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EXPERIMENTAL DETERMINATION OF LATERAL SWAY OF A PNEUMATIC SPRING WHEN PASSING THROUGH A RAILROAD SWITCH IN CONDITIONS OF PROVISION OF HIGH-SPEED TRAINS` SAFETY

Summary. *The operation of railway rolling stock under high-speed conditions is crucial for Ukraine, as it will increase the throughput and carrying capacity of the railway network and improve the mobility of people in large cities. The dynamic behavior of the pneumatic spring, as the main structural element of the suspension system of high-speed rolling stock, has been studied. It is noted that the issue of the dynamic performance of the pneumatic spring is of broad scientific interest, as it directly affects the dynamic indicators and safety of the rolling stock when interacting with the track. Since the force interaction is random, depending on the condition of the rolling stock and the track, the study is based on experimental research on the dynamic behavior of the pneumatic spring. A methodology for the experimental determination of the lateral sway of the pneumatic spring of high-speed rolling stock when moving through a rail switch has been developed. It included testing the movement of a test stand over the switch and crossing in both forward and reverse directions. The vertical deformations of the pneumatic spring were recorded at diametrically opposite points in the longitudinal direction. It was found that the deformation of the pneumatic spring causes a tilt angle of the spring, with the average values being 0.667 degrees for forward movement, 0.697 degrees for the reverse for the switch blade area, and 0.369 degrees for forward movement, 0.468 degrees for the reverse for the crossing area. The results obtained can be used in the study of the dynamic characteristics of the pneumatic spring, allowing for the evaluation of its dynamic and safety indicators even at the design stage of rolling stock. In addition, the results will enable monitoring of the technical condition of the pneumatic spring, ensuring key safety indicators in high-speed operation.*

Keywords*: rolling stock, pneumatic spring, rail switch, tilt angle, deformation, rubber-cord shell.*

1. INTRODUCTION

Ensuring the safety of rolling stock during its operation on the railway track is one of the main tasks in the functioning of railway transport. One of the key factors influencing the level of safety is the force interaction between the rolling stock and the railway track, which depends on the speed of the rolling stock and the design features of the rolling stock and the track.

The EKr-1 “Tarpan” electric trains with a design speed of 200 km/h have been built and put into operation to organize high-speed transportation on Ukraine's railways (Fig. 1). The main feature of these trains is the use of a pneumatic suspension system in the second stage of the suspension system [1].

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Fig. 1. High-speed electric train EKr-1 "Tarpan"

The main elements of the pneumatic spring suspension system are a pneumatic spring (Fig. 2), an additional tank, a connecting pipeline, measuring equipment, etc.

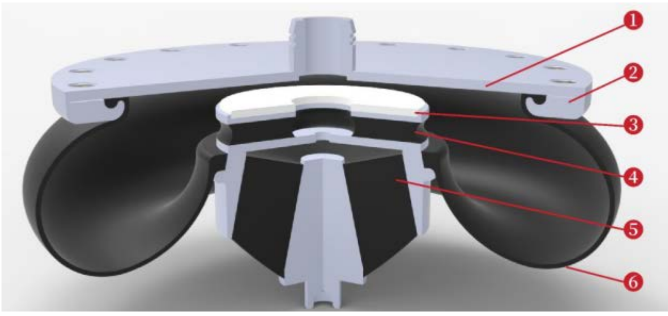


Fig. 2. Diaphragm-type pneumatic spring:
1 – top plate; 2 – clamping ring; 3 – sliding plate;
4 – emergency spring; 5 – auxiliary spring; 6 – air bellow

During the operation of the rolling stock, the pneumatic spring undergoes spatial oscillations due to the deformation of the rubber-cord shell, which changes the stiffness and damping characteristics of the pneumatic suspension system. Thus, the dynamic behavior of the pneumatic spring and the system as a whole significantly influence the forces between the structural elements of the rolling stock and between the wheelset and the railway track [2].

In addition, the level of force interaction depends on the design features of the railway track. Rail switches are often encountered along the route of the rolling stock and are one of the main factors limiting the speed of the rolling stock. The primary disturbance zones at a rail switch are (Fig. 3) the switch blade zone (Zone 1) and the crossing zone (Zone 2).

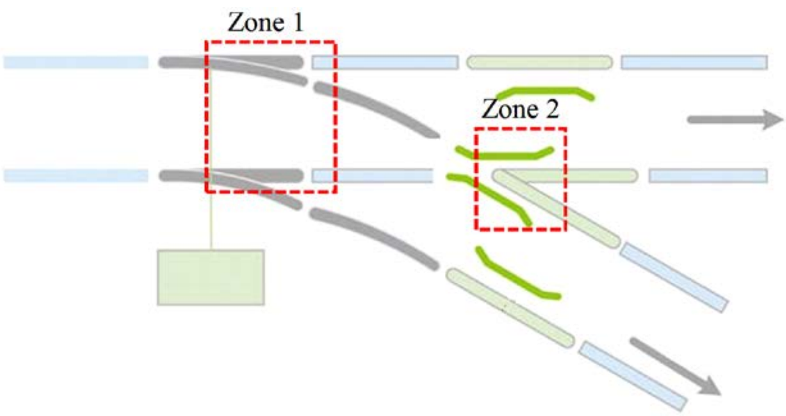


Fig. 3. Force Disturbance Zones on the Rail Switch

Experimental studies of the dynamic behavior of the pneumatic spring of high-speed rolling stock when passing through the force disturbance zones of a rail switch is a relevant scientific task. From a practical perspective, such studies will help identify deviations in the performance of the pneumatic spring during the operation of rolling stock, ensuring an acceptable level of dynamic indicators and safety parameters for high-speed rolling stock.

2. RESEARCH STATEMENT

Currently, the issue of the dynamic operation of pneumatic springs is of great scientific interest. However, most studies are theoretical, with only a few having an experimental focus.

Depending on the type of equations used, pneumatic spring models are divided into mechanical, thermodynamic, and finite-element models. The main mechanical models are the linear model by S. Nishimura [3], the Simpack model [4], the Vampire model (vertical and lateral) [5], and Berg's model [6]. Thermodynamic models vary depending on the number of described elements (pneumatic spring, connecting pipeline, orifice, additional reservoir, and regulating valves) and physical phenomena (friction losses, air inertia, heat transfer potential, etc.) [7–8].

As for the finite element method, this type of modeling allows for the most accurate recreation of the dynamic behavior of a pneumatic spring, but the cost and time for such modeling are significant. The main works analyzing models created using the finite element method are [9–10].

Since the force interaction is random and depends on the condition of the rolling stock and the railway track, we will analyze studies that have an experimental focus on investigating the dynamic behavior of pneumatic springs.

To compare alternative approaches to mathematical modeling of the pneumatic suspension system, the authors of [11] developed two different experimental approaches: a quasi-static approach and a dynamic approach. The first approach neglects the frequency-dependent behavior of the suspension but considers the relationship between shear stiffness and roll. In the second one, frequency-dependent vertical behavior is represented by a thermodynamic model, and the dependency of lateral stiffness parameters on load is also considered. In the quasi-static approach, the pneumatic spring was deformed at 0.05 Hz under various static load conditions. Three different deformation modes were applied: vertical deformation, lateral deformation, and roll deformation (Fig. 4).

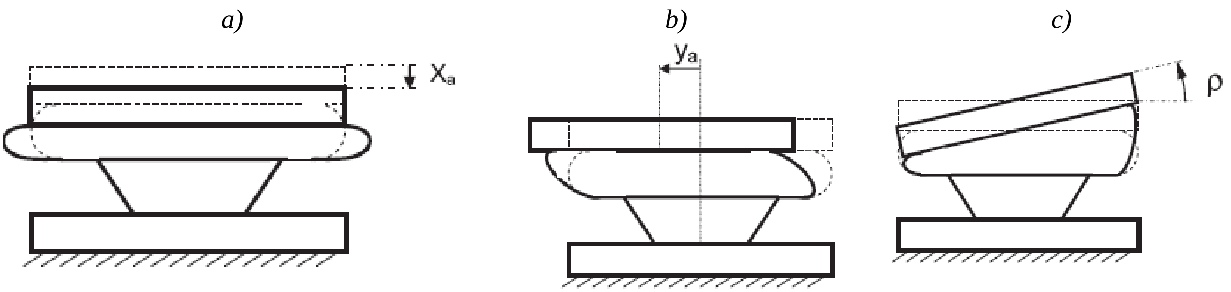


Fig. 4. Deformation Modes of the Pneumatic Spring:
a – Vertical Deformation; b – Lateral Deformation; c – Roll Deformation

It was established that vertical force is not affected by lateral deformation or roll deformation of the pneumatic spring. At the same time, lateral force and torque are not influenced by vertical deformation. However, a slight correlation was observed between the lateral and roll deformation components and the corresponding force/torque components.

Dynamic tests were conducted to obtain the dynamic behavior characteristics of the pneumatic spring in the frequency range of 0–20 Hz. These tests were performed under different pre-loading conditions by applying sinusoidal disturbances to the pneumatic spring with a specified amplitude and frequency.

It was found that neglecting the interaction effects between shear and roll deformation in the pneumatic spring could result in underestimating the maximum vertical load on the track, particularly when navigating curved track sections.

In [12], a sensitivity analysis was used to examine the impact of the pneumatic spring's geometric parameters on its lateral stiffness characteristics. Furthermore, the influence of lateral displacement, roll angle, and disturbance frequency on the pneumatic spring's lateral characteristics was discussed, along with an analysis of the impact on the rolling stock's mechanical properties. It was found that the lateral stiffness of the pneumatic spring increases with internal pressure and decreases with an increase in disturbance amplitude. Additionally, as the pressure coefficient of a pneumatic spring increases, the damping coefficient initially increases and then decreases, while the damping coefficient decreases with an increase in orifice diameter. Thus, too high and too low pressure coefficients and orifice diameters negatively affect the damping characteristics of the pneumatic spring.

In [13], the dynamic behavior of the pneumatic suspension system was experimentally studied in the frequency range of 0–400 Hz. Three frequency ranges where different suspension resonances occur were identified: a low range (up to 30 Hz) due to airflow between the pneumatic spring and the additional reservoir, a mid-range (30–150 Hz), and a high range (above 150 Hz) due to the structural dynamics of the pneumatic spring.

In [14], the analysis of the pneumatic spring and suspension construction (lever length, lever eccentricity) on the durability of the pneumatic spring was presented. It was found that factors inherent to the design of the pneumatic spring have a much more significant impact on its durability than factors related to the suspension design. The interaction between these factors also revealed that there is no optimal fiber cord angle for all pneumatic springs.

In [15], the deformation behavior of the rubber-cord shell of the pneumatic spring for high-speed rolling stock in both vertical and horizontal directions was studied under different internal pressures. It was established that horizontal deformation of the rubber-cord shell increases more intensively than vertical deformation as the internal pressure in the pneumatic spring rises. The authors also obtained polynomial equations that describe the deformation behavior of the rubber-cord shell of the pneumatic spring.

In [16–17], the influence of the pneumatic suspension system parameters (additional reservoir volume, connecting pipeline parameters) on system characteristics (dynamic stiffness) was studied, and these parameters were then optimized to minimize the Sperling ride comfort index. The results showed that modifying the parameters of the pneumatic suspension system improves passenger comfort, reducing the ride comfort index by about 10 %. Experimental tests were conducted with an amplitude of ±10 mm at frequencies between 0.5 and 10 Hz.

In [18], a test rig was used to determine the vertical dynamic stiffness of the pneumatic suspension system under various conditions (pneumatic spring pressure, additional reservoir volume, pipeline diameter, presence of calibrated orifices, etc.). It was found that the pneumatic suspension system exhibits apparent nonlinearity in the mid-frequency range (in this case, from 6 to 14 Hz). As the frequency increases or decreases, the stiffness value reaches a stable value (static and dynamic stiffness of the pneumatic spring). The results were also compared with some theoretical models. For future improvements in dynamic performance, it is recommended to introduce a variable-area orifice in the pipeline between the pneumatic spring and the additional reservoir.

In [19], the dynamic behavior of different types of pneumatic suspension systems with varying leveling systems (two-point suspension and four-point suspension) was analyzed. It was found that the four-point configuration generates greater wheel force oscillations than the two-point suspension. However, the four-point suspension limits the roll angle of the car body when passing through curved track sections by adding air to the outer pneumatic springs and removing air from the inner springs.

In [20], experimental tests on the dynamic behavior of the pneumatic suspension system with different connections between the pneumatic spring and the additional reservoir were conducted. Various disturbance amplitudes and frequencies were applied during the experiments. It was found that for damping low-frequency disturbances, the “bellow-orifice-pipe-reservoir” connection is the most effective. For high-frequency disturbances, the “bellow-orifice-reservoir” connection is most effective.

In [21], experimental tests were conducted following the EN13597 standard to determine the precise parameters of the pneumatic spring. The vertical load was set at 109.8 kN with an amplitude of ±10 mm and a frequency range of 0.5 to 10 Hz. The authors studied the influence of additional reservoir volume, pipeline length, and diameter on system characteristics.

In [22], four experimental methods were used to study the pneumatic spring's static and quasi-static vertical stiffness. It was found that the resulting experimental stiffness-load curves are not strictly linear. It was noted that the stiffness of the rubber-cord shell makes a significant contribution when the load is low; however, this contribution becomes insignificant when the load is very high.

In [23], two sets of experiments were conducted to study the polytropic process of pneumatic springs. The test results confirmed that a polytropic index 1.4 is appropriate for frequencies above 5 Hz. It means that the thermodynamic process of closed air in the pneumatic spring can be considered adiabatic when the frequency is above 5 Hz and polytropic when it is below 5 Hz.

In [24], a dynamic model of vertical stiffness based on thermodynamics and hydrodynamics was developed, and geometric parameters were determined using an approximate analytical method. Experimental tests were conducted to verify the model's accuracy, with vertical disturbances modeled as a sinusoidal wave with frequencies ranging from 0 Hz to 20 Hz and amplitudes from 2 mm to 10 mm. A rational ratio between the volume of the pneumatic spring and the additional reservoir was obtained.

In [25], the authors developed a special test rig to simulate the dynamic behavior of the pneumatic suspension system in all its possible configurations and operating conditions. The main focus was on the vertical direction due to its significant influence on ride comfort, safety, and the dynamic interaction between the rolling stock and the track. Additionally, considerable dependence on amplitude, frequency, and pre-loading was identified during the experiments.

In [26], a series of experimental tests were conducted to validate the theoretical model of the pneumatic suspension system, which includes height control and pressure differential valves. The tests involved the movement of rolling stock along a curve with a small radius, including a failure of the height control valve. The influence of the valve flow characteristics on wheel load imbalance during movement through the curved section was also considered. The results indicated the importance of such modeling for assessing the safety of rolling stock operation at low speeds and in curved track sections.

Additionally, the influence of the angle of the valve lever of the height control on wheel load imbalance was studied during the passage of rolling stock through curved track sections with a small radius [27].

Therefore, based on the analysis of papers [10–27], a wide range of experimental studies on the dynamic behavior of pneumatic springs conducted under laboratory conditions can be noted. However, such studies do not fully replicate the actual operating conditions of rolling stock and its force interaction when passing through a rail switch. Thus, the unresolved task is to investigate the dynamic behavior of the pneumatic spring of high-speed rolling stock, particularly its lateral sway under movement through a rail switch.

The aim of this study is to establish experimentally the patterns of lateral sway of the pneumatic spring of high-speed rolling stock under movement through a rail switch. It will allow the technical condition of the pneumatic spring to be monitored throughout its service life and any changes to be identified.

The following tasks must be completed to achieve this aim:

- to develop a methodology for experimental research on the lateral sway of the pneumatic spring of high-speed rolling stock under movement through a rail switch;
- to determine the deformations of the pneumatic spring that cause its lateral sway;
- to identify the tilt angle of the pneumatic spring of high-speed rolling stock when passing through the main disturbance zones of the rail switch.

3. CHARACTERISTICS OF THE RESEARCH OBJECTS AND METHODS

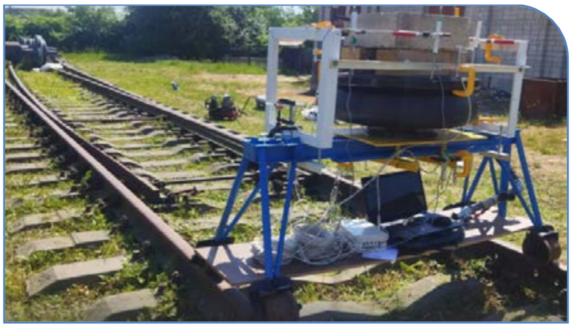
When high-speed rolling stock moves through a rail switch, lateral sway occurs, affecting passenger comfort and operational safety. Therefore, evaluating the lateral sway of high-speed rolling stock using pneumatic springs is essential. Experimental studies of the lateral sway of the pneumatic spring in high-speed rolling stock were conducted on a specially developed test rig. The test rig for the spring is shown in Fig. 5.

Fig. 5. Movable test rig for researching the lateral sway of the pneumatic spring of high-speed rolling stock

The rest rig consists of a supporting metal frame on four wheels, a pneumatic spring, KTR 100 mm potentiometer sensors of linear displacement, an analog-to-digital converter, and a laptop.

The pneumatic spring, with the lower metal plate, is rigidly attached to the top of the metal frame of the test rig. Potentiometric sensors of linear displacements are used to measure the vertical and horizontal deformations of the rubber cord sheath of the pneumatic spring. They are connected to a programmed analog-to-digital converter (ADC). At the same time, the sampling frequency of reading vertical deformations was 0.001. Records of spring deformations are transferred via the USB port to a laptop and stored in its memory for further analysis.

The method of researching the patterns of lateral sway of the pneumatic spring of the high-speed rolling stock involved the movement of the test rig along the arrow and the cross of the railway switch (Fig. 6). At the same time, the movement of the test rig was in the forward and reverse directions.



Movement of the test rig along the switch point

Movement of the test rig by the switch cross

Fig. 6. Study of the swaying of the pneumatic spring during the movement of the test rig along the switch point and the switch cross

The movement of the test rig along the switch point and the switch cross causes the pneumatic spring to oscillate. It leads to deformations of the spring in the vertical and horizontal directions. In the vertical direction, the maximum possible deformation of the pneumatic spring is 33 mm. The lateral sway of the pneumatic spring was evaluated based on the records of the vertical displacement sensors, which are located diametrically opposite from the bottom of the spring in the longitudinal direction. The deviation of the sensor readings from the initial value is the amount of lateral sway of the pneumatic spring. To verify the results ' reliability, the field tests included six passes of the moving test rig along the switch point in the forward and reverse directions.

4. MAIN PART

After conducting field tests, records of vertical deformations of the pneumatic spring were obtained at its diametrically opposite points in the longitudinal direction (Fig. 7–10).

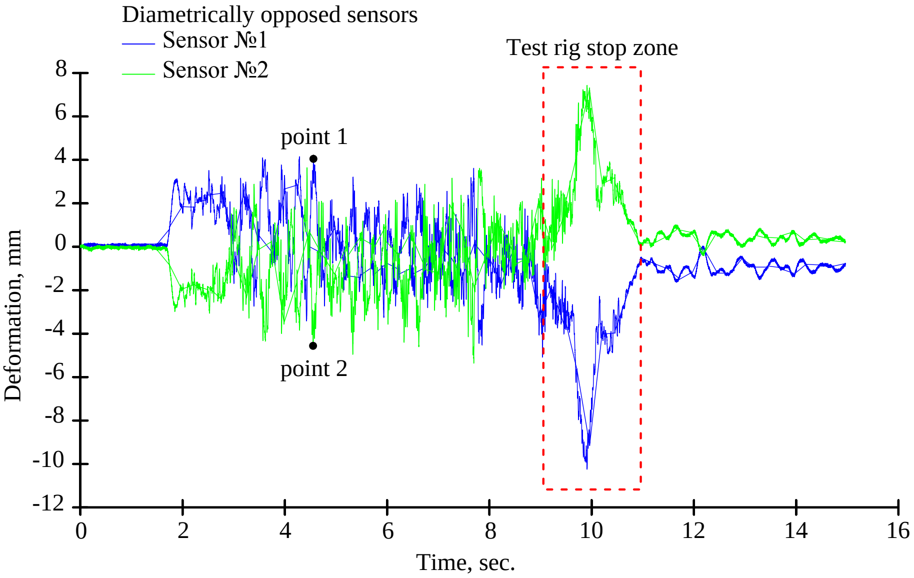


Fig. 7. Record of vertical deformations of the pneumatic spring in the switch blade area in the reverse direction of movement of the test rig

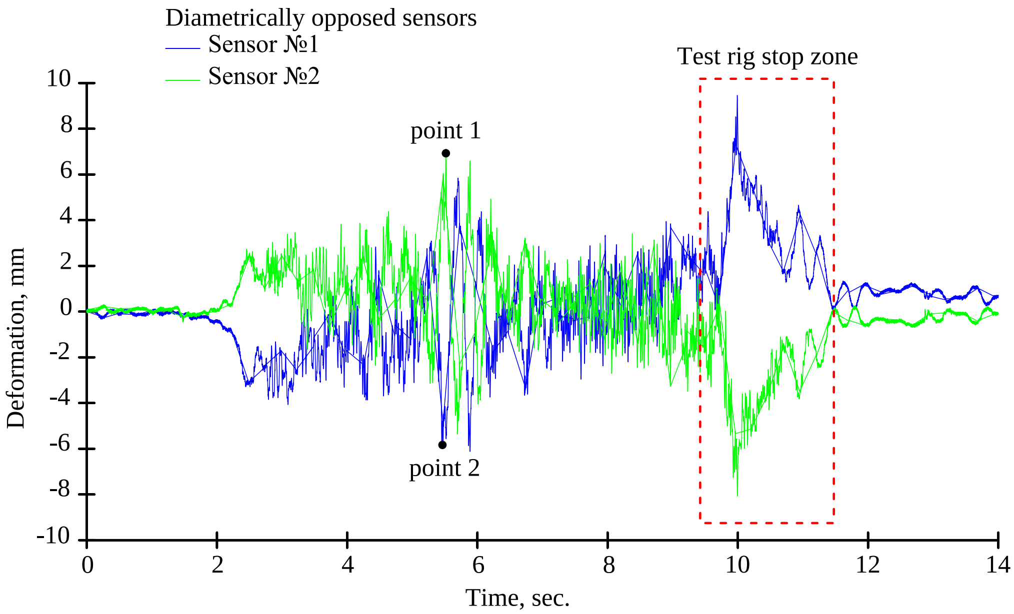


Fig. 8. Record of vertical deformations of the pneumatic spring in the switch blade area in the forward direction of movement of the test rig

From Fig. 7–8, it is observed that the deformation of the pneumatic spring occurs during the movement of the test rig along the switch blade area (zone No. 1) (Fig. 3). Points No. 1 and No. 2 show that the deformation occurs in opposite directions, which leads to the tilt of the pneumatic spring. The maximum amount of deformation is within the following limits: (3.53÷6.87) mm for forward movement and (3.82–5.73) mm for reverse movement. The stop zone of the test rig was not considered during the research since the lateral sway that occurs in such cases is caused by external restraining forces.

Taking into account the diameter of the pneumatic spring, which is equal to 760 mm, and the presence of its deformations, the angles of inclination of the pneumatic spring in the longitudinal direction during the movement of the test rig in the zone No. 1 of the switch point were determined (Fig. 9).

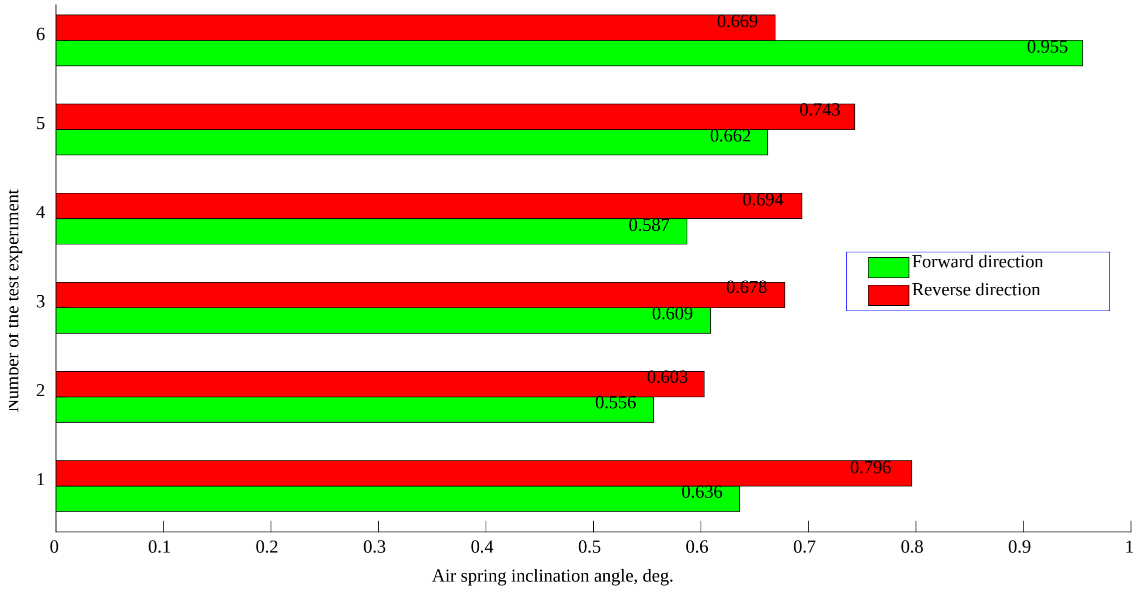


Fig. 9. Angles of inclination of the pneumatic spring in the longitudinal direction during the movement of the test rig along zone № 1 of the switch point

It was established that the angle of inclination of the pneumatic spring during the movement of the test rig through zone No. 1 of the switch point varies within 0.556–0.955 degrees for the forward direction and 0.603–0.796 degrees for the reverse direction. The average statistical value of the angle of inclination for the forward movement is 0.667 degrees, for the reverse movement – 0.697 degrees. In terms of percentage, the difference in the different directions of movement of the test rig in zone № 1 of the switch point does not exceed 4.3 %.

Similarly, the records of the vertical deformations of the pneumatic spring during the movement along the switch cross were obtained (Fig. 10–11), and its inclination angles were determined (Fig. 12).

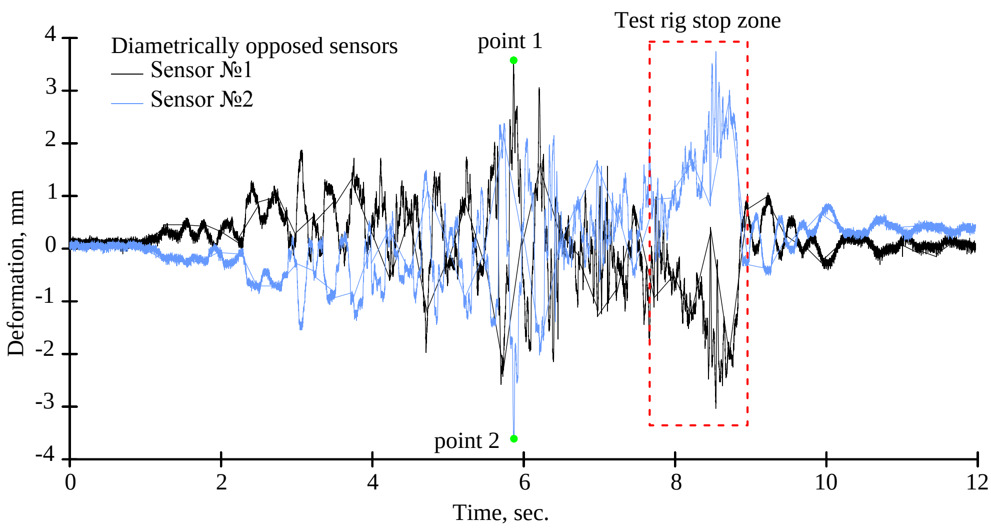


Fig. 10. Record of vertical deformations of the pneumatic spring in the area of the switch cross in the reverse direction of movement of the test rig

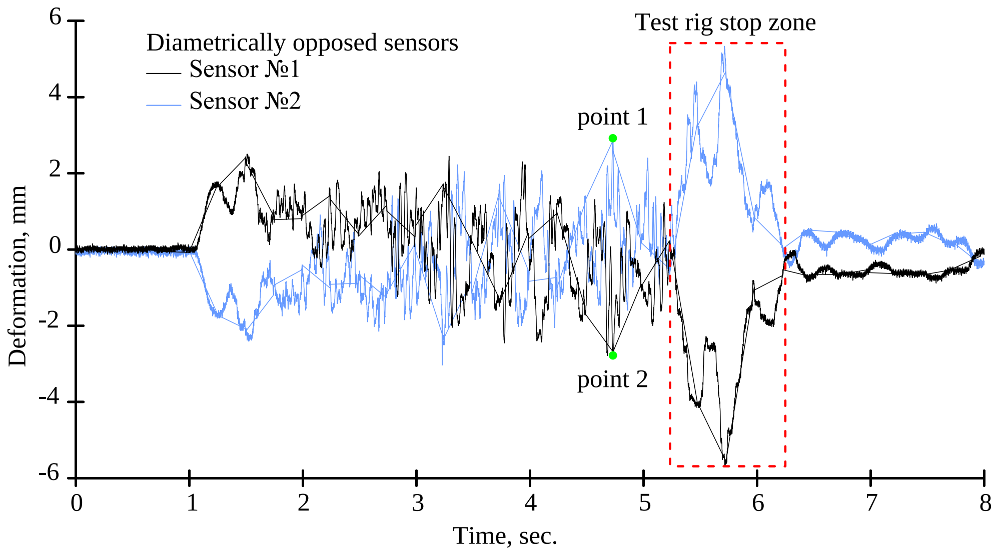


Fig. 11. Record of vertical deformations of the pneumatic spring in the area of the switch cross in the forward direction of the test rig

It was established that the maximum deformation of the pneumatic spring during its movement along the switch cross is within (1.89÷2.84) mm for forward movement and (2.14÷4.59) mm for reverse movement. The analysis of the angles of inclination of the pneumatic spring in the longitudinal direction showed that when the test rig moves along the switch cross, their average value is 0.369 degrees within the forward movement and 0.468 degrees within the reverse movement. The difference in average values does not exceed 21.15 %.

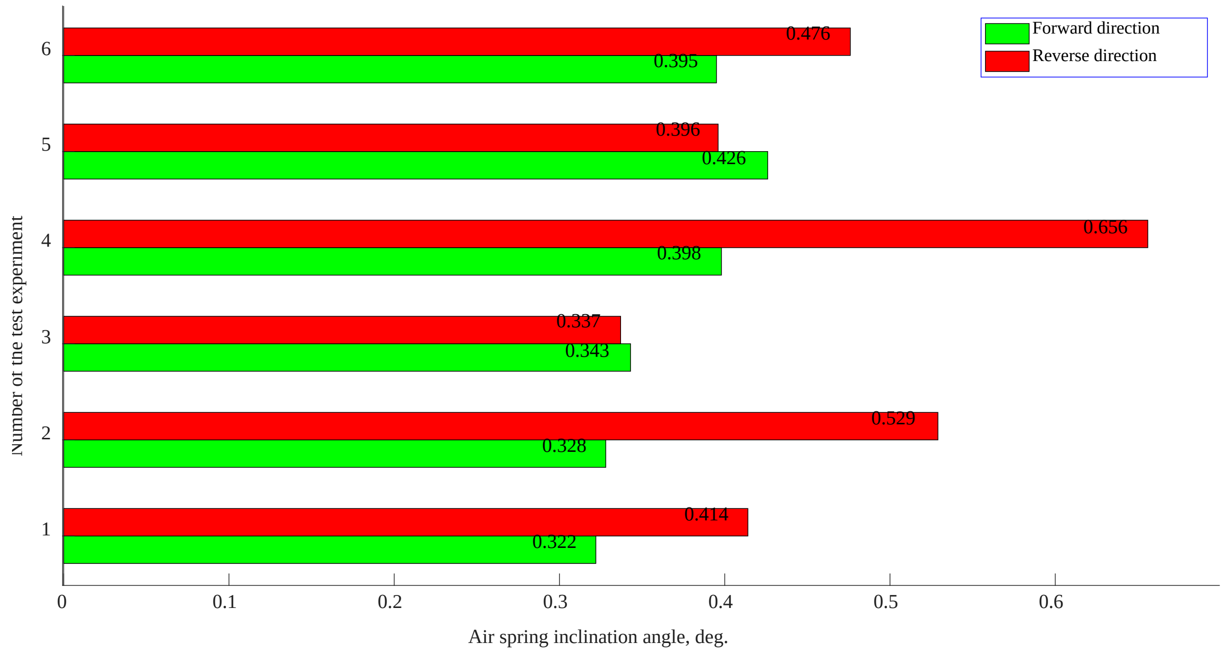


Fig. 12. Inclination angles of the pneumatic spring in the longitudinal direction during the test rig movement through zone № 2 of the switch

Therefore, continuous monitoring of the dynamic performance of the pneumatic spring during the operation of high-speed rolling stock will allow for the detection of changes in the pneumatic spring's characteristics and their impact on dynamic indicators and safety performance.

5. CONCLUSIONS AND RESEARCH PERSPECTIVES

This study is based on the experimental investigation of the dynamic behavior of the pneumatic spring in high-speed rolling stock during movement along a switch, significantly affecting dynamic and safety performance indicators. Research on this topic has predominantly employed theoretical approaches, which do not account for the array of random factors that arise during the actual operation of rolling stock.

A test rig with an installed pneumatic spring was used to study the dynamic behavior of the pneumatic spring in high-speed rolling stock. The lateral sway of the pneumatic spring was investigated using potentiometric sensors of linear movement installed at diametrically opposite points on the pneumatic spring.

Based on field tests, records of the vertical deformations of the pneumatic spring in the switch blade and cross zones were obtained, allowing for determining its dynamic behavior, specifically lateral sway in the longitudinal direction.

It was found that during the movement of the test rig along the switch blade area, the average statistical value of the pneumatic spring inclination angle in the longitudinal direction is 0.667 degrees for the forward direction and 0.697 degrees for the reverse direction. When moving along the switch cross, the inclination angle is 0.369 degrees for the forward direction and 0.468 degrees for the reverse direction.

The obtained results will enable future assessments of the technical condition of the pneumatic spring and the influence of operational conditions on the dynamic characteristics of the pneumatic spring of the high-speed rolling stock. It will allow continuous monitoring of dynamic performance and safety indicators of high-speed rolling stock under various operating conditions.

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ЕКСПЕРИМЕНТАЛЬНЕ ВИЗНАЧЕННЯ БОКОВОГО ХИТАННЯ ПНЕВМАТИЧНОЇ РЕСОРИ ПРИ РУСІ СТРІЛОЧНИМ ПЕРЕВОДОМ

Анотація. *Експлуатація залізничного рухомого складу в умовах швидкісного руху для України критично важлива, оскільки дасть змогу збільшити пропускну і провізну здатність залізничної мережі та мобільність людей у великих містах України. Досліджено динамічну поведінку пневматичної ресори як основного конструктивного елемента пневматичної системи ресорного підвішування швидкісного рухомого складу. Відзначено, що питання динамічної роботи пневматичної ресори привертає широкий науковий інтерес, оскільки прямо впливає на динамічні показники та показники безпеки руху рухомого складу під час його взаємодії із рейковою колією. Оскільки силова взаємодія є випадковою і залежить від стану рухомого складу та рейкової колії, у роботі за основу взято праці із експериментальним дослідженням динамічної поведінки пневматичної ресори. Розроблено методологію експериментального визначення бокового хитання пневматичної ресори швидкісного рухомого складу в умовах руху стрілочним переводом. Вона передбачала рух випробувального стенда по стрілці та хрестовині залізничного стрілочного переводу у пошерстному та протишерстному напрямах. Отримано записи вертикальних деформацій пневматичної ресори у діаметрально протилежних її точках в поздовжньому напрямі. Встановлено, що деформація пневматичної ресори викликає кут нахилу ресори, середньостатистичне значення якого становить: для зони вістряків стрілочного переводу 0,667 град – пошерстний рух, 0,697 град – протишерстний; для зони хрестовини стрілочного переводу 0,369 град – пошерстний рух, 0,468 град – протишерстний. Отриманими результатами можна скористатися для дослідження динамічних характеристик пневматичної ресори, що дасть змогу ще на етапі проєктування рухомого складу оцінювати його динамічні показники та показники безпеки руху. Крім цього, отримані результати дадуть змогу контролювати технічний стан пневматичної ресори, забезпечуючи основні показники безпеки в умовах швидкісного руху.*

Ключові слова: *рухомий склад, пневматична ресора, стрілочний перевід, кут нахилу, деформація, гумокордна оболонка.*