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Research of the impact of geometric unevenness of the railway track on the dynamic parameters of the railway rolling stock with two-stage spring suspension

A Kuzyshyn[1,4], S Kostritsa[1], L Ursulyak[1], A Batig[2], J Sobolevska[3] and O Voznyak[3]

[1] Dniprovsk National University of Railway Transport named after Academician V. Lazaryan, 49000 Dnieper, Ukraine
[2] Lviv Research Institute of Forensic Expertise, 79000 Lviv, Ukraine
[3] Lviv branch of Dniprovsk National University of Railway Transport named after Academician V. Lazaryan, 79052 Lviv, Ukraine

[4] E-mail: kuzyshyn1993@gmail.com

Abstract. The paper studies the possibility of using previously developed by the authors spatial mathematical model of the modern diesel train DPKr-2 for parameters determination, with the help of which the dynamic properties of the mechanical part are evaluated. The dependences of maximum accelerations of the body in the vertical and horizontal planes, the coefficients of vertical and horizontal dynamics both in the primary and in the secondary suspension on the speed of the car movement, the amplitude and the length of geometrical unevenness of the railway track were obtained. It is established at what speeds, depending on the parameters of geometrical unevenness of the railway track, the phenomenon of resonance and danger for the diesel train car movement appears. For a particular length of geometrical unevenness, the maximum permissible value of its amplitude over the entire range of speed movement, where the coefficients of vertical and horizontal dynamics in the primary suspension do not exceed permissible limits, has been studied. The adequacy of the mathematical model is checked by comparing the results obtained during calculations with the experimental ones.

1. Introduction

The study of the processes of interaction between the track and the railway rolling stock began with the birth of the railway engineering, since the results of this type of research were needed to create a new railway rolling stock and a track, setting standards for their maintenance and repair rules.

Practical needs demanded the immediate study and solution of interrelated tasks such as:

- studying the data and characteristics of the railway rolling stock and tracks during train movement;
- studying the magnitude and direction of the forces that arise between the rails and the wheels of the car, separate structural elements of the railway rolling stock;
- studying deformations, necessary structural dimensions of the elements of the track and the railway rolling stock, requirements for materials manufacture that provide sufficient strength, durability and reliability in operation.

The use of railway rolling stock is allowed only in case when the acceptable level of dynamic characteristics is ensured throughout its lifetime.

On the domestic railways the following indices of dynamic qualities are adopted:

- indices that assess the dynamic properties of the mechanical part;
- traffic safety indices.

The main indices that assess the dynamic properties of the mechanical part of the railway rolling stock are:

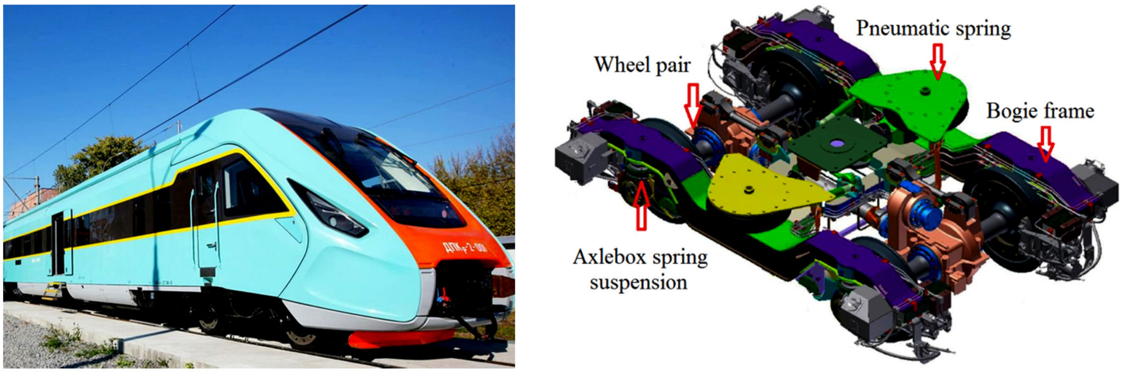
- maximum acceleration of the body both in the vertical and in the horizontal plane;
- coefficients of vertical and horizontal dynamics of the primary and the secondary suspension.

At present, the modern diesel train DPKr-2, which is intended for provision of commuter passenger traffic, is gradually being put into operation on the territory of Ukraine.

The peculiarity of this diesel train is the presence of the two-stage spring suspension (figure 1):

- primary – with the use of cylindrical springs;
- secondary – with the use of pneumatic springs.

To ensure its safe operation, "Branch Research Laboratory of Railway rolling stock Dynamics and Strength" of Dniprovsky National University of Railway Transport named after Academician V. Lazaryan tested the train to determine the main indicators of the dynamic qualities of its mechanical part.



(a) (b)

Figure 1. Diesel train DPKr-2: (a) general form of the train; (b) the main units of the bogie of the diesel train car DPKr-2.

It should be noted that the unevenness of railway lines is a source of forced fluctuations in the above spring structure of the freight car, which ultimately causes dynamic loads on the elements of the structure of the railway rolling stock and the railway track. This leads to an increased impact of the railway rolling stock on the track and, finally, to its derailment.

Studying the impact of a rail track geometric unevenness in the trail dynamics is not possible without the knowledge of the unevenness parameters, like its size, form, spectral properties, etc. Moreover, rail track geometry is subjected to deterioration during the track lifecycle. The most intensive deterioration usually takes place in high loaded parts of the track: railway turnouts and transition zones of engineering structures. The modelling of the track and turnout geometric unevenness during its lifecycle is presented in studies [1-2]. An intensive deterioration of track geometry after tamping works is studied in [3]. The impact interaction of a wheel and rails in the zone of common crossings during the lifecycle of turnouts is presented in experimental studies [4-6]. The studies demonstrate a significant variation in geometric unevenness and dynamic interaction depending on the track condition.

However, theoretical studies of diesel train DPKr-2 carriage for determining its basic parameters and assessing the dynamic properties of the mechanical part, namely, the maximum accelerations of the body, the coefficients of vertical and horizontal dynamics depending on the speed of motion and the parameters of geometric unevenness of the track have not been carried out. It should also be noted that the solution to this problem must be carried out with the help of computer simulation methods, which will allow for a more accurate assessment of railway transport safety [7-9].

The research of safety indicators of modern diesel-train DPKr-2 is a separate task that is considered and solved in works [10-11].

Therefore, to ensure traffic safety under different operating conditions, it is relevant to determine the indices that assess the dynamic properties of the railway rolling stock.

2. Purpose and objectives of the research

The purpose of the present study is to determine the indices that estimate the dynamic properties of the mechanical part of the modern diesel-train DPKr-2.

To achieve this goal, the following tasks must be solved:

- construct dependences of the maximum accelerations of the body in the vertical and horizontal plane, the coefficients of vertical and horizontal dynamics both in the primary and in the secondary suspension on the speed, amplitude and length of geometrical unevenness of the track;
- establish at which velocities of motion, depending on the parameters of geometric unevenness of the railway, the phenomenon of resonance and the danger for diesel train DPKr-2 carriage movement starts to occur;
- study the adequacy of the mathematical model by comparing results obtained through calculations with experimental ones.

3. Mathematical model for determining dynamic parameters

To determine the dynamic characteristics that are included in the indices, with help of which the dynamic properties of the mechanical part of the diesel train are estimated, analysis of the car design and its spatial mechanical model should be carried out [12].

The spatial mechanical model consists of 7 solids (body, two bogies, four wheel pairs), connected together by elastic-dissipative joints.

The spatial mathematical model, consisting of 30 differential equations of the second order, was obtained for describing diesel train car fluctuations [13].

The peculiarity of the mathematical model is the possibility of taking into account longitudinal and transverse forces of the creep that arise at the point of interaction between working surfaces of the wheel and the rail [14–16].

At each instant of time, by means of integrating the differential equations of motion, the values of all generalized coordinates were determined, which made it possible to find necessary values for calculating the parameters, such as forces in the primary and in the secondary suspension, frame forces, etc.

The maximum acceleration of the body both in the vertical and horizontal plane characterizes dynamic forces that act on the equipment of the car. To find them, the following equations were used:

$$\ddot{z}_k = \left(-4\beta_{21}\dot{z}_k - 4\beta_2\dot{z}_k - 4s_{21}z_k + 2s_{21}z_{b1} + 2s_{21}z_{b2} + 2\beta_{21}\dot{z}_{b1} + 2\beta_{21}\dot{z}_{b2} + 2\beta_2\dot{z}_{b1} + 2\beta_2\dot{z}_{b2}\right)/m_k \quad (1)$$

$$\ddot{y}_k = \frac{1}{m_k}\Big[-4s_{2\text{pt}}\left(y_k + a_5\theta_k\right) - 4\beta_{2\text{pt}}\left(\dot{y}_k + a_5\dot{\theta}_k\right) + 2s_{2\text{pt}}\left(y_{b1} - a_6\theta_{b1}\right) +$$
$$+ 2s_{2\text{pt}}\left(y_{b2} - a_6\theta_{b2}\right) + 2\beta_{2\text{pt}}\left(\dot{y}_{b1} - a_6\dot{\theta}_{b1}\right) + 2\beta_{2\text{pt}}\left(\dot{y}_{b2} - a_6\dot{\theta}_{b2}\right)\Big] \quad (2)$$

where s_{21} is equivalent stiffness of the pneumatic spring, kN/m; $s_{2\text{pt}}$ – horizontal stiffness of the pneumatic spring in the transverse direction, kN/m; β_{21} – equivalent coefficient of attenuation determined by the flow of air through the throttle, (kN·sec)/m; β_2 – damping coefficient of the vertical hydraulic quencher in the secondary suspension, (kN·sec)/m; $z_{\text{b}1,2}$, $y_{\text{b}1,2}$, $\theta_{\text{b}1,2}$, z_k, y_k – generalized coordinates of the diesel train movement obtained through calculations of the spatial mathematical model, m and radian; a_5, a_6 – linear parameters, m; m_k – body weight, tone.

The coefficients of vertical $K_{\text{d}}^{\text{ver}}$ and horizontal $K_{\text{d}}^{\text{hor}}$ dynamics can be determined on the basis of deflections Δ or forces F that arise in a separate set of spring hanging:

$$K_{\text{d}}^{\text{ver}} = \Delta_{\text{d}}^{\text{ver}} / \Delta_{\text{st}} = F_{\text{d}}^{\text{ver}} / F_{\text{st}} \qquad K_{\text{d}}^{\text{hor}} = \Delta_{\text{d}}^{\text{hor}} / \Delta_{\text{st}} = F_{\text{d}}^{\text{hor}} / F_{\text{st}} \tag{3}$$

The dynamic index corresponds to the lower index of "d", statics – "st". Vertical deflections are forces that have upper index "ver", horizontal – "hor".

The coefficients of vertical and horizontal dynamics in the primary suspension are determined:

$$K_{\text{d c.b.}}^{\text{ver}} = \left(z_{\text{b}j} \pm a_1\varphi_{\text{yb}j} \mp a_4\theta_{\text{b}j}\right) - \left(z_{\text{w.p.}i} \mp a_4\theta_{\text{w.p.}i}\right) / \Delta_{\text{st}} \tag{4}$$

$$K_{\text{d c.b.}}^{\text{hor}} = \left(y_{\text{b}j} \pm a_1\psi_{\text{b}j} - y_{\text{w.p.}i}\right) / \Delta_{\text{st}} \tag{5}$$

The coefficients of vertical dynamics in the secondary suspension are determined:

$$K_{\text{d k.}}^{\text{ver}} = \left(z_{\text{k}} \pm a_2\varphi_{y\text{k}} \mp a_3\theta_{\text{k}}\right) - \left(z_{\text{b}j} \mp a_3\theta_{\text{b}j}\right) / \Delta_{\text{st}} \tag{6}$$

In the paper [1-2] the quantitative distribution of various types of unevenness that occur on the railway track during railway rolling stock operation is presented, where the most common types are sinusoidal geometric unevenness. This type of unevenness makes up 60% of all other types of unevenness that are on the railroad tracks. Thus, in this work, sinusoidal geometric unevenness of the left and right rails was taken as perturbations both in the vertical and in the horizontal plane, which were determined by the formulas:

$$\eta_{\text{ver}} = H_{\text{ver}} \cdot \sin\left[2\pi vt / L_{\text{ver}}\right] \qquad \eta_{\text{hor}} = H_{\text{hor}} \cdot \sin\left[2\pi vt / L_{\text{hor}}\right] \tag{7}$$

where H_{ver}, H_{hor} are amplitude of vertical and horizontal unevenness, mm; L_{ver}, L_{hor} – length of vertical and horizontal unevenness, m; v – speed of movement, m/sec; t – time, sec.

It should be noted that according to regulatory norms used in Ukraine [17]:

- for the first degree of spring hanging:
- – the coefficient of vertical dynamics should not exceed 0.35;
- – the coefficient of horizontal dynamic – 0.3.
- for the second degree of spring hanging:
- – the coefficient of vertical dynamics should not exceed 0.25;
- – maximum acceleration in the vertical plane in fractions g should not be more than 0.25;
- – maximum accelerations in the horizontal plane in fractions g should not be more than 0.15.

According to European standards BS EN 14363: 2005 [18]:

- for the first degree of spring hanging:
- – the wheel unloading coefficient of the wheel coupling must not exceed 0.6;
- for the second degree of spring hanging:
- – maximum acceleration in the vertical plane should not be more than 3 m/s^2;
- – maximum acceleration in the horizontal plane should not be more than 3 m/s^2.

Comparing the level of admissible values that assess the dynamic properties of the mechanical part of the railway rolling stock, it can be concluded that the requirements of Ukrainian regulatory norms are more rigorous than the requirements according to the norms of European Union countries.

After calculating the mathematical model, we construct and analyse the dependences of the maximum accelerations of the body in the vertical and horizontal planes, the coefficients of vertical and horizontal dynamics both in the primary and in the secondary suspension on the speed of a car, the amplitude and the length of geometrical unevenness of the railway track (figures 2 – 5).

Analysing the results (figure 2) it can be stated that with the increase of the velocity of motion at any length of geometrical unevenness, the coefficients of vertical dynamics in the primary and in the secondary suspension increase at first and then fall for specific speed ranges.

The maximum value of the coefficient of vertical dynamics is observed when the frequencies of its own and forced oscillations coincide. For example, with the length of geometrical unevenness of the track for 20 m, the maximum value of the coefficient of vertical dynamics occurs at the speed of 35 m/s.

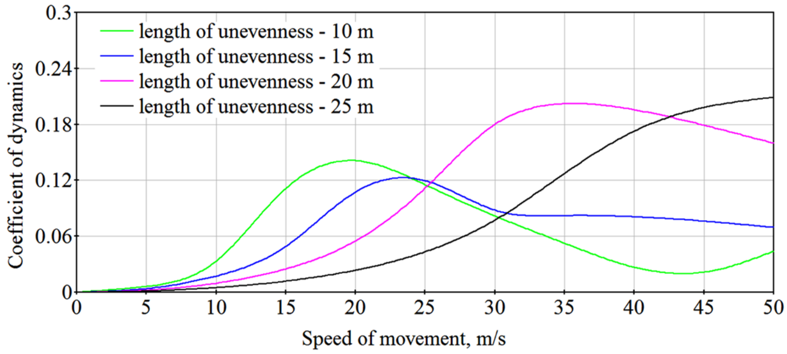


Figure 2. The dependences of the coefficients of vertical dynamics in the primary suspension on the speed of motion and the length of geometrical unevenness.

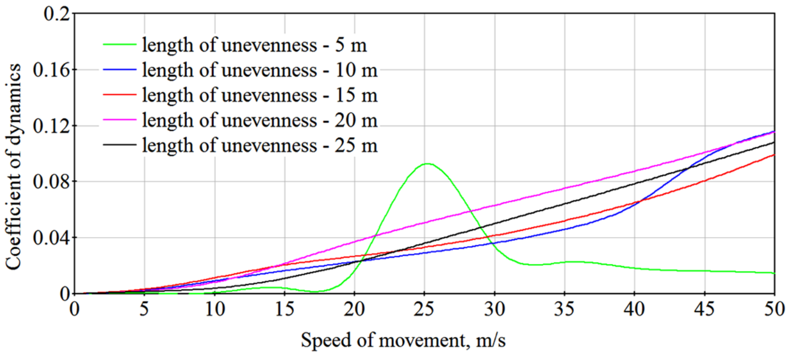


Figure 3. The dependences of the coefficients of horizontal dynamics in the primary suspension on the velocity of movement and the length of geometrical unevenness.

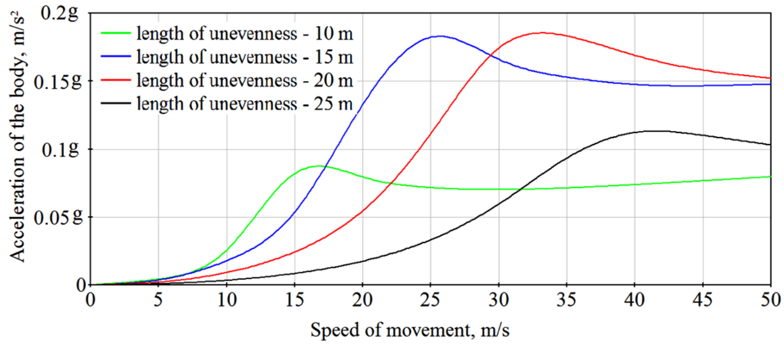


Figure 4. The dependences of maximum accelerations of the body in the vertical plane on the velocity and the length of geometrical unevenness.

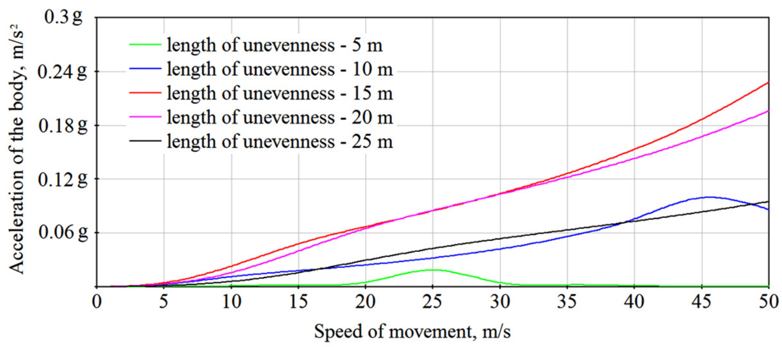


Figure 5. The dependences of maximum accelerations of the body in the horizontal plane on the velocity and the length of geometrical unevenness.

As can be seen from, with reduced geometrical unevenness the maximum value of the vertical dynamics coefficient will be shifted on figure 2-3 towards speeds decreasing. Since the frequency is directly proportional to the velocity of motion and is inversely proportional to the length of unevenness. Thus, for resonance appearance under condition of unevenness length decrease, a lower velocity of motion is required.

The analysis (figure 3) showed that the phenomena, which are characteristic for vertical dynamics, are observed for horizontal ones too. However, it should be noted that the stiffness of elements that connect solids of the spacious mechanical model in the horizontal plane is greater than the one in the vertical plane. Therefore, the resonance phenomenon will occur at higher frequencies, which make up about 5 Hz. For example, with geometrical unevenness of 5 m, the maximum value of the horizontal dynamics coefficient rises at the speed of 25 m/s. With the increase of the length of unevenness, the resonance zone will deviate towards the increase of speeds of motion and may not fall into the range of operating speeds.

The analysis of the results in figures 4 and 5 shows that the character of changes in the maximum accelerations of the body in both the vertical and horizontal planes is similar only in the other range of their changes.

The obtained dependencies of the coefficients of vertical and horizontal dynamics will further allow us to assess the safety of motion against wheel derailment [19–20].

Let us turn to the determination of the maximum allowable velocity of diesel train DPKr-2 carriage depending on the state of the railway track. According to paper [21], the state of the track is estimated by the degree of deviations from the standards of maintenance in terms of width, level and plan. There are five degrees for all deviations from the regulatory norms of track maintenance depending on their size and length.

On the basis of the analysis of the main dynamic factors of the diesel train carriage, obtained as a result of calculations, the maximum allowed speed of diesel train-DPKr-2 carriage was established, depending on the deviations on the level, including smoothness deviations, as well as distortions (deviations on a length of up to 20 m) (table 1).

These studies can be used in the analysis of traffic safety and in conducting forensic rail-transport expertise.

Table 1. Permissible speed of diesel-train DPKr-2 movement depending on the deviations on the level.

<table>
<tr><th>Degree of deviation</th><th>Smoothness deviations, mm</th><th>Allowable speed obtained as a result of calculations, km/h</th><th>Deviation on the length of up to 20 m, mm</th><th>Allowable speed obtained as a result of calculations, km/h</th></tr>
<tr><td>I</td><td>up to 6 including</td><td rowspan="3">180</td><td>up to 8 including</td><td rowspan="3">180</td></tr>
<tr><td>II</td><td>over 6 up to 12 including</td><td>over 8 up to 12 including</td></tr>
<tr><td>III</td><td>over 12 up to 20 including</td><td>over 12 up to 16 including</td></tr>
<tr><td>IV</td><td>over 20 up to 25 including</td><td>120</td><td>over 16 up to 20 including</td><td>150</td></tr>
<tr><td rowspan="4">V</td><td>over 25 up to 30 including</td><td>110</td><td>over 20 up to 30 including</td><td>105</td></tr>
<tr><td>over 30 up to 35 including</td><td>75</td><td>over 30 up to 40 including</td><td>55</td></tr>
<tr><td>over 35 up to 50 including</td><td>15</td><td>over 40 up to 50 including</td><td>movement stops</td></tr>
<tr><td>over 50</td><td>movement stops</td><td>over 50</td><td>movement stops</td></tr>
</table>

4. Experimental determination of dynamic indices

To check the adequacy of the mathematical model of the diesel train car, we will compare the values of the coefficients of vertical and horizontal dynamics of the primary suspension, which are obtained by calculation, with the data from experimental studies [22].

Since during the test it was not known at what parameters of geometrical unevenness the diesel-train movement took place, the following comparison will be performed with the length of horizontal and vertical unevenness of 15 m and its amplitude of 0.006 m, which corresponds to the good state of the railway track.

As can be seen from figures 6 and 7, the experimental values of the coefficients of vertical and horizontal dynamics are in the range of values obtained by theoretical calculations according to formula (3).

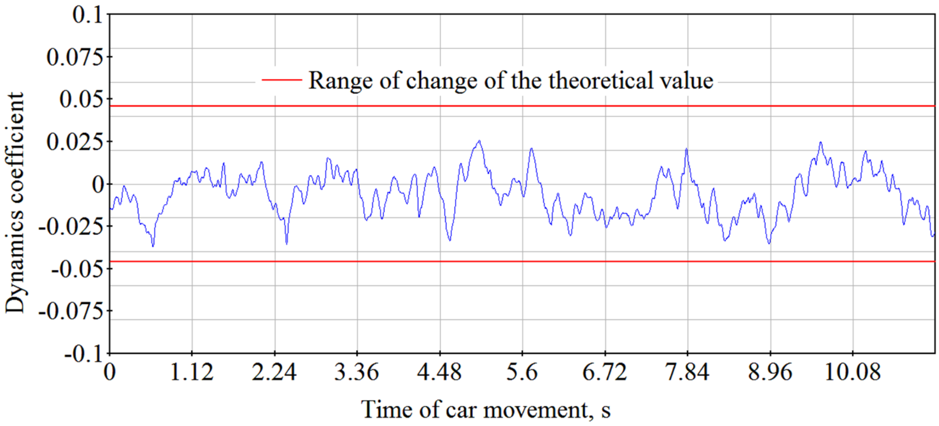


Figure 6. Comparison of experimental and theoretical values of the coefficient of vertical dynamics on the first wheel pair at speed of 35 m / s on the straight section of the track.

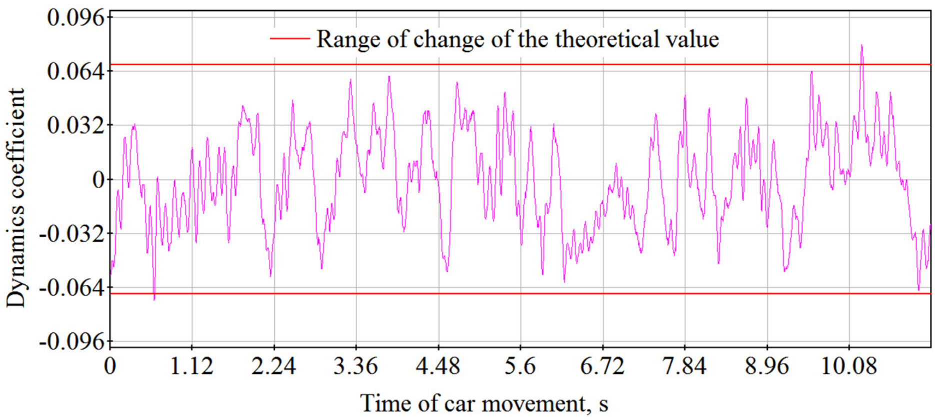


Figure 7. Comparison of experimental and theoretical values of the coefficient of horizontal dynamics on the first wheel pair at speed of 35 m / s on the straight section of the track.

The maximum experimental value of the coefficient of vertical and horizontal dynamics at a speed of diesel train carriage of 35 m / s is 0.038 and 0.08 respectively. The maximum theoretical value of these coefficients was 0.045 and 0.068. The difference in the results does not exceed 15%.

The comparison of the results of the theoretical research with the experimental ones shows that the developed spatial mathematical model provides sufficient accuracy of determination of the coefficients of vertical and horizontal dynamics and can be used in solving problems in the study of dynamic parameters of the mechanical part of the modern diesel train.

5. Conclusions

The paper shows the possibility of using the previously developed spatial mathematical model for solving problems related to research of the dynamic parameters of the mechanical part of the diesel train car. By means of the given mathematical model, forces were determined in the primary and in the secondary suspension, the frame forces that have major impact on the dynamic parameters.

It is established this is not the right verb to use, pls change that at any length of geometrical unevenness, the coefficients of vertical and horizontal dynamics increase at first, and then fall for specific speed ranges. This is due to the presence of resonance phenomena.

It is established that there is overlapping of the frequencies of its own and forced oscillations: in the vertical plane at the frequency of 2 Hz. and in horizontal plane at the frequency of 5 Hz. This allows us to establish that with the reduction of the length of geometrical unevenness, the maximum value of the coefficients of dynamics will be shifted towards the reduction of velocities.

While studying the dynamic properties of the mechanical part of the railway rolling stock, it was established that the requirements of the Ukrainian regulatory norms are more rigorous than the requirements according to the norms of European Union countries.

The maximum permissible speeds of diesel train DPKr-2 carriage, depending on the condition of the railway track, have been established, which allows us to determine safe conditions of its operation.

The comparison of the results of theoretical studies with experimental ones proves the adequacy of the developed model and the possibility of its use for solving problems in the study of dynamic diesel-train indices. The difference in the results does not exceed 15%.

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