A new way to determine the indicators of vertical and horizontal of a subway car

R. Rahimov1*, Yu. Boronenko2, A. Tretyakov2, and Sh. Sultonov2

1Tashkent State Transport University, 1, str. Adilhodzhaeva, Tashkent, Uzbekistan
2St. Petersburg State University of Railway Transport of Emperor Alexander I, 9 Moskovsky pr., 190031, St. Petersburg, Russia

Abstract. The issues of measuring the coefficients of vertical and horizontal dynamics of a subway car during running dynamic tests are reviewed. The theoretical research of bogie frame loading by finite element method has been done. Analysis of complex calculation outcomes and stress distribution diagrams on bogie frame under the action of vertical, longitudinal, and lateral forces has allowed defining the place of strain gauges installation on the elements of the bogie and the signal processing method for measuring vertical and lateral forces acting on bogie frame of the subway car. The new measuring circuit with strain gauges connected in two full bridges with a four-wire connection scheme will provide simultaneous measurement of vertical and lateral forces acting on the subway car bogie frame. The running tests on the evaluation of dynamic qualities of subway car model 81-714Uz confirmed the effectiveness of the developed measuring scheme for determining the indicators of vertical and horizontal dynamics of a subway car. Keywords: Running dynamic tests, bogie frame, vertical and lateral forces, strain gauge installation locations, strain gauge connection scheme, car dynamic properties, approbation.

1 Introduction

The subway is one of the main types of urban passenger transport in modern Tashkent, which has a high route speed and carrying capacity. In recent years, to develop the infrastructure of the Tashkent Metro, additional underground and elevated metro lines and metro stations are being built. As a outcome of the works carried out in 2016-2021, the total length of the metro line has been increased from 38 km to 59 km, the number of stations from 29 to 43, and the capacity of passenger traffic in the Tashkent Metro has doubled compared to 2016, and the daily passenger traffic has been increased from 160 thousand to 360 thousand.

Today, the subway performs the most important economic, social and strategic functions, being an integral part of the passenger transport complex of Tashkent, which necessitates a high level of safety subway [1].

Increased requirements for the reliability of metro rolling stock are caused by the movement of trains in tunnels and on elevated tracks at short intervals in conditions of poor track development. Therefore, the most important characteristic of metro rolling stock is, first
of all, its reliability and serviceability. At the same time, the indicators of the dynamic qualities of cars, which directly relate to the safety issues during the movement of rolling stock, are also important parameters to ensure passenger comfort [2, 3].

When assessing the dynamic qualities of rolling stock, accurate measurement of the coefficients of vertical and horizontal dynamics of the car, which are calculated from the outcomes of measurements of dynamic processes occurring during the interaction of rolling stock and track, is important [4-6].

According to American and European standards [7-9], the forces of wheels on rails during running dynamic tests are determined by measuring deformations on the wheelset axle or wheel disc using strain gauge wheelsets equipped with strain gauges and data transmission devices [10-13]. In such measurements, the points of determination of forces are closer to the contact between the wheel and the rail but require the transfer of information from the rotating parts. It is impossible to remove such information from typical wheelsets, so for the period of testing, standard wheelsets are replaced by specially prepared strain gauge wheelsets equipped with strain gauges and data transmission devices [14, 15].

Most strain gauge wheelsets measure the force by the “point” method only at the moment when the strain gauge is near the point of contact of the wheel with the rail and do not provide a continuous process of measuring dynamic forces [16, 17]. In addition, when using strain gauge wheelsets, it is difficult to test cars with worn roll profiles, which is important for assessing the safety of cars in operation. In general, this measurement method is characterized by the high cost of equipment and does not allow estimating dynamic forces without replacing conventional wheelsets.

A simpler and cheaper method of determining vertical and lateral forces is used on 1520 mm gauge railroads. For this purpose, the frames themselves with glued strain gauges of the tested bogie are used as measuring elements, because vertical and lateral forces are transmitted through them [18, 19]. In this case, the processing of measurement outcomes is simplified, because the forces are measured continuously. Based on the outcomes of measurements of the forces of interaction between the wheel and the rail on 1520 mm gauge railroads, the indices of the car's dynamic qualities are calculated [10, 19, 20].

2 Analysis of existing methods for determining the indicators of vertical and horizontal dynamics of the subway car

In the current normative document GOST 34451-2018 for the measurement of vertical and lateral forces, by which the coefficients of vertical and horizontal dynamics of motor rolling stock, (for example, in our case, the subway car) are not specified specific places of installation of strain gauges on the elements of the car bogie and their connection scheme, but there are requirements for their installation.

It is only possible to determine the exact locations of the strain gauges and the pattern of their connection through theoretical studies or numerous experiments.

Since the bogies of passenger cars and subway cars are structurally similar to each other and the frames of both bogies are an all-welded H-shaped structure consisting of two longitudinal and two transverse beams, it is possible to take as a basis the presented measurement scheme for passenger cars of locomotive traction, according to GOST 33788-2016 in determining the vertical and horizontal dynamics of subway cars.

3 Measuring vertical force

According to GOST 33788-2016 to measure the vertical force, which is used to determine the coefficient of dynamic addition of the bogie passenger car, two active strain gauges 1 and
According to GOST 33788-2016, measurement schemes for passenger cars of locomotive traction, a continuous process of measuring vertical and horizontal dynamics of the subway car is important, and the forces of interaction between the wheel and the rail on 1520 mm gauge railroads. For this purpose, the frames themselves are replaced by specially prepared strain gauge wheelsets, (for example, in our case, the subway car is equipped with strain gauges used by test centers; d – connection scheme of strain gauges according to GOST 33788-2016; e – connection scheme of strain gauges used by test centers; 1-2 – numbers of strain gauges; K – compensation strain gauge; U – voltage of the measurement bridge; ΔU – change in the output voltage of the measurement bridge.)

It is only possible to test cars with worn wheelsets, because the forces are measured co-transmitted through them [18, 19]. In this case, the processing of measurement results is simplified, because the forces are measured continuously. Based on the strain gauge data, it is possible to calculate the coefficients of vertical and horizontal dynamics of the car, which are calculated from the formulas (1) as shown in Fig. 1, d.

In this case, the vertical force value is determined by the difference of strains εi registered by the i-th strain gauge according to the expression:

\[ P_{ver} = C_{ver} \cdot \frac{E}{1-\mu^2} (\varepsilon_i - \varepsilon_2), \]

Where \( C_{ver} \) – constant scaling factor for vertical force measurement, determined when calibrating strain gauge circuits; \( E \) – flexural modulus; \( \mu \) – Poisson’s ratio; \( \varepsilon_i \) – deformations caused by normal stresses \( \sigma_i \), registered by the i-th strain gauge, installed on the side longitudinal beam of the bogie frame.

It is difficult to use this measuring scheme for a subway car because the possibility of symmetric installation of strain gauges is excluded, as the overlapping joints of longitudinal and transverse beams reinforcing pressed brackets 6 mm thick are welded to the frame along the whole contour and additionally over longitudinal beams to increase the frame strength and create a smooth transition of sections (Fig. 2, a), including in its middle part, through the holes fully welded along the contour. In addition, from below to the longitudinal beams in the middle part are welded brackets, to which are attached hydraulic dampers vibration (Fig. 2, b).

\[ \text{Fig. 1. Schemes of installation and connection of strain gauges for measuring the coefficient of vertical dynamics of a passenger car.} \]

Where: a – general view of the bogie frame with measuring sections; b – installation scheme of strain gauges according to GOST 33788-2016; c – installation scheme of strain gauges used by test centers; d – connection scheme of strain gauges according to GOST 33788-2016; e – connection scheme of strain gauges used by test centers; 1-2 – numbers of strain gauges; K – compensation strain gauge; U – voltage of the measurement bridge; ΔU – change in the output voltage of the measurement bridge.
There is also a measuring scheme for determining the coefficient of vertical dynamics of the car, used by the testing centers, which includes two active strain gauges 1 and 2 (Fig. 1, c), installed in the middle part of the lateral longitudinal beam of the bogie frame at the edges at sections A-A and B-B and determine the vertical forces acting on the bogie frame, by summing the output signals according to the measuring scheme shown in Fig. 1, e and by the expression:

$$P_{ver} = C_{ver} \cdot \frac{E}{1-\mu^2} \left(\varepsilon_1 + \varepsilon_2\right).$$

(2)

Applying the measuring scheme used by the test centers is also difficult because the middle part of the side longitudinal beam of the bogie frame has welded seams on top of the edges of the reinforcing pressed brace (Fig. 3).

As studies show, the displacement of the center of the measuring circuits relative to the middle of the frame side longitudinal beam in the longitudinal and transverse directions, as well as the asymmetrical location of the strain gauges, leads to a significant increase in measurement errors.
4 Lateral force measurement

The scheme for measuring the lateral (frame) force acting on the bogie frame from the wheelset axle box, according to GOST 33788-2016, includes the installation of four strain gauges 1-4 (Fig. 4) on the side longitudinal beam of the bogie frame in sections A-A, B-B, C-C and D-D (Fig. 4, a). Strain gauges 1 and 2 are located on the upper part of the side longitudinal beam of the bogie, and strain gauges 3 and 4 – are in the lower part (Fig. 4, b).

![Fig. 4. Schemes of installation and connection of strain gauges for measuring lateral (frame) force on the bogie frame of a passenger car: a – general view of the bogie frame with measuring sections; b – installation scheme of strain gauges according to GOST 33788-2016; c – connection scheme of strain gauges according to GOST 33788-2016; 1-4 – numbers of strain gauges.](image)

Then to measure the lateral (frame) forces, strain gauges 1-4 are connected in one measuring bridge as shown in Fig. 4, c. In this case, the value of the lateral forces is determined by the following formula:

\[
P_{lat} = C_{lat} \frac{E}{1-\mu^2} \left( \varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4 \right),
\]

where \( C_{lat} \) – constant scaling factor for measuring lateral (frame) force, determined during calibration of strain gauge circuits.

This scheme can be used to determine the horizontal dynamics index of the subway car, since the installation of strain gauges, according to GOST 33788-2016, on the side longitudinal beam of the frame is not prevented by its structural design.

Considering the above, to determine the vertical dynamics index of the first stage of the subway car spring suspension, it was required to find the places of installation of strain gauges on the elements of the bogie and the way of processing the signals obtained, which according to the requirements of GOST 34451-2018 allow eliminating the influence of horizontal forces on the bogie as much as possible.
Development of a new method for measuring vertical and lateral forces acting on the subway car bogie frame

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

At the first stage of the research, a design model of the bogie frame of subway car model 81-717/714 was developed (Fig. 5), which is an H-shaped all-welded structure consisting of two longitudinal and two transverse beams, connected at the butt joint with the overlapping of the joint place by reinforcement plates.

![Fig. 5. Design model of the subway car bogie frame: 1 – longitudinal beam; 2 – a pedestal with a bracket for attaching axle box leashes; 3 – reinforcing scarf; 4 – transverse beam; 5 – bracket for fixing the brake cylinder; 6 – bracket for safety brackets of the central suspension; 7 – bushing for the safety pin axle boxes.](image)

The ANSYS Workbench software package was used for calculations using the finite element method (FEM).

At the next stage, the loading of the subway car bogie frame was investigated. As a outcome of multivariant calculations, the stress distribution diagrams on the bogie frame under the action of vertical, longitudinal, and lateral forces were obtained.

Analysis of the calculation outcomes showed that the most promising is the determination of vertical and lateral forces, which are used to calculate the indicators of vertical and horizontal dynamics of the car, by measuring the normal stresses with the installation of four strain gauges on both sides on the lateral longitudinal beam of the bogie frame in sections A-A, B-B, C-C, and D-D, as shown in Fig. 6.
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Fig. 6. Scheme of installation of strain gauges for measuring vertical and lateral forces on the bogie frame of a subway car.

In this case, to determine the vertical force acting on the frame of the cart, four strain gauges 1-4 (Fig. 6) should be connected in a power connection diagram, as shown in Fig. 7, a. To determine the lateral force as shown in Fig. 7, b.

Fig. 7. Connection schemes of strain gauges for measuring vertical force (a) and lateral force (b) on the bogie frame.

This will make it possible to eliminate as much as possible the influence of horizontal forces on the cart when determining vertical forces, and when determining the lateral forces—the influence vertical and longitudinal forces.

Then the values of vertical and lateral forces, expressed in terms of deformations $\varepsilon_{xi}$, are of the form:

$$
\begin{align*}
P_{\text{ver}} &= C_{\text{ver}} \cdot \frac{E}{1-\mu^2} (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4), \\
P_{\text{lat}} &= C_{\text{lat}} \cdot \frac{E}{1-\mu^2} (\varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4).
\end{align*}
$$

(4)

Considering that
\[ S_1 = \varepsilon_1 - \varepsilon_4, \]
\[ S_2 = \varepsilon_2 - \varepsilon_3, \]

then formula (4) can be written as follows

\[ P_{\text{ver}} = C_{\text{ver}} \cdot \frac{E}{1 - \mu^2} (\varepsilon_1 - \varepsilon_4) = C_{\text{ver}} \cdot \frac{E}{1 - \mu^2} (S_1 - S_2), \]
\[ P_{\text{lat}} = C_{\text{lat}} \cdot \frac{E}{1 - \mu^2} (\varepsilon_1 - \varepsilon_4) = C_{\text{lat}} \cdot \frac{E}{1 - \mu^2} (S_1 + S_2). \]

Therefore, to apply the arrangement of strain gauges shown in Fig. 6, for simultaneous measurement of vertical and lateral forces, according to expression (6), it is advisable to connect the strain gauges in two full bridges with a four-wire connection scheme, as shown in Fig. 8.

![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 – strain gauges compensatory.](image)

Fig. 8. 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 – strain gauges compensatory.

Thus, the new measuring circuit, when connecting strain gauges in two full bridges with a four-wire connection scheme, as shown in Fig. 8, and with further signal processing, according to expression (6), will provide simultaneous measurement of vertical and lateral forces acting on the subway car bogie frame. This makes it possible to determine with sufficient accuracy the values of vertical and horizontal dynamics coefficient, and reduce the number of strain gauges to determine the indicators of dynamic properties of the subway car during the running dynamic tests.

Testing of a new measuring scheme for determining the vertical and lateral forces acting on the subway car bogie frame

The proposed measuring scheme was tested during the running tests to assess the dynamic qualities of the intermediate non-motor subway car model 81-714 Uz manufactured by JSC “TashVSRZ” on the Chilanzar line of the Tashkent subway.
Before the tests, strain gauges were installed on the side longitudinal beams of the bogie frame closest to the head car of the subway, according to the scheme discussed in Fig. 6, and connected to the measuring bridges according to Fig. 8.

The placement of strain gauges on the bogie frame of intermediate non-motor subway car model 81-714 Uz is shown in Fig. 9.

![Fig. 9. Locations of strain gauges and their connection on the bogie frame of the transition type non-motor subway car of the model 81-714 Uz.](image)

The constant scale factors for measuring vertical and horizontal forces were determined by gradual lifting and lowering of the car body through a dynamometer, installed between the heel and the car footplate (Fig. 10).

![Fig. 10. The process of calibrating measuring schemes by gradually raising and lowering the subway car body with jacks.](image)

To determine the experimental dependences between the readings of the measuring schemes and the acting forces, the graded loading of the subway car bogie frame was carried out. An example of the oscillogram of deformations in the process of loading and unloading the subway car bogie frame, registered by the new measuring scheme is shown in Fig. 11.
In the course of running tests vertical and lateral forces acting on the subway car bogie frame were measured and recorded. The dynamic properties of the subway car were assessed in empty and loaded modes over the entire range of operating speeds, every 10–20 km/h up to the design speed.

Graphs of continuous registration of the coefficients of vertical dynamics of the first stage of spring suspension and horizontal dynamics, recorded by the new measuring scheme as an outcome of the running tests to assess the dynamic qualities of the subway intermediate non-motorized car model 81-714 Uz are shown in Fig.s 12-13.

**Fig. 11.** Oscillogram of the loading and unloading process of a subway car bogie frame.

**Fig. 12.** 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. 12. 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. 13. 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 outcomes of the conducted running tests to assess the dynamic qualities of intermediate non-motor subway car model 81-714 Uz confirmed the effectiveness of the developed measuring scheme to determine the vertical and lateral forces acting on the subway car bogie frame.

5 Conclusion

The work included a set of studies and the development, theoretical justification, and validation of a new measuring scheme for determining the indicators of vertical and horizontal dynamics of a subway car during the running dynamic tests.

It is found that the most promising is the determination of vertical and lateral forces, by which the indicators of 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.

It is determined that the new measuring circuit when the strain gauges are connected in two full bridges with a four-wire connection scheme will provide simultaneous measurement of vertical and lateral forces acting on the subway car bogie frame. This will make it possible to exclude the influence of horizontal forces on the bogie when determining vertical forces, and the influence of vertical and longitudinal forces when determining lateral forces.

The running tests to assess the dynamic qualities of an intermediate non-motor subway car model 81-714Uz confirmed the effectiveness of the developed measuring scheme to determine 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 vertical and horizontal dynamics of a subway car, which will allow to determine with sufficient accuracy the values of vertical and lateral forces acting on the bogie frame and reduce the number of strain gauges to determine the indicators of dynamic qualities of the car during the running dynamic tests.

References


