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# NUMERICAL STUDIES ON MODELING VERTICAL OSCILLATIONS OF THE LEAD CAR OF THE AFROSIAB HIGH-SPEED ELECTRIC TRAIN

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**ABSTRACT**

*The article presents the results of numerical studies on the simulation of vertical vibrations oscillations of the lead car of the high-speed electric train AFROSIAB, numerical analysis was conducted in the MATHCAD 15 programming environment using the Gauss matrix method.*

Efforts are underway globally to enhance the speed and capacity of railways through research and development. The focus is on improving the dynamic properties of high-speed electric trains by ensuring the appropriate selection and stability of hydraulic and hydrofriction vibration dampers, as well as optimizing spring suspension parameters. Enhancing the dynamic properties of electric rolling stock, improving the interaction forces between the wheel and the rail, ensuring wheel stability on the rail, and enhancing the smoothness of high-speed electric transport are crucial objectives. Simultaneously, a pressing task involves developing new designs and enhancing existing spring suspension systems for electric rolling stock, along with devising methods to calculate their dynamic strength. Addressing this challenge is vital to ensuring traffic safety and passenger comfort [1, 2, 3, 4].

Research has been conducted and is being conducted on this topic by leading scientists worldwide such as S.A. Brebbia (Wessex Institute of Technology, UK), G.M. Carlomagno (University of Naples di Napoli, Italy), A. Varvani-Farahani (Ryerson University, Canada), S.K. Chakrabarti (USA), S. Hernandez (University of La Coruna, Spain), S.-H. Nishida (Saga University, Japan). Authoritative scientific schools and prominent scientists in the CIS countries from MIIT, PGUPS, MAI, VNIIZhT, JSC VNIKTI, JSC Russian Railways, etc. worked on these issues. A significant contribution to solving many complex problems and checking theoretical conclusions related to the study of the processes of oscillations of the spring suspension of the rolling stock was made by the Russian Research Institute of Railway Transport (CNII MPS) and the Russian Research Institute of Railcar Building (NIIV), where along with theoretical studies, a large number of experimental studies (bench and full-scale ones) were conducted. In Uzbekistan, the academician of the Academy of Sciences of the

Republic of Uzbekistan, professor, doctor of technical sciences Glushchenko A.D., professors Fayzibaev Sh.S., Khromova G.A., Shermukhamedov A.A., Z.G. Mukhamedova, D.O. Radjibayev, associate professors Kh.M. Tursunov, S.A. Khromov, M.A. Makhamadalieva and their students dealt with the problems of optimizing the systems of spring suspension of rolling stock.

Figure 1 shows a spatial kinematic diagram of vertical vibrations of the car model of the high-speed electric train AFROSIAB. The car body rests on two two-axle bogies through the central stage of the spring suspension, and each of the bogies through the axle box stage on two wheelsets; springs and hydraulic dampers installed in parallel to them are used in the central stage of the spring suspension.

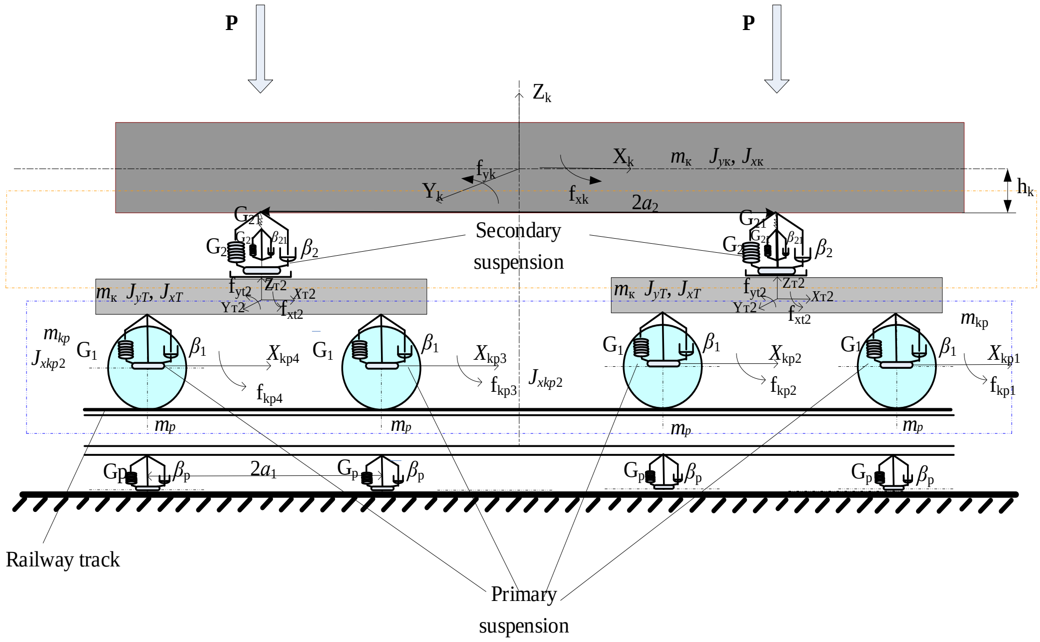


Figure 1. Spatial kinematic diagram of vertical oscillations of the car model of the high-speed electric train AFROSIAB

The following notations are used in Figure 1 and equations of the system of differential equations (1): $m_k$ , $m_p$ are the body mass and the mass of the track reduced to the wheel; $m_T$ is the spring mass of the bogie; $m_{kp}$ is the mass of the wheelset; $J_{yk}$ , $J_{xk}$ are the moments of inertia of the body relative to the *y* and *x*-axes; $J_{yT}$ , $J_{xT}$ are the moments of inertia of the bogie frame relative to the *y* and *x*-axes; $J_{xkp}$ is the moment of inertia of the wheelset relative to the *x*-axis; $\beta_1$ is the damping coefficient in the axlebox stage of the spring suspension; $G_1$ is the rigidity of the axlebox stage of the spring suspension; $\beta$п is the damping coefficient of the railway track; $G$p is the rigidity of the track; $2a_2$ and $2a_1$ are the body base and the bogie base; $2b_2$ and $2b_1$ are the distances across the track axis between the elastic and dissipative elements of the central and axle-box stages of the spring suspension of an electric train car; $2s$ is the distance between the points of contact with the rails of the wheels of one wheelset.

The system of coupled differential equations describing forced vertical oscillations of the car model of the high-speed electric train AFROSIAB in the form of a five-mass system has the following form:

$$m_k\ddot{z}_k + 4\beta_2\dot{z}_k + 4G_2z_k - 2\beta_2(\dot{z}_{т1} + \dot{z}_{т2}) - 2G_2(z_{т1} + z_{т2}) = 0;$$

$$J_{yk}\ddot{\varphi}_{yk} + 4\beta_2a_2^2\dot{\varphi}_{yk} + 4G_2a_2^2\varphi_{yk} + 2\beta_2a_2(\dot{z}_{т1} - \dot{z}_{т2}) + 2G_2a_2(z_{т1} - z_{т2}) = 0;$$

$$m_{т1}\ddot{z}_{т1} + (4\beta_1 + 2\beta_2)\dot{z}_{т1} + (4G_1 + 2G_2)z_{т1} - 2\beta_2\dot{z}_k - 2G_2z_k + 2\beta_2a_2\dot{\varphi}_{yk} +$$
$$+2G_2a_2\varphi_{yk} \pm 2\beta_1(\dot{z}_{кр1} + \dot{z}_{кр2}) - 2G_1(z_{кр1} + z_{кр2}) = 0;$$
$$m_{т2}\ddot{z}_{т2} + (4\beta_1 + 2\beta_2)\dot{z}_{т2} + (4G_1 + 2G_2)z_{т2} - 2\beta_2\dot{z}_k - 2G_2z_k - 2\beta_2a_2\dot{\varphi}_{yk} -$$
$$-2G_2a_2\varphi_{yk} \pm 2\beta_1(\dot{z}_{кр1} + \dot{z}_{кр2}) - 2G_1(z_{кр1} + z_{кр2}) = 0;$$
$$(m_{кр1} + 2m_p)\ddot{z}_{кр1} + (2\beta_1 + 2\beta_p)\dot{z}_{кр1} + (2G_1 + 2G_p)z_{кр1} = P_{p1};$$
$$(m_{кр2} + 2m_p)\ddot{z}_{кр2} + (2\beta_1 + 2\beta_p)\dot{z}_{кр2} + (2G_1 + 2G_p)z_{кр2} = P_{p2}, \qquad (1),$$

where $P_p(t) = P_{p1}(t) = P_{p2}(t) = m_p\ddot{\eta}_H(t) + \beta_p\dot{\eta}_H(t) + G_p\eta_H(t)$, (2),

$P_p(t)$ – is the dynamic load that occurs when an electric train car moves over track irregularities, and $\eta_H(t) = \eta_0 \cdot \sin\omega t$, (3),

where $\eta_0$ –is the track irregularity height, and ω is the frequency of the irregularity variation over time.

$\omega = \frac{2\pi \cdot V}{L_H}$, where $L_H$ is the length of track irregularity;

$V$ – is the speed of the electric train car, m/s;

$2m_т$ - the mass of two bogies together with the reduced mass of part of the railway track $2m_т = m_{т1} + m_{т2} + 4m_p$, (4),

$\eta_c$ - average vertical movement of wheelsets of an electric train car on track unevenness $\eta_c = \frac{1}{4} \cdot (\eta_1 + \eta_2 + \eta_3 + \eta_4)$, (5).

In accordance with the calculation scheme (Figure 1) and the accepted assumptions when considering only vertical oscillations, the system has six degrees of freedom:

- bouncing $z_k$ and galloping $\varphi_{yk}$ of the electric train car body and bouncing of the wheelsets $z_{т1}$, $z_{т2}$ and wheelsets $z_{kp1}$, $z_{kp2}$.

Let us find the frequencies of natural oscillations determined by system (1) for homogeneous equations. We will seek solutions to these equations in the following form $z_k = z_{ak} \cdot \sin\lambda t$; $\varphi_{yk} = \varphi_{ayk} \cdot \sin\lambda t$; $z_{т1} = z_{aт1} \cdot \sin\lambda t$;

$$z_{т2} = z_{aт2} \cdot \sin\lambda t;\ z_{kp1} = z_{akp1} \cdot \sin\lambda t;\ z_{kp2} = z_{akp2} \cdot \sin\lambda t \qquad (6),$$

Where $\boldsymbol{\lambda}$ –is the frequency of vertical natural oscillations in the “car body–bogie–track” system.

Substituting equations (6) and their derivatives into system (1), we obtain

$$a_{11}z_{ak} + a_{12}z_{aт} + a_{13}\varphi_{ak} = b_1;$$
$$a_{21}z_{ak} + a_{22}z_{aт} + a_{23}\varphi_{ak} = b_2;$$
$$a_{31}z_{ak} + a_{32}z_{aт} + a_{33}\varphi_{ak} = b_3;$$
$$a_{41}z_{ak} + a_{42}z_{aт} + a_{43}\varphi_{ak} = b_4;$$
$$a_{51}z_{ak} + a_{52}z_{aт} + a_{53}\varphi_{ak} = b_5;$$
$$a_{61}z_{ak} + a_{62}z_{aт} + a_{63}\varphi_{ak} = b_6; \qquad (7),$$

We will find the solution to system (7) using the Gauss method in the MATHCAD 15 programming environment [5,6,7].

The determinant of system (7) is

$$\Delta=\begin{vmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} \end{vmatrix} \quad (8).$$

and the solutions for $z_{ak}, \varphi_{ayк}, z_{aт1}, z_{aт2}, z_{akp1}$ and $z_{akp2}$ are, respectively,

$$\Delta1=\begin{vmatrix} b_1 & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ b_2 & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ b_3 & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\ b_4 & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\ b_5 & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\ b_6 & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} \end{vmatrix}, \quad \Delta2=\begin{vmatrix} a_{11} & b_1 & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & b_2 & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & b_3 & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & b_4 & a_{43} & a_{44} & a_{45} & a_{46} \\ a_{51} & b_5 & a_{53} & a_{54} & a_{55} & a_{56} \\ a_{61} & b_6 & a_{63} & a_{64} & a_{65} & a_{66} \end{vmatrix},$$

$$\Delta3=\begin{vmatrix} a_{11} & a_{12} & b_1 & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & b_2 & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & b_3 & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & b_4 & a_{44} & a_{45} & a_{46} \\ a_{51} & a_{52} & b_5 & a_{54} & a_{55} & a_{56} \\ a_{61} & a_{62} & b_6 & a_{64} & a_{65} & a_{66} \end{vmatrix}, \quad \Delta4=\begin{vmatrix} a_{11} & a_{12} & a_{13} & b_1 & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & b_2 & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & b_3 & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & b_4 & a_{45} & a_{46} \\ a_{51} & a_{52} & a_{53} & b_5 & a_{55} & a_{56} \\ a_{61} & a_{62} & a_{63} & b_6 & a_{65} & a_{66} \end{vmatrix},$$

$$\Delta5=\begin{vmatrix} a_{11} & a_{12} & a_{13} & a_{14} & b_1 & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & b_2 & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & b_3 & a_{36} \\ a_{41} & a_{42} & a_{43} & a_{44} & b_4 & a_{46} \\ a_{51} & a_{52} & a_{53} & a_{54} & b_5 & a_{56} \\ a_{61} & a_{62} & a_{63} & a_{64} & b_6 & a_{66} \end{vmatrix}, \quad \Delta6=\begin{vmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & b_1 \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & b_2 \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & b_3 \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & b_4 \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & b_5 \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & b_6 \end{vmatrix},$$

where

$$z_{ak}=\frac{\Delta1}{\Delta};\ \varphi_{ayк}=\frac{\Delta2}{\Delta};\ z_{aт1}=\frac{\Delta3}{\Delta};\ z_{aт2}=\frac{\Delta4}{\Delta};\ z_{akp1}=\frac{\Delta5}{\Delta};\ z_{akp1}=\frac{\Delta6}{\Delta}. \quad (9)$$

The system of differential equations (1) is solved by the Gauss matrix method using the MATHCAD 15 programming environment. As a result, the amplitude-frequency response of the "car body-bogie-track" system is investigated considering the influence of spring suspension using for example the high-speed electric train AFROSIAB, moreover, the first and second bogies vibrate with different amplitudes, and the wheel pairs also vibrate differently. Graphs are plotted for the bouncing $z_k$ and galloping $\varphi_{yk} \approx 0$ oscillations of the car body of the electric train, and for the bouncing oscillations of wheelsets $z_т$ (Figure 2).

As a result, we have developed an analytical and numerical model using the Gauss method, which allows us to analyze the amplitude-frequency spectrum of vertical oscillations of the AFROSIAB electric train car model, and to determine the influence of hydraulic and pneumatic damping in the system.

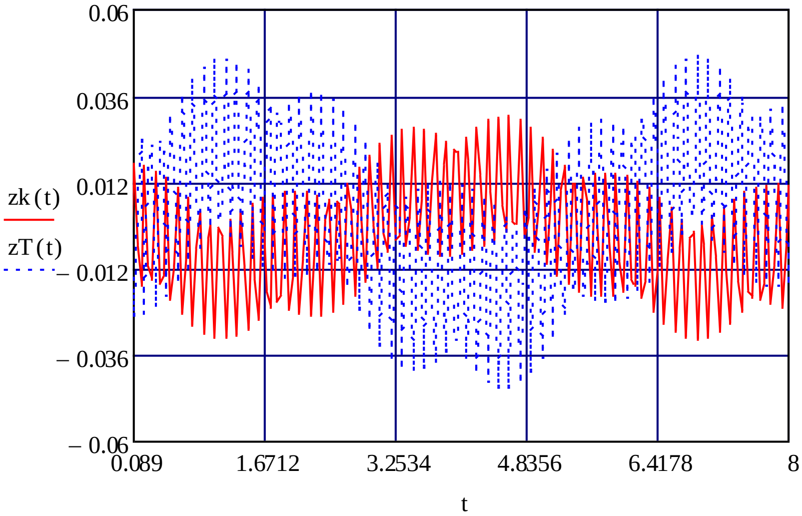


Figure 1. Graph of bouncing $z_k(t)$ oscillations of the body of the electric train car and recoiling oscillations of wheelsets $z_T(t)$

Based on the presented mathematical model using formulas (1)÷(9), considering the actual dimensions of the spring suspension of the high-speed electric train AFROSIAB, a numerical calculation was performed to justify rational parameters and to build the amplitude-frequency response of the "track-wheel-bogie-body" system.

Based on the theoretical and numerical studies conducted, the following general conclusions can be drawn:

1. We developed an algorithm and a program for the MATHCAD 15 programming environment to describe the vertical oscillations of the high-speed electric train AFROSIAB. We then conducted numerical studies for the proposed mathematical model.
2. As a result, we developed an analytical and numerical model using a method similar to the Gauss method. This model allows us to analyze the amplitude-frequency spectrum of vertical oscillations of the high-speed electric train AFROSIAB.
3. Based on the numerical results, we identified the most dangerous zones, where the amplitudes of vertical oscillations are most considerable. It is evident (see Figure 3) that different vertical oscillations of the wheelsets $\boldsymbol{z_{kp1}}$ and $\boldsymbol{z_{kp2}}$ cause significant bouncing oscillations of the first and second bogies $\boldsymbol{z_{т1}}$, $\boldsymbol{z_{т2}}$. These oscillations are then transferred to the car body of the high-speed electric train AFROSIAB within the "track-wheel-bogie-body" system, leading to a deterioration in its smoothness. Therefore, it is necessary to implement pneumatic spring suspension in the central stage to optimize the functions of the spring suspension and enhance its elastic-dissipative properties at high speeds of the electric rolling stock.

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