Experimental studies of pantograph head suspension equipped with controlled pneumatic elements

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Abstract. The article describes factors which affect the panhead elastic elements performance during their operation. An analysis of these factors shows the need to use elastic elements with a controlled static characteristic at constant stiffness to ensure reliable current collection. The existing controlled pneumatic elements used in the panhead suspension of electric rolling stock are considered. Authors offer to use intra-spring pneumatic elements in panhead suspension. A study of the interaction of a pantograph and an overhead contact line is described. A methodology for experimental studies of pantographs equipped with controlled elastic elements in a head suspension has been developed. The experimental oscillation test system is described. An experiment was carried out according to the developed experiment design. The obtained data allow to build a regression model that characterises the standard deviation of the contact force on the frequency of vertical oscillations generated by the contact wire, the static force of the pantograph and the pressure in the intra-spring pneumatic element. The results of experimental studies indicate the preservation of the stiffness of the intra-spring pneumatic element within its static characteristics.

1 Introduction

Nowadays, the trend towards an increase in the speed of movement continues on electric railways. One of the systems that limit the growth of the speed of movement is the current collection system, since along with the increase in speed, the operating conditions of the electric sliding contact deteriorate significantly. The current collection process is significantly affected by dynamic processes in the overhead contact line, aerodynamic effects, vibrations of the electric rolling stock and other factors. Therefore, for the further development of high-speed electric railways, it is necessary to improve the designs of pantographs, including their head suspension.

Panhead suspension makes it possible to reduce the effect of the pantograph frames inertia on the current collection process due to the elastic dismemberment of the lumped mass of the frames and the panhead, which is especially important at high frequencies of vertical vibrations, and accordingly, at high speeds.

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Most of the currently used panhead suspension of electric rolling stock pantographs has cylindrical springs with a constant static characteristic as elastic elements. The stiffness of the panhead suspension is chosen such that the geometric value of the deformation of their elastic elements when exposed to a force equal to the pantograph static force, is from 20 to 50% of their full deflection [1].

To improve the process of the current collection, pantographs of electric rolling stock use automatic control devices to regulate pantograph static force [2, 3]. They provide a more stable contact during the current collection process. Currently, the technology of automatic control of static force is used in pantographs designed by Siemens, Faiveley, Schunk, and others.

The influence of the aerodynamic component of the contact force on the current collection process increases significantly at high speeds of the electric rolling stock, which leads to a change in the deflection of the panhead suspension elastic elements and an exit of the elastic element deflection from the specified range of its allowable deformation [4].

In addition, contact elements wear out during operation on the pantographs of the electric rolling stock, which leads to a decrease in their mass, and, accordingly, a change in the deflection of the elastic elements of the panhead suspension.

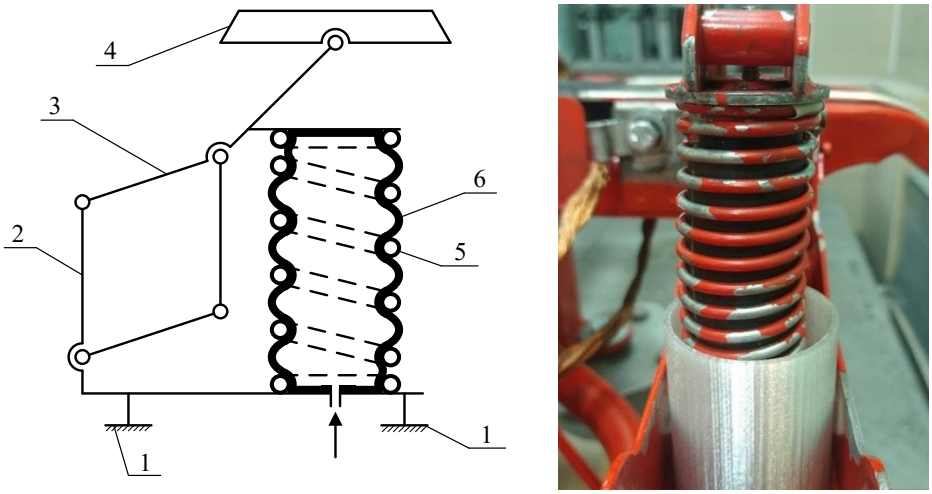
Based on the above factors, the average contact force can change in the process of the current collection, which requires regulation of the panhead suspension static force characteristics to maintain the deformation of the elastic elements within their working stroke. Since their full deflection leads to vertical impacts and insufficient - to breakaway.

At the same time, it is important to maintain the predetermined stiffness of the elastic elements, since the quality of the interaction of the pantograph and the overhead contact line depends on its value.

2 Materials and Methods

The change in the static force of the panhead suspension is possible by the use of controlled elastic elements, for example, pneumatic cylinders, rubber-cord air bags, etc. [57]. The use of panhead suspension equipped with the specified elastic elements makes it possible to reduce the spread of contact force by 5-10% and provide a specified working range of deflection of the elastic elements of the panhead suspension.

Specialists of the Omsk State Transport University offer to use intra-spring pneumatic elements as controlled elastic elements of panhead suspension [8]. It is a cylindrical spring installed inside which an air bag, made of a hyperelastic material (Fig. 1). By the feed of excess air pressure inside the air bag, an additional force is created, aimed at decompressing the spring. In this case, the effect on the total stiffness of the intra-spring elastic element is minimal, which is due to the very low intrinsic stiffness of the air bag. The use of such elastic elements in the design of panhead suspension of electric rolling stock will make it possible to control the panhead suspension static force characteristic with a minimum change in their stiffness.



1 – upper sleeve, 2 – panhead suspension fixed part, 3 – panhead suspension movable part, 4 – panhead, 5 – cylindrical spring, 6 – air bag

Fig. 1. Panhead suspension equipped with an intra-spring pneumatic element: a – scheme, b – overall view.

Fig. 2 shows the conception of the control of the panhead suspension static characteristic. The impact on the panhead of the static force leads to the deflection of the elastic elements. In case of their deformation by more than 50% of their maximum stroke, excess pressure is applied to the cavity of the air bag, which allows returning the panhead suspension static characteristic to the working area and avoids possible breakdowns of the springs. The panhead suspension's summary static characteristic is represented by a solid line in Fig. 2.

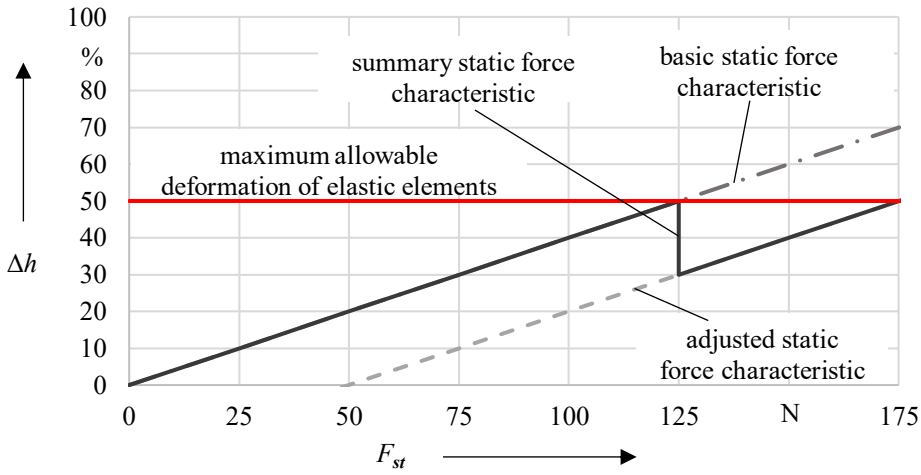
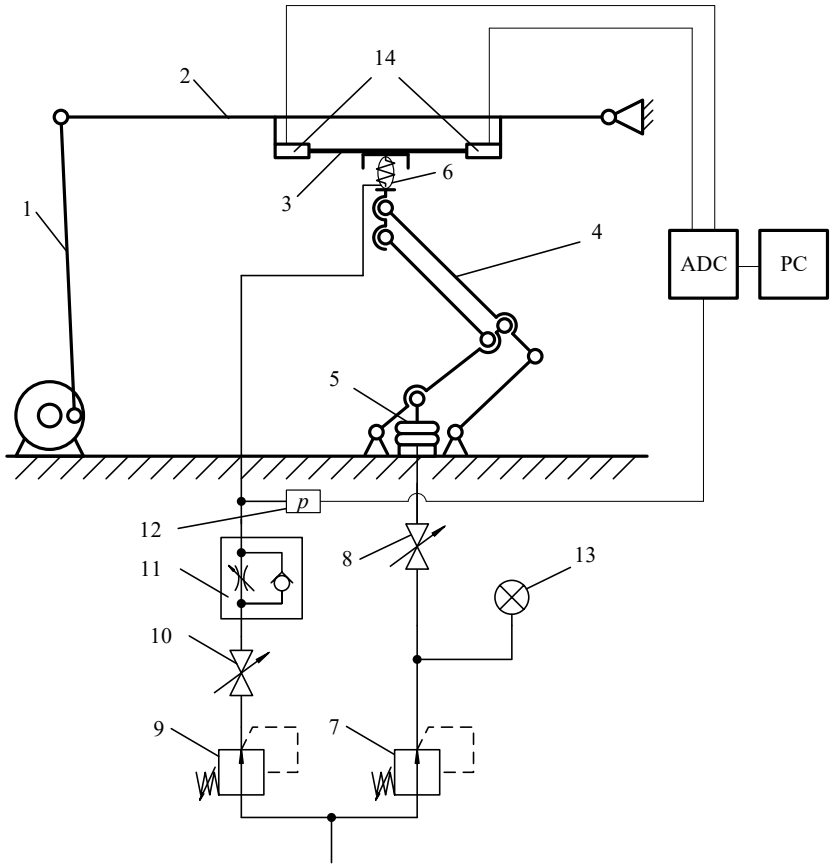


Fig. 2. The concept of regulating the panhead suspension static force characteristic.

An analytical study of the work of intra-spring pneumatic elements in the panhead suspension of electric rolling stock requires considering many factors associated with the process of its operation. Therefore, it is expedient to carry out a cycle of experimental studies to obtain the parameters and characteristics of the intra-spring pneumatic element that provide the required quality of the current collection during the interaction of the pantograph and the overhead contact line under vertical oscillations of the contact wire in a wide range of frequencies typical for operating conditions, and considering changes in the pantograph static force.

For experimental studies of pantographs equipped with intra-spring pneumatic elements a vertical oscillation test system was used. It is located in the laboratory "Designs of overhead contact lines, power lines and the current collection named after Professor V.P. Mikheev" of Omsk State Transport University and modernised to be able to control pneumatic elements in panhead suspension [8]. The scheme of the test system and the installation of measuring equipment is shown in Fig 3.



1 – crank mechanism, 2 – beam, 3 – contact wire, 4 – pantograph, 5 – lifting mechanism, 6 – intra-spring pneumatic element, 7 – lifting mechanism pressure regulator, 8 – lifting mechanism valve, 9 – intra-spring pneumatic element pressure regulator, 10 – intra-spring pneumatic element valve, 11 – check valve throttle, 12 – air pressure sensor 13 – manometer, 14 − strain gauges

Fig. 3. Scheme of the oscillatory test system.

An oscillatory test system consists of a horizontal beam on which a contact wire is installed, which is brought into contact with the pantograph head. On the one side, the beam is hinged, and on the other side, it is connected to a crank mechanism that provides vertical oscillations with a given frequency.

Strain gauges are connected to an analogue-to-digital converter to determine the contact force. The data from which is transmitted to a computer and processed, which allows to obtain contact force data.

Pressure regulators are used to control the lifting mechanism and the intra-spring pneumatic elements of the panhead suspension.

An overall view of the test system is shown in Fig. 4.

Fig. 4. The test system's overall view.

The provisions of the theory of design of experiments are used to optimise the experiment process. It is advisable to use the rotatable central composite experiment design for an experimental study of the controlled elastic elements in the design of electric rolling stock panhead suspension. It allows minimising the systematic deviations caused by the use of second-order polynomials.

High-quality current collection requires minimization of the spread of contact force to maintain it in the zone of minimal wear of the contact elements. Therefore, to assess the quality of the current collection, the standard deviation of the contact force was chosen as a criterion.

The static force of the pantograph, the pressure in the intra-spring pneumatic element and the frequency of vertical oscillations were chosen as variable factors.

The methodology for experimental studies of pantographs equipped with intra-spring pneumatic elements includes the following steps:

1) determination of intervals of factor variation;
2) creation of an experimental design;
3) experimenting;
4) compiling a regression model and assessing the influence of parameters.

The static force (F_{st}) range of the pantograph is based on the regulatory documentation and must be in the range of 70 to 110 N for the tested pantograph. These values were taken as low and high levels, respectively, and the centre of the regulated range was taken as the zero level.

Currently, the speed of movement of electric rolling stock on high-speed railways in Russia is limited by design restrictions to 250 km/h (~ 70 m/s). The overhead contact line project KS-250 is designed for this speed. The maximum span length is 65 m, however, the span length may be shorter. In this case, the maximum vertical oscillation frequency (υ) is approximately 1.17 Hz. As a zero level, a frequency of 0.75 Hz can be taken, corresponding to a speed of 160 km/h (45 m/s), which can be reached by passenger trains. And as a high level, it is advisable to take the level of 1 Hz, corresponding to movement at a speed of 210 km/h (60 m/s). Then the low level will be 0.5 Hz or 110 km/h (30 m/s). Vertical oscillation amplitude is ±5 mm.

Compressed air is used to regulate the force created by the pneumatic elastic element of the panhead suspension. The approximate value of the force created by the pneumatic element can be obtained using the following formula:

$$F_{PE} = p_{PE} \cdot S_{PE}, \tag{1}$$

where p_{PE} – a pressure in the pneumatic element of the panhead suspension, Pa;
S_{PE} – a cross-section of the pneumatic element of the panhead suspension, m^2.

Since the cross-section of the controlled pneumatic element of the panhead suspension is approximately $50 \cdot 10^{-6}$ m^2, then a pressure of 100 kPa is required to create a force equal to 50 N, this level was taken as zero. To ensure the regulation of the forces created by the controlled elastic element in the panhead suspension, it is sufficient to ensure their change by ± 50% relative to the base level, which will correspond to the points of 50 kPa and 150 kPa.

The parameters of a second-order three-factor rotatable experiment design can be taken following the reference data [10]. Variation intervals and levels of factors are shown in Table 1.

Table 1. Variation interval and factor levels.

Variation interval and factor levels	Factor		
	F_{st}, N	υ, Hz	p_{PE}, kPa
Zero level, z_{i0} ($x_i = 0$)	90	0.75	100
Variation interval, Δz_i	20	0.25	50
Low level z_i ($x_i = -1$)	70	0.5	50
High level z_i ($x_i = +1$)	110	1	150
Star point: z_i^* ($x_i = -\alpha$) z_i^* ($x_i = +\alpha$)	 56 124	 0.33 1.17	 16 184

3 Results

Fig. 5 shows an example of the contact force (F_c) curve obtained during the experiment.

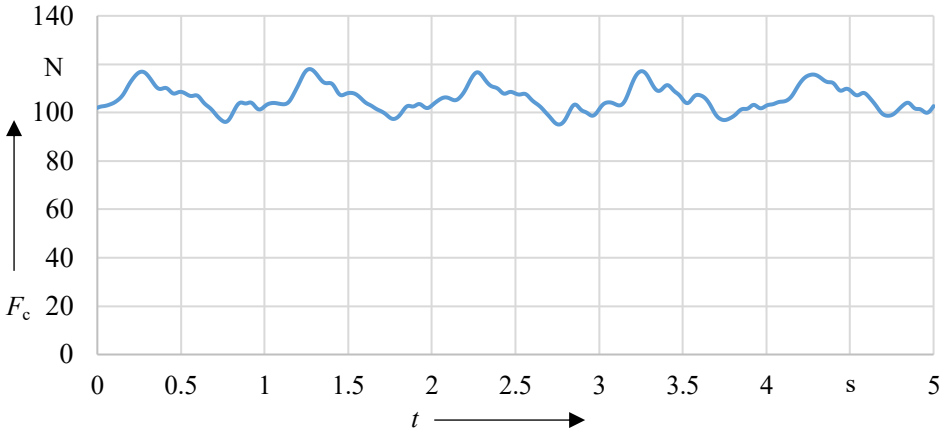


Fig. 5. Contact force curve for point "4" of the experiment design.

Table 2 shows the experimental data obtained as a result of the experiment according to the described design. The average values of the contact force for each of the points of the design correspond to the static force of the pantograph, which indicates the reliability of the obtained data. The minima and maxima of the contact force also don't go beyond the range of permissible values, which confirms the possibility of operating the pantograph in the study modes.

Table 2. Results of the experiment.

Design	№	F_{st}, N	υ, Hz	p_{PE}, kPa	σ, N	$F_{c\,avg}$, N	$F_{c\,min}$, N	$F_{c\,max}$, N
Core points (FFE 2^3)	1	70	0.5	50	1.81	68.45	44.92	92.10
	2	110	0.5	50	1.83	108.87	101.83	114.30
	3	70	1	50	5.71	68.34	57.74	79.80
	4	110	1	50	5.46	105.27	93.67	118.10
	5	70	0.5	150	1.87	68.30	62.57	73.30
	6	110	0.5	150	2.11	110.39	103.57	116.20
	7	70	1	150	5.79	67.96	57.44	81.40
	8	110	1	150	5.74	109.78	98.37	122.00
«Star» points	9	56	0.75	100	3.15	55.41	48.41	63.40
	10	124	0.75	100	2.95	125.10	118.15	133.00
	11	90	0.33	100	1.80	88.65	82.73	92.90
	12	90	1.17	100	8.27	89.13	72.63	102.90
	13	90	0.75	16	3.04	92.67	86.35	99.50
	14	90	0.75	184	2.74	93.51	87.06	100.00
Center Points	15 - 20	90	0.75	100	2.65	89.04	84.07	95.89

Specialised statistical software allows getting second-order regression equation based on the obtained data:

$$\sigma = 7.763 - 0.064F_{st} - 11.769\nu - 0.012p_{PE} - 0.013F_{st}\cdot\nu + 5\cdot10^{-5}F_{st}\cdot p_{PE} + \\ +1.7\cdot10^{-3}\nu\cdot p_{PE} + 3.7\cdot10^{-3}F_{st}^2 + 13.731\nu^2 + 3\cdot10^{-5}p_{PE}^2 \quad (2)$$

The corrected R^2 value is 0.995 and indicates a high correlation of the experimental contact force standard deviation and the resulting regression equation. Thus, the resulting polynomial can be used to draw surfaces of the standard deviation of contact force and allow evaluation of the influence of the selected factors.

The resulting surface of the standard deviation of the contact force (Fig. 6) indicates a low influence of pressure changes in the intra-spring pneumatic element of the panhead suspension on the current collection process. Thus, the use of intra-spring pneumatic elements in the design of panhead suspension of electric rolling stock pantographs allows to regulate the static characteristic of the panhead suspension without stiffness change, which is the purpose of their implementation.

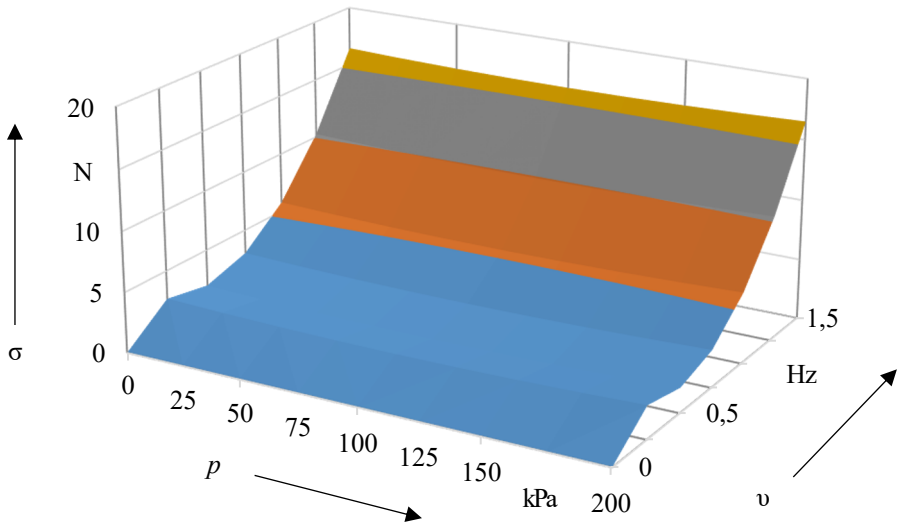


Fig. 6. The surface of the standard deviation of contact force on the frequency of vertical oscillations and pressure in the pneumatic element when the pantograph static force is 100 N.

4 Conclusions

1. To maintain the deformation of the elastic elements of the panhead suspension within the required limits, it is necessary to use controlled elastic elements that have a constant stiffness, but a variable static force characteristic.

2. Omsk State Transport University proposes to use intra-spring pneumatic elements in the design of panhead suspension. This construction is protected by a patent of the Russian Federation.

3. A technique for experimental studies of the interaction of overhead contact line and pantographs equipped with head suspension with controlled elastic elements using a test system has been described.

4. The standard deviation of the contact force is practically independent of the change in pressure in the intra-spring pneumatic element at different frequencies of vertical vibrations of the contact wire and levels of pantograph static force, which confirms the possibility of using intra-spring pneumatic elements as controlled elastic elements of current panhead suspension.

5 Acknowledgments

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