EFFECTS OF MOVEMENT DIRECTION THROUGH A SWITCH ON ACCELERATIONS AND NATURAL FREQUENCIES OF A PNEUMATIC SUSPENSION OF HIGH-SPEED ROLLING STOCK

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Resume

The research object is a pneumatic spring of the second stage of spring suspension of the high-speed railway rolling stock in movement conditions by a switch. Full-scale dynamic tests of a pneumatic spring for the high-speed railroad rolling stock were carried out. It was found that the average values of vertical accelerations in the trailing and facing directions in the wind turbines moving by the switch are 1.307 m·s^{-2} and 1.279 m·s^{-2}, respectively. The ratio of the average values of longitudinal accelerations in the trailing and facing directions within the wind turbines is 1.01, and at the wind turbine bases is 2.15. It is found that the average value of the first natural frequency of oscillations of the pneumatic spring is 3.53 Hz, while the logarithmic decrement of the oscillation attenuation is 0.321.

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1 Introduction

One of the reasons for the increase in the level of vibrations of the structural elements components of rolling stock, the force of the wheelset‘s interaction with the rail track, is the movement of the rolling stock by the switch (Figure 1) [1]. It should be emphasized that the influence of the switch on dynamic indicators and rolling stock safety indicators is usually more sensitive at increased traffic speeds [2-3].

The design feature of the mechanical part of the diesel trains DPKr-2 and DPKr-3 and the electric train EKr-1 “Tarpan” is the use of a pneumatic spring suspension system in the second stage of the spring suspension. The specified spring suspension system consists of a pneumatic spring, an additional tank, a connecting pipeline and other structural elements [5].

The design of the pneumatic spring (Figure 2) allows the use of a rubber cord shell to improve the vibration protection properties of the rolling stock and the comfort of passenger transportation.

One of the conditions for the high-quality rolling stock operation is assessing its vibration-proof properties. These include, first of all, the frequency characteristics of individual components of the mechanical part of the rolling stock, in particular, the pneumatic spring (Figure 2).

A significant disturbing factor in the interaction of the rolling stock with the railroad track is a switch. Therefore, it is important and relevant to establish the frequency characteristics of the pneumatic spring of the high-speed rolling stock in the movement conditions by the switch. From a practical point of view, this would make it possible to control the dynamic characteristics of the rubber cord shell of the pneumatic spring and detect their deviations during the rolling stock operation.

2 Analysis of literature data and problem statement

Both theoretical and experimental methods are used to study the dynamic operation of a high-speed rolling stock pneumatic spring. Theoretical methods are

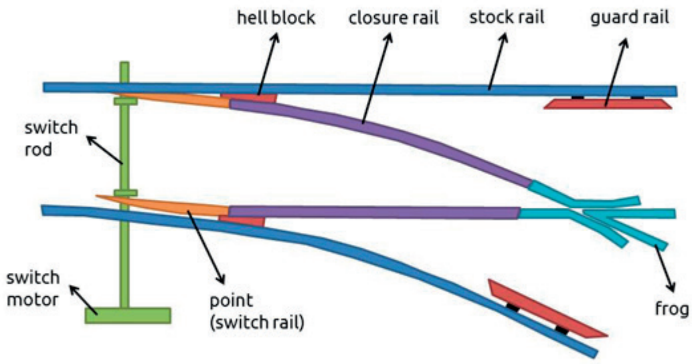


***Figure 1** Structural elements of the switch [4]*

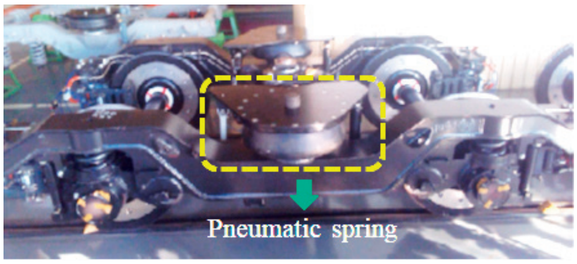


***Figure 2** Structural installation of a pneumatic spring for the high-speed railway rolling stock*

mainly based on mathematical models and specialized software. The main mathematical models describing the dynamic behaviour of a pneumatic spring are mechanical, thermodynamic, and finite element models.

Authors of [6] presented a nonlinear thermodynamic model of an air spring, which is a combination of two different models: the Berg model [7] and the Haupt and Sedlan model [8], which allows taking into account the elastic and viscoelastic parameters of the rubber cord shell of an air spring. To verify the adequacy of the proposed model, the authors conducted tests, where it was found that the maximum body vibrations at a speed of 80 $km \cdot h^{-1}$ occur in the frequency range of 1.5-3 Hz. Subsequently, by selecting the appropriate parameters of the structural elements of the pneumatic spring suspension system, the Sperling ride comfort index was investigated [9]. However, the authors did not take into account the effect of the switching gear on the dynamic behavior of the pneumatic spring.

In [10], the authors considered the classical and dynamic models of a pneumatic spring based on the MATLAB/Simulink software package. It was established that the pneumatic springs, in the second stage of the spring suspension, in the equation with elastic-damping elements, reduce the acceleration and displacement of the body by 27 % and 10 %, respectively.

Paper [11] presents a study of driving comfort by assessing accelerations in the body, which shows the difficulties in choosing the optimal damping coefficient of the secondary suspension. Using a valve with a variable orifice in the connection between the pneumatic spring and the additional reservoir is proposed.

In [12], the authors experimented in the laboratory to determine the quasi-static and dynamic behaviour of a pneumatic spring suspension system.

The effect of the volume of the additional reservoir, and the length and diameter of the connecting pipeline on the characteristics of the pneumatic spring suspension system was investigated in [13].

A series of experiments was conducted in [14] to determine the vertical stiffness of a pneumatic spring.

In [15], a nonlinear model of the air suspension system was developed to take into account the influence of nonlinear flow characteristics of altitude control valves and the pressure drop. Experimental studies have shown the importance of such consideration when assessing the safety of the rolling stock at low speeds in a curved section of a small-radius railway track. In addition, the influence of the lever angle of the pneumatic spring height adjustment valve on the wheel load imbalance during the passage of curved sections of a small-radius track is studied in [16].

In [17], based on experimental studies, the authors developed an analytical model of the operation of a pneumatic spring suspension system. It is established that the dimensions of the connecting pipeline, additional tank and pneumatic spring are the most important design parameters to determine the behaviour of the pneumatic spring suspension system. In the tests, the authors determined the vertical stiffness, reaction of the spring-loaded mass, and damping of the pneumatic system.

In [18], the authors conducted two groups of experiments: quasi-static and dynamic. That made it possible to study the force-displacement hysteresis loop and the damping effect of the rubber cord shell of a pneumatic spring.

In [19], the stiffness of a pneumatic spring in the vertical and horizontal directions was experimentally studied. In the modelling process, the movement of rolling stock in a straight and curved section of a railway track was considered.

In [20], the authors performed dynamic tests of the transverse stiffness of a pneumatic spring. It is established that the lateral stiffness of the pneumatic spring increases with increasing internal pressure and decreases with increasing disturbance amplitude.

It should be noted that the interaction of the rolling stock wheelset with the rail track, when moving by a switch, compared to moving on a straight and curved section of the railroad track, is special, which causes additional dynamic loads on the rolling stock. Namely, studies [21-22] found that the magnitude of dynamic impact loads depends on the speed and geometry of the switch, as well as the stiffness of the track [23-24]. To study the effect of the switch stiffness on the force interaction of the "rolling stock-switch" system, numerical calculation models were developed in [25-26].

To determine the vertical and horizontal transverse forces of interaction, the authors in [27] conducted complex experimental studies using a strain gauge wheelset. In [28-29], it was found that an increase in the speed of movement leads to an increase in the horizontal transverse force in both trailing and facing directions of the switch. The direction of movement of the switch has no significant effect on the vertical force.

In addition, as a result of the force interaction, significant vibrations of the rolling stock-switch system occur. The study of the rolling stock dynamic behaviour, and establishment of the resonance phenomenon in the movement conditions by a switch of rolling stock, are given in [30].

Taking into account the influence of changes in the rail profile and its local flexibility on the force interaction of the switch with rolling stock is given in [31]. In [32], the nature of changes in the equivalent taper of the wheel and rail in the switch zone, depending on the change in the wheel profile, was studied. In addition, the influence of the wheel profile and the coefficient of friction on the magnitude of contact forces and stresses is studied in [33]. The study of three-dimensional contact geometry, which takes into account the combined influence of different rail profiles and the angle of deviation in the direction of the rolling stock movement, is presented in [34].

The influence of the technical condition of the switch elements and undercarriage of the rolling stock on the power interaction „rolling stock - track" was studied in [35-36]. In addition, in [37], it was found that the dynamic interaction of the rolling stock and the switch leads to the accumulation of stresses on the rolling surface of the crosspiece. This further affects the formation of defects that cause additional dynamic of forces.

In works [38-40] the influence of the railway track ballast disorder on the increase of dynamic load on the rolling stock is studied. In addition, in works [41-43] the authors investigated the issues of wear of the cores of switches. It was found that the amount of core wear affects the level of dynamic interaction between the rolling stock and the crossing.

The analysis of research works shows that the main attention is paid to determining the forces of interaction, on the value of which the dynamic performance of the rolling stock and traffic safety indicators depend. However, increasing the speed of the rolling stock suggests the need to study its vibration-proof properties, based on determining the vertical and horizontal accelerations of structural elements. Considering that the pneumatic spring suspension system is the main structural component of the rolling stock mechanical part, determination and study of vertical accelerations of its structural elements when passing through the switch is an urgent task and requires further research.

The analysis of [6-20] shows the importance of studying the dynamic characteristics of a pneumatic spring of high-speed rolling stock. However, most studies are conducted in laboratory conditions (a sinusoidal bump is taken as a disturbance), which does not take into account the real conditions of interaction between the rolling stock and a track.

This study aims to determine the accelerations of the rubber cord shell of the pneumatic spring of high-speed rolling stock when interacting with the switch wind turbines in the trailing and facing movement. This would make it possible to set the natural frequencies and logarithmic decrements of the vibration attenuation of the air spring rubber cord shell.

To achieve this goal, the following tasks were set:

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

3 Methodology of the full-scale tests of a pneumatic spring in movement conditions by a switch

Dynamic tests of the pneumatic spring of the high-speed rolling stock were carried out within the arrow of the switch. The view of the test unit on the switch is shown in Figure 3.

Mobile installation for testing the pneumatic spring of the high-speed rolling stock within switch *1*, consists of a pneumatic spring *4*, which is rigidly fixed to the supporting structure of the stand *5*. The spring is loaded

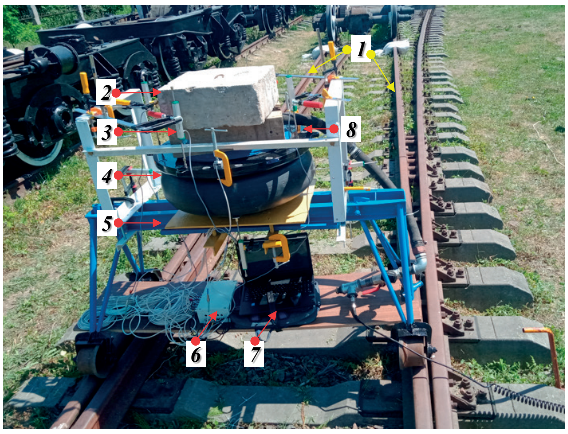


Figure 3 *Movable installation on the switch to test the pneumatic spring: 1 - switch; 2 - concrete block; 3 - high-frequency potentiometric linear displacement sensor; 4 - pneumatic spring; 5 - supporting structure of stand; 6 - analogue-to-digital converter; 7 - laptop; 8 - analogue acceleration sensor*

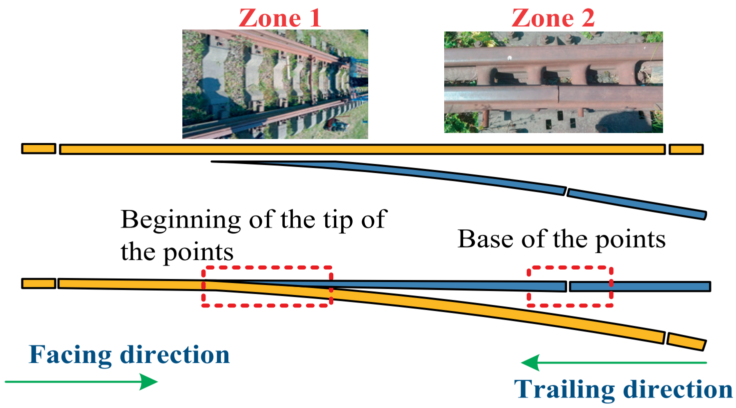


Figure 4 *Characteristic sections of the switch when the test unit is moving*

with a reinforced concrete block *2*.

When the unit moves by the switch, the spring oscillates, which is associated with the design features of the switch: the presence of joints, a transition curve, etc. [36-37]. Spring vibrations are recorded by an analogue acceleration sensor *8*. The signal is read by an analogue-to-digital converter *6* and it is transmitted to the laptop *7* and stored in its memory.

In this study, the experimental program provided for recording acceleration vibrations when the unit moves in the facing (from the tip of the points towards the crosspiece) and trailing (from the crosspiece to the tip of the points) directions. Spring accelerations were recorded seven times in different directions of the moving unit motion.

Special attention is paid to two sections when the unit moves by the switch (Figure 4): the beginning of the tip of the points and the base of the points.

When moving along Zone 1 (the beginning of the tip of the points) and Zone 2 (the base of the points), in addition to vertical action, there is a significant horizontal action on the test unit, as well. This causes lateral vibrations of the pneumatic spring of the high-speed rolling stock.

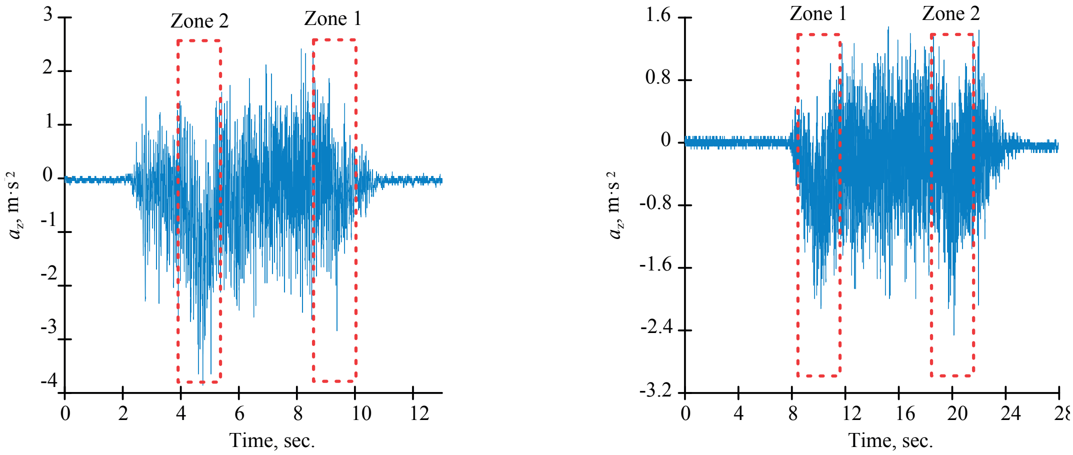
Based on the results of seven passes in the facing and trailing directions of the switch, graphs of acceleration records were obtained. Later, accelerations were analyzed and dynamic parameters of the pneumatic spring were determined using the frequency analysis methods, such as natural oscillation frequencies and logarithmic decrees of oscillation attenuation.

4 Results of experimental studies of vibration-proof properties of a pneumatic spring

4.1 Determination of accelerations of the rubber-cord shell of a pneumatic spring of the high-speed rolling stock when interacting with the points of the switch

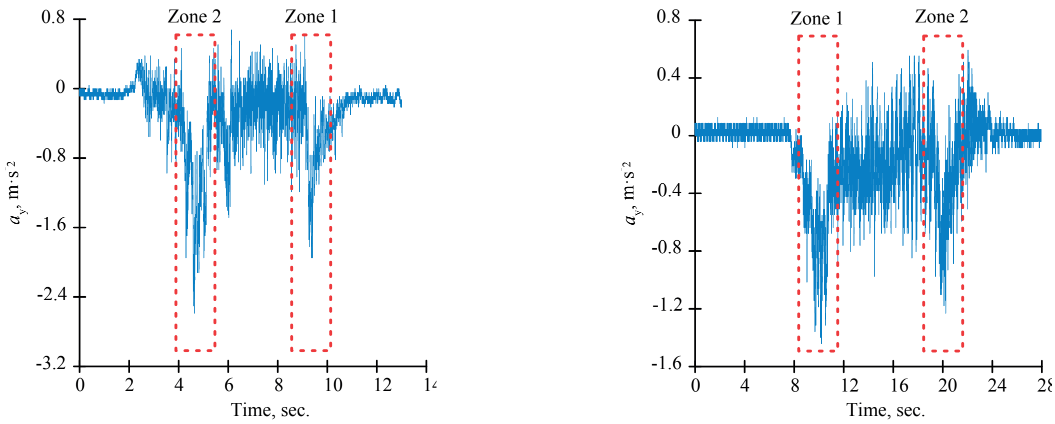
During the full-scale tests, records of vertical, transverse and longitudinal accelerations of the rubber-cord shell of a high-speed rolling stock pneumatic spring were obtained when the test unit interacted with the points and base of the wind turbines of the switch in the trailing and facing directions, Figures 5-7.

According to the obtained records, the two zones of a sharp increase in accelerations of the rubber-cord shell of a pneumatic spring in the vertical, transverse and longitudinal directions, are distinguished, namely Zone 1 - this is the beginning of the tip of the points and



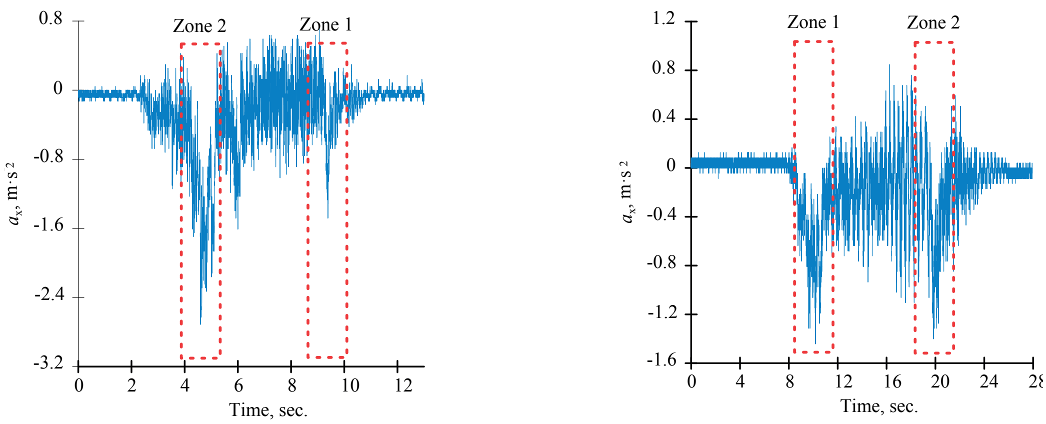
a) b)

***Figure 5** Record of vertical accelerations of the rubber-cord shell of a pneumatic spring in the trailing (a) and facing (b) directions*



a) b)

***Figure 6** Record of transverse accelerations of the rubber-cord shell of a pneumatic spring in the trailing (a) and facing (b) directions*



a) b)

***Figure 7** Recording of longitudinal accelerations of the rubber-cord shell of a pneumatic spring in the trailing (a) and facing (b) directions*

Zone 2 - the base of wind turbines. The sharp increase in accelerations in these zones is due to their geometric features, which leads to an increased force interaction of the wheelset with the rail track.

Using the selected zones, for each experiment performed, the maximum values of accelerations are found in all the considered planes, when the test unit moves in the trailing and facing directions (Figure 8-9).

As shown in Figure 8, it was established that the maximum values of vertical accelerations of the rubber cord shell of the pneumatic spring, during the gravity and anti-gravity movement of the test installation in Zone 1 of the switch, vary within 1.017-1.593 m·s^{-2} and 0.893-1.677 m·s^{-2}, respectively. When the test unit moves in Zone 2, the maximum values of vertical accelerations are within 1.091-2.859 m·s^{-2} and 1.075-1.691 m·s^{-2}, Figure 9.

Comparing the average values of vertical accelerations in the trailing and facing directions, when moving wind turbines of the switch, it was found that their values are 1.307 m·s^{-2} and 1.279 m·s^{-2}, respectively. However, when moving through the root of the windmills of the switch, the vertical accelerations of the rubber-cord shell of the pneumatic spring in the trailing and facing directions have discrepancies, the value of which in percentage terms is 29.04 %.

It should be noted that determination of the value of transverse accelerations of elements of the high-speed rolling stock mechanical part is the main factor in the study of the driving comfort criterion. As shown in Figure 8, it was found that when the windmill zone moves in the trailing direction, the maximum values of transverse accelerations are in the range of 0.936-1.816 m·s^{-2}, and in the facing direction within 0.932-1.571 m·s^{-2}. At the same time, the average acceleration values are 1.594 m·s^{-2} and 1.343 m·s^{-2}, respectively. This percentage is 15.74 %. When moving in Zone 2 (wind turbine base) in the trailing direction, the maximum values are within 1.344 -2.404 m·s^{-2}, and in the facing one within 0.586-1.372 m·s^{-2}. This difference in transverse accelerations of the pneumatic spring rubber-cord shell of the high-speed rolling stock in the trailing and facing directions is

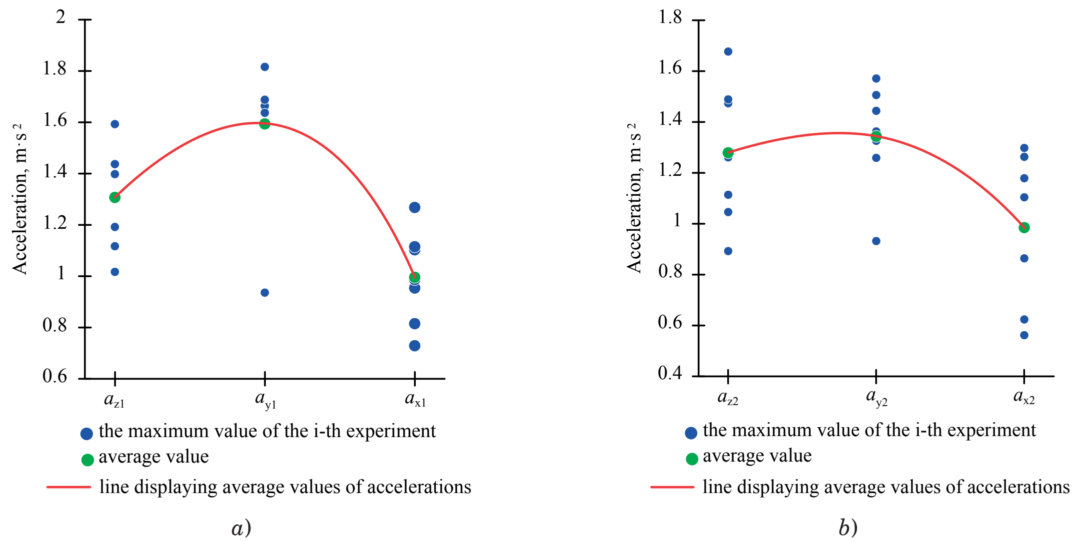


Figure 8 *Average of vertical (a_{z1}, a_{z2}), lateral (a_{y1}, a_{y2}) and longitudinal (a_{x1}, a_{x2}) acceleration values of the rubber-cord shell of a pneumatic spring in the trailing (a) and facing (b) directions when passing Zone 1 of the switch*

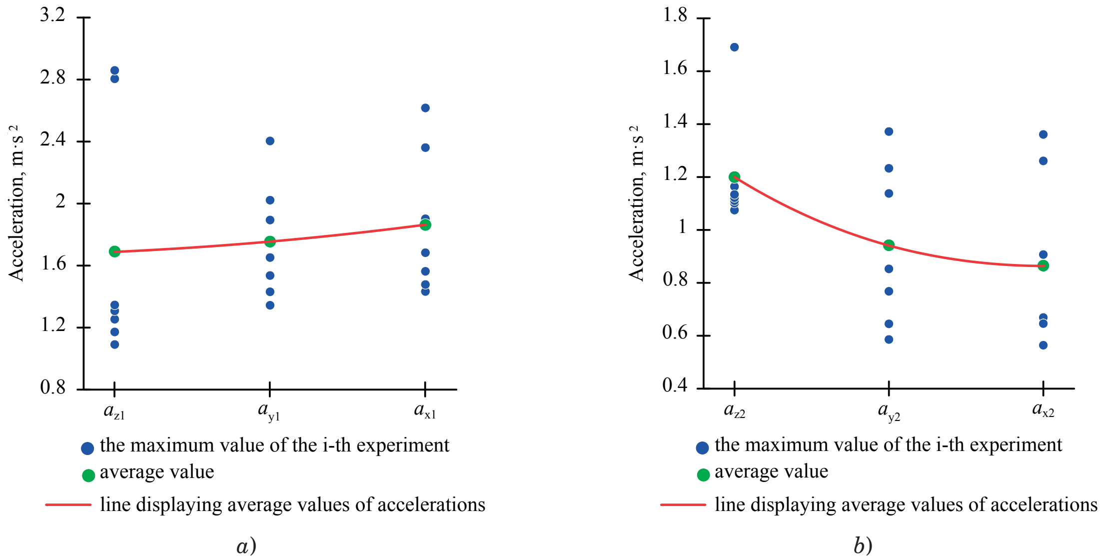


Figure 9 *Average of vertical (a_{z1}, a_{z2}), lateral (a_{y1}, a_{y2}) and longitudinal (a_{x1}, a_{x2}) acceleration values of the rubber-cord shell of a pneumatic spring in the trailing (a) and facing (b) directions when passing Zone 2 of the switch*

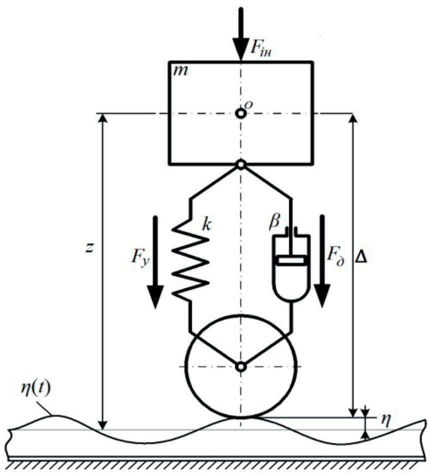


***Figure 10** Flat model with one degree of freedom under kinematic perturbation: k - stiffness of the rubber-cord shell of the pneumatic spring; β - damping coefficient; N is the amplitude of the unevenness; m is the mass that falls on the pneumatic spring; z is the absolute displacement; δ is the relative displacement (deflection)*

explained by the peculiarities of rolling the wheels of the rolling stock from the frame rails to the points and from the points to the frame rails of the switch, which causes lateral vibrations.

A comparison of the longitudinal accelerations average values of the pneumatic spring rubber-cord shell, during the movement with the points of the switch, showed a slight difference in trailing and facing movement, which cannot be said about the zone of the root of wind turbines. The ratio of the average values of accelerations during the trailing movement to accelerations that occur in the facing direction in the zone of wind turbines is 1.01, and in the zone of the base of the points is 2.15. This is caused by the passage of the wheel ridge between the frame rail and the point of the switch, which causes an additional longitudinal effect on the pneumatic spring.

The maximum values of longitudinal accelerations in the trailing direction in the wind turbine zone are 0.729-1.268 $m \cdot s^{-2}$, and in the facing direction - 0.562-1.298 $m \cdot s^{-2}$. In the wind turbine base zone, the maximum acceleration values are 1.433-2.617 $m \cdot s^{-2}$ and 0.564-1.361 $m \cdot s^{-2}$, respectively.

Next, using the obtained records of vertical, transverse and longitudinal accelerations of the pneumatic spring rubber-cord shell, the natural frequency of vibrations of the rubber-cord shell of a pneumatic spring of high-speed rolling stock and the logarithmic decrement of vibration attenuation are determined.

4.2 Determination of the natural frequency and attenuation decrement of vibrations of the rubber-cord shell of a pneumatic spring

Natural vibrations occur when an elastic mechanical system is thrown out of equilibrium. This can be done by quickly removing the static load or by instantly applying and removing external force. Displacements with variable acceleration appear as a result.

The frequency of natural vibrations can be found using the calculation scheme of a dynamic model with one degree of freedom (Figure 10).

During the system movement, kinematic perturbation causes vertical fluctuations in the super-spring structure characterized by a generalized coordinate z. The system has the following forces:

- inertial force:

$$F_{iH} = -m\ddot{z}\,, \tag{1}$$

- elastic force:

$$F_y = -k\Delta = -k(z-\eta)\,, \tag{2}$$

- dissipative force:

$$F_\partial = -\beta\dot{\Delta} = -\beta(\dot{z}-\dot{\eta})\,. \tag{3}$$

Using the D'alembert principle, the oscillation equation of the model under consideration is:

$$F_{iH} + F_y + F_\partial = 0\,. \tag{4}$$

Taking into account Equations (1)-(3), the oscillation equation can be written as:

$$m\ddot{z} + \beta\dot{z} + kz = \beta\dot{\eta} + k\eta\,. \tag{5}$$

The obtained Equation (5) is the equation of vertical vibrations of the model, the left-hand side of which is eigenvalues, and the right-hand side is forced. Solving the oscillation equation will allow to get the value of vertical displacements z, speeds $\dot{z}$ and accelerations $\ddot{z}$ masses m and evaluate the dynamic properties of the model.

To determine the first natural frequency of vibrations of the pneumatic spring rubber-cord shell of the high-speed rolling stock, when passing through the switch,

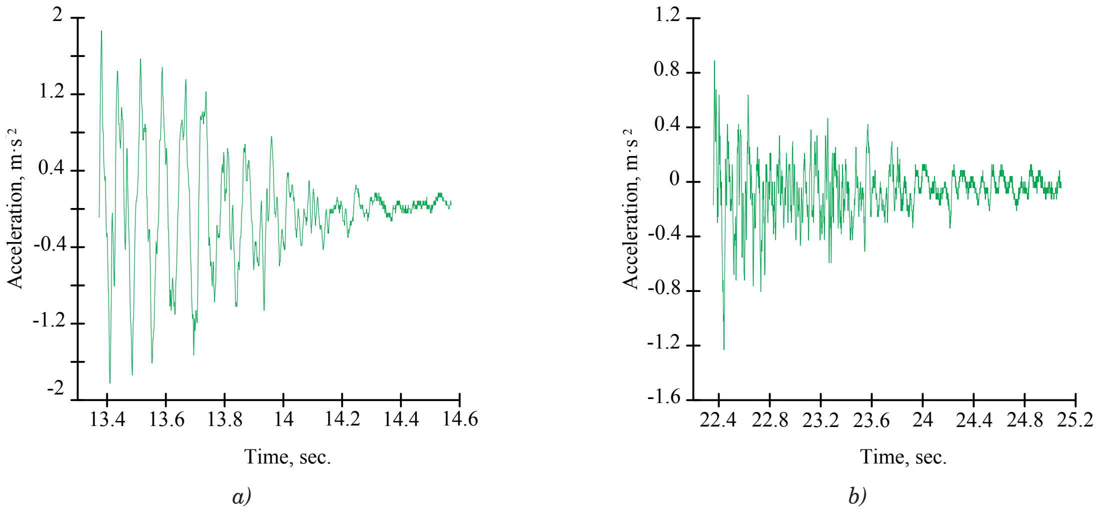


***Figure 11** Record of vertical accelerations during the free vibrations of the rubber-cord shell of a pneumatic spring: a) trailing direction; b) facing direction*

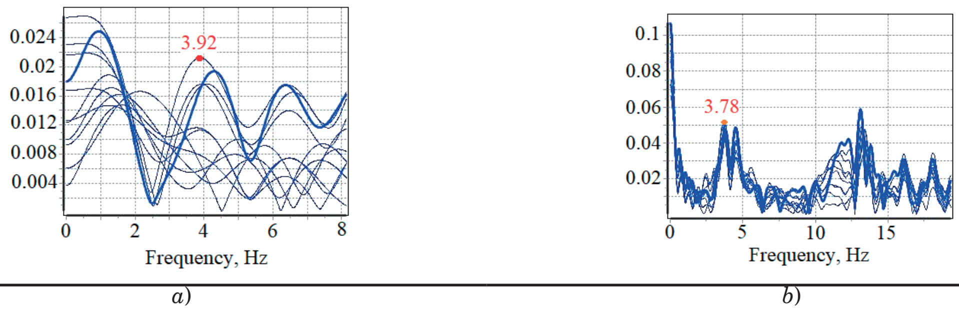


***Figure 12** Graphs of the amplitude spectrum of free vertical vibrations of the rubber-cord shell of a pneumatic spring in conditions of movement by the switch: a) in the trailing direction; b) in the facing direction*

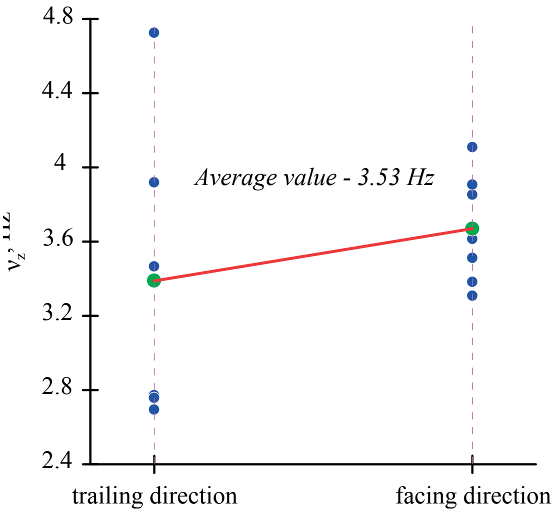


***Figure 13** Natural frequencies of vertical vibrations of the rubber-cord shell of a high-speed rolling stock pneumatic spring*

zones of free vibrations of the system in the trailing and facing directions of movement by the switch are highlighted (Figure 11) and the method used [44].

The result of frequency analysis is to obtain graphs of the amplitude spectrum of vibrations shown in Figure 12, which determine the first natural frequency of vibrations of the rolling stock pneumatic spring rubber-cord shell.

Based on the results of experimental driveways of the test unit in Zone 1 and Zone 2 of the switch, in the trailing and facing directions, the average values of the frequency of vertical natural vibrations of the pneumatic spring were obtained (Figure 13).

Analysis of the amplitude spectrum graphs showed that the natural frequencies of the pneumatic spring of the high-speed rolling stock vary between 3.31 and 4.11

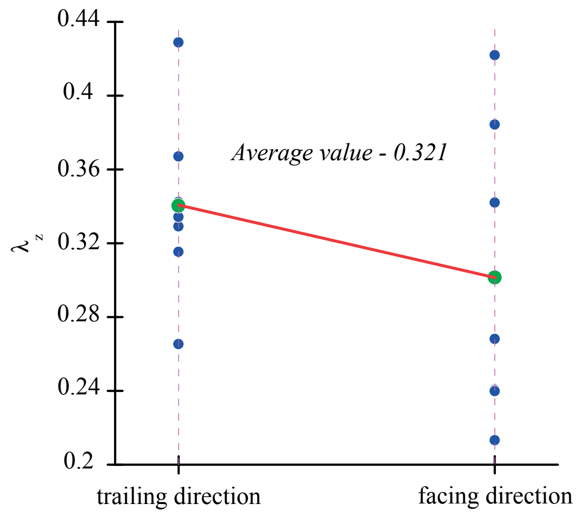


***Figure 14** Logarithmic decrement of attenuation of vibrations of the rubber-cord shell of a pneumatic spring of high-speed rolling stock*

Hz in the direction of movement of the switch and 2.76 to 4.72 Hz in the conditions of the trailing direction and facing the direction of movement. It is established that the average value of the natural oscillation frequency of a pneumatic spring is 3.53 Hz, which can later be used in establishing resonant zones and impact zones of a mechanical system of the high-speed rolling stock.

Next, the logarithmic attenuation decrement is used to quantify the attenuation of vibrations.

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

$$\lambda = \ln\frac{A(t)}{A(t+T)} = \ln\frac{A_0 e^{-\beta t}}{A_0 e^{-\beta(t+T)}} = \frac{2\pi\beta}{\omega}, \qquad (6)$$

where ω is the cyclic frequency of attenuated vibrations.

Therefore, by analyzing the records of vertical deformations of the rubber-cord shell of a pneumatic spring, in the zones of its free vibrations, the average values of the logarithmic decrement of oscillation attenuation are obtained (Figure 14).

The logarithm value of the rate of decrease in the amplitude of vibrations is in the range of 0.265-0.43 for the trailing direction by a switch, and for the facing direction - 0.213-0.422. It is established that the average value of the logarithmic decrement of attenuation of pneumatic spring vibrations is 0.321.

These values can later be used to determine the damping properties of the pneumatic spring of high-speed railway rolling stock.

5 Discussion of results of the dynamic behaviour of a pneumatic spring by a switch

To determine the dynamic properties of a pneumatic spring of high-speed railway rolling stock, a comprehensive methodology for the full-scale testing of a pneumatic spring using a mobile test unit has been developed, Figure 3. This made it possible to obtain accelerograms of vertical, transverse and longitudinal accelerations of the pneumatic spring when the test unit moves in the trailing and facing directions of the switch, Figures 5-6. As a result, special areas of acceleration changes of the rubber-cord shell of the pneumatic spring are established: the beginning of the tip of the points and the base of the points.

Comparison of the average values of vertical accelerations in the trailing and facing directions, during the movement of the test unit by wind turbines of the switch, showed their practical coincidence, which cannot be said about the number of accelerations in the zone of the root of windmills, where the percentage difference is 29.04 %. In the transverse direction, the difference in the average acceleration values in the trailing and facing directions for the zone of the tip of the points does not exceed 15.75 %, and for the zone of the wind turbine base is 46.31 %. In the longitudinal direction, the difference is 1.11 % for the tip zone of the points and 53.55 % for the zone of the wind turbine base.

Frequency analysis of oscillation records showed that the average value of the first natural oscillation frequency of the pneumatic spring is 3.53 Hz, and the logarithmic decrement of oscillation attenuation is 0.321.

One of the limitations of the conducted research is that the natural oscillation frequencies of the pneumatic spring of high-speed rolling stock are obtained without taking into account the manometric air pressure in it. The next stage of research and development will be to conduct field tests of the pneumatic spring at a certain initial gauge pressure. This would make it possible to study its influence on the dynamic characteristics of the pneumatic spring suspension system in the movement conditions by a switch.

6 Conclusions

1. A comprehensive methodology for the full-scale testing of a pneumatic spring of high-speed rolling stock, while moving along a switch, has been developed. A mobile test unit has been developed to determine the vibration-proof properties of a pneumatic spring. It consists of a load-bearing structure, a pneumatic spring of high-speed railway rolling stock and measuring equipment. This made it possible to conduct experimental tests of the pneumatic spring when the installation moves in the facing and trailing directions.
2. When the test unit moves along the switch elements, records of vertical, transverse and longitudinal accelerations of the rubber-cord shell of the pneumatic spring are obtained. It was found that in the vertical direction, the maximum difference between the average acceleration values in the trailing and facing directions is 29.04 %, in the transverse direction - 46.31% and in the longitudinal direction-53.55 %.
3. Based on the obtained graphs of the amplitude spectrum, it is established that the average value of the first natural frequency of vibrations of a pneumatic spring is 3.53 Hz, and the logarithmic decrement of attenuation of vibrations is 0.321.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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