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Research into the track/vehicle interaction processes for underground railways

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Abstract. The article deals with determination of dynamic forces in interaction between a rail vehicle and underground track for working out recommendations in terms of a longer service life of the permanent track without extra charges. The issue is of importance for enterprises under limited resources. The research was conducted with mathematical model methods for the vehicle/track dynamic system (the principles were developed earlier), as the experimental work in the underground tunnels was complicated by intensive train traffic during a day. A special feature of the research was consideration of a rail as a bar rested on discrete elastic-dissipative supports in a design diagram of the vehicle/track dynamic system. Thus, the authors established the effects of unequal elasticity of the track rail support on the value of vertical dynamic forces when a metro coach moves on the track. In particular, the dependencies of dynamic factors and amplitude ratios of vertical forces on speeds of metro coaches along the discrete elastic- dissipative track were obtained. An exceptional value of the research is consideration of both vertical and horizontal lateral forces on the vehicle/track interaction. It allowed the authors to define the value of vertical and horizontal lateral forces which occurred when metro coaches moved along straight and curved sections of the track according to the speed and curve radius.

1. Introduction

The underground railway is a kind of urban public transport providing regular, safe and reasonably-priced services which favorably differs it from other types of city transport.

The research into the track/vehicle interaction was conducted in the Kharkiv Metro. It operates a continuous welded rail track on wooden ties with “Metro” fastenings. The wooden sleepers are grouted in track concrete. Specialized and reference literature provide few research on the forces acting on the track, especially in underground systems.

The analysis of the design standards for underground tracks and technical characteristics of the rolling stock makes it possible to establish the basic factors which affect the stressed state and

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operational life of rails in the Kharkiv Metro. Among such factors are a great number of small-radius curves on the Kharkiv Metro lines. The minimal radius of the curves is 300 meters, which accounts for 0.7% out of the total number. Considerable horizontal lateral forces in the curved sections lead to both rail wear and development of contact fatigue defects.

Besides, metro coaches must transfer a great number of passengers and function properly under harsh conditions; they operate in the conditions of highly-intensive traffic. Therefore, they should meet strict requirements for safety and efficiency.

A more efficient use of permanent track elements can be achieved through the research into a longer service life of the track without extra charges and under limited resources. The article is aimed at finding solution to the problem.

The development of recommendations for more efficient use of tracks in underground systems under limited resources requires research into the vehicle/track interaction with consideration of horizontal lateral forces.

Experiments conducted on metro tracks were complicated by heavy traffic throughout a day. Besides, the current requirements for safety have considerably complicated the managerial procedures for such research.

The objective is investigation into the vehicle/track interaction for revealing the actual operational life of rails under various operational conditions with consideration of horizontal lateral forces. It is needed for implementation of recommendations for higher service operational life of the metro track systems.

A great many studies deal with dynamic processes between the vehicle and the track on railways of various purposes: [1-7] and others. However they do not provide research for metro lines, though movement on these lines is of special character.

Study [8] presents characteristics of metro tracks which operate on the territory of CIS, parameters of a vertical modulus of elasticity of the track, and also characteristics of rail rigidity under horizontal lateral forces. But a level of vertical and horizontal lateral forces of the rail/vehicle interaction was not defined. The level of vertical dynamic forces was only studied in a range of 90-92 kN [9-12].

2. Main part

The level of forces on the rail from the vehicle was analyzed with consideration of many factors being just components which directly or indirectly effect the interaction. In order to evaluate how the factor influences the rail damageability in the track profile curvature, and horizontal lateral forces in the Kharkiv Metro, the authors processed the statistical observation data on removal of rails and findings obtained from the research into horizontal lateral forces. The correlation coefficient was taken as the criterion of impact factor [13].

Besides, the authors researched an impact of basic types of metro coaches on the track. The basis of this research was a mathematical model of the spatial dynamic vehicle/track system [11]. It should also be mentioned that the model considered the vehicle and the track as a single spatial design system.

And multiple-variant calculations for some selected test track sections were conducted. The following factors were taken as the basic design data:

- metro coaches of the types Eg3, Em-508T,81-718, 81-719 and 81-717, 81-714 of a speed of up to 80 km/h;
- R50 rails, the basic model for metro lines (rail characteristics, inertia moments, resistance moments and cross-sections varied according to the rail wear);
- 100-150-meter straight sections;
- 50-100-metre circular curves (transition curve length and cants in circular curves were taken according to the current standards, respectively [12]).

The following track characteristics were taken as variables:

- radii of circular curves from 200 to 600 meters;
- length of vertical irregularities from 2 to 25 meters;
- depth of vertical irregularities from 0.05 to 0.010 meters;

- length of horizontal irregularities from 1 to 8 meters;
- versine of horizontal irregularities from 0.03 to 0.09 meters;
- track operational life from 0 to 15 years.

The following steps were taken to approach the real operational conditions for the research:

1. The different places for vertical and horizontal irregularities along a test section were chosen, and irregularities in a straight, transition and circular curves were considered.

2. Spatial rigidities and reduced equivalent dissipations of rail supports were taken in accordance with the track operation life.

Thus, the authors conducted calculations of over 100 variants of the metro coach/track interaction of various characteristics.

The general analysis of dependencies of changes in vertical and horizontal lateral forces on the track from metro coaches on the operational metro track parameters is presented below.

Vertical forces. As long as vertical forces on the track from metro coaches are constantly changing in motion, it is more convenient and informative to use dynamic factors and amplitude ratios rather than their absolute values for the comparative analysis. And the dynamic factor was taken as a ratio of maximum vertical dynamic forces occurred in motion to the static wheel load value:

$$Kd = \frac{P_{\max}}{P_{st}}\ , \tag{1}$$

where K_d – the dynamic factor;

P_{max} – the maximum vertical forces;

P_{st} – static wheel load.

But in motion the vertical forces may be greater of lower than the static values; therefore the amplitude ratio was applied for evaluation (2):

$$K_a = \frac{P_{\max dyn}}{P_{\min dyn}}\ . \tag{2}$$

where K_a – the amplitude ratio;

$P_{\ max\ dyn}$ – the maximum vertical dynamic forces;

$P_{\ min\ dyn}$ – the minimal vertical dynamic forces.

It should be mentioned that the design research diagram considered a rail as a bar rested on the solid elastic foundation. Therefore, for dynamic analysis of the vehicle/track interaction in a vertical plane at constant motion along a straight section without irregularities, the dynamic factor and amplitude ratio were equal to 1. However, the actual vertical forces are constantly changing and these coefficients considerably differ from 1. Figure 1 presents the chart of vertical forces on the rail from the wheel. The data were obtained in calculation for metro coaches Eg3 and 81-718 at a speed of 60 km/h. The X-coordinate presents the distance covered by the coaches and the Y-coordinate presents the vertical forces. In the example the spatial rigidity values of the rail supports were taken constant.

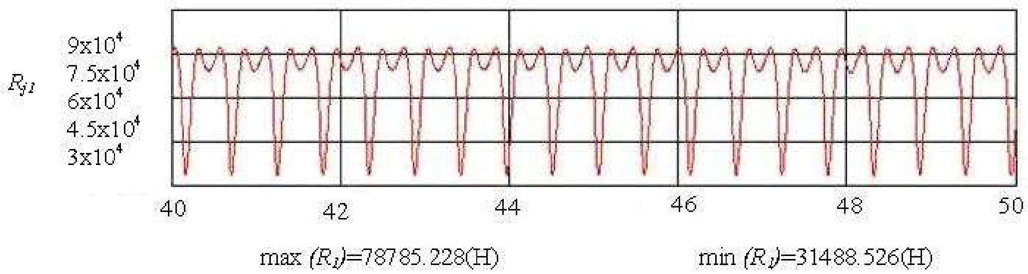

Figure 1. Diagram of vertical forces for metro coaches 81-718 in motion along a straight line with a speed of 60 km/h

Figure 2 and 3 present diagrams of dependencies of dynamic factors (Figure 2) and amplitude ratios (Figure 3) on the speed for various operational periods for the track (0 and 10 years). When speeds changed from 10 to 80 km/h the dynamic factor changed from 1.01-1.014 to 1.072-1.081.

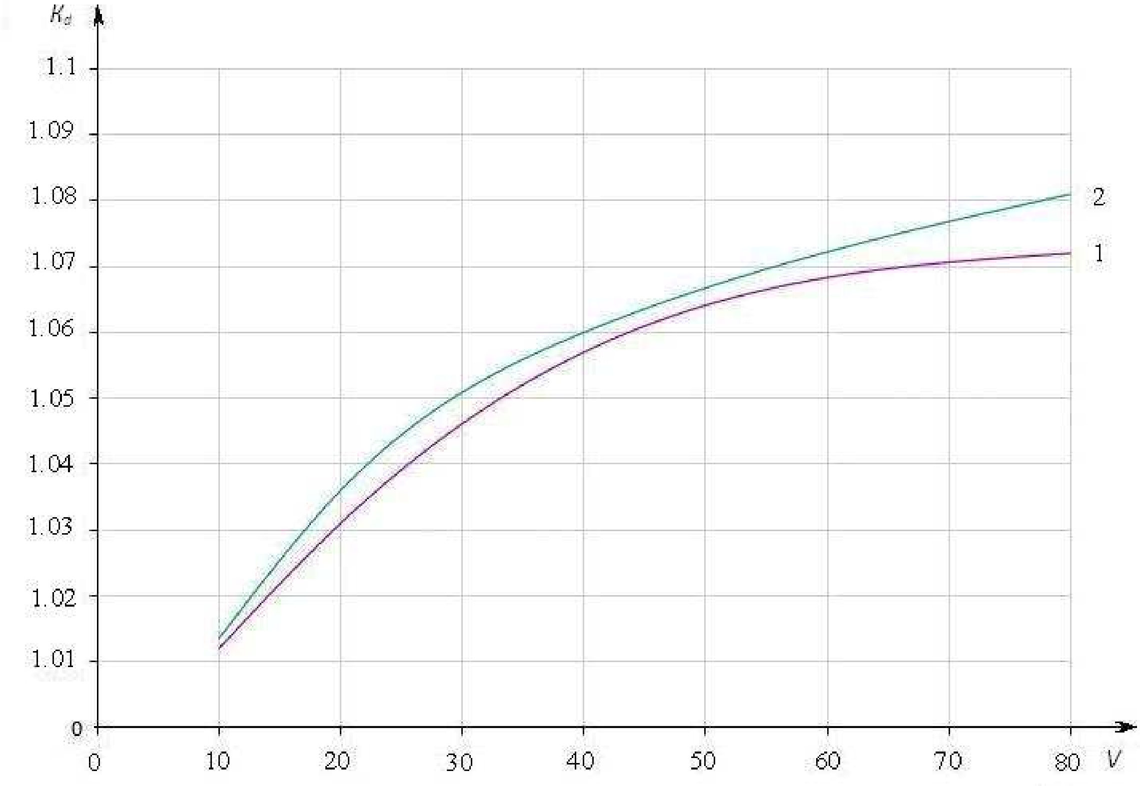

Figure 2. Diagram of the dynamic factor–speed dependency:
1 – K_d at top.l.= 0; 2 – K_d at top.l. =10 years.

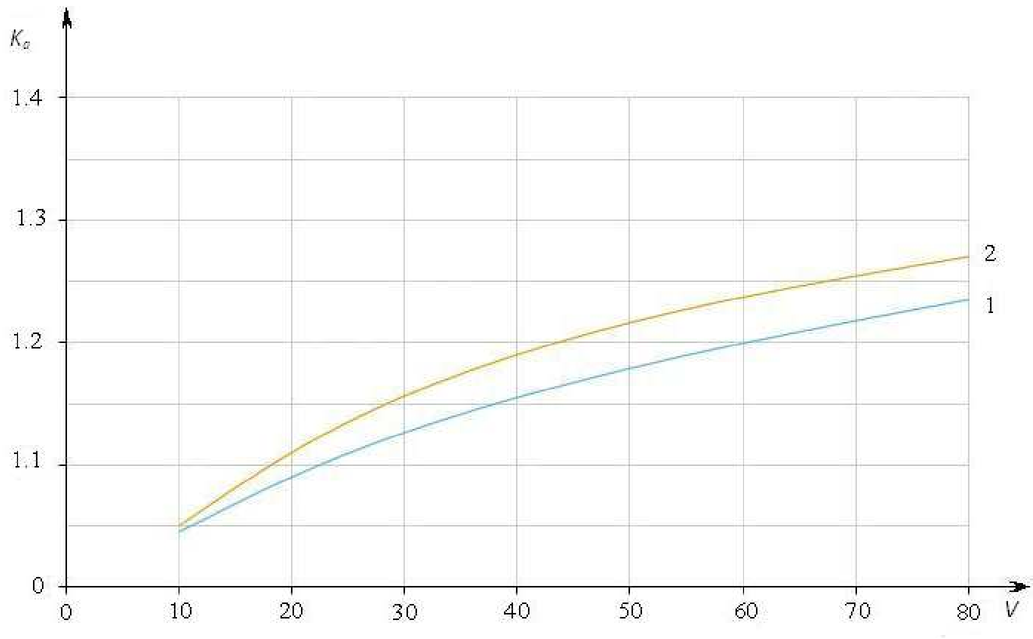

Figure 3. Diagram of the amplitude factors–speed dependency:
1 – K_a at top.l. = 0; 2 – K_a at top. l = 10 years.

The amplitude factor values were from 1.05 to 1.24-1.26. The operational track life affected the dynamic factors and amplitude ratios by 15-20%.

The unequal elasticity of rail supports put into calculations considerably affected the interaction processes. Thus, at a speed of 60 km/h a change in the unequal elasticity factor (K_{uneq}) from 1.0 to 1.2 led to an increase in dynamic factors from 1.15 to 1.23 (Figure 4).

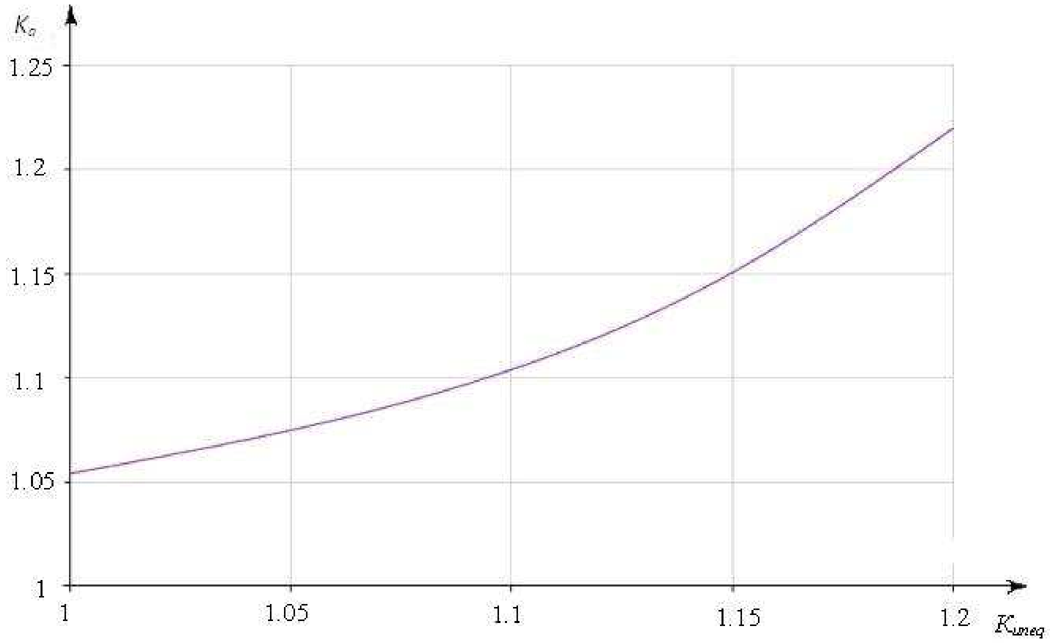

Figure 4. Diagrams of dependencies of amplitude ratios on non-equal elasticity of rail supports in motion along curved sections at a speed of 60 km/h

In metro systems the vertical dynamic forces are mostly affected by isolated profile irregularities of up to 6 meters. Figure 5 and 6 present diagrams of dynamic factors and amplitude ratios along vertical isolated irregularities of the length 2 and 4 meters.

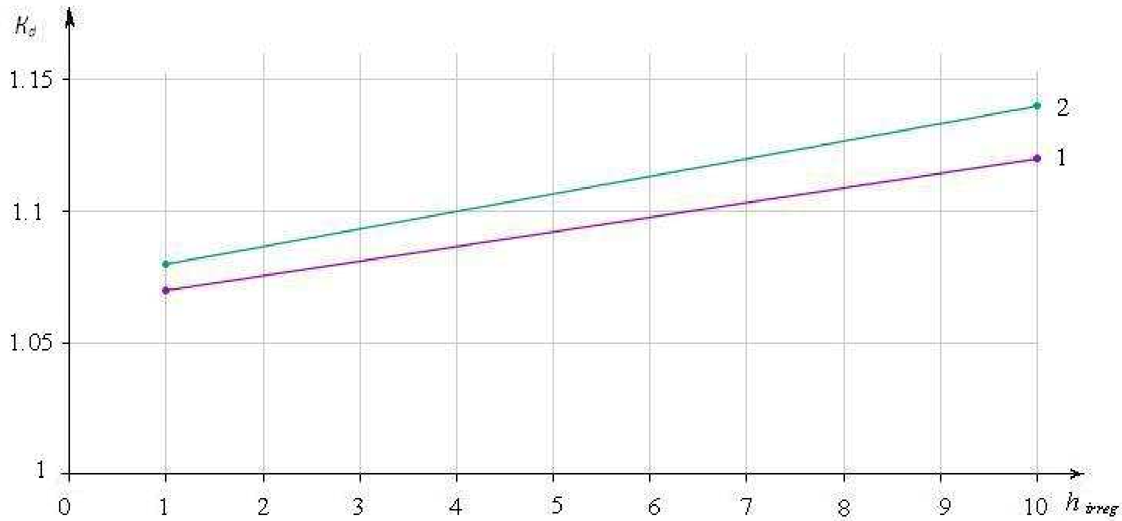

Figure 5. Diagram of dynamic factors at vertical isolated irregularities of the length lirreg = 2 and 4 m: 1 - K_d at l_{irreg} =4 m; 2 - K_d at l_{irreg}. =2 m.

where h_{irreg} – the irregularity depth on the track.

To determine the influence of an irregularity depth on the impact dynamics of a vehicle on the track, the non-equal elasticity factor of rail supports was taken equal to 1.

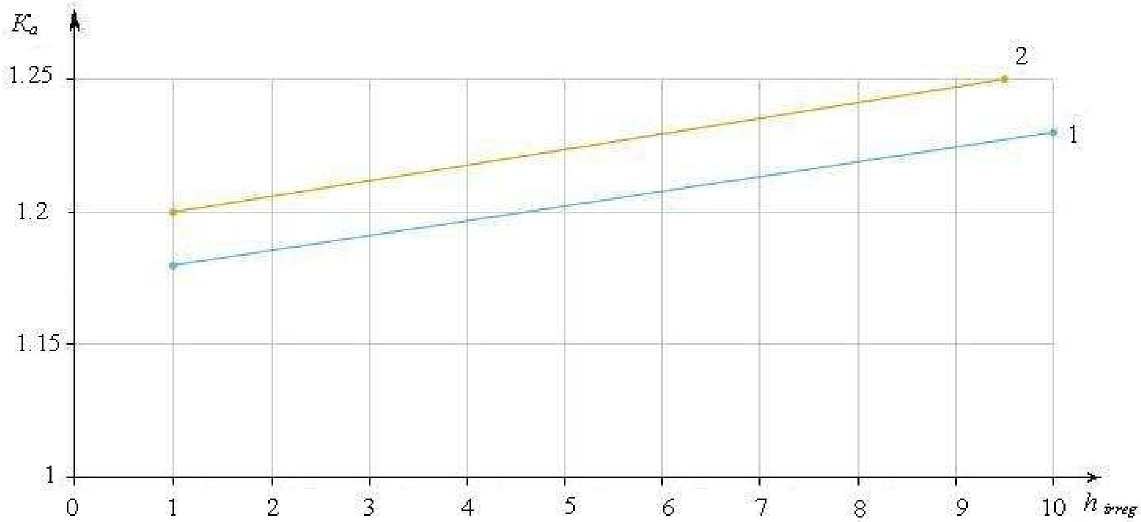

Figure 6. Diagram of amplitude ratios at vertical isolated irregularities of 2 and 4 meter long: 1 - K_a at $l_{irreg.}$ = 4 m; 2 - K_a at $l_{irreg.}$ = 2 m.

At a speed of 60 km/h on a straight section with vertical isolated irregularities of 2 and 4 meter long, the dynamic factor reached values of 1.123 and 1.129 according to an irregularity depth.

The amplitude ratio is 1.235-1.28. When the non-equality of rail supports put into calculation, the dynamic factors increased by 12-20% and amplitude ratios – by 8-17%.

Horizontal lateral forces. The authors studied a level of horizontal lateral forces on the track from the first wheelset (in the direction of travel) on the section with a 50-m straight segment, transition curve, circular curve of the 400-m radius and 120-mm cant. Figure 7 gives a diagram of horizontal lateral forces on the track. The speed in the research was taken 80, 60 and 40 km/h. The maximum horizontal lateral forces were in a range from 4.57 to 9.89 kN.

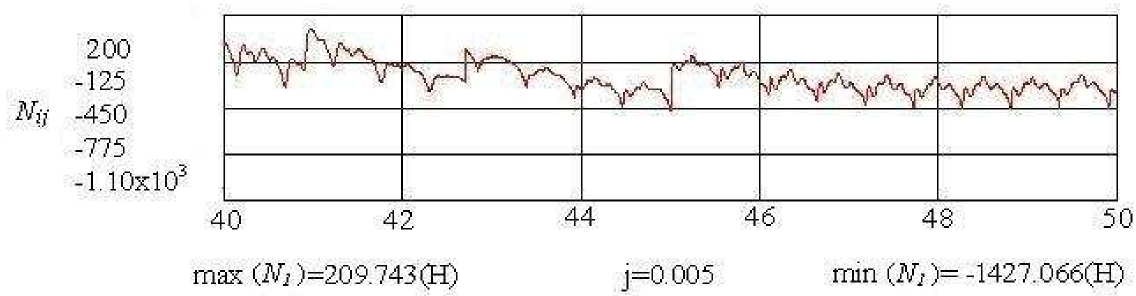

Figure 7. Diagram of horizontal lateral forces on the track.

Figure 8 presents diagrams of dependencies of horizontal lateral forces on speeds along the circular curves without irregularities.

The level of horizontal lateral forces at speeds in metro systems was in a range from 0.29 to 11.183 kN.

As an example, Figure 9 shows a diagram of horizontal lateral forces for a wheelset in motion on isolated profile irregularities of 4 meters long.

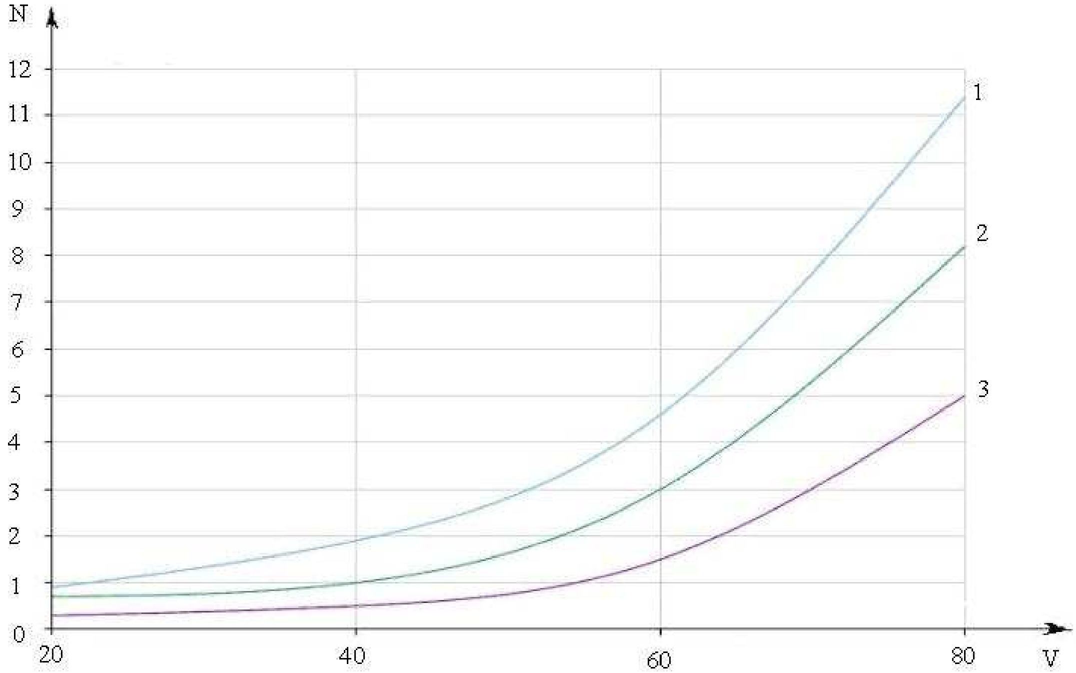

Figure 8. Diagram of dependency of horizontal lateral forces on speeds in curves:
1 - R=400 m, h=120 mm; 2 - R=600 m, h=120mm; 3 - R=800 m, h=120mm.

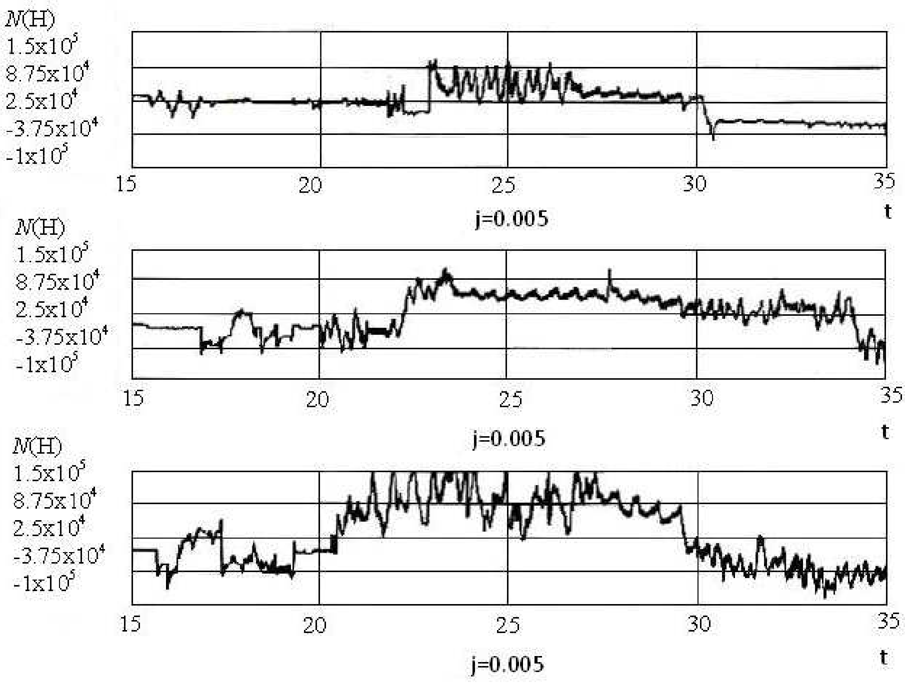

Figure 9. Diagram of horizontal lateral forces for the metro coach Еж-3 in motion along a horizontal irregularity 4 m long in a straight section at a speed of 60 km/h:
1 – versine – 3mm; 2 – versine – 6mm; 3 – versine – 9mm.

Dependencies of the horizontal lateral forces on the amplitude of horizontal irregularities of 2 and 4 meters are given in Figure 10. The curve radius was taken equal to 400 m. When a speed changed from 40 to 80 km/h the horizontal lateral forces achieved values of 12.5-14.8 kN according to the amplitude and irregularity length.

The research demonstrated that the vertical and horizontal lateral forces as well as stresses in the rail changed according to the curve radius in the sections. And the highest design values of the horizontal lateral forces were achieved in curved sections with R=400. These sections are affected by the greatest stresses. They were followed by curves of the radius 600 m.

3. Conclusions

Application of a design diagram of a bar on multiple elastic-dissipative supports made it possible to establish the influence of non-equal elasticity of the rail foundation on the value of vertical dynamic forces for metro systems in motion.

1. The authors obtained dependencies of dynamic factors and amplitude ratios of the vertical forces on the speed of metro coaches along the discrete elastic-dissipative track. It has been established that discrete character and non-equal elasticity of rail supports lead to appearance of dynamic forces exceeding the static vertical load by 1.2 times. The vertical track irregularities increase the values of vertical dynamic forces by 1.08-1.15 times.

2. The authors conducted a multiple-variant calculation of interaction forces for metro coaches. The vertical and horizontal lateral forces for metro coaches moving along straight and curved lines at various speeds were defined. They also studied impact of curve radii, vertical and horizontal irregularities, and operational life periods.

3. And for the first time a level of horizontal lateral forces in metro systems was validated; and the effects of discrete character of non-equal elastic supports and track irregularity were established. Besides, it was established that for metro systems there can appear horizontal lateral forces of up to 12.5-14.8 kN.

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