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Yuriy BORONENKO
Emperor Alexander I St. Petersburg State Transport University
Moskovsky av. 9, Saint Petersburg, 190031, Russia
Rustam RAHIMOV*
Tashkent State Transport University
Temiryo'lchilar str. 1, Tashkent, 100167, Uzbekistan
**Corresponding author*. E-mail: rakhimovrv@yandex.ru

EXPERIMENTAL DETERMINATION OF FORCES THROUGH MEASUREMENTS OF STRAINS IN THE SIDE FRAME OF THE BOGIE

Summary. This paper investigates the influence of longitudinal and lateral forces on the accuracy of measurements of vertical forces for three-piece bogies. Theoretical studies of the loading of the bogie side frame have been carried out using the finite element method under the action of forces from a wheelset. The places of installation of strain gauges and the method of processing the received signals are determined. A method has been developed for measuring the vertical and lateral forces, which makes it possible to increase the accuracy of measurements of the vertical force, with the help of which the safety of movement is assessed during running dynamic tests and to ensure the simultaneous measurement of vertical and lateral (frame) forces transmitted to the bogie side frame, which will allow to reduce the number of strain gauges for measuring the considered forces during tests.

1. INTRODUCTION

Running dynamic tests are one of the main stages in the design of a new rolling stock and to assess its dynamic qualities.

The requirements for these tests are regulated in the European Union by the standard EN 14 363 [1] and UIC CODE [2], in North America by the AAR standard [3] and in Russia and the countries of the former USSR by the State Standard 33211-2014 [4]. Despite their significant differences, during testing, all regulatory documents require determination of the vertical forces Q and lateral forces Y acting from the wheels on the rails. In the future, these values and their ratios can be used to assess the stability of the rolling stock against derailment [5-8].

European and American standards of the force of action of wheels on rails during testing use "The Axle Method" according to deformations of the wheelset axle or "The Wheel Method" according to the deformations of the wheel disc, that is, the axle of the wheelset or the wheel disc is used as a dynamometer [9-12]. With such measurements, the points of determination of the forces have closer contact with the wheel and rail, but require transfer of information from the rotating parts. It is impossible to retrieve such information from typical wheelsets; therefore, for the test period, standard wheelsets are replaced with specially prepared strain gauge wheelsets equipped with strain gauges and data transmission devices.

Most strain gauge wheelsets only measure force when the gauge is close to the point of contact and do not provide continuous measurements. In addition, when using strain gauge wheelsets, it is difficult to test wagons with a worn rolling profile, which is important for assessing the safety of wagon movement in operation. In general, this method of measurement is characterized by a high cost of equipment and does not allow assessment of the vertical forces Q and lateral forces Y without replacing conventional wheelsets.

In the Russian Federation, a simpler and cheaper method is used to determine the Q and Y forces. For this, the side frames themselves with glued strain gauges of the tested three-element bogie are used as measuring elements, since vertical and lateral forces are transmitted through them, and there is no damping in the frame–axle joint of the wheelset. In this case, the processing of the measurement results is simplified since the interaction forces are measured continuously.

Based on the results of measurements of the forces Q and Y on 1520 mm gauge railways, two indicators of the dynamic qualities of the wagon are calculated [13]:

- coefficient of dynamic addition k_g of unsprung parts of the three-element bogie, which is the ratio of the vertical dynamic force Q acting from the bogie frame to the axle box of the wheelset to the static gravity Q_{st} acting from the bogie frame to the same axle box:

$$k_g = \frac{Q}{Q_{st}} < 0.9\,; \tag{1}$$

- the instantaneous value of the safety factor of stability from the derailment of the wheel from the rail k_{us}, representing the inverted Nadal formula [14, 15]:

$$k_{us} = \frac{\tan y - \mu}{1 + \mu \tan y} \frac{< Q >}{< Y >} < 1.3\,, \tag{2}$$

where y is the angle of inclination of the generatrix of the wheel flange to the horizontal (y = 60°); μ is the coefficient of friction between the wheel and the rail (μ = 0.3); and < > is an operator denoting the definition of a moving average with a window width of 2 m.

2. EXISTING METHOD FOR MEASURING THE VERTICAL FORCE

A schematic diagram for determining the vertical force Q is shown in Fig. 1.

Bending moments $M_Q = f(Q)$ are generated in the side frames proportional to the vertical force Q. Bending moments in the section C–C lead to deformations $\varepsilon_i = M_i / (w_i \cdot E)$.

The measured deformations ε_i are used to restore the vertical force Q_i acting on the wheel according to the formula $Q_i = k_{Q_i} \cdot \varepsilon_{Q_i}$.

The coefficient k_{Qi} is determined experimentally when calibrating the force-measuring scheme by gradually raising and lowering the loaded wagon through the dynamometer installed between the body center plate and the bolster thrust bearing of the wagon (Fig. 2).

The main difficulty is the choice of the location of the sensors, so that they do not register longitudinal and lateral forces. According to the current regulatory and technical documentation on 1520 mm gauge railways [4], the traditional scheme for measuring the vertical force consists of two active strain gauges 1-2 (Fig. 3, a) and the compensatory – K_1 and K_2. Strain gauges are assembled into a scheme that sums up the signals from these strain gauges (Fig. 3, b).

Sticking strain gauges at the bottom of the bogie side frame in sections A-A and B-B pose difficulty since, for their placement, wheelset rollout is required. In addition, this scheme does not provide the specified measurement accuracy, since the total deformations arising from the action on the side frame not only by vertical forces but also by lateral and longitudinal forces are recorded [5]. Therefore, for convenience, the measurement scheme used by test centers [16] is used, where strain gauges 1′-2′ are located in sections C–C and D–D on the upper belt of the bogie side frame, as shown in Fig. 3.

An even more simpler, from the point of view of mounting strain gauges, method of measuring vertical forces, described in [5, 16], is used, in which strain gauges (active 1 and compensatory 2) are installed on the upper belt of the bogie side frame, above the axle box zone, T-shaped (Fig. 4, a) or in the form of a cross (Fig. 4, b).

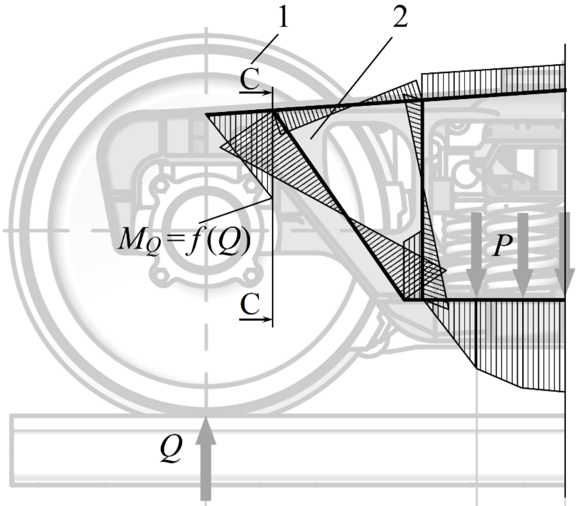


Fig. 1. Scheme for determining the vertical force Q acting on a wheelset from the deformations of the bogie side frames in the vertical plane: a diagram of the application of loads and a diagram of bending moments from the action of a vertical load

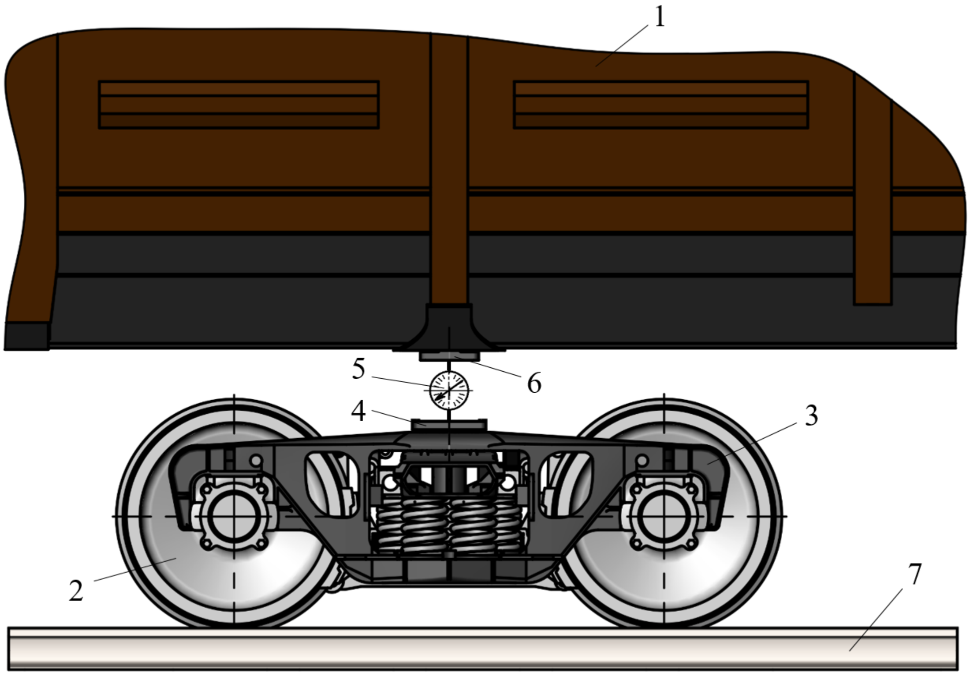


Fig. 2. Scheme of graduation of side frames with vertical load: 1 – wagon body; 2 – wheelset; 3 – side frame; 4 – bolster thrust bearing; 5 – dynamometer; 6 – body center plate; and 7 – rail

3. EXISTING METHOD FOR MEASURING THE LATERAL FORCE

A schematic diagram for determining the lateral force Y is shown in Fig. 5.

The lateral (frame) force acting on the wheelset is equal to the reactions of the bogie side frames in the horizontal plane:

$$Y = H1 + H2, \tag{3}$$

where $H_1 + H_2$ are side frame reactions.

During the tests, the lateral force acting on the wheelset is restored by the formulas:

$$Y_i = K_{y1_i}\varepsilon_{y1_i} + K_{y2_i}\varepsilon_{y2_i}. \tag{4}$$

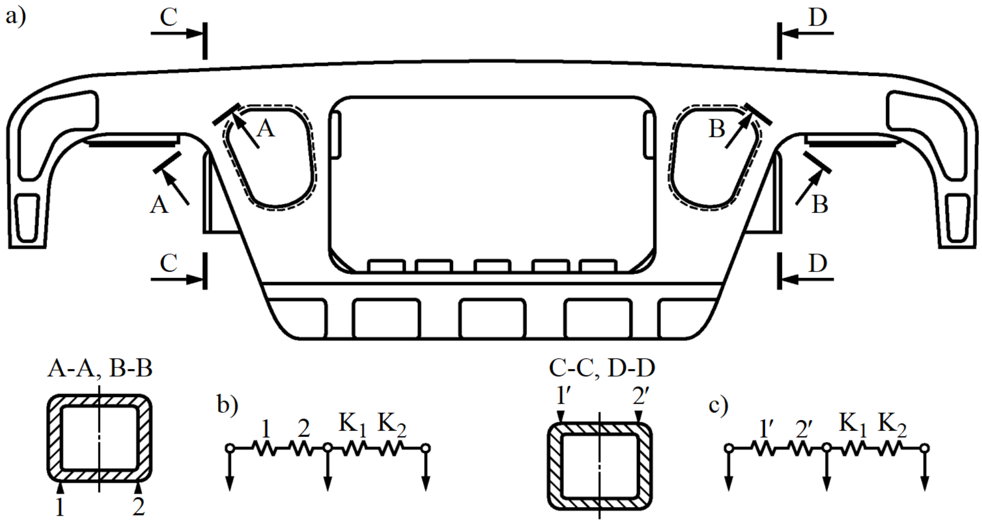


Fig. 3. Schemes for measuring the vertical force by deformations of the bogie side frame: a) the location of the design sections; b) and c) places of installation of strain gauges and schemes of their connection

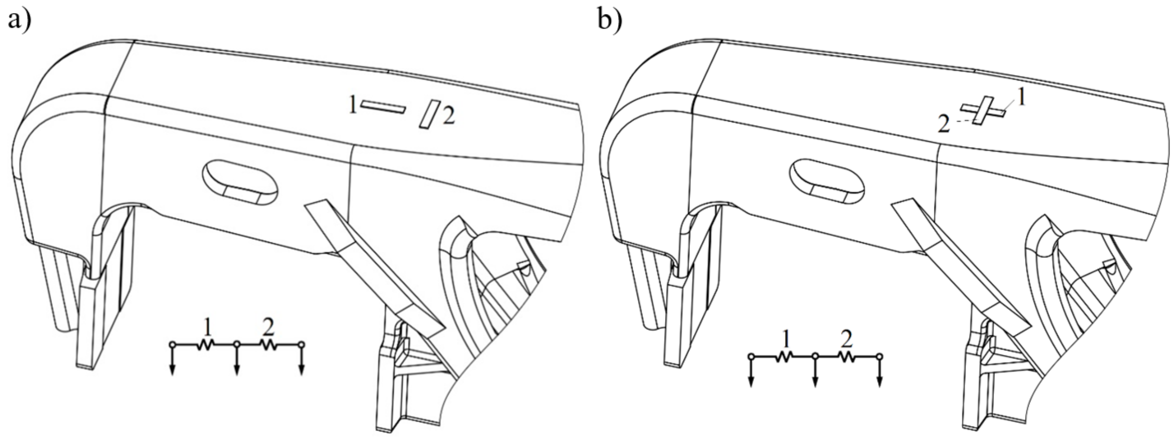


Fig. 4. Measurement scheme for determining the vertical force on the bogie side frame

Coefficients K_{y1_i} and K_{y2_i} are determined experimentally when calibrating measurement schemes with a special tie (Fig. 6). To do this, one of the wheelsets is rolled out of the bogie, and in its place, special rods with a dynamometer are installed, which tighten the side frames of the bogie using a lanyard 2, which has a left and right thread by rotating a handle inserted into hole 3.

Threaded rod ends are connected to stops 7 imitating axle boxes or wheelset adapters. A dynamometer 5 is installed between the tips of one of the rods. When the lanyard 2 rotates, a lateral force is created and a connection is established between the readings of the dynamometer 5 and the level of the output voltage of the strain gauge schemes. The main requirement with this method of determining the loads on the wheelset is to choose the location of the load cells so that they are sensitive only to vertical or lateral horizontal forces.

The measurement scheme for determining the lateral force includes the installation of eight strain gauges on the bogie side frame. In this case, four strain gauges (Fig. 7) are installed above the technological window, and four others are installed under the technological window. Such a scheme for measuring the lateral dynamic force, based on measurements of deformations on the bogie side frame, is currently included in the State Standard 33788-2016 [4] normative and technical documentation to determine the magnitude of the lateral (frame) force. The connection scheme of the strain gauges is shown in Fig. 7, b.

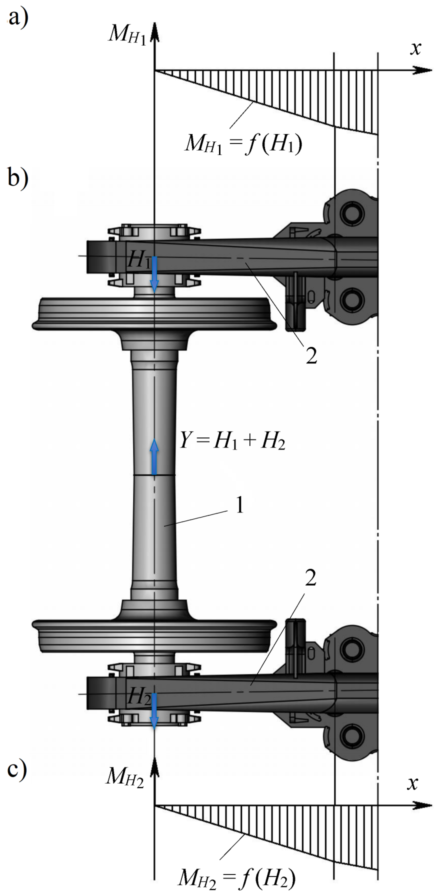


Fig. 5. Scheme for determining the lateral force acting on the wheelset by measuring the deformations of the bogie side frames in the horizontal plane: a) and c) diagrams of bending moments in the frame from the action of lateral forces H_1 and H_2; b) diagram of the application of forces to the frame of a three-piece bogie; 1 – wheelset; and 2 – side frame

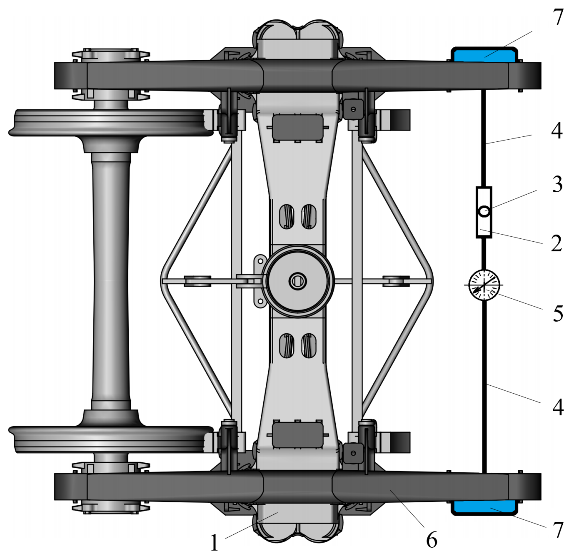


Fig. 6. Scheme of calibration of strain gauges glued to the side frames of a three-element bogie to determine the lateral force: 1 – bogie bolster; 2 – lanyard with right and left threads; 3 – hole for the handle; 4 – traction; 5 – dynamometer; 6 – side frames; and 7 – stops imitating axle boxes or wheelset adapters

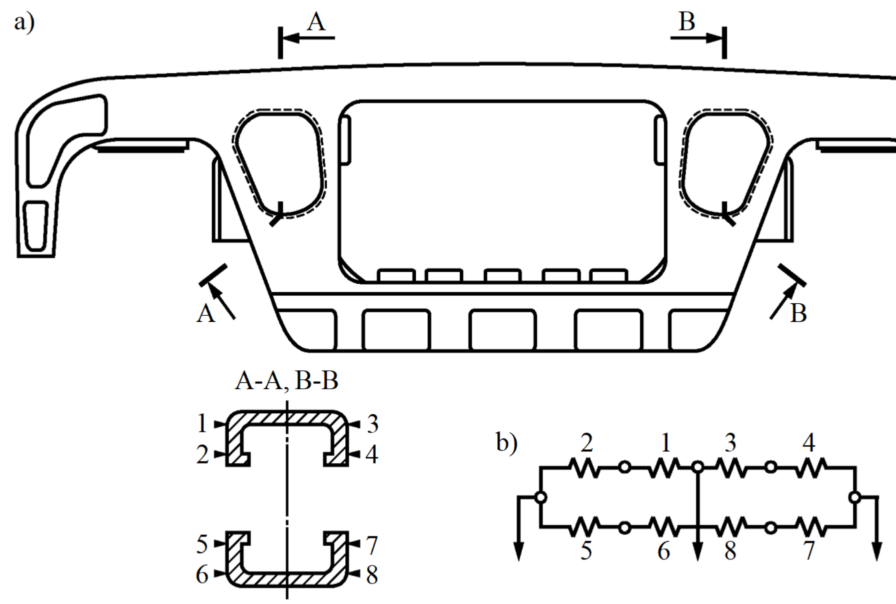


Fig. 7. Measurement scheme for determining the lateral force on the bogie side frame

Measurements of forces, according to [4], should be performed with a relative error of no more than ± 2 %.

The measurement methods described above are simple, but not without drawbacks. The specified accuracy is often not guaranteed. Strain gauges record the total deformations arising from the action of not only vertical and lateral forces but also from longitudinal forces.

In a number of studies, the method of measuring vertical forces used has been criticized. Then, the method of measuring vertical forces was improved by many scientists [16].

To improve the measurement method, it was proposed to install four strain gauges on the upper belt of the bogie side frame, which will allow more accurate measurements of the values of vertical forces, excluding the influence of additional forces arising during tests on the railway track. However, this scheme also does not allow to sufficiently exclude the influence of longitudinal forces.

Later, a new measurement scheme was proposed for determining vertical forces with the installation of strain gauges on an inclined belt on both sides of the bogie side frame at an angle of 45° to the horizon (Fig. 8), in which there is a minimum influence of additional factors. However, this method eliminated the influence of the lateral force on the measurements of the vertical, but did not exclude the influence of the longitudinal force.

In work [17], to exclude the influence of the lateral force, employees of the Tikhvin Test Center of Railway Equipment are suggested to install strain gauges 1-2 (Fig. 8) from different edges on the upper belt of the bogie side frame, in places that are least sensitive to the action of additional forces, where deformations from vertical forces are the same in magnitude and different in sign. This method has not been verified experimentally in testing.

In paper [18], on the basis of theoretical calculations, a method for measuring vertical forces with four strain gauges installed on the upper belt of the bogie side frame was proposed. However, this method was also not verified experimentally in running tests.

4. DEVELOPMENT OF A NEW METHOD FOR MEASURING FORCES

The tests carried out show that the vertical forces and the coefficient of dynamic addition of unsprung parts in curves and on turnouts are significantly higher (by 1.5-2.0 times) than in straight sections of the track (Fig. 9). This is especially true when testing empty freight wagons (Fig. 9, a).

For studying the revealed feature of the obtained results, the influence of longitudinal forces acting on the side frame in curved track sections on the measurement of vertical forces was evaluated using analytical calculations and the finite element method. Studies have shown that under the action of a longitudinal force on the inner bearing stop of the axle-box opening, as well as along the contact area of the wedge and the spring opening wall with the traditional measurement scheme according to the State Standard 33788-2016 [14], the value of the vertical force decreases, while under the action of the longitudinal force on the outer bearing stop of the axle box opening, its value increases. Consequently, this leads to significant errors in determining the coefficient of dynamic addition of unsprung parts.

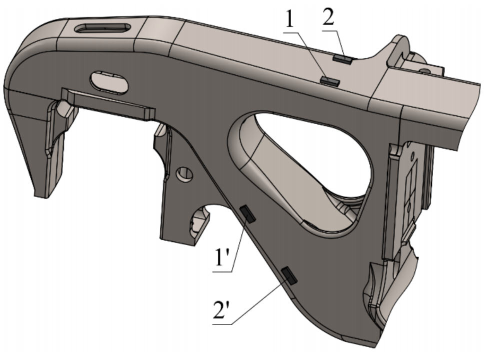


Fig. 8. Schemes of measuring the vertical force, proposed in [17]

To eliminate the significant disadvantages of the measurement schemes considered, select new optimal places for installing strain gauges and determine an effective method of signal processing, which will achieve accurate measurements of the loads acting on the bogie side frame from the wheel pair, theoretical studies of the bogie side frame loading were carried out using the finite element method under the action of loads from the wheelset.

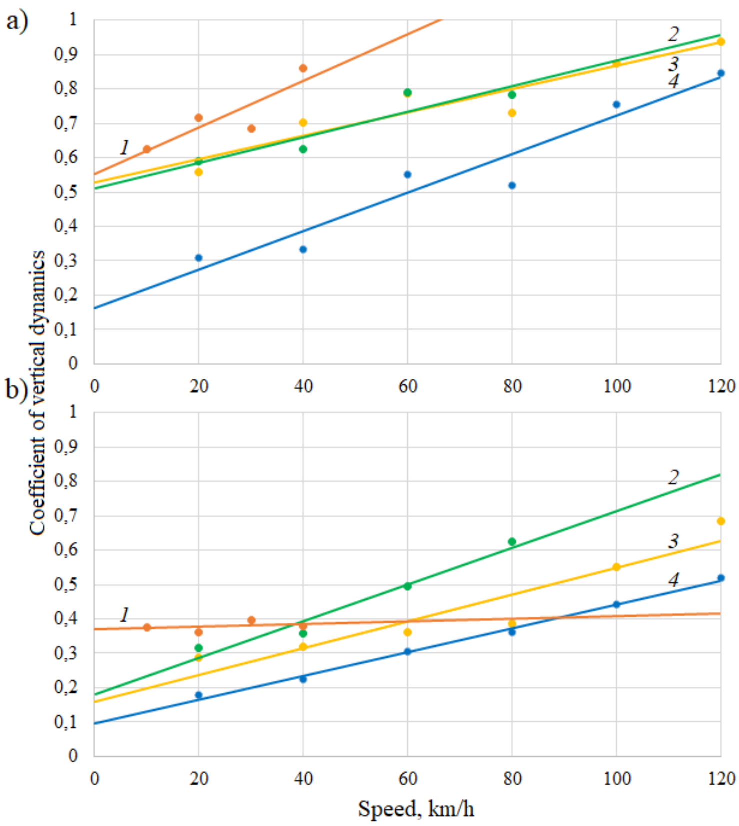


Fig. 9. Dependence of the coefficient of vertical dynamics $k_g = Q / Q_{st}$ of unsprung parts of the fright wagon on the speed of the train: a) empty wagon; b) loaded wagon; 1 – turnouts; 2 – curve with a radius of 350 m; 3 – curve with a radius of 650 m; and 4 – straight

To determine normal stresses on the bogie side frame under the action of only longitudinal forces $P_{\text{longitudinal}}$, only lateral forces P_{lateral} and only vertical forces P_{vertical}, as well as their combined action, various loading schemes were used. The kinematic and force boundary conditions of these schemes are shown in Fig. 10.

Diagrams of the distribution of normal stresses on the right and left sides of the bogie side frame model 18-9855, caused only by longitudinal forces, only by lateral forces and only by vertical forces, as well as their combined action, are presented in Fig. 11 (along the section A–A for the placement of strain gauges; see Fig. 12).

The results of the research showed that if we modernize the traditional installation scheme of strain gauges for measuring lateral forces, according to the State Standard 33788-2016, by placing the sensors according to the scheme shown in Fig. 12 and connecting them as shown in Fig. 13, it can be used to measure both vertical and lateral forces.

The values of the vertical and lateral (frame) forces, expressed in terms of deformations ε_{xi}, have the form:

$$P_{\text{vertical}} = K_{\text{vertical}} \cdot \frac{E}{1-\mu^2}\left(\varepsilon_{x1} + \varepsilon_{x2} + \varepsilon_{x3} + \varepsilon_{x4} - \varepsilon_{x5} - \varepsilon_{x6} - \varepsilon_{x7} - \varepsilon_{x8}\right),$$
$$P_{\text{lateral}} = K_{\text{lateral}} \cdot \frac{E}{1-\mu^2}\left(\varepsilon_{x1} + \varepsilon_{x2} - \varepsilon_{x3} - \varepsilon_{x4} + \varepsilon_{x5} + \varepsilon_{x6} - \varepsilon_{x7} - \varepsilon_{x8}\right), \tag{5}$$

where K_{vertical} and K_{lateral} are constant coefficients for measuring vertical and lateral forces, respectively, determined when calibrating strain gauge schemes; E is the modulus of elasticity; μ is the Poisson's ratio; and ε_{xi} are linear deformations caused by longitudinal normal stresses σ_{xi} at measuring points located on the surface of the bogie side frame.

However, the bridge scheme cannot measure the vertical and lateral (frame) forces at the same time, since it is necessary to include strain gauges 3-6 in different bridge arms. Installation of double the number of strain gauges increases the complexity of the tests.

Considering that:

$$S_1 = \varepsilon_{x1} + \varepsilon_{x2} - \varepsilon_{x7} - \varepsilon_{x8},$$
$$S_2 = \varepsilon_{x3} + \varepsilon_{x4} - \varepsilon_{x5} - \varepsilon_{x6}, \tag{6}$$

formulas (5) can be written as follows:

$$P_{\text{vertical}} = K_{\text{vertical}} \frac{E}{1-\mu^2}\left(\left(\varepsilon_{x1} + \varepsilon_{x2} - \varepsilon_{x7} - \varepsilon_{x8}\right) + \left(\varepsilon_{x3} + \varepsilon_{x4} - \varepsilon_{x5} - \varepsilon_{x6}\right)\right) = K_{\text{vertical}} \frac{E}{1-\mu^2}\left(S_1 + S_2\right),$$
$$P_{\text{lateral}} = K_{\text{lateral}} \frac{E}{1-\mu^2}\left(\left(\varepsilon_{x1} + \varepsilon_{x2} - \varepsilon_{x7} - \varepsilon_{x8}\right) - \left(\varepsilon_{x3} + \varepsilon_{x4} - \varepsilon_{x5} - \varepsilon_{x6}\right)\right) = K_{\text{lateral}} \frac{E}{1-\mu^2}\left(S_1 - S_2\right). \tag{7}$$

To use one scheme for installing strain gauges to measure the vertical and lateral (frame) forces acting on the bogie frame from the wheelset, it is advisable to connect the strain gauges into two full bridges with a four-wire connection scheme, as shown in Fig. 14. This will add and subtract signals S_1 and S_2.

Then, from expressions (6) and (7), we obtain formulas for calculating the vertical and lateral (frame) forces:

$$P_{\text{vertical}} = K_{\text{vertical}} \frac{E}{1-\mu^2}\left(S_1 + S_2\right),$$
$$P_{\text{lateral}} = K_{\text{lateral}} \frac{E}{1-\mu^2}\left(S_1 - S_2\right). \tag{8}$$

To further assess the measurement accuracy of the proposed methods, virtual tests of the bogie side frame were carried out by applying possible loading modes that arise when the wagon moves along the railway tracks. The values of forces were determined from the results of modeling the movement of a loaded and an empty freight wagon along straight and curved track sections using the Universal Mechanism software package. At the same time, it was found that in the loaded and unladen modes, the maximum values of the longitudinal and lateral forces are almost the same fraction of the value of the vertical forces. Therefore, in the calculations, the values of the vertical, longitudinal and lateral forces were considered only in the loaded mode. The loading scheme and measurement results are shown in the table.

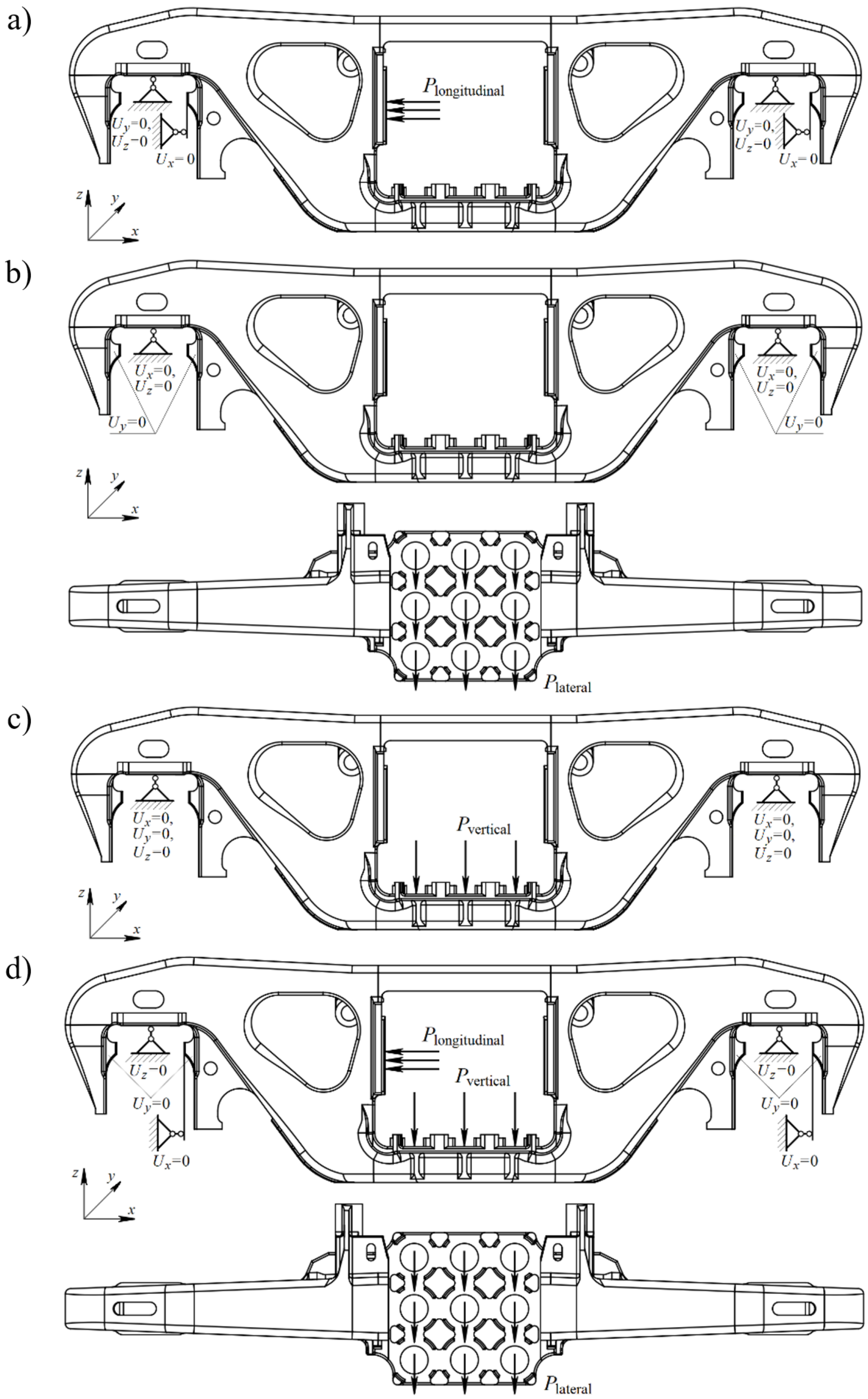


Fig. 10. Kinematic and force boundary conditions when loading the side frame: a) only with longitudinal force; b) only with lateral force; c) only with vertical force; d) with the combined action of vertical, lateral and longitudinal forces

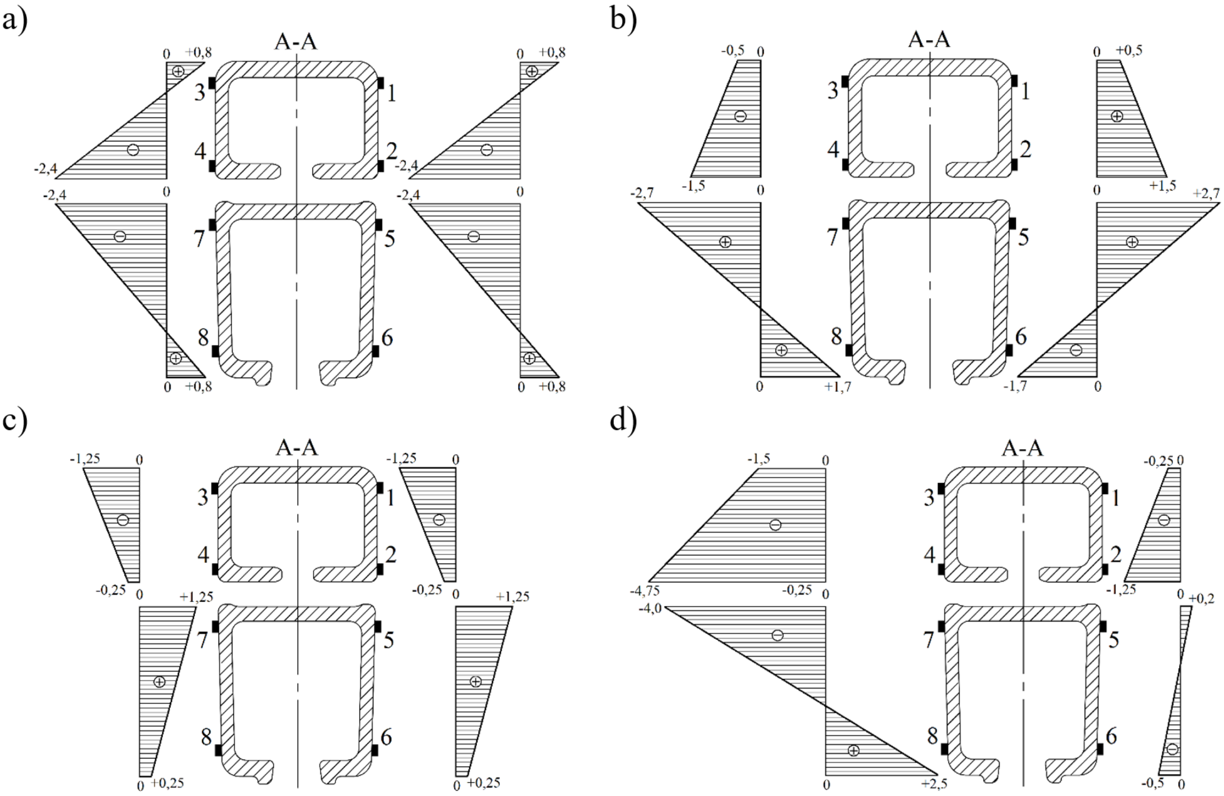


Fig. 11. Diagrams of the distribution of normal stresses on the right and left sides of the bogie side frame (along section A–A for the placement of strain gauges; see Fig. 12) from the action of a longitudinal force of 10 kN (a), a lateral force of 10 kN (b) and a vertical force of 10 kN (c), as well as their combined action (d): 1-8 – numbers of strain gauges

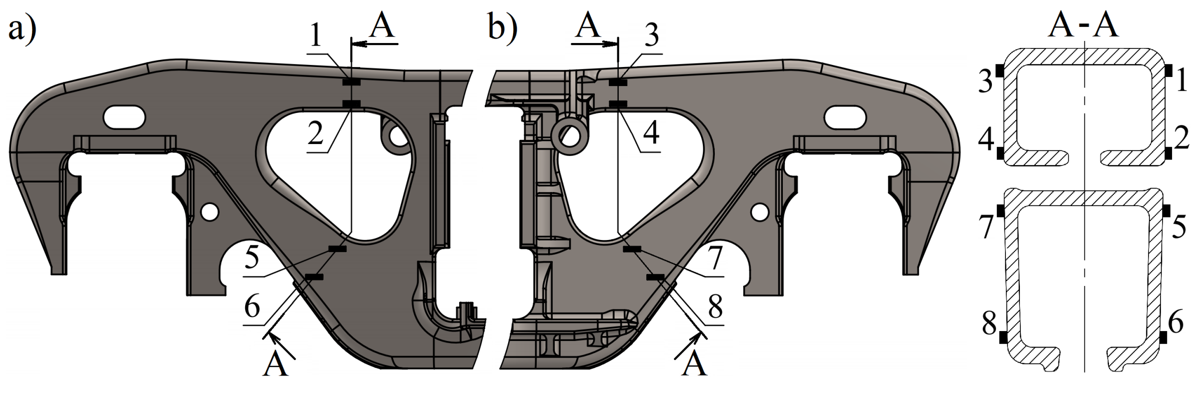


Fig. 12. Proposed installation scheme of strain gauges for measuring vertical and lateral forces on the bogie side frame: a) front side; b) back side; 1-8 – numbers of strain gauges

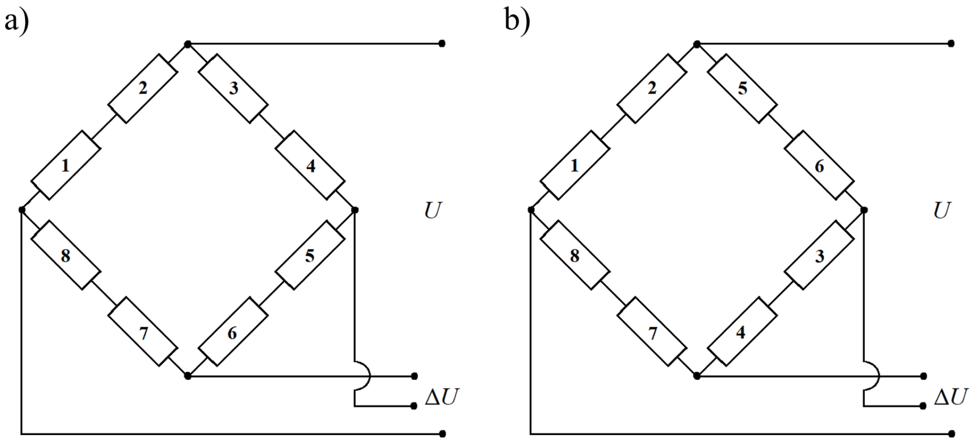


Fig. 13. Schemes measuring lateral (frame) force (a) and vertical force (b) on the bogie side frame: 1-8 – numbers of strain gauges; U – the voltage of the measuring bridge; and ΔU – change in the output voltage of the measuring bridge

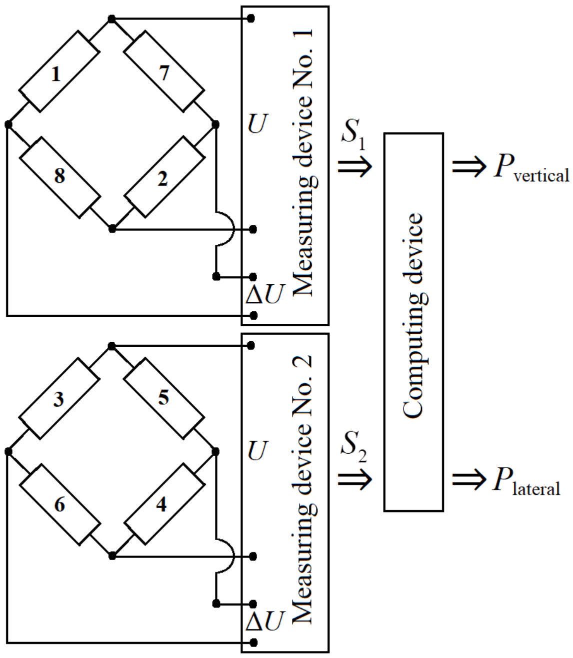


Fig. 14. Scheme of connection of strain gauges in two bridges for calculating vertical and lateral (frame) forces

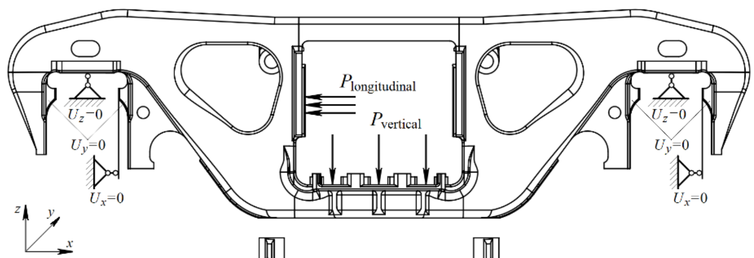
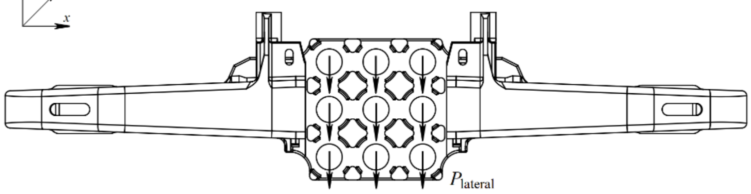
It was found that such a modernized measurement scheme with a symmetrical installation of strain gauges relative to the longitudinal plane of the bogie side frame provides measurements of vertical forces with an error of no more than 2 % and measurements of lateral (frame) forces with an error of no more than 4 %.

5. CONCLUSIONS

Thus, on the basis of the studies carried out, it was determined that under the action of a longitudinal force on the inner support stop of the axle-box opening, as well as along the contact area of the wedge and the wall of the spring opening with the traditional measurement scheme according to the State Standard 33788-2016, the vertical force decreases, while under the action of force on the outer bearing stop of the axle box opening, its value increases. This leads to significant errors in determining the coefficient of dynamic addition of unsprung parts of the wagon during tests. It has been established that the modernized scheme for installing strain gauges for measuring lateral forces acting on the bogie side frame from a wheelset, according to the State Standard 33788-2016, when connecting strain gauges into two full bridges with a four-wire connection scheme with further signal processing, allows use of the scheme simultaneously for measuring vertical and lateral (frame) forces. This makes it possible to increase the accuracy of measurements of the vertical force, with the help of which the coefficient of dynamic addition of unsprung parts of the wagon is calculated during running dynamic tests, and to ensure the simultaneous measurement of vertical and lateral (frame) forces, which will enable reduction of the number of strain gauges for measuring the considered forces during tests.

Table 1

Results of virtual measurements of forces under the action of a longitudinal force of 20 kN

Loading scheme	Recovered values of forces		
	Values of applied forces, kN	Values of restored forces, kN	Error, %
	$P_{vertical}$ = 225	222.94	0.92
	$P_{lateral}$ = 20	19.23	3.85

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