vibration accelerations of the mechanical rolling stock system. It is established that the characteristics of transverse movement of high-speed trains passing through switches are significantly affected by the degree of wheel wear. When the operating mileage is less than or equal to 100,000 km, the conicity in contact near the nominal rolling circle increases, which leads to a slight increase in the amplitude of transverse vibrations of the wheelset. However, the main frequency of transverse movement of the wheelset practically does not change, is determined by the structure of the switch and is approximately 1.33 Hz. When the mileage is equal to or exceeds 150,000 km, the amplitude of transverse movement of the wheelset decreases and the frequency of transverse vibrations increases. It is found that the main frequency of transverse movement of the wheelset at 150,000 km and 200,000 km of mileage is 7.98 Hz and 9.32 Hz, respectively.

The paper (Gao et al., 2020) a finite element model of a wheelset that moves through a switch is presented. The model allows you to take into account the arbitrary geometric profile of the wheel-rail system, the non-linearity of material characteristics, and the actual variable position of the wheelset. To check the adequacy of the mathematical model, the authors used a laser method that can record the lateral displacement of the wheelset.

It should also be noted a significant number of scientific papers related to the study of the influence of the technical condition of the wheelset and switch elements on their force interaction (Chang et al., 2022). The paper (Xu et al., 2016, Zhu, 2006), the influence of switch stiffness on the dynamic wheel-rail interaction under high-speed traffic conditions was considered. The influence of deviations in the geometric parameters of switches on the dynamic characteristics of rolling stock was considered in the paper (Chen et al., 2011). In addition, the dynamic parameters of the pneumatic spring will be affected by the condition of the railway track ballast and the quality of track repair work.

The above analysis of the works shows that most scientific studies solve the issues of power interaction of a wheelset with elements of a switch. However, increasing the speed of movement and the use of high-speed rolling stock with a pneumatic spring suspension system requires studying the vibration-proof properties of spring suspension based on determining the vertical and horizontal accelerations of its structural elements and body.

Therefore, in this paper, the vertical and horizontal accelerations of the rubber-cord shell of a pneumatic spring of high-speed rolling stock during the passage of the switch frog were studied. For this purpose, an installation for full-scale testing of the pneumatic spring of high-speed rolling stock was developed and experimental measurements of the vibration parameters of the rubber-cord shell were carried out.

The purpose of the work is to determine the accelerations of the rubber-cord shell of the pneumatic spring of high-speed rolling stock during the passage of the installation with the frog of the switch in trailing direction and facing direction movements, which will allow setting the proper frequencies and logarithmic decrement of the extinction of vibrations of the rubber-cord shell of the pneumatic spring.

To achieve this goal, the following tasks were set:

- develop a methodology for full-scale testing of a pneumatic spring of high-speed rolling stock when interacting with a rail track;
- determine the vertical, transverse and longitudinal accelerations of the rubber-cord shell of the pneumatic spring;
- determine the natural frequencies and logarithmic damping of vibrations of the rubber-cord shell of a pneumatic spring.

3. Methodology for experimental determination of accelerations of the rubber-cord shell of a pneumatic spring in conditions of movement of the switch frog

A mobile installation has been developed to conduct dynamic tests of the pneumatic spring of high-speed railway rolling stock. The placement of the installation on the frog of the switch is shown in Fig. 3.

The unit consists of a rigid metal frame on which a pneumatic spring of high-speed rolling stock is installed. The pneumatic spring is loaded with reinforced concrete blocks weighing 100 kg.

Acceleration recording is performed using the ADXL335 (Fig. 4 *a*) analog acceleration sensor using an analog-to-digital converter and specialized software installed on the laptop. The location of the acceleration sensors on the pneumatic spring is shown in Fig. 4 b.

Accelerations that are fixed in the longitudinal direction during rear joint (facing direction movement) and back (trailing direction movement) by the crosspiece of the switch correspond to the X – axis. Accelerations that occur in the transverse direction of vibrations of the pneumatic spring correspond to the Y-axis, and in the vertical direction-to the Z-axis.

The main properties of the ADXL-335 analog acceleration sensor: supply voltage – is 3.3-5 V; power consumption – is 350 μA; sensor measurement range – is -3.6 g/+3.6 g; sensitivity – is 300 mV/g and dimensions – is 21x16 mm. The acceleration sensor was calibrated in the laboratory of the Dresden University of Technology using a hydropulse.

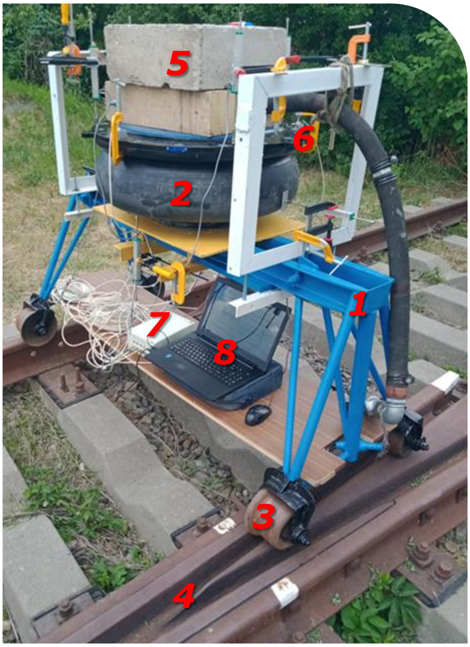
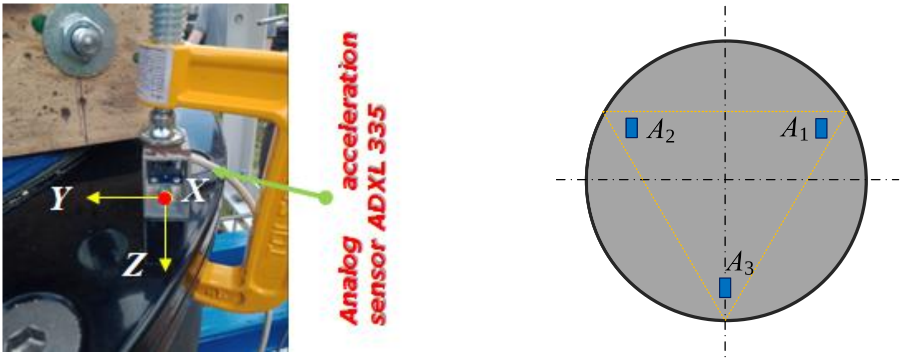


Fig. 3. Mobile installation for testing the pneumatic spring of high-speed rolling stock: 1-load-bearing frame; 2-pneumatic spring of high-speed railway rolling stock; 3-metal wheel; 4-frog of the railroad switch; 5-reinforced concrete loading blocks; 6-analog acceleration sensor; 7-high-frequency analog-to-digital converter; 8-laptop

The method of experimental determination of the frequency parameters of the new pneumatic spring provided for the establishment of accelerations, natural frequencies and logarithmic damping of vibrations only of the rubber-cord shell of the spring. To install them, it is enough to set the mobile installation in motion in order to set the perturbation factor. For this factor, the crosspiece of the railway track switch is taken. In particular, in this case, the speed of movement of the installation along the crosspiece, the diameter of its wheels and the overload weight of the pneumatic spring do not affect the natural frequencies and decrements of vibration attenuation. Since these parameters are determined by the recordings of accelerograms (which are recorded by a high-frequency acceleration sensor) at the moment when the vibrations of the rubber-cord shell of the pneumatic spring fade.

The acceleration sensor is placed in a special metal box and rigidly fixed with a clamp to the upper metal plate of the pneumatic spring.

The program of experimental tests of the pneumatic spring provided for measuring accelerations when the installation moves from the mathematical center of the turnout in the direction of the rear joint (facing direction movement) and back (trailing direction movement). As part of the study, twelve passes were made, six in each direction of the frog. As a result, records of accelerations in the vertical, longitudinal, and transverse directions were obtained. This will allow for a frequency analysis of the parameters of the pneumatic spring of high-speed rolling stock.



a) b)

Fig. 4. Location of the acceleration sensor on the pneumatic spring: *a*) general view of the ADXL335 analog acceleration sensor; *b*) geometric arrangement of acceleration sensors on the upper metal plate of the pneumatic spring

4. Results of experimental studies of vibration-proof properties of the rubber-cord shell of a pneumatic spring

4.1. Determination of vertical, transverse and longitudinal accelerations of the rubber-cord shell of a pneumatic spring in the conditions of movement of the switch frog

Experimental studies of the movement of the test unit along the frog of the 1/11 switch in the facing direction and trailing direction were carried out. During the movement of the test unit, records of vertical, transverse and longitudinal accelerations of the rubber-cord shell of the pneumatic spring of high-speed rolling stock were obtained (fig. 5-7).

The experimental test program included twelve test field passes, six in each direction of the frog. This made it possible to establish the maximum values of accelerations in all the planes under consideration separately when moving in the trailing direction and facing direction (Fig. 8). It is established that the maximum values of accelerations of the rubber-cord shell of a pneumatic spring of high-speed rolling stock in the vertical direction vary within: for trailing direction movement from 1.74 m/s^2 to 2.25 m/s^2, for facing direction movement from 1.32 m/s^2 to 1.69 m/s^2. In the transverse direction for trailing direction movement from 0.47 m/s^2 to 0.98 m/s^2, and for facing direction movement from 0.64 m/s^2 to 0.93 m/s^2. In the longitudinal direction for trailing direction movement from 0.55 m/s^2 to 0.80 m/s^2, and for facing direction movement from 0.38 m/s^2 to 0.85 m/s^2.

The values of vertical accelerations a_z in the trailing direction and facing direction are higher in comparison with horizontal transverse a_y and horizontal longitudinal a_x. The values of the transverse accelerations of a_{y1} and the longitudinal accelerations of a_{x1} are almost identical in trailing direction movement, but in the case of facing direction movement, the transverse accelerations of a_{y2} are higher than the longitudinal accelerations of a_{x2}. The comparison of the average values of vertical, transverse, and longitudinal accelerations is shown in Fig. 9. In the trailing direction of movement, accelerations are 1.95 m/s^2 in the vertical direction, 0.74 m/s^2 in the transverse direction and 0.71 m/s^2 in the longitudinal direction, and in the facing direction movement they are 1.47 m/s^2, 0.74 m/s^2 and 0.61 m/s^2 respectively.

In Fig.9 it can be seen that the value of the average vertical accelerations in the trailing direction and facing direction is higher than the transverse and longitudinal accelerations. The difference in the average acceleration values of a_{z1}-a_{y1} in the trailing direction is 1.216 m/s^2, and in the facing direction is 0.735 m/s^2. Accordingly, the difference between a_{z1}-a_{x1} is 1.245 m/s^2 and 0.863 m/s^2.

The average value of statistical error in the study of vertical accelerations is 7.2%, of transverse accelerations it is 16.02%, and of longitudinal accelerations it is 10.66%.

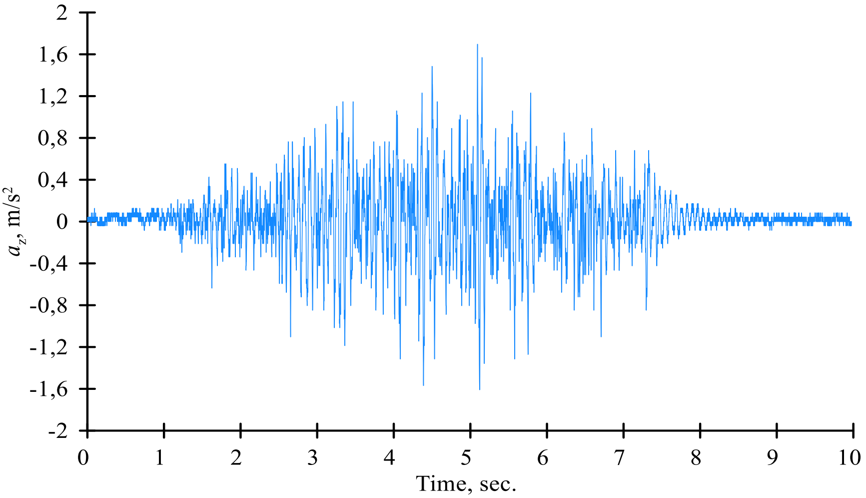


Fig. 5. Recording of vertical accelerations of the rubber-cord shell of a pneumatic spring.

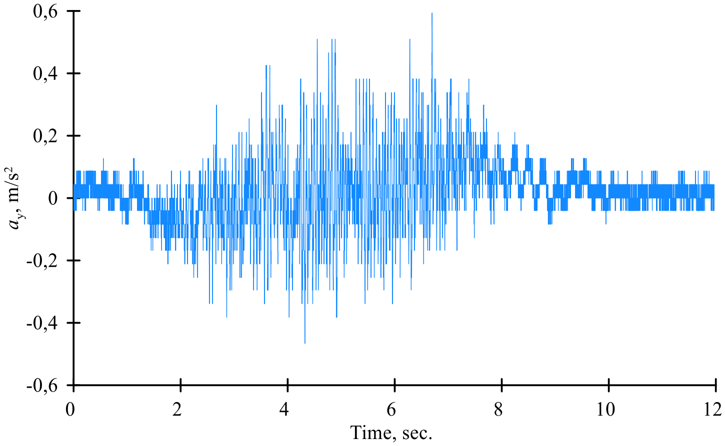


Fig. 6. Recording of transverse accelerations of the rubber-cord shell of a pneumatic spring

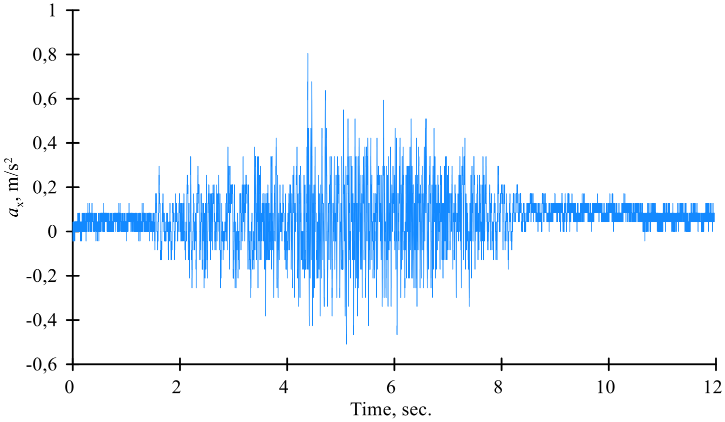


Fig. 7. Recording of longitudinal accelerations of the rubber-cord shell of a pneumatic spring

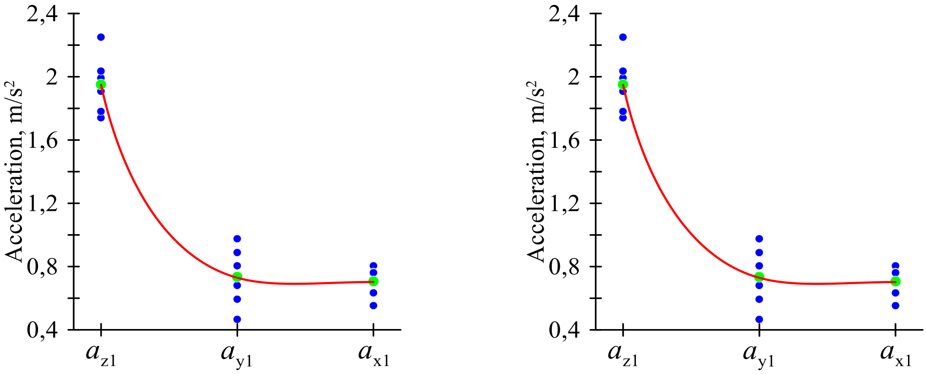


Fig. 8. Acceleration of the rubber cord shell of a pneumatic spring in conditions of movement by the switch: a) trailing direction movement; b) facing direction movement

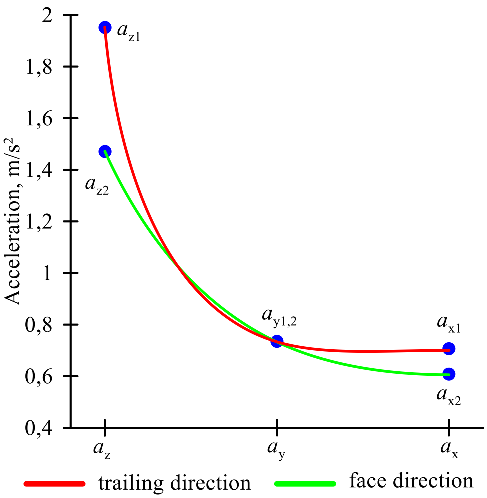


Fig. 9. Average values of accelerations of the rubber-cord shell of a pneumatic spring in the conditions of movement by the frog of the switch: a) trailing direction movement; b) facing direction movement

The value of the average values of vertical accelerations in the trailing direction movement a_{z1} is higher than the value of acceleration in the facing direction motion a_{z2}. The percentage ratio of a_{z1}/a_{z2} is 24.6%. This is due to the peculiarity of rolling the wheel from the wing rail of frog to the frog in the facing direction and from the frog to the wing rail of frog in the trailing direction, which is associated with the design parameters of the frog. As a result, there is a significant dynamic addition of vertical forces, which causes vibrations of the pneumatic spring. Results of studies of the values of dynamic force addition showed that the magnitude of vertical forces in the facing direction is higher than that of the trailing direction. This allows us to explain the difference in vertical accelerations in the anti-stroke and trailing directions.

However, the values of the average values of transverse accelerations in the trailing direction a_{y1} and facing direction a_{y2} are equal. This indicates approximately the same operation of the rubber-cord shell of the pneumatic spring in the transverse direction, which is explained by the slight difference in the transverse forces that occur in the facing direction and trailing direction of the wheel along the crossbar.

Comparison of the average values of longitudinal accelerations in the trailing direction of a_{x1} with the facing direction of a_{x2} showed that the percentage ratio of a_{x1}/a_{x2} is 13.9%. This difference in acceleration is caused by a higher longitudinal impact of the wheel when moving from the frog to the wing rail of frog in comparison with the movement from the wing rail of frog to the frog of the frog.

Further, based on the obtained lines of vertical, transverse and longitudinal accelerations of the rubber-cord shell of the pneumatic spring (Fig. 5-7), we will conduct its frequency analysis.

4.2. Frequency analysis of experimental results

Frequency analysis of the obtained experimental results includes determination of the natural oscillation frequencies of the rubber-cord shell of a pneumatic spring. In addition, logarithmic decrees of oscillation attenuation were determined. The research was conducted for vertical, transverse, and longitudinal directions.

Determination of oscillation parameters is performed by analyzing the spectral functions of free vibrations. The research used the methodology by (Radchenko et al., 2011).

It should be noted that free vibrations of systems in real conditions occur in the presence of resistance forces. The action of these forces leads to a decrease in the amplitude of vibrations.

The differential equation of damped vibrations, in general, has the form:

$$\frac{d^2x}{dt^2} + 2\beta\frac{dx}{dt} + \omega_0^2 x = 0 \qquad (1)$$

where β is attenuation coefficient; ω_0 is the frequency of free harmonic vibrations.

Several values are used to quantify the attenuation of vibrations: the attenuation coefficient, relaxation time, logarithmic attenuation decrement, and Q-factor.

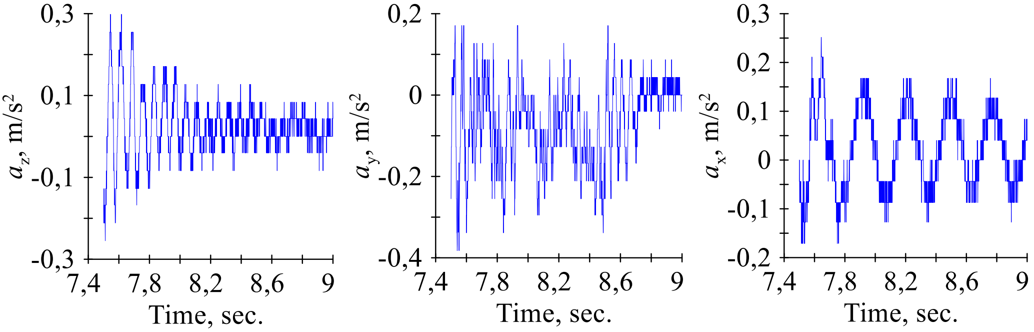
Consider the logarithmic decrement of oscillation attenuation, which is the logarithm of the ratio of two amplitudes that are separated by a time interval of one period:

$$\lambda = ln\frac{A(t)}{A(t+T)} = ln\frac{A_0e^{-\beta t}}{A_0e^{-\beta(t+T)}} = \frac{2\pi\beta}{\omega} \qquad (2)$$

where ω is cyclic frequency of attenuated vibrations.

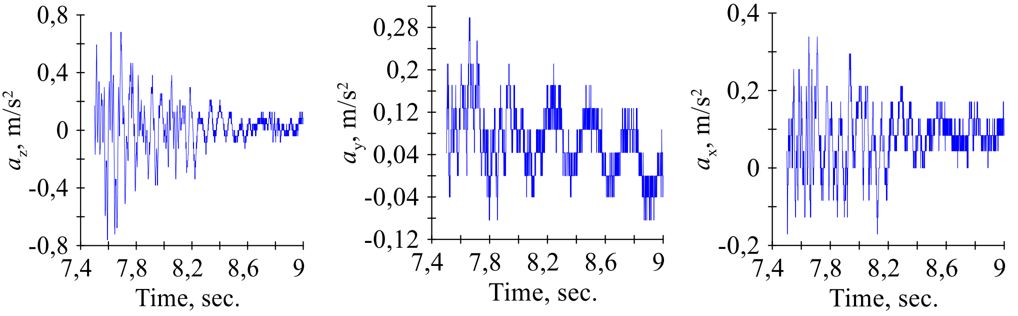
The initial stage of research is to identify the zone in which free vibrations of the system occur. The zones of free vibrations of the rubber-cord shell of a pneumatic spring of high-speed rolling stock in the conditions of movement by the frog of the switch in the trailing direction and facing direction are shown in Fig. 10-11.

Method applied in (Radchenko et al., 2011), graphs of the amplitude spectrum of vibrations are obtained, shown in Fig. 12-13. According to the obtained graphs, the first natural frequency of vibrations of the rubber-cord shell of a pneumatic spring of rolling stock is determined.



(a) (b) (c)

Fig. 10. Zones of free vibrations of the rubber-cord shell of a pneumatic spring in conditions of facing direction movement of the switch frog: a) in the vertical direction; b) in the transverse direction; c) in the longitudinal direction



(a) (b) (c)

Fig. 11. Zones of free vibrations of the rubber-cord shell of a pneumatic spring in conditions of trailing direction movement of the switch frog: a) in the vertical direction; b) in the transverse direction; c) in the longitudinal direction

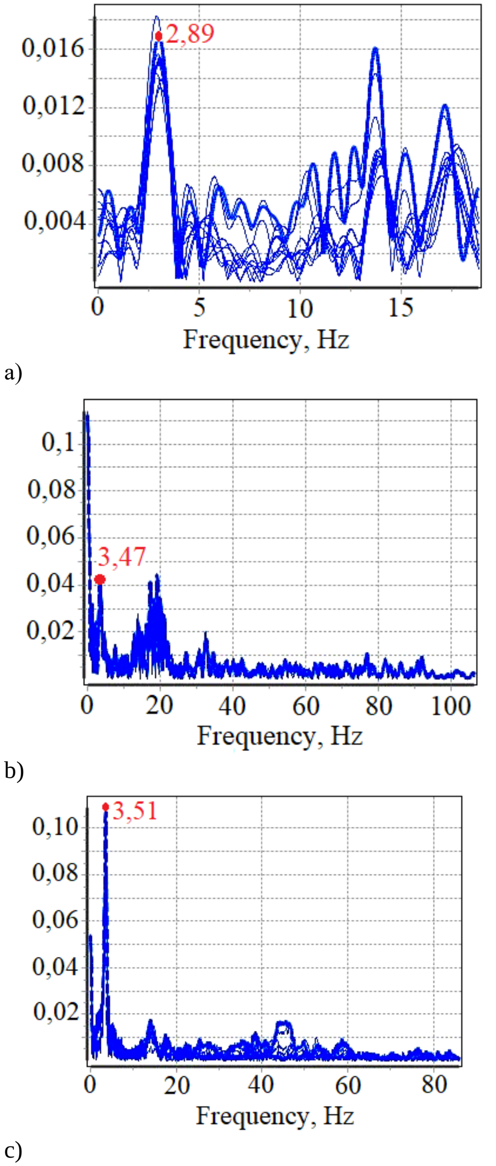


Fig. 12. Graphs of the amplitude spectrum of free vibrations of the rubber-cord shell of a pneumatic spring in conditions of facing direction movement of the switch frog: a) in the vertical direction; b) in the transverse direction; c) in the longitudinal direction

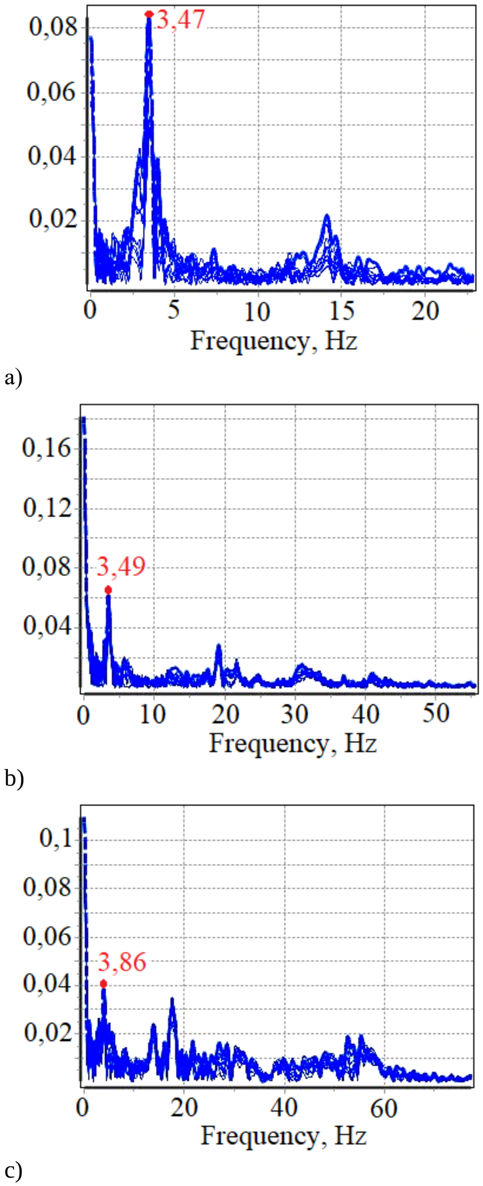


Fig. 13. Graphs of the amplitude spectrum of free vibrations of the rubber-cord shell of a pneumatic spring in conditions of trailing direction movement of the switch frog: a) in the vertical direction; b) in the transverse direction; c) in the longitudinal direction

Based on the results of six experimental passes of the installation along the frog of the switch in the trailing direction and facing directions, the average values of natural oscillation frequencies were obtained (Fig. 14) and logarithmic decrees of oscillation attenuation (Fig. 15) rubber-cord shell of the pneumatic spring.

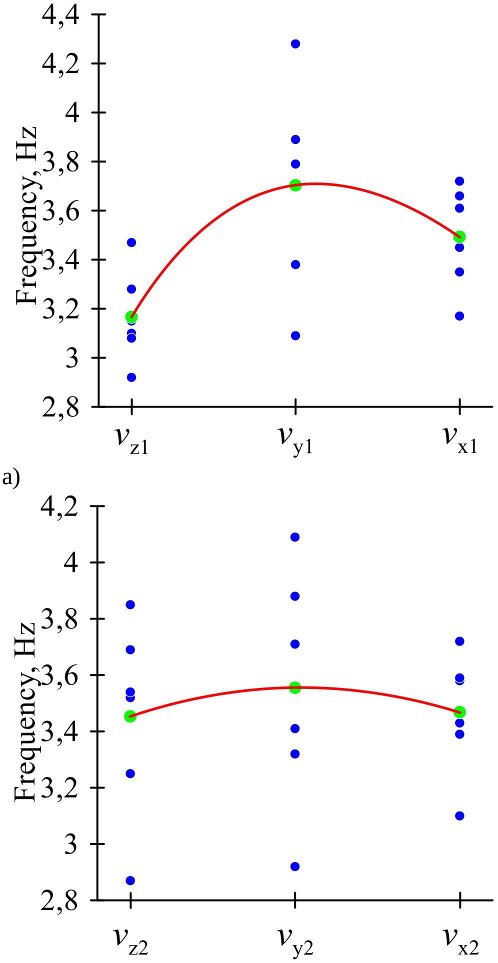


Fig. 14. Natural frequencies of the rubber-cord shell of a pneumatic spring in conditions of movement by a switch: a) trailing direction movement; b) facing direction movement

In the vertical direction, the natural frequency and logarithmic decrement of attenuation of vibrations of the rubber – cord shell of the pneumatic spring of high-speed rolling stock for trailing direction movement by the frog of the switch are in the range of 2.92÷3.47 Hz and 0.30÷0.71, and for facing direction movement-2.87÷3.85 Hz and 0.24÷0.46, respectively.

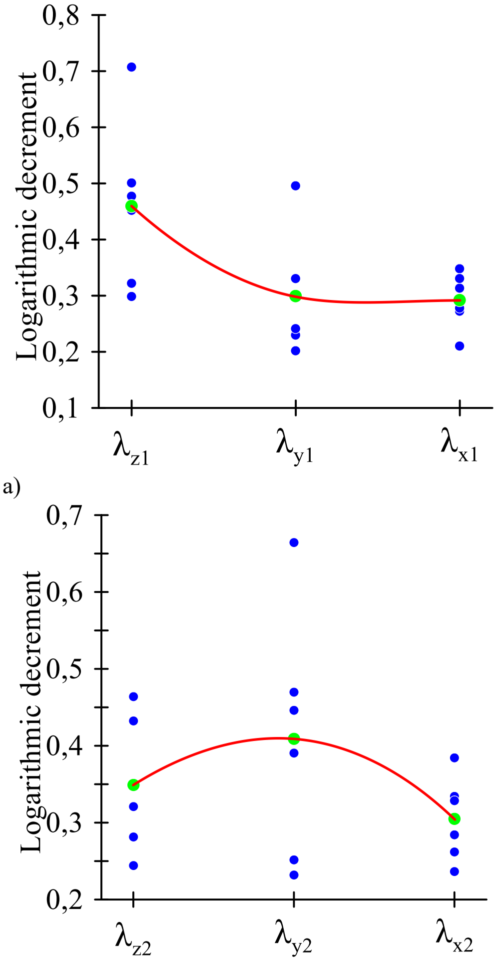


Fig. 15. Logarithmic damping of vibrations of the rubber-cord shell of a pneumatic spring in conditions of movement by a switch: a) trailing direction movement; b) facing direction movement

In the transverse direction, when moving the frog of the switch in trailing direction movement it is from 3.09 Hz to 4.28 Hz and from 0.20 to 0.49, and when moving the frog in facing direction movement it is from 2.92 Hz to 4.09 Hz and from 0.23 to 0.66.

In the longitudinal direction, the natural frequency and logarithmic decrement of attenuation of vibrations of the rubber – cord shell of the pneumatic spring of high-speed rolling stock in the trailing direction are in the range of 3.17÷3.72 Hz and 0.27÷0.35, and in the facing direction they are in the range of 3.1÷3.72 Hz and 0.24÷0.38, respectively.

When studying the first natural frequency of oscillations of an pneumatic spring, the average value of the statistical error in the vertical direction is 5.98%, in the transverse direction it is 8.97%, and in the longitudinal direction it is 4.76%.

A comparison of the average values of the natural oscillation frequencies in the vertical, transverse, and longitudinal directions is shown in Fig. 16, and the logarithmic decrements of oscillation attenuation in Fig. 17.

In the case of movement of the installation in the trailing direction, the average value of the natural frequency of the rubber-cord shell of the pneumatic spring of high-speed rolling stock in the vertical direction ν_{z1} is less than the natural frequency in the facing direction ν_{z2}. The natural frequency difference is 0.28 Hz. However, the natural frequencies of vibrations in the transverse and longitudinal directions in trailing direction movement are higher than the natural frequencies of vibrations in facing direction movement. The natural frequency difference is 0.15 Hz and 0.025 Hz, respectively.

Analysis of the average values of logarithmic decrements of attenuation of vibrations of the rubber-cord shell of a pneumatic spring showed that in the vertical direction, the value of the logarithmic decrement in the trailing direction movement λ_{z1} is greater than the logarithmic decrement in the facing direction movement λ_{z2}. The difference between logarithmic decrements is 0.11. However, the logarithmic decrements of attenuation of vibrations in the transverse and longitudinal directions in facing direction movement are higher than the logarithmic decrees in trailing direction movement. The difference between decrements is 0.11 and 0.013, respectively.

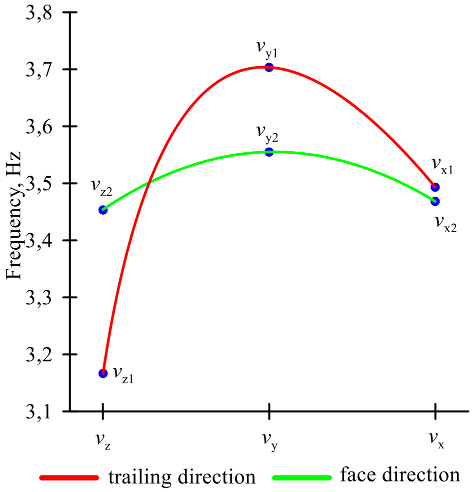


Fig. 16. Average values of the natural frequency of the rubber-cord shell of a pneumatic spring in conditions of movement by the switch

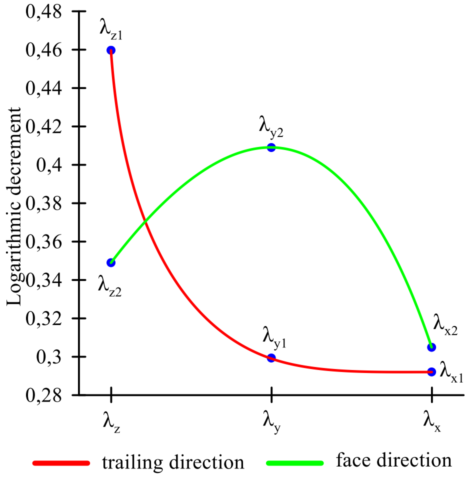


Fig. 17. Average values of logarithmic decrements of attenuation of vibrations of the rubber-cord shell of a pneumatic spring in conditions of movement by the switch

5. Results of discussion of the dynamic behaviour of a pneumatic spring when tracing a turnout crossing zone

To assess the dynamic parameters of the rubber-cord shell of the pneumatic spring of high-speed rolling stock of the railway when interacting with the frog of the switch, an experimental installation was developed, which included a frame, an installed pneumatic spring, power and measuring equipment (Fig. 3).

The developed methodology for full-scale testing of the rubber-cord shell of a pneumatic spring provided for six passes of the experimental installation from the mathematical center of the turnout in the direction of the rear joint and back. At the same time, analog acceleration sensors ADXL 335 recorded vertical transverse and longitudinal accelerations (Fig. 4).

According to the obtained acceleration accelerograms, it was found that the maximum values of accelerations of the rubber-cord shell of the pneumatic spring of high-speed railway rolling stock in the vertical direction vary within: for trailing direction movement it is from 1.74 m/s^2 to 2.25 m/s^2, for facing direction movement it is from 1.32 m/s^2 to 1.69 m / s^2. In the transverse direction for trailing direction movement it is from 0.47 m/s^2 to 0.98 m/s^2, and for facing direction movement it is from 0.64 m/s^2 to 0.93 m/s^2. In the longitudinal direction for trailing direction movement it is from 0.55 m/s^2 to 0.80 m/s^2, and for facing direction movement it is from 0.38 m/s^2 to 0.85 m/s^2 (Fig. 8).

It should be noted that the values of vertical accelerations during trailing direction and facing direction movements are higher in comparison with transverse and longitudinal ones. The values of transverse accelerations and longitudinal accelerations are almost the same in the case of trailing direction movement, but in the case of facing direction movement, transverse accelerations are higher than longitudinal ones (Fig. 9).

Comparison of the average values of vertical accelerations (fig. 9) shows that their value in the trailing direction movement is higher than in the facing direction movement.

The difference between the obtained experimental results of acceleration of the pneumatic spring during rear joint (facing direction movement) and back (trailing direction movement) of the switch crosspiece is explained by the trajectory of the wheel of the wheelset. It was found that it has different parameters depending on the direction of travel (Fig. 18), which will affect the dynamic behavior of the pneumatic spring in the wheel-rail interaction (Kuzyshyn et al., 2024).

As a result of different parameters of the trajectory of the wheel of the wheelset to the crosspiece of the switch, different values of accelerations of the pneumatic spring occur in rear joint (facing direction movement) and back (trailing direction movement). Also, within the statistical error of the studies, which is 5.98%, there is a difference between the first eigenfrequencies and logarithmic decrees of oscillation attenuation.

The conducted frequency analysis allowed us to establish that the average value of the first natural frequency of vibrations of the rubber-cord shell of a pneumatic spring in the vertical, transverse and longitudinal directions during the trailing direction movement of the frog of the switch is 3.17 Hz, 3.7 Hz and 3.49 Hz, and the logarithmic decrement of the attenuation of vibrations is 0.46, 0.30 and 0.29, respectively. For facing direction movement, the natural frequency is 3.45 Hz, 3.56 Hz, and 3.47 Hz, and the logarithmic attenuation decrement is 0.35, 0.41, and 0.31, respectively. (Fig. 14-17). It should be noted that the obtained results of experimental studies of the rubber-cord shell of a pneumatic spring are in the ranges of values given in the paper (Moheyeldein et al., 2018; Kuzyshyn et al., 2024b).

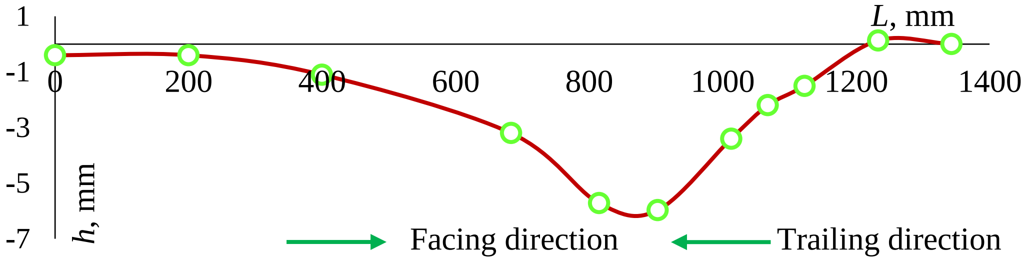


Fig. 18. Trajectory of the wheel of the wheelset along the crosspiece of the switch

From a practical point of view, the obtained frequency analysis indicators (natural frequency and attenuation decrement) of the new pneumatic spring of high-speed rolling stock are the identifier of non-degraded physical and mechanical parameters of its rubber-cord shell, which corresponds to its rational rigid parameters. Further monitoring of the frequency analysis of the pneumatic spring depending on the mileage of rolling stock will allow us to determine the degradation of the rubber-cord shell of the pneumatic spring, and, accordingly, the change in stiffness. This will allow us to take into account the change in the stiffness of the pneumatic spring in its mathematical modeling, which is included in the spatial mathematical model of the rolling stock-track interaction when determining dynamic indicators and traffic safety indicators.

At the first stage of the research, the oscillation frequencies of the rubber cord shell were determined without taking into account the changes in manometric air pressure in it. In the future, it would be advisable to investigate how the creation of an initial overpressure in a pneumatic spring will affect the dynamic characteristics of the spring suspension when moving the switch frog.

Also, with further scientific research, changes in natural frequencies and other parameters of the pneumatic spring will be monitored depending on the period of its operation

6. Conclusions

1. A methodology for full-scale testing of the rubber-cord shell of a pneumatic spring of high-speed railway rolling stock in the conditions of movement of the switch frog was developed. An experimental setup was developed for conducting field tests. Using analog acceleration sensors, accelerograms were obtained in the vertical, transverse and longitudinal directions in the conditions of trailing direction and facing direction movements of the frog of the switch.

2. It was found that in trailing direction movement, the average acceleration values are 1.95 m/s^2 in the vertical direction, 0.74 m/s^2 in the transverse direction and 0.71 m/s^2 in the longitudinal direction, and in facing direction movement it is 1.47 m/s^2, 0.74 m/s^2 and 0.61 m/s^2, respectively. It is noted that the value of the average values of vertical and longitudinal accelerations in trailing direction movement is 24.6% and 13.9% higher than the average value of accelerations in facing direction movement. It is emphasized that the values of the average values of transverse accelerations in trailing direction and facing direction movements are equal.

3. Based on the frequency analysis, it is established that in the vertical direction, the average value of the natural frequency and logarithmic decrement of attenuation of vibrations of the rubber–cord shell of the pneumatic spring of high-speed rolling stock for trailing direction movement by the frog of the switch is 3.17 Hz and 0.46, and for facing direction movement it is 3.45 Hz and 0.35, respectively. In the transverse direction for trailing direction movement it is 3.7 Hz and 0.30, and for facing direction movement it is 3.56 Hz and 0.41. in the longitudinal direction-for trailing direction movement it is 3.49 Hz and 0.29, and for facing direction movement it is 3.47 Hz and 0.31.

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