Development of a New Measuring Scheme for Determining the Indicators of Horizontal and Vertical Dynamics of a Subway Car

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***Abstract*—The paper analyzes the measuring schemes to determine the vertical and lateral forces, with the help of which the indicators of the vertical and horizontal dynamics of the subway car are calculated. Theoretical studies of the loading of the subway car bogie frame by the finite element method have been carried out. The locations for the installation of strain gauges on the elements of the carriage and the method of signal processing has been determined. A new measuring scheme has been developed to determine the coefficients of the vertical and horizontal dynamics of a subway car, which makes it possible to measure with sufficient accuracy the values of the vertical and lateral forces acting on the bogie frame. Testing of a new measuring scheme during performance trials of the transition type non-motorized subway car model 81-714 Uz confirmed its effectiveness, which is recommended for use in determining the indicators of the dynamic qualities of a car during dynamic performance trials.**

Keywords—running dynamic tests, bogie frame, vertical and lateral forces, locations for the installation of strain gauges, connection scheme of strain gauges, dynamic qualities of a subway car.

I. Introduction

Rolling stock is a complex mechanical system, which, when moving along the railway track, is subject to various operational loads, which are usually random in nature [1-3]. Modern analytical and numerical methods for studying the dynamic processes arising from the interaction of rolling stock and a railway track are constantly being improved and become more and more effective in assessing the dynamic qualities of rolling stock using mathematical modeling, which is implemented using modern automated software systems [4]. However, theoretical methods are approximate, since they have simplifications when taking into account various factors, therefore, to develop the design of innovative rolling stock with the best dynamic qualities and indicators of its impact on the railway track, along with theoretical methods, experimental methods are provided, which are the most important component of scientific research in the design and construction of rolling stock units [5-7].

According to American and European standards [8-10], the forces acting from the wheel to the rail during running dynamic tests are determined by measuring the deformations on the axle of the wheel pair or wheel disc using strain gauge wheel pairs equipped with strain gauges and data transmission devices [11-14].

Most strain gauge wheel pairs do not provide continuous measurement of dynamic forces, since the determination of loads is carried out by the "point" method - at the moment the strain gauge is located above the point of contact between the wheel and the rail [15]. In addition, this measurement method has a high cost of equipment and does not allow the assessment of forces without replacing conventional wheel pairs.

On 1520 mm gauge railways, a simpler and cheaper method of determining forces is used. For this, the test bogie frames with glued strain gauges are used themselves as measuring elements, since vertical and lateral forces are transmitted through them (through the frames) [16, 17]. In this case, the processing of the measurement results is simplified, since the forces are measured continuously.

Based on the results of measurements of the forces of interaction of a wheel with a rail on railways with a gauge of 1520 mm, indicators of the dynamic qualities of a car are calculated, which are directly related to safety issues during the movement of rolling stock [7, 18, 19]:

- coefficient of vertical dynamics;
- coefficient of horizontal dynamics;
- coefficient of roll stability reserve;
- coefficient of the stock of resistance against derailment.

II. Analysis of Existing Methods for Determining Indicators of Vertical and Horizontal Dynamics of a Subway Car

According to the current regulatory document State Standard 34451-2018 [16], to determine the dynamic qualities of a multi-unit rolling stock (for example, in our case, a subway car), standard locations for the installation of strain gauges are not given, but only the requirements for their installation are described:

- for the indicator of the vertical dynamics of the first stage of spring suspension – on the elements of the bogie so that the influence of horizontal forces on it is maximally excluded;
- for the indicator of vertical dynamics of the second stage of spring suspension – on the elements of the carriage part in such a way that the influence of horizontal forces on it is maximally excluded;
- for the indicator of horizontal dynamics – on the elements of the bogie in such a way that the influence of vertical and longitudinal forces on it is maximally excluded.

The specific installation locations of the strain gauges can only be determined when performing theoretical studies or numerous experiments [6, 18].

Since the bogies of passenger cars and subway cars are structurally similar to each other, it is possible to take as a basis the presented measurement scheme for passenger cars of locomotive traction, according to the State Standard 33788-2016 [17].

According to the current normative document State Standard 33788-2016 for measuring the vertical force, with the help of which the coefficient of dynamic addition (coefficient of vertical dynamics) of the spring suspended parts of the passenger car bogie is determined, two active strain gauges 1 and 2 are installed in the middle part of the side longitudinal beam of the bogie frame from above and below in sections A-A and A′-A′, as shown in Fig. 1.

The use of this measurement scheme for a subway car is difficult, since the possibility of symmetrical installation of strain gauges is excluded, since the upper and lower reinforcing plates (gussets) are welded to the frame along the entire perimeter and additionally above the longitudinal beams (Fig. 2, *a*), including in the middle part, by means of holes completely welded along the contour, and from the bottom due to the presence of support for hydraulic oscillation damper (Fig. 2, *b*).

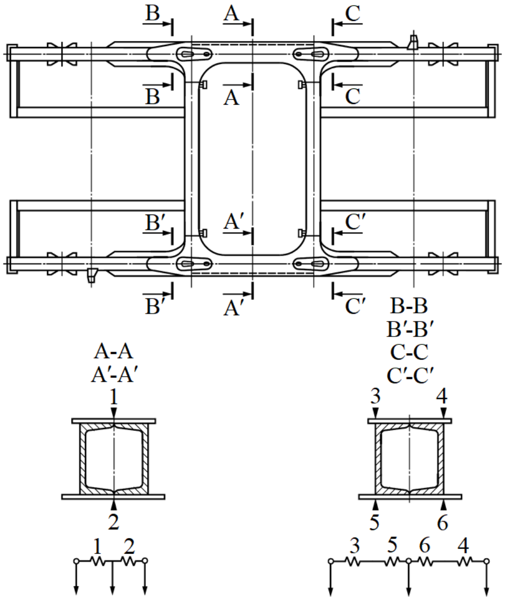


Fig. 1. Installation and connection scheme of strain gauges for measuring the horizontal force and the coefficient of dynamic addition (coefficient of vertical dynamics) of the passenger carriage bogie spring suspended parts: 1-6 – numbers of strain gauges.

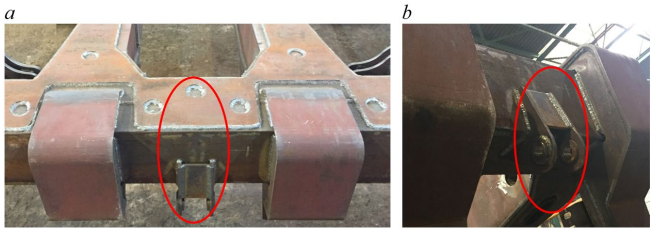


Fig. 2. Side longitudinal beam of the frame with welded reinforcing linings (gussets) and supports for hydraulic oscillation damper: *a* – top view; *b* – bottom view.

The horizontal force with which the frame force is calculated, according to State Standard 33788-2018, is determined by four strain gauges 3-6 installed above and below along the edges of the side longitudinal beam of the bogie frame in sections B-B, B′-B′, C-C, C′-C′ as shown in Fig. 1.

This scheme can be used to determine the indicator of the horizontal dynamics of a subway car, since the installation of strain gauges, according to State Standard 33788-2018, on the side longitudinal beam of the frame does not prevent its constructive implementation.

Taking into account the above, in order to determine the vertical dynamics indicator of the first stage of the spring suspension of a subway car, it was necessary to find the locations for the installation of strain gauges on the bogie elements and a method for processing the received signals, which, according to the requirements of State Standard 34451-2018, make it possible to maximally exclude the influence of horizontal forces on the bogie.

III. Development of a New Method for Measuring Vertical and Lateral Forces Acting on the Bogie Frame of a Subway Car

The purpose of the research was to choose the locations for the installation of strain gauges on the elements of the bogie and the method of signal processing – the development of a measuring scheme for indicators of the vertical and horizontal dynamics of a subway car.

At the first stage of the research, a design model of the subway car bogie frame of Model 81-717/714 (Fig. 3) was developed, which is an H-shaped all-welded structure, consisting of two longitudinal and two transverse beams, butt-connected with overlapping of the joint with reinforcing linings.

For calculations by the finite element method, the ANSYS Workbench software suite, version 18 was used. The finite element mesh applied to the model of the bogie frame included 60362 elements and 185701 nodes. Finite elements of the Solid186 type with a size of 10 mm were used.

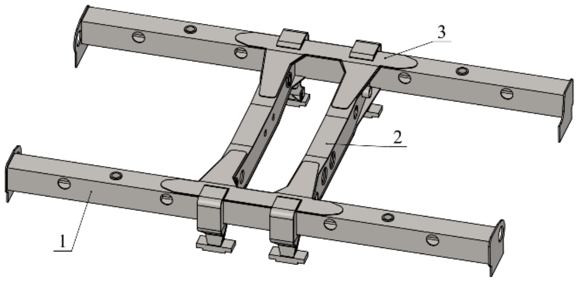


Fig. 3. Design model of the subway car bogie frame: 1 – longitudinal beam; 2 – transverse beam; 3 – reinforcing lining.

The coordinate system was adopted as follows: the x – axis is the longitudinal axis; y – axis is the lateral axis; and z – axis is the lateral axis.

In the next stage, load studies of the subway car bogie frame were carried out using the finite element method. As a result of multivariate calculations, diagrams of stress distribution on the bogie frame were obtained under the action of vertical, longitudinal and lateral forces on it.

Analysis of the results of calculations and diagrams of stress distribution on the bogie frame showed that the most promising is the determination of the vertical and lateral forces, with the help of which the indicators of the vertical and horizontal dynamics of the car are calculated, by measuring the normal stresses (along the longitudinal x – axis) with the installation of four strain gauges on both sides on the side longitudinal beam of the bogie frame in sections A-A, A′-A′, B-B, B′-B′, as shown in Fig. 4.

This will allow, when determining vertical forces, to exclude the influence of horizontal forces on the bogie as much as possible, and when determining lateral forces – the influence of vertical and longitudinal forces.

Then the values of the vertical and lateral forces, expressed in terms of deformations ε_{xi}, have the form

$$P_{ver} = C_{ver} \cdot \frac{E}{1-\mu^2}\left(\varepsilon_{x1} - \varepsilon_{x2} + \varepsilon_{x3} - \varepsilon_{x4}\right), \quad (1)$$
$$P_{lat} = C_{lat} \cdot \frac{E}{1-\mu^2}\left(\varepsilon_{x1} + \varepsilon_{x2} - \varepsilon_{x3} - \varepsilon_{x4}\right).$$

Where C_{ver} and C_{lat} – are constant coefficients for measuring vertical and lateral forces, respectively, determined when calibrating strain gauge schemes; E – is the modulus of elasticity; μ – is Poisson's ratio; ε_{xi} – linear deformations caused by normal longitudinal stresses σ_{xi}, measured by strain gauges installed on the side longitudinal beam of the bogie frame.

If we consider that

$$S_1 = \varepsilon_{x1} - \varepsilon_{x4}, \quad (2)$$
$$S_2 = \varepsilon_{x2} - \varepsilon_{x3},$$

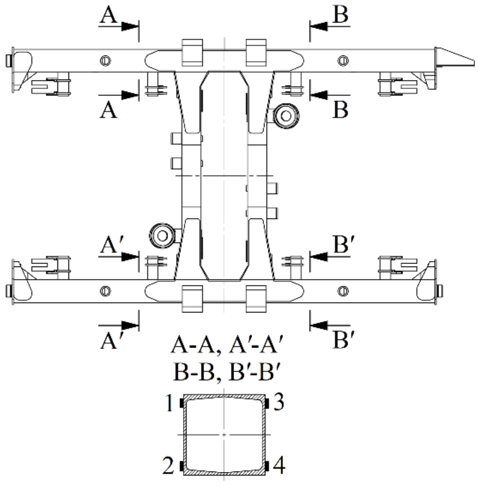


Fig. 4. Installation scheme of strain gauges for measuring vertical and lateral forces on the bogie frame of a subway car: 1-4 – numbers of strain gauges.

then formula (1) can be written as follows:

$$P_{ver} = C_{ver} \cdot \frac{E}{1-\mu^2}\left(S_1 - S_2\right), \quad (3)$$
$$P_{lat} = C_{lat} \cdot \frac{E}{1-\mu^2}\left(S_1 + S_2\right).$$

In this case, to determine the vertical force acting on the bogie frame, four strain gauges 1-4 (Fig. 4) must be connected into a full bridge connection scheme, as shown in Fig. 5, *a*. For determining the lateral force, gauges should be connected as shown in Fig. 5, *b*.

Therefore, in order to apply the installation scheme of strain gauges shown in Fig. 4 for the simultaneous measurement of vertical and lateral forces, according to expression (3), it is advisable to connect the strain gauges in two full bridges with a four-wire connection scheme, as shown in Fig. 6.

Thus, the new measurement scheme, when the strain gauges are connected into two full bridges with a four-wire connection scheme, as shown in Fig. 6, and with further signal processing, according to expression (3), will provide simultaneous measurement of the vertical and lateral forces acting on the bogie frame of a subway car. This makes it possible to determine with sufficient accuracy the values of the coefficient of vertical and horizontal dynamics, to reduce the number of strain gauges for determining the indicators of the dynamic qualities of a subway car while running dynamic tests.

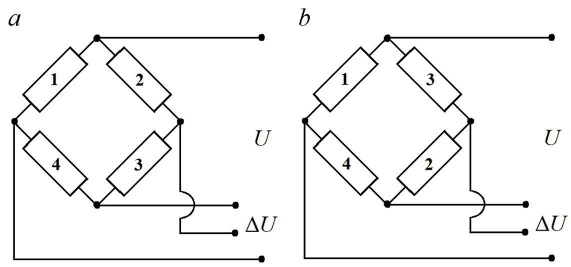


Fig. 5. Connection schemes of strain gauges for measuring vertical force (*a*) and lateral force (*b*) on the bogie frame: 1-4 – numbers of strain gauges; U – is the voltage of the measurement bridge; ΔU – change in the output voltage of the measurement bridge.

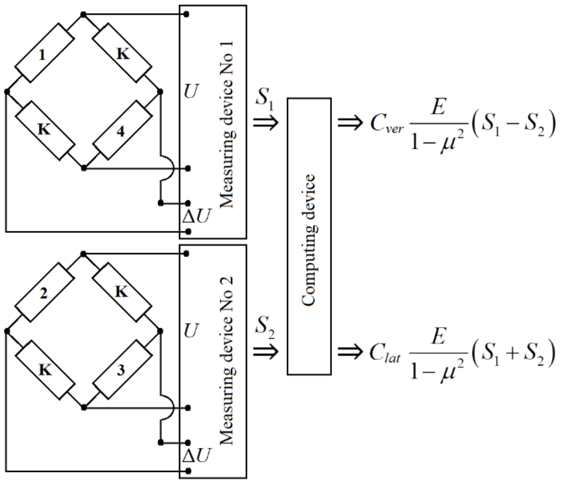


Fig. 6. Connection scheme of strain gauges for measuring vertical and lateral forces on the bogie frame of the subway car: 1-4 – numbers of strain gauges; K – compensatory strain gauges.

IV. Testing of a New Measuring Scheme for Determining the Vertical and Lateral Forces Acting on the Bogie Frame of a Subway Car

The proposed measuring scheme was tested during performance trials to assess the dynamic qualities of the transition type non-motorized metro car model 81-714 Uz manufactured by JSC "Tashkent plant for construction and repair of passenger cars" on the Chilanzar line of the Tashkent metro.

Before testing the side longitudinal beams of the bogie frame closest to the head car of the metro, strain gauges were installed, according to the scheme shown in Fig. 4 and connected to measuring bridges according to Fig. 6.

Placement of strain gauges on the bogie frame of the transition type non-motor subway car of the model 81-714 Uz is shown in Fig. 7.

To determine the experimental dependencies between the readings of the measuring schemes and the acting forces, the calibration loads of the subway car bogie frame were carried out. An example of an oscillogram of deformations in the process of loading and unloading of a subway car bogie frame, registered according to the new measuring scheme, is shown in Fig. 8.

To determine the scale of the strain gauge measuring scheme, graphs of the dependence of the readings of the device on the loading and unloading of the subway car bogie were built. The obtained values were approximated by the least squares method, and as a result of the statistical analysis of the data obtained, the average value of the measurement scale of the strain gauge measuring scheme was chosen.

During performance trials, the vertical and lateral forces acting on the subway car bogie frame were measured and recorded. Evaluation of the dynamic qualities of a subway car was carried out in empty and loaded modes in the entire range of operating speeds, every 10-20 km/h up to the design speed.

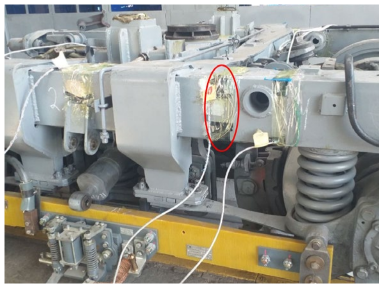


Fig. 7. Placement of strain gauges and their connection on the bogie frame of the transition type non-motor subway car of the model 81-714 Uz.

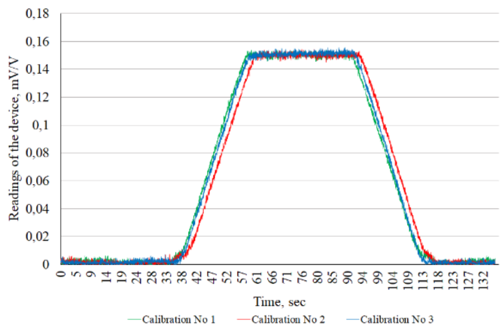
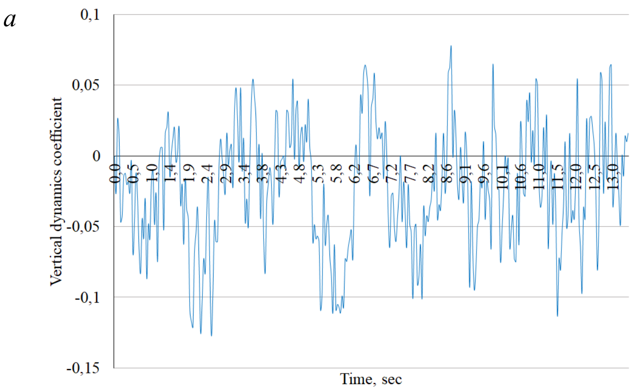
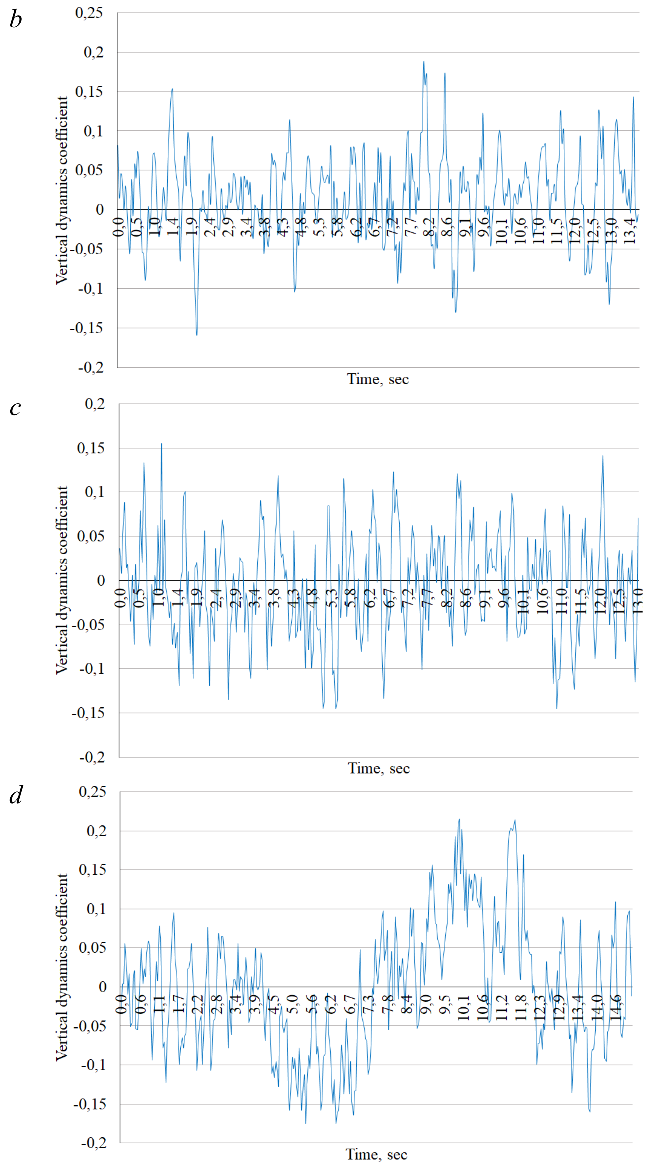


Fig. 8. Oscillogram of the loading and unloading process of a subway car bogie frame.

Examples of the graphs of continuous registration of the vertical dynamics coefficients of the first stage of spring suspension and horizontal dynamics, recorded according to a new measuring scheme as a result of performance trials to assess the dynamic qualities of the transition type non-motorized subway car model 81-714 Uz, are shown in Fig. 9-10.





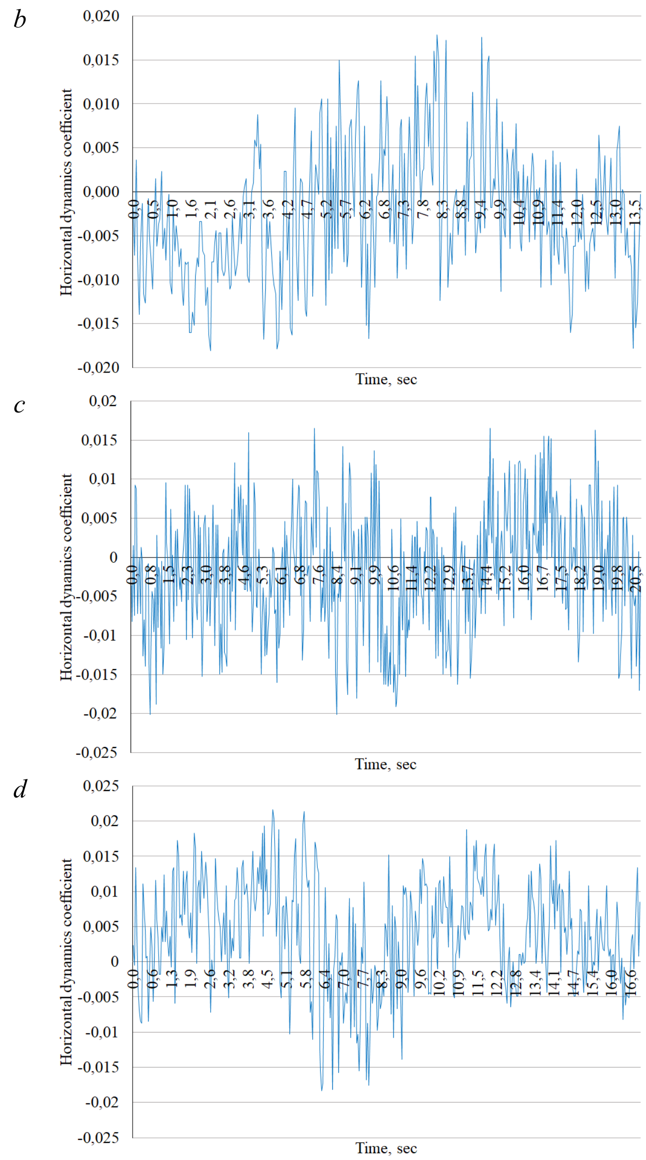


Fig. 9. Dependences of the vertical dynamics coefficient of the first stage of spring suspension on time (empty mode): *a* – on tangent tracks at a speed of 20 km/h; *b* – on tangent tracks at a speed of 50 km/h; *c* – on the middle radius curved tracks at a speed of 50 km/h; *d* – on small radius curved tracks of at a speed of 50 km/h.

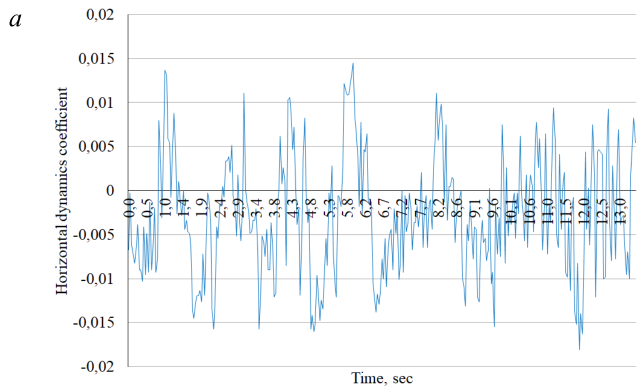


Fig. 10. Dependences of the horizontal dynamics coefficient on time (empty mode): *a* – on tangent tracks at a speed of 20 km/h; *b* – on tangent tracks at a speed of 50 km/h; *c* – on the middle radius curved tracks at a speed of 50 km/h; *d* – on small radius curved tracks of at a speed of 50 km/h.

Thus, the results of the performance trials carried out to assess the dynamic qualities of the transition type non-motorized subway car model 81-714 Uz confirmed the effectiveness of the developed measuring scheme for determining the vertical and lateral forces acting on the subway car bogie frame.

V. Conclusion

- In the work, a set of studies was carried out and a new measuring scheme was developed, theoretically substantiated and tested during dynamic performance trials for determining the indicators of vertical and horizontal dynamics of a subway car.
- It was found that the most promising is the determination of vertical and lateral forces, with the help of which the indicators of the vertical and horizontal dynamics of the car are calculated, by measuring the normal stresses (along the longitudinal axis) with the installation of four strain gauges on both

sides on the side longitudinal beam of the bogie frame (Fig. 4).

- It has been determined that the new measuring scheme, when the strain gauges are connected to two full bridges with a four-wire connection scheme, will provide simultaneous measurement of the vertical and lateral forces acting on a subway car bogie frame (Fig. 6). This will allow, when determining vertical forces, to exclude as much as possible the influence of horizontal forces on the bogie, and when determining lateral forces – the influence of vertical and longitudinal forces.
- The performance trials carried out to assess the dynamic qualities of the transition type non-motorized subway car model 81-714 Uz confirmed the effectiveness of the developed measuring scheme for determining the vertical and lateral forces acting on the subway car bogie frame.
- Thus, the developed measuring scheme is recommended for use in determining the coefficients of the vertical and horizontal dynamics of a subway car, which will allow to determine with sufficient accuracy the values of the vertical and lateral forces acting on the bogie frame and reduce the number of strain gauges to determine the indicators of the dynamic qualities of the car during performance trials.

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