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DETERMINING THE INFLUENCE OF WHEELSET ARRANGEMENT IN THE MODEL 18-100 BOGIES ON THE LEVEL OF STEERING EFFORTS IN THE WHEEL-RAIL FLANGE CONTACTS

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The object of this study is the process of directing the bogies of model 18-100 freight cars along a rail track, in particular, along curved sections of the track. The task to be solved was to determine the influence of wheelset arrangement on the level of steering forces in the flange contacts.

A calculation diagram and a mathematical model of fitting the bogie into the curved section of the track have been built. The bogie loading scheme by external forces, including lateral rocking forces acting on the car in a curve, has been refined. In this case, the method of pseudo-statics of the mechanical system, which is a system of nonlinear algebraic equations, was applied. The calculation module Given-Find in the Mathcad software package (USA) was used to solve the mathematical model.

It was established that the misalignment of wheelsets in the frames of model 18-100 bogies was of an accumulative nature. At the maximum operating angles of misalignment of wheelsets, the lateral steering forces in the flange contacts increase by 40–60 % compared to the rated setting. These angles can be up to 0.015 rad (0.85 degrees).

The field of practical application of the results is railroad transportation, in particular, the system of maintenance and repair of freight cars on bogies of the 18-100 model. At the same time, the condition for the practical application of the research results is the expediency of introducing into the maintenance system the technological operation of controlling the deviation of wheelset arrangement in the bogie relative to the rated one.

The current study will contribute to the construction of a measuring system for monitoring the deviation of wheelset arrangement in the bogie relative to the rated one. This proves the expediency of introducing into the trolley maintenance system the technological operation of controlling the deviation of wheelsets and designing a device for monitoring this parameter

Keywords: railroad transport, 18-100 bogies, steering forces, flange, interaction of wheels and rails

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1. Introduction

A structural feature of the model 18-100 bogies and their analogs is a three-element frame with a non-rigid connection of frame sides with an intermediate beam [1, 2]. Such a design of the bogie creates prerequisites for wheelsets in the bogies to warp during operation, which in turn is the cause of increased steering forces in the flange contacts of wheels with rails. According to statistics, more than 80 % of cars with the model 18-100 bogies have misaligned wheelsets.

As is known, the level of steering effort affects a number of important technical and economic indicators of freight cars operation: the intensity of wear of the rolling surfaces of the wheels, resistance to movement, stability in relation to derailment.

The maintenance system of freight cars does not provide for technological operations to check the misalignment of wheelsets in bogies. Even in the bogies of model 18-100 after modernization with the installation of elements of the company “A. Stucki” and wheelsets with a non-linear profile of the ITM-73 wheels do not provide control of wheelset arrangement relative to the rated one.

In this regard, there is a need to clarify the dependence of the steering forces in the flange contacts of the wheels with rails on the distortions of wheelsets in the bogies of freight cars. This clarification can be a justification for the introduction of additional technological operations of monitoring the wheelset arrangement relative to the bogie frame in the maintenance system.

Therefore, studies on determining the influence of wheelset arrangement in the model 18-100 bogies on the level of steering forces in the flange contacts of the wheels with rails are relevant.

2. Literature review and problem statement

The dynamics and characteristics of wheel-rail contact have been the subject of numerous studies since the middle of the 19th century [3]. However, there is very little data in open information sources regarding the statistics of deviations in the installation of wheelsets in bogies.

It is a general opinion that the misalignment of wheelsets in the model 18-100 cars is typical and covers more than

80 % of cars. There are a number of reasons for this phenomenon. These include, for example, gaps in the box joints, horizontal deformations of springs, technological deviations in the geometric parameters of the side frames during the production process, etc. Together, these factors can create a stable skew of wheelsets in the bogie relative to the rated position up to 1.0° (0.018 rad) [4]. At the same time, the researchers confine themselves to a general statement about the presence of the influence of the geometric parameters of wheelset arrangement in bogies on the level of steering forces and wear in the flange contacts of the wheels with rails without specific quantitative dependences.

The development of modern railroad vehicles requires effective modeling taking into account complex operating conditions, especially this applies to switches, as noted in study [5]. Modeling the movement in turnouts of a freight car with a misalignment of the wheelset could expand and complement the theory of contact interaction.

Studies [6, 7] revealed a fundamental difference in the character of the wear of wheel flanges of wheelsets in the bogies of different designs: bogies with a rigid frame on passenger cars and bogies with a non-rigid two-element frame of model 18-100. At the same time, possible changes in the position of the wheelset and its effect on the wear of the flanges were not considered.

There are also opinions about the negative impact on flange wear of the use of heavy types of rail track [8] without calculations of the contact interaction between the wheel and rail with increased hardness.

The analysis of the main directions of reducing the intensity of wear of the wheel flanges is given in papers based on the justification of the optimal ratio of the wheel steel hardness to the rail steel hardness [9, 10]. At the same time, research is not conducted on a specific type of rolling stock, without taking into account design features.

It is believed that with a rigid track, most of this energy of the dynamic interaction of wheels and rails is transformed into the work of frictional forces. Even with 3D modeling of the high-frequency interaction between the wheel and rail, authors do not consider possible state changes due to the structural features of the railroad transport unit [11].

In studies [12, 13], the dynamic loading of the load-bearing structures of the main types of freight cars with actual dimensions and bogies of the 18-100 model was considered. These cars have an above-standard service life. Therefore, deviations from the rated wheelset arrangement in the bogies of these cars also occur. Without checking these structural deviations, it is not possible to give recommendations for extending the service life of the cars.

With the use of classical provisions of theoretical mechanics, different methods for building a calculation model of the rolling flange of a wheelset of a car due to the movement of rolling stock on a curved section of the track are reported [14]. But the influence of the angles of approach of wheelsets on the rail and the gap in the track is not taken into account.

Ideas regarding the effect of steering forces in the contact of wheelsets with rails on the kinematic resistance of locomotives and cars were developed in works [15, 16]. In these studies, there is no analogy of the effect of skew on the resistance of rolling stock of railroads.

The mechanism for pressing the flanges of wheelsets to rails in straight sections of the track is considered in [17]. The role of the geometric parameters of wheelset arrangement and their deviation from the parallel position is noted. The impact of the deviation on the dynamic indicators, however, is not determined.

When studying many causes of increased wear of wheel flanges, modeling of the dynamic interaction of the wheel and rail is used, which makes it possible to obtain more accurate values of dynamic characteristics [18, 19]. To check the reliability of the obtained data in dynamic contact studies, developed and existing bench installations and mathematical models [20, 21] are used, which in no way take into account the angles of change of wheelset installation relative to the base of the bogie.

Our review of the literature [3–21] reveals that in most sources the contact interaction between the wheel and rail is investigated, the reasons for the wear of wheel flanges are proved on the basis of mathematical modeling and laboratory research. At the same time, none of these studies prove that the result of cumulative misalignment of wheelsets during the operation of cars is the wear of wheel flanges, increased resistance to movement, and the occurrence of a dangerous situation of car derailment.

This allows us to state that it is appropriate to conduct a study into the influence of deviation from the rated setting of wheelsets in the model 18-100 bogies on the level of steering forces in the flange contacts of wheels with rails. This will make it possible to determine the limits of permissible deviations of wheelset arrangement in bogie frames from the rated one, as a criterion for making a decision on the need for bogie repair.

3. The aim and objectives of the study

The purpose of our study is to determine the characteristics of influence of the deviation in wheelset arrangement in the 18-100 bogies on the level of steering forces in the flange contacts of the wheels with rails. This will provide an opportunity to justify changes to the procedure for maintenance and repair of the model 18-100 bogies, namely the introduction of a technological operation to control accumulated operational distortions of wheelsets in bogies.

To achieve the goal, the following tasks were set:

– to build a kinematic diagram of the movement of a bogie in a circular curve;

– to construct a mathematical model of the dynamic fitting of the 18-100 bogie into the curved section of the track.

4. The study materials and methods

The object of our research is the process of directing the bogies of the model 18-100 freight cars along the rail track, in particular, in the curved sections of the track.

The main hypothesis of the research assumes that the running of the sidewalls of the bogie frames and, as a result, the skew of wheelsets in the bogies of freight cars is the main reason for the increased intensity of wear in the contacts of wheel flanges with rails.

Frames of the model 18-100 bogies have a so-called three-element structure and consist of two side panels and a spring (pivot) beam.

These include models of the following bogies: 18-1711; 18-9817; 18-9902; 18-4129; 8-9844; 18-1750; 18-7020; 18-4129, etc.

Each of the modifications was designed with the hope of improving the operational characteristics of cars. The latest, most innovative modifications are bogies of models 18-4129 and 18-9817, which are a joint development by the companies ASF Keystone (USA) and PIG "Inter-Car-Group" (Ukraine). The bogie exploits technical solutions and technologies similar to the Motion Control bogie, which is successfully used in the USA and Canada. In particular, polymer adapters "AdapterPlus" are installed in the bushing holes of the sidewalls, the use of which significantly reduces the wear of wheels and rails.

Using the example of the 18-7055 bogie of the 12-7023 semi-car model by the Kryukiv Car Building Plant, a mathematical model was developed for fitting into the curved section of the track.

The study of fitting the bogie in curves is carried out to determine the influence of the geometric parameters of wheelset arrangement in the bogies on the wear indicators of wheel flanges.

The pseudo-static method of steady motion in a circular curve under the action of external forces of interaction with the rail track and the car body was used to simulate the movement of the bogie in the curved section of the track. The mathematical model of fitting a bogie into a curve is a system of d'Alembert-Lagrange equilibrium equations. This method was chosen as the simplest reliable method for describing the movement of a mechanical system with undeformed bodies, which provides a sufficient level of calculation accuracy. The Given-Minerr-Find calculation module in the Mathcad software package was used to solve the system of equilibrium equations.

5. Studying the influence of wheelset arrangement on the level of steering forces in the flange contacts of wheels with rails

5. 1. Construction of the kinematic scheme of bogie movement in a circular curve

To study the influence of the deviation from the rated setting of wheelsets on the level of steering forces in flange contacts, we shall build a kinematic diagram of the movement of a bogie in a circular curve, which is shown in Fig. 1. Parameters for calculations (the letters *ij* in the parameter indices mean the wheel number and the wheelset number, respectively):

– V_{ij} – peripheral velocities of the centers of the corresponding wheels, associated with the rotation of wheelsets in the horizontal plane around the center of the curve, which depend on the radius of the curve of the track section ρ_i:

$$V_{ij} = V \cdot \frac{\rho_i}{\rho}, \tag{1}$$

where V is the speed of the car;

ρ, ρ_i are, respectively, the radii of the curved section of the track and the outer (i=1) and inner (i=2) rails:

$$\rho_1=\rho+A;\ \rho_2=\rho-A, \tag{2}$$

where A is half the distance between the contact points of the wheels of a wheelset and rails. For a track of 1520 mm, this is approximately equal to 780 mm;

– α_j – angles of attack, or approach angles, of wheelsets on the rails:

$$\alpha_1 = -\gamma - \vartheta + \sigma_1, \tag{3}$$

$$\alpha_2 = -\gamma - \vartheta + \sigma_2, \tag{4}$$

where γ is the angle of the radial wheelset arrangement in the curved section of the track:

$$\gamma = \frac{C}{\rho}, \tag{5}$$

where C is the bogie base, the distance between the axles;

σ_1, σ_2 – angles of deviation in wheelset arrangement in the bogie from the rated one;

ϑ – angle of skew of the bogie in the track due to the transverse displacement of wheelsets within the gaps between the wheel flanges and rails:

$$\vartheta = \frac{y_{k2} - y_{k1}}{C}, \tag{6}$$

where y_{k1}, y_{k2} are the lateral displacements of wheelsets, which determine their position in the curve;

– $V_{\varphi ij}=\omega_j \cdot R_{ij}$ – circumferential velocities of contact points of wheels and rails in the plane of wheel rotation;

– ω_j – angular speeds of rotation of wheelsets;

– R_{ij} – current wheel radii in contact with rails – contact radii.

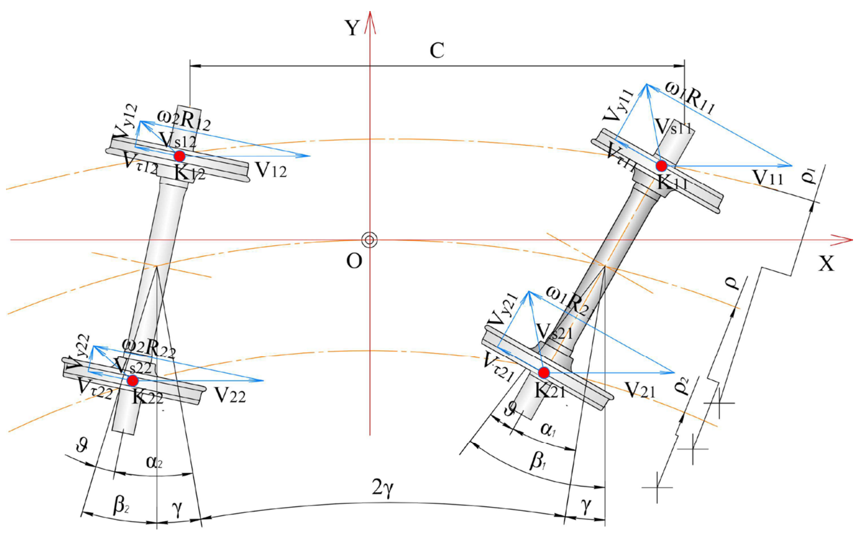


Fig. 1. Kinematic diagram of bogie movement in a circular curve: velocity vectors of the relative movement of the contacting surfaces of the wheels and rails at the points of contact

5. 2. Mathematical modeling of the dynamic fitting of the 18-100 bogie into the curved section of the track

The following functions are used to describe the geometric parameters of contact:

– $R_{ij}(y_{ij})$ – dependence of the rolling radius of wheels R_{ij} on the transverse coordinate of the profile y_{ij};

– $y_{ij}(y_{cj})$ – dependence of the coordinates of the points of contact of the wheel with rail y_{ij} on the lateral movement of the wheelset in the track y_{cj};

– $R_{ij}(y_{cj})$ – dependence of the rolling radii of the wheels R_{ij} on the lateral movement of the wheelset in the track $y_{кj}$;

– $\lambda_{ij}(y_{cj})$ – dependence of the profile slopes at the contact points on the lateral movement of the wheelset in the track y_{cj}.

Fig. 2 shows the contact scheme of the wheelset and the rails: K_{ij} – contacts of the wheels with rails; D is the difference between the track width and the distance between the inner surfaces of the wheel rim.

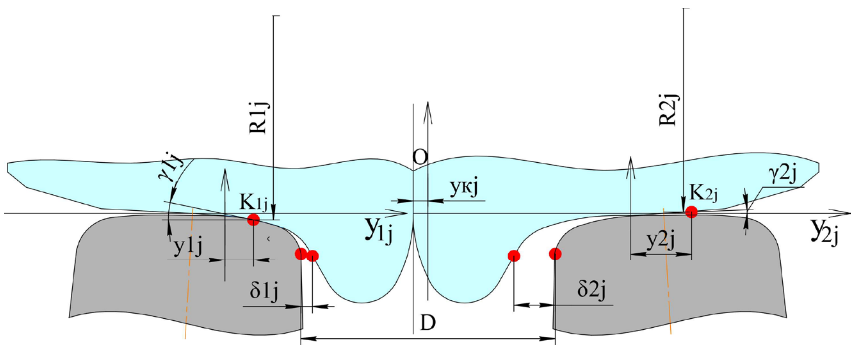


Fig. 2. Contact scheme of the wheelset and rails

An important component of the mathematical model is the determination of the sliding speeds in contact between the wheels and rails V_{sij}:

$$V_{sij}=\sqrt{V_{ij}^2+V_{\varphi ij}^2-2\cdot V_{ij}\cdot\cos(\alpha_{ij})}, \qquad (7)$$

$$V_{yij}=V_{ij}\cdot\sin(\alpha_{ij});\;\; V_{\tau ij}=\sqrt{V_{sij}^2-V_{yij}^2}, \qquad (8)$$

where V_{yij} is the sliding speed in the longitudinal direction, which is directed perpendicular to the plane of rotation of the wheels, that is, along the axis of the wheelset;

$V_{\tau ij}$ is the sliding speed of the transverse direction, which is directed perpendicular to the plane of rotation of the wheels, that is, along the axis of the wheelset.

The sliding velocities are necessary for the calculation of contact forces of adhesion.

Fig. 3 shows the vectors of external forces acting on the bogie during steady motion in a circular curve. The following designations are used: F_{ij} – gravitational components of normal contact reactions; $F_{\tau ij}$ – longitudinal coupling forces acting in the plane of the wheels; F_{yij} – transverse coupling forces acting in contacts and directed parallel to the axes of rotation of wheelsets; F_{inb} is the centrifugal force of inertia of the bogie acting in the center of mass of the bogie along the radius of curvature of the curved track from its center; F_{ind} is the centrifugal force of inertia from the body acting in the pivots of the bogie from the center of the curve:

$$F_{inb}=\frac{m_b\cdot V^2}{\rho};\;\; F_{ind}=\frac{m_d\cdot V^2}{\rho}, \qquad (9)$$

where m_b is the total weight of the bogie;

m_d – half the mass of the body;

V is the speed of the car;

F_g is the centripetal force applied at the center of mass of the bogie radially to the center of curvature of the track.

The force F_g is the component of the weight of the car Q, which is related to the tilt of the car due to the rise of the outer rail h. Adhesion contact forces $F_{\tau ij}$, F_{yij} are determined as functions from pseudo-slippage in wheel-rail contact determined according to the methodology outlined in [22].

The mathematical model of fitting a bogie into a circular curve is constructed as a system of equations of the bogie's balance under the action of external forces and moments. The mechanical system of the bogie is represented as three subsystems: the bogie frame system; the system of the first wheelset; the system of the second wheelset.

Fig. 4 shows the diagram of horizontal forces acting on the first subsystem – the bogie frame. Four equilibrium equations can be drawn up for this subsystem.

Equation 1: the sum of the projections of the forces acting on the bogie frame onto the horizontal longitudinal axis of the OX coordinates:

$$\sum Fx=-(Fbx_{11}+Fbx_{12})\cdot\cos(\chi_1)+$$
$$+(Fbx_{21}+Fbx_{22})\cdot\cos(\chi_2)-$$
$$-Fby_1\cdot\sin(\chi_1)-Fby_2\cdot\sin(\chi_2)=0. \qquad (10)$$

Equation 2: the sum of the projections of the external forces acting on the bogie frame onto the horizontal transverse axis of coordinates OY:

$$\sum Fy=Fin-Fg-Fby_1\cdot\cos(\chi_1)+$$
$$+Fby_2\cdot\cos(\chi_2)+(Fbx_{12}-Fbx_{11})\cdot\sin(\chi_1)+$$
$$+(Fbx_{21}-Fbx_{22})\cdot\sin(\chi_2)=0. \qquad (11)$$

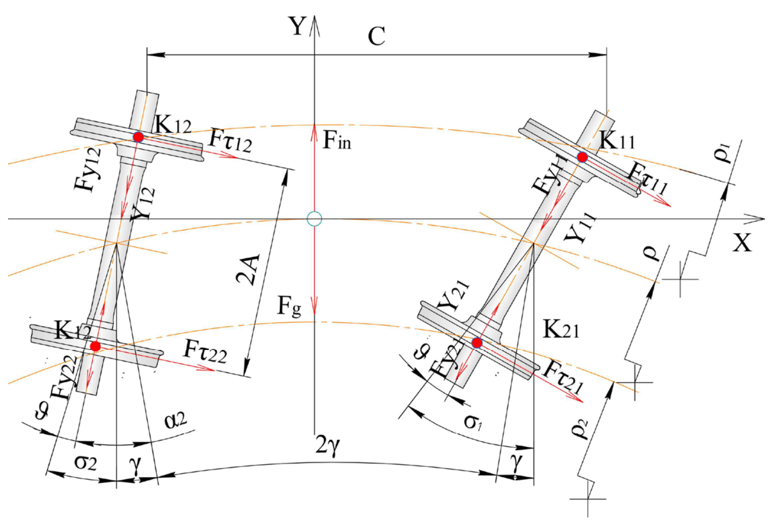


Fig. 3. Scheme of external forces acting on the bogie (projection of forces onto the horizontal plane XOY)

In equations (10), (11): χ_1, χ_2 are the angles determining the position of the wheelsets relative to the OY coordinate axis. Angles χ_1, χ_2 take into account the technological deviation in wheelset arrangement in the bogie from the rated – angles σ_1, σ_2 and the skew of the bogie in the track as a whole – angle ϑ, which is determined from formula (6):

$$\chi_j = \sigma_j - \vartheta. \qquad (12)$$

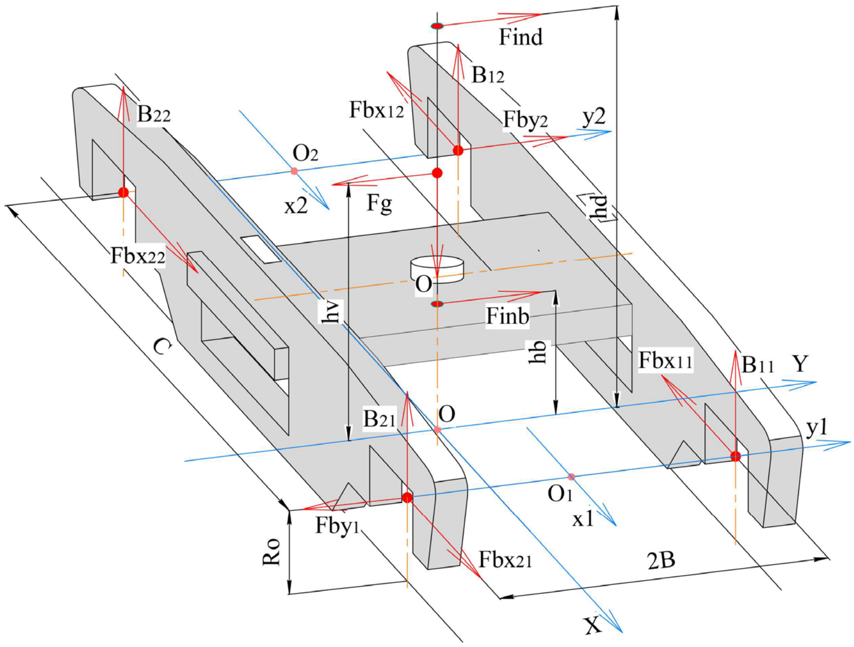


Fig. 4. Diagram of external forces acting on the bogie frame

Equation 3: the sum of the moments of external forces acting on the bogie frame relative to the center of the OXY coordinate system in the horizontal plane:

$$\sum M_{OXY} = \left(Fby_1 \cdot \cos(\chi_1) + Fby_2 \cdot \cos(\chi_2)\right) \cdot C/2 - -\left(Fbx_{11} + Fbx_{21}\right) \cdot \cos(\chi_1) \cdot B - -\left(Fbx_{12} + Fbx_{22}\right) \cdot \cos(\chi_2) \cdot B = 0. \qquad (13)$$

Equation 4: the sum of moments of external forces acting on the bogie frame relative to the center of the OYZ coordinate system in the transverse vertical plane:

$$\sum M_{OYZ} = Find \cdot hd + Finb \cdot hb - Fg \cdot hv + +\left(Fby_2 - Fby_1\right) \cdot Ro - \left(P_{11} + P_{12} - P_{21} - P_{22}\right) \cdot B = 0. \qquad (14)$$

The scheme of external forces acting on wheelsets is shown in Fig. 5.

Equations 5, 6: the sums of the projections of the forces acting on the wheelsets onto the horizontal longitudinal axes of the coordinates O_jx_j:

$$\sum Fx_1 = \left(F\tau_{21} - F\tau_{11} + Fbx_{11} - Fbx_{21}\right) \cdot \cos(\chi_1) + +\left(Y_{21} - Y_{11} - Fy_{11} - Fy_{21} + Fby_1\right) \cdot \sin(\chi_1) = 0; \qquad (15)$$

$$\sum Fx_2 = \left(F\tau_{12} - F\tau_{22} + Fbx_{22} - Fbx_{12}\right) \cdot \cos(\chi_2) + +\left(Y_{22} - Y_{12} - Fy_{12} - Fy_{22} - Fby_2\right) \cdot \sin(\chi_2) = 0. \qquad (16)$$

Equations 7, 8: sums of torques acting on wheelsets in the horizontal plane relative to the proper centers of the $O_jx_jy_j$ coordinate systems:

$$\sum M_{O_1x_1y_1} = \begin{bmatrix} \left(Fbx_{11} + Fbx_{21}\right) \cdot B - \\ -\left(F\tau_{11} + F\tau_{21}\right) \cdot A \end{bmatrix} \cdot \cos(\chi_1) = 0; \qquad (17)$$

$$\sum M_{O_2x_2y_2} = \begin{bmatrix} \left(Fbx_{12} + Fbx_{22}\right) \cdot B - \\ -\left(F\tau_{12} + F\tau_{22}\right) \cdot A \end{bmatrix} \cdot \cos(\chi_2) = 0. \qquad (18)$$

Equations 9, 10: sums of torques acting on wheelsets in the transverse vertical plane relative to the proper centers of the $O_jy_jz_j$ coordinate systems:

$$\sum M_{O_1y_1z_1} = \left(B_{11} - B_{21}\right) \cdot B + +\left(P_{21} - P_{11}\right) \cdot A + +\left(Fy_{11} + Y_{11} + Fy_{21} - Y_{21}\right) \cdot A = 0; \qquad (19)$$

$$\sum M_{O_2y_2z_2} = \left(B_{12} - B_{22}\right) \cdot B + +\left(P_{22} - P_{12}\right) \cdot A + +\left(Fy_{12} + Y_{12} + Fy_{22} - Y_{22}\right) \cdot A = 0. \qquad (20)$$

Equations 11, 12: sums of torques acting on wheelsets relative to their own axes of rotation:

$$\sum M_1 = F\tau_{11} \cdot R_{11} - F\tau_{21} \cdot R_{21}; \qquad (21)$$

$$\sum M_2 = F\tau_{12} \cdot R_{12} - F\tau_{22} \cdot R_{22}. \qquad (22)$$

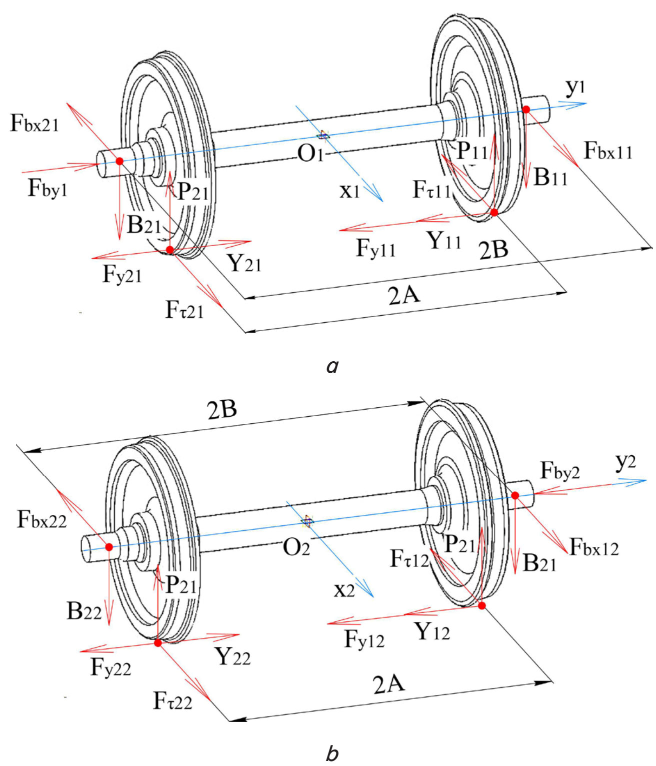


Fig. 5. Scheme of external forces acting on wheelsets from the track and the bogie frame: *a* – 1st wheelset; *b* – 2nd wheelset

The field of the numerical experiment is limited by the combination of the following input parameters: curve radii – ρ; speed of movement – V; raising the outer rail in the curve – h; the maximum permissible outstanding lateral acceleration $[a_y]$.

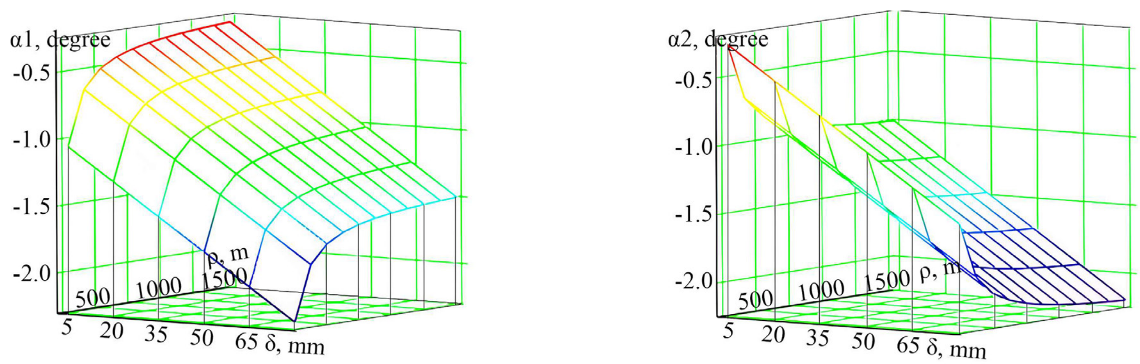
The range of values of the outstanding lateral acceleration is selected in accordance with the Memorandum of the Organization for Co-Operation between Railroads (OSJD) [23], namely:

$$1.0 \geq a_y \geq -0.4 \text{ m/s}^2.$$

The clearances of the wheelset in the rail track in operation can take values in the range from 9 to 76 mm [24]. The gap in the rail track has a significant effect on the approach angles of the wheelsets when the bogies are installed at an angle. Fig. 6 shows the estimated dependences of the approach angles of wheelsets installed in the carriage without skew α_1, α_2 on the gap of the wheelset in the rail track δ and the radius of the curve ρ. The following signs are used for approach angles: "+" – for lagging wheelset; "–" – for the approaching wheelset.

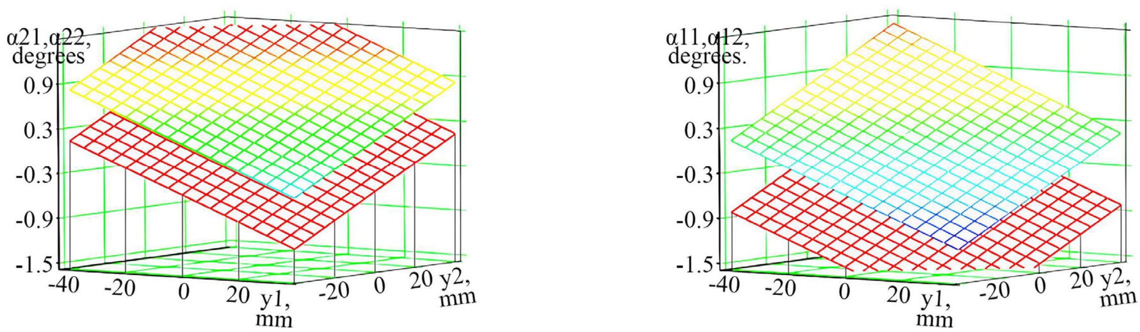
Fig. 7 shows the dependence of the approach angles of wheelsets α on the lateral movement of wheelsets y_1, y_2 relative to the track axis for different curve radii. For internal and external chord installations, the approach angles of wheelsets are: for a 300 m curve – first wheelset α_{11}=–0.28° (–0.005 rad), second wheelset α_{12}=0.28° (0.005 rad); for the 1200 m curve α_{21}=–0.114° (–0.002 rad); α_{22}=0.114° (0.002 rad).

The estimation dependences of the guiding flange force Y on the skew angles of the wheelsets in the bogie σ, the speed of movement V, and the radius of the curve ρ are shown in Fig. 8.



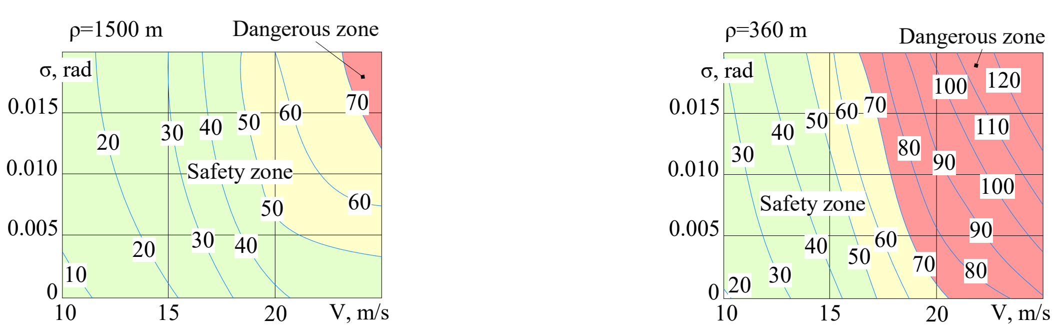
a *b*

Fig. 6. Dependences of wheelsets approach angles α (degrees) on track clearances δ (mm) and curve radius ρ (m): *a* – 1st wheelset; *b* – 2nd wheelset



a *b*

Fig. 7. Dependences of the approach angles of wheelsets $\alpha_{11}...\alpha_{22}$ (degrees) on the transverse movements of wheelsets y_1, y_2 (mm) and the radius of the curve ρ (m): *a* – ρ=300 m; *b* – ρ=1500 m



a *b*

Fig. 8. Dependences of steering forces Y (kN) on the skew angles of wheelsets in the bogie σ (rad), speed of movement V (m/s), and curve radius ρ (m): *a* – ρ=1500 m; *b* – ρ=360 m

Dependences are represented in the form of level lines, i.e., constant values of guiding forces Y. This made it possible to determine the zone of safe combinations of distortions σ and movement speeds V – the "safety zone" (green-yellow zone) and the "dangerous zone" (red zone). The dangerous zone is limited by the maximum permissible value of the guiding force [Y]=70 kN.

6. Discussion of results of determining the influence of wheelset arrangement on the level of steering forces in flange contacts

The lack of uniform international requirements for the maintenance of freight cars with bogies of type 18-100 and their analogs leads to the fact that the misalignment of wheelsets is not controlled. As a result of its occurrence, the wear of wheel flanges increases, resistance to movement grows, which lead to the occurrence of a dangerous situation of derailment of the car.

Our research is based on the fact that, according to statistics, the majority of 18-100 bogies in operation have misalignment of wheelsets in the bogies. Moreover, these misalignments have an accumulative progressive nature and can be up to 0.02 rad in operation. This is confirmed by the significant operational difference in the thicknesses of the flanges of the right and left wheels of wheelsets, as a result of long-term pressing of one side of the wheelset against one of the rails [6, 7].

Our research results can be explained by the fact that the structural distortions of the wheelsets in bogies increase the angles of approach of the wheelsets on rails and, as a result, increase the forces of pressing the flanges against the side surfaces of the rails. This, in turn, is the cause of increased wear of wheel flanges and side surfaces of the rails, as well as the deterioration of a number of operational indicators of the cars: an increase in movement resistance, a decrease in the margin of resistance against derailment, etc.

The results (Fig. 8) showed that an increase in the misalignment angles of wheelsets from σ=0 for the rated position to the maximum possible misalignment angles in operation (σ=0.02 rad) leads to an increase in the steering forces Y by an average of 1.5–2.0 times. Moreover, the degree of increase practically does not depend on the radius of the curve and on the speed of movement.

According to the results of our calculations (Fig. 6), it was confirmed that the angles of approach of wheelsets on rails increase significantly with the increase in the total clearances in the rail track. For example, when a bogie is installed diagonally in a track in a curve with a radius of 250 m, with a gap of 14 mm, the angle of approach of the first pair of wheels is –0.84° (–0.002 rad), and with a gap of 50 mm – 1.95° (–0.034 rad). In the 1000 m curve – 0.54° (–0.009 rad) and –1.65° (–0.029 rad), respectively. Thus, in the range of possible operational clearances of wheelsets in the rail track – from 14 to 65 mm – the angles of attack of wheelsets increase from minimum to maximum by 2.3–3.5 times for different curve radii. The nature of the change in the angles of approach of the wheelsets to rails due to the gaps in the track δ does not depend on the skew angles of the wheelsets σ (Fig. 6). The difference in the angles of attack of the first and second wheelsets Δα of the bogie depends on the radius of the curve and does not depend on wheelset arrangement in the bogie and the clearances of the wheelsets in the track. Moreover, Δα decreases from 0.5° (0.01 rad) for ρ=300 m to 0.15° (0.003 rad) for ρ=1250 m. These results indirectly contradict the conclusions by some researchers regarding the influence on the intensity of wear of transition flanges of the Ukrainian Railroads from the 1524 mm gauge to the 1520 mm gauge. It was found that a slight narrowing of the track, on the contrary, reduces the value of the probable angles of contact of the wheels on rails and, as a result, should reduce the intensity of wear of wheel flanges.

When the misalignment of wheelsets in the bogie increases from 0° to +0.5°, the approach angles of the approaching wheelsets increase by 2–3 times.

Analysis of the calculated results confirms the assumption of a significant dependence of the steering contact forces on wheelset arrangement in the bogie, which is determined by the misalignment of the axles relative to their rated position. At the maximum operating angles of misalignment of the wheelsets, the lateral steering forces in the flange contacts increase by 40–60 % compared to the rated setting in a wide range of speeds and curve radii.

The chosen calculation scheme can be considered correct because it takes into account the geometric and kinematic parameters of wheel and rail contact, both for new rolling surface profiles and for worn ones. Expressions (1) to (6) describe the dependence of the contact angles of wheelsets on the rails on movement parameters.

The results shown in Fig. 9 prove the significant dependence of the steering forces in the flange contacts of wheels with the rails on wheelset arrangement in the bogie frame, namely the misalignment of the axles relative to their rated position. The value of the skew should be a criterion for making a decision about the need to repair the bogie.

Countries that operate freight cars with bogies of type 18-100 and their analogs (Poland, Ukraine, Lithuania, Latvia, etc.) should pay attention to such an important factor as the cumulative skew of wheelsets in bogies.

As a further advancement of this study, we consider it expedient to carry out extensive monitoring of the condition of 18-100 bogies in the fleet of freight cars regarding the presence of misalignment of wheelsets. Taking into account that there are currently no devices for monitoring the parameters of wheelsets in bogies, designing such a measuring system is planned in the further research by our team.

7. Conclusions

1. The calculation scheme, based on a detailed description of the geometric and kinematic parameters of the flange contact of wheels and rails, is correct. On the basis of the developed calculation scheme, the dynamic fitting of bogies with different profiles of the surfaces of wheels and rails, both new and worn, can be investigated.

2. The study of the process of fitting 18-100 bogies into the curve of the track section was performed on the mathematical model of the dynamic equilibrium of the bogie when moving in a circular curve. The value of the structural deviations in the position of wheelsets in the bogies from the rated value was obtained. They significantly affect the level of lateral steering forces in the flange contacts of the wheels with rails. This, in turn, is the cause of one-sided wear of the flanges of wheelsets. At the maximum values of skew angles of 0.5° and more, the lateral steering forces in the flange con-

tacts of wheels with rails exceed the load by 40–60 % during normal installation at any speed and in curves of any radius. Therefore, there is a need to introduce into the maintenance system of model 18-100 bogies the technological operation of controlling the deviation in wheelset arrangement in the bogie.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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