METHODOLOGY FOR MAINTAINING THE DYNAMIC CHARACTERISTICS OF PASSENGER CARS

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Resume

The work presents the results of a statistical analysis of random processes of the coefficient of vertical dynamics of a passenger car variation. To determine the dynamic performance of cars the tests were running on the tracks of JSC "Ukrzaliznytsia". The main statistical characteristics of random processes are determined for various modes of car movement along curved and straight sections of the track. As a result of statistical processing of experimental data, correlation functions have been constructed that characterize the degree of connection between different time sections of the process of changing the coefficient of vertical dynamics. The obtained indicators of the law of distribution of the vertical dynamics coefficient values, approximating the models of correlation functions and the numerical values of their parameters, make it possible to further simulate the process of loading a passenger car without carrying out lengthy expensive tests.

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1 Introduction

Facing the growing competition between different kinds of transport one must pay more attention not only to ensure fast transportation of passengers with maximum comfort, but to reliable and coordinated operation of all the parts of railway transport, as well.

In recent years, due to insufficient investment in railways of Ukraine, there has been an increase in physical wear and tear and obsolescence of the operational fleet of passenger cars of JSC "Ukrzaliznytsia".

Most of the passenger car fleet was built in the 70s and 90s of the last century, at the railcar-building plants in Germany (Waggonbau Ammendorf) and the Russian Federation (Kalinin Carriage Plant, nowadays Tver). According to the Passenger Company branch of JSC "Ukrzaliznytsia", most of the cars in the inventory fleet have served their assigned service life. As a result, the current wear of the passenger car fleet is approaching 92 %. Therefore, an urgent issue to increase the competitiveness of rail passenger transport is to overcome the high degree of wear of the passenger cars fleet of JSC "Ukrzaliznytsia".

In recent years, JSC "Ukrzaliznytsia" has been renovating passenger cars in order to extend their service life. That resulted in partial restoration of technical and operational characteristics of the car. However, it is necessary to understand that it is impossible to completely restore cars to the initial condition. Therefore, the analysis of dynamic characteristics of the passenger cars, which have undergone renovation, is an urgent task.

2 Analysis of recent research and publications

The dynamic loading of rail vehicles depends on many factors. Therefore, a significant number of works in different countries of the world are devoted to the study of these issues. A number of scientific studies have been devoted to the issues of rolling stock dynamics, the determination of vertical and horizontal forces and the study of their influence on stability, strength and traffic safety.

It should be noted that both theoretical and experimental methods for studying dynamics of the rolling stock are constantly being improved with the development of measuring instruments and information processing. The use of modern computer technology makes it possible to obtain results that are important for design of the modern rolling stock.

In article [1], the authors compare the dynamic performance of freight cars equipped with three different types of bogies (models 18-100, Y25, 18-9771). The researchers came to the conclusion that the values of the coefficient of vertical dynamics of the non-sprung part of the car are almost the same for all three models of bogies, on a straight section of the track. The authors also recommend improving the dynamic performance of the car bogies by choosing rational parameters of the spring suspension.

The studies of the specialists of the Faculty of Mechanical Engineering University of Žilina are devoted to issues of dynamic interaction of the rolling stock with the superstructure of the track [2-4]. The authors have developed the solid-state models of passenger cars that allow simulating the real dynamic interactions of the rolling stock, taking into account the rigidity-damping parameters of the railway track. The paper presents simulation calculations for three different models and determines the stiffness-damping parameters of a rail vehicle.

Thus, when modeling the dynamic load of passenger cars, in order to simplify the mathematical model, the authors of papers [5-6] considered the body and bolsters as one inertial element of the car. However, if it was necessary to determine the acceleration of the body capabilities of such models, that turn out to be insufficient. To determine the forces of interaction and mutual displacements of the body and bolsters of the car in studies [7-8], experts considered these structural elements as separate. It is considered that the body rests on the bolsters in four points (slides).

The article [9] shows the results of mathematical modeling of spatial oscillations of passenger cars by determining the forces of dynamic interaction of bodies and bogies, which are used to determine the dynamic running characteristics and strength. The publication [10] evaluates the dynamic qualities of a passenger compartment car model 61-779, constructed by OJSC "Kryukiv Railway Car Building Plant".

Hydraulic vibrations play an important role in ensuring the smooth running of bogies. In the study [11], the authors considered the influence of the parameters of hydraulic vibration dampers of bogies on the dynamics of cars. Numerical analysis has shown that the critical velocity and the stability index increase with an increase in the damping diaphragm and flow area. As the spring stiffness increases, the critical velocity increases and the stability index decreases.

In the rolling stock dynamics, in describing the contact interaction of a wheel with a rail, the theory of creep (elastic sliding) has found application. In [12], a wheel pair is considered as a nonlinear dynamic system. By means of computer simulation, the authors determined the range of the car speeds within which a stable trivial solution and a stable solution of the limit cycle coexist. Their dependence on the car speed is shown.

Issues of the influence analysis of the wheel tread surface taper parameters and the transverse movement of the wheel along the rails are considered in articles [13-15]. The authors show the influence of the geometric parameters of the wheels and the speed of the car on the value of the maximum contact force and its distribution in the contact zone.

The use of analytical methods of the rolling stock dynamics had serious limitations until the middle of the 20th century, since it was based on linear differential equations that do not take into account important features of the design and modes of movement of the rolling stock.

With introduction of the computer technology, there has been a qualitative leap in theoretical studies of dynamics, as well as in processing the results of dynamic tests. The results of computer simulation of the damaged wheels interaction with rails are analyzed in papers [16-19]. The analyzes were focused on evaluating the smoothness of the rail vehicle and its damaging effect on the vehicle. The issues of influence of the vertical static and dynamic loads on the load in the zone of a wheel with a rail, as well as methods of their transmission, are considered in [20].

However, it should be noted that in the scientific literature not much attention is paid to the study of the statistical dynamics of the rolling stock. It is known that the change in time of the dynamic indicators of the car is a random process. However, the characteristics of these processes have not been studied enough and require further in-depth study.

3 Problem statement

The study of loads acting on the rolling stock from the rail track is the most responsible section of the rolling stock dynamics. This is due to the complexity of the interaction of the rolling stock and the track structure.

Conventionally, all the forces of interaction of cars and tracks can be divided into two groups. The first group includes vertical forces acting on the wheelsets of cars, while the second one includes the horizontal loads. They depend on many factors. Therefore, it is advisable to reduce the variety of random factors to one or more equivalents.

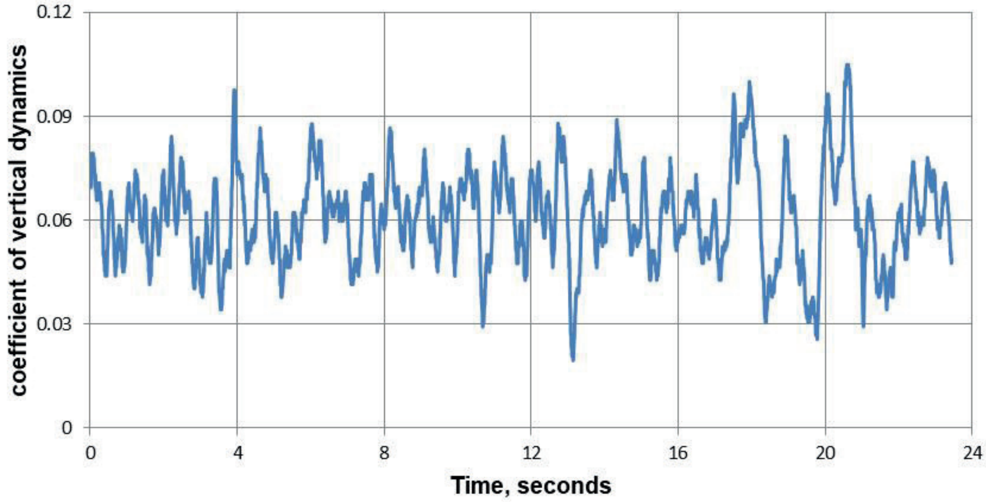

Figure 1 *Change of the coefficient of vertical dynamics at a speed of 40 km/h on a straight track section*

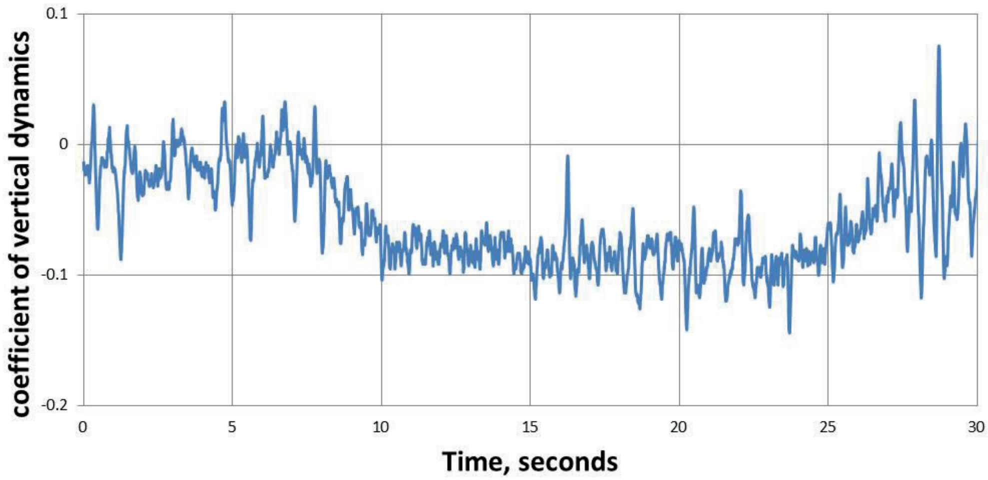

Figure 2 *Change in the coefficient of vertical dynamics at a speed of 110 km/h on the track curved section*

The main indicators that characterize the dynamic qualities of the rail rolling stock in accordance with the requirements of current regulations [21-22] are coefficients of vertical load of bolsters and bogie frames of passenger cars.

To determine the dynamic performance of rigid compartment cars, which were renovated, were running tests on the tracks of JSC "Ukrzaliznytsia". During the tests, the ambient temperature did not exceed 28 °C and the relative humidity was 80 %.

The tests were carried out on straight sections of the track, as well as on curves sections of the track of small (R ≤ 350 m), medium (350 < R< ≤650 m) and large (R > 650 m) radius.

According to the requirements of the JSC Ukrzaliznytsia, one passenger car was subjected to dynamic tests. Since all the passenger cars of this type have the same design and technical characteristics, the results can be extended to the entire fleet of wagons.

Dynamic loading processes of cars, which were registered on magnetic media, were processed by the program for calculating instantaneous values of process amplitudes. Test results were recorded were conducted in both directions of train movement with a total duration of at least 300 s in each speed range. The sampling frequency of records of dynamic processes was chosen more than 128 Hz, which allowed determining the indicators in the required frequency range. For each random process, calculations were performed and the maximum values of the probability of vertical loads were determined. At the first stage, one indicator value was determined within each speed range, starting from a speed of 40 km/h. Some results for speed of 40 km/h and 110 km/h are presented in Figures 1 and 2, respectively.

Analyzing the results, partly shown in Figures 1 and 2, it can be concluded that with increasing the car speed the general amplitude of the vertical dynamic coefficient, considered without the second-order oscillations, becomes more clearly defined with a pronounced cyclicality.

The process the coefficient of vertical dynamics variation in time is a random process.

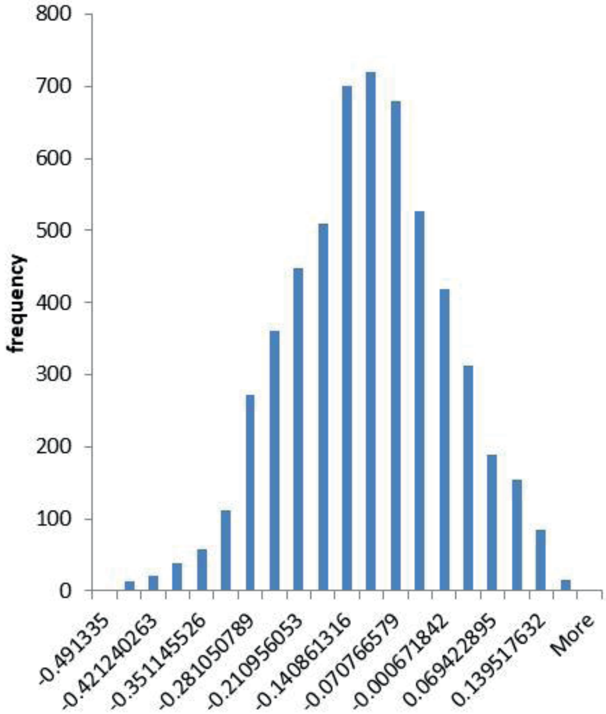

***Figure 3** Distribution of instantaneous values of the vertical dynamics' coefficient at 100 km/h on the track straight section*

It should be noted that when evaluating the driving performance of a car, a check is made to see if the maximum values of the vertical dynamics' coefficient exceed the threshold values regulated by the regulatory document. The influence of high-frequency oscillations on the stress-strain state was not considered in this case.

The second stage determined the following characteristics of a random process, namely mathematical expectation, variance and minimum and maximum efforts values.

The results of statistical processing show that the random processes that characterize the coefficient of vertical dynamics are distributed according to the normal law (Figure 3).

The parameters characterizing this law were obtained and are presented in Table 1.

Testing the hypothesis about the correspondence of the empirical distribution was carried out according to the well-known goodness of fit criteria of mathematical statistics. Thus, for the results of processing the instantaneous values of the coefficient of vertical dynamics, at a speed of 100 km/h on a straight section of the track (Figure 4), at a significance level of 0.05, the value of the coefficient χ^2 was 2.8 at $\chi_{cr} = 6.2$. Therefore, the hypothesis of a normal distribution is not rejected.

Mathematical expectation and variance are important characteristics of a random process, but they do not give a sufficient idea of the nature of individual implementations of a random process.

The correlation function (CF) of a random process is called the non-random function of two arguments, which, for each pair of arbitrarily selected values of arguments (time points), is equal to the mathematical expectation of the product of the two random variables of the corresponding sections of the random process, [23].

***Table 1** The value of the distribution parameters*

Speed (km/h)	Movement mode	Mathematical expectation	Variance
40	straight track section	0.06129	0.00018
	curved track section	0.062302	0.00015
80	straight track section	-0.012078	0.00017
	curved track section	-0.02671	0.00083
110	straight track section	-0.00947	0.00034
	curved track section	-0.00772	0.00056
160	straight track section	-0.09838	0.00076
	curved track section	-0.09804	0.00056

$$K_x(t,t_1) = M[X(t)X(t_1)] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} X(t)X(t_1)\times \times\omega_2(X,t,X_1,t_1), \quad (1)$$

where ω_2 (X, t, X_1, t_1) is a two-dimensional probability density.

That is, the CF determines the dependence of the random variable at the next time point x (t_1) on the previous value of $X(t)$ at time tt; i.e. it is a measure of the relationship between them, namely a correlation measure between them.

The need to approximate the CF arises whenever it is necessary to have an analytical description of the experimental correlation function to solve certain problems.

Finding an approximating expression for CF can be done as follows:

- a linear combination of a finite number of functions (approximation by functions of the form $\varphi_x(\tau) = \sigma_x^2 e^{-\alpha_x\tau}\cos\beta_x\tau$);
- a finite series of exponential functions system;
- an infinite series of some definite system of functions (possible partial approximation by step series, orthogonal functions, asymptotic series, etc.).

Denote by $X[i] = X(t_i), t_i = i\Delta t; i = \overline{1,n}$ stationary ergodic random sequence, where Δt is the interval of discreteness of measurements of a stationary random process $X(t)$.

The random processes of change of vertical dynamics coefficients are considered as stationary and ergodic.

The CF estimation of the ergodic stationary random process $X(t)$ can be determined by one of its implementations $x(t)$. From this point on, the sequence $x[i] = x(t_i), i = \overline{1,n}$ is used.

The CF estimation $\hat{K}_x[j] = \hat{K}_x(t_j)$, $(t_j = j\Delta t; j = \overline{1,n})$ is determined by the following formulas:

$$\hat{K}_x[j] = \frac{1}{n-j}\sum_{i=1}^{n-j}[x(i) - \hat{m}_x][x(i+j) - \hat{m}_x], \quad j = \overline{0,m}, \quad (2)$$

where,

$$\hat{m}_x = \frac{1}{n}\sum_{i=1}^{n} x(i). \quad (3)$$

In Equation (3) - $x(i+j); t_{i+j} = (i+j)\Delta t; \hat{m}_x$ is the estimation of the mathematical expectation of the sequence $x(i), i = \overline{1,n}$.

To approximate the obtained estimate of CF in this case, it is advisable to use the analytical dependence in the form of a decaying cosine.

$$\hat{K}_x[j] \approx \sigma_x^2 e^{-\alpha_x\tau}\cos\beta_x j\Delta t, \; j = \overline{0,m}, \quad (4)$$

where $\sigma_x, \beta_x, \alpha_x$ are the parameters to be determined.

The parameter σ_x is defined as follows:

$$\sigma_x = \sqrt{\hat{K}_x[0]}. \quad (5)$$

If one uses a normalized correlation function, σ_x will be equal to unity.

To obtain the value of the parameter β_x, determine the estimate of the one-sided spectral density $\hat{G}[k] = \hat{G}[f_k], k = \overline{0,m}$ according to the following Equation [24]:

$$\hat{G}[k] = 2\Delta t\left[\hat{K}_x[0] + 2\sum_{r=1}^{m-1}\hat{K}_x[r]\cos\left(\frac{\pi rk}{m}\right) + (-1)^k\hat{K}_x[m]\right], k = \overline{0,m}, \quad (6)$$

$$\left.\begin{aligned} f_k &= \frac{kf_c}{m} = k\Delta f, k = \overline{0,m},\\ f_c &= \frac{1}{2\Delta t}; \Delta f\frac{f_c}{m}, \end{aligned}\right\} \quad (7)$$

where, $\Delta f = f_{k+1} - f_k, = \overline{0,m-1}$;

f_c is the cutoff frequency, Hz.

Smoothed estimate spectral density $G^*[k], k = \overline{0,m}$ according to [13] is defined as follows:

$$\left.\begin{aligned} &G^*(0) = 0.5\hat{G}(0) + 0.5\hat{G}(1,)\\ &G^*(k) = 0.25\hat{G}(k-1) + 0.5\hat{G}(k) +\\ &+ 0.25\hat{G}(k+1), k = \overline{1,m-1},\\ &G^*(m) = 0.5\hat{G}(m-1) + 0.5\hat{G}(m). \end{aligned}\right\} \quad (8)$$

Further on, it is necessary to find the maximum element in the array $G^*[k], k = \overline{0,m}$ and index of this element $k = k_2^*$. Then the parameter β_x is defined as follows:

$$\beta_x = 2\pi k_2^*\Delta f. \quad (9)$$

The parameter α_x can be determined from the following condition:

$$F(\alpha_x) = \sum_{j=0}^{m1}\left[\hat{K}_x(j) - \sigma_x^2 e^{-\alpha_x j\Delta t}\cos\beta_x j\Delta t\right] = \min \quad (10)$$

To find α_x from Equation (10) one obtains the following equation:

$$W(\alpha_x) = \frac{dF(\alpha_x)}{d\alpha_x} = 0 = \sum_{j=0}^{m1}\left[\hat{K}_x(j) - \sigma_x^2 e^{-\alpha_x j\Delta t}\cos\beta_x j\Delta t\right]\times \times[j\Delta t]e^{-\alpha_x j\Delta t}\cos\beta_x j\Delta t. \quad (11)$$

To solve the equation, it is advisable to use Newton's method. As a result, one can get:

$$\alpha_x^{(l+1)} = \alpha_x^l - \frac{W(\alpha_x^{(l)})}{W'(\alpha_x^{(l)})}, l = 0,1,2,\ldots, \quad (12)$$

where

$$W'(\alpha_x^{(1)}) = \frac{dW(\alpha_x)}{d\alpha_x} = \sum_{j=0}^{m1}\left[2\sigma_x^2 e^{-\alpha_x j\Delta t}\cos\beta_x j\Delta t\right] - \hat{K}_x(j)[j\Delta t]^2 e^{-\alpha_x j\Delta t}\cos\beta_x j\Delta t.$$

The initial approximation of the parameter $\alpha_X^{(0)}$ of the parameter α_X is determined by the following formula [25]

$$\alpha_X^{(0)} = \frac{1}{T_0}\ln\left(\frac{\hat{K}_x[0]}{\hat{K}_x[1]}\right), \quad (13)$$

$$T_0 = \frac{T}{2}; \quad T = \frac{2\pi}{\beta_x}. \quad (14)$$

The best approximation, which is calculated by Equation (12), will be achieved when realizing the inequality:

$$\left\| \frac{W(\alpha_x^{(l)})}{W'(\alpha_x^{(l)})} \right\|_{l=l^*} < \varepsilon.$$

Then, the parameter α_X is determined as follows:

$$\alpha_X = \alpha_X^{(l^*)}. \quad (15)$$

The values obtained for different speeds on the straight section of the track are given in Table 2.

The corresponding graph of the CF estimation, for changing the vertical dynamics coefficient, at a speed of 40 km/h on a straight section of track and its approximation are shown in Figure 4.

4 Conclusions

1. The work presents the results of a statistical analysis of random processes of changing the coefficient of vertical dynamics of a passenger car. It is confirmed that the distribution law of the vertical dynamics coefficient values is a normal one. It is established that the value of the expectation of the coefficient of vertical dynamics at a speed of 40 km/h is 0.062. As the speed increases to 160 km/h, the expectation value will be 0.09838. Such results are typical for both straight and curved sections of the track.
2. As a result of statistical processing of experimental data, correlation functions have been constructed that characterize the degree of connection between different time sections of the process of changing the vertical dynamics coefficient.
3. To approximate the correlation functions, dependences in the form of a damped cosine curve were used. For each of the motion modes, the parameters α_X and β_x, which characterize them, are obtained.
4. The obtained characteristics of the distribution law of the coefficient of vertical dynamics instantaneous values, approximating the models of correlation functions and the numerical values of its parameters,

***Table 2** Values of the parameters of the approximating CF*

Speed (km/h)	Parameter values		
	σ_x^2	α_X	β_x
40	1	3.23	5.8
80	1	2.8	6.5
110	1	2.6	7.8
160	1	3.1	6.5

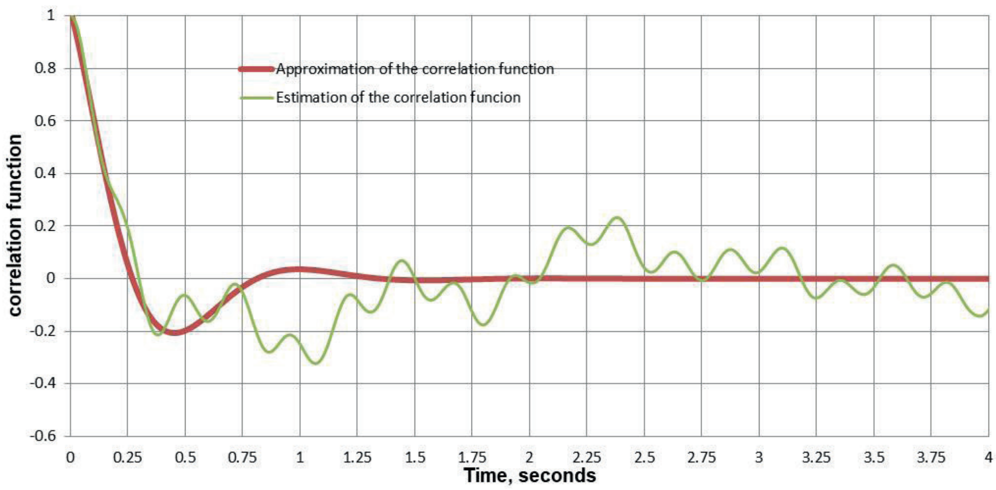

***Figure 4** Correlation function for changing the vertical dynamics coefficient at the speed of 40 km/h on the straight section of the track*

make it possible to further simulate the process of loading a passenger car without carrying out the lengthy expensive tests.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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