

The Issue of Improving of the Design of a Railway Wheelset

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Abstract

The article analyses one of the significant drawbacks of traditional wheelsets of rail vehicles, which consists in the occurrence of elastic deformations of bending of its axis in operation. It has been established that this is due to the irrational scheme of transferring vertical loads from the topsides of the rail vehicle. The magnitudes of these angles determine the additional (elastic or plastic) displacements of the points of the contact of wheels with the rails transversely of the rail gauge when the wheelset is subjected to the static and dynamic loads during the movement. A possible way to eliminate this disadvantage of the traditional wheel pair is to change the loading scheme of its wheels with vertical loads. This is possible to perform by changing the traditional design of a wheelset and abandoning its traditional axis using independently rotating wheels (IRW). The use of wheel pairs with IRW eliminates another significant disadvantage of traditional wheelsets. It is associated with high torsion stiffness of the axles of such structures, which does not allow the wheels to rotate relatively to each other. This causes increasing of wheel slip on rails when moving in curved sections of the track and it also limits the speed of steady movement of rail vehicles in straight tracks. However, when using wheel pairs with the IRW, they are not centred in the rail gauge. At the same time there is long contacting of a flange of one of the wheels on the rail with a high level of wear. Improving the dynamics of rail vehicles with IRW and reducing wear of wheels and rails is possible by means of mechatronic systems to control the position of wheelsets in the track gauge.

KEY WORDS: *a wheel, a load scheme, a wheelset, independently rotating wheels (IRW)*

1. Introduction

When rail vehicles are moving in a track, the safety of this movement and acceptable levels of force and wear processes of interaction between a bogie and the rails should be ensured. The showing of these processes is influenced by a significant number of factors. The main ones are the construction and condition of the crew and the rail track, as well as the speed of movement. They largely determine the level of dynamic loads in curves and in straight sections of the rail gauge.

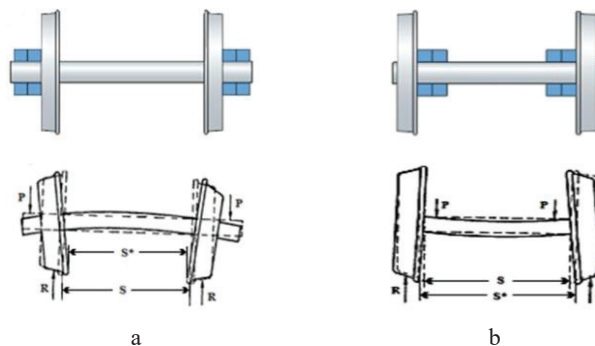


Fig. 1 Schemes of an application of loads and deformation of the axes of traditional wheelsets: a – external location of axle boxes; b – internal location of the axle boxes

Wheelsets are one of the most critical units of rail vehicles. In traditional wheelsets wheels are rigidly mounted on an axle and transfer the weight of the rail vehicle's upper structure to rails and perceive the corresponding efforts when interacting with the rail track. That is, they implement the functions of the reference, guide and brake mechanism, as well as the mover [1, 17, 24, 27]. Modern conditions of operation of wheelsets of rail vehicles determine the

increased requirements for their structural and dynamic characteristics [24].

The schematic diagram of a wheel pair consisting of an axle with two wheels mounted on it has remained unchanged for almost two centuries.

In the interaction of a rail vehicle and a track under operating conditions, the wheelsets are exposed to significant static and dynamic loads [12, 15, 16]. As a result, wheels slip occurs on the rails with elastic and plastic deformations in the contact surfaces [9, 18-20]. It also intensively proceeds the processes of wear of wheels and rails. Therefore, even with it massive constructions with large safety factors, in operation elastic deformations of the bending of the axis of the wheelset occur [8, 9]. They are due to the fact that the transfer points of the vertical loads P (Fig. 1) from rail vehicle's upper structure are offset from the sections of axle in which the wheels are mounted. The reactions R from the side of the rail track herewith act at the points of contact of the wheels with the rails. Fig. 1 shows the main schemes of application of loads and deformations of the axles of traditional wheelsets for structures with external and internal axle boxes [2, 25, 31]. Here, P_0 is the given axial load.

Considering the axis of the wheelset as a straight beam, it can be established that under the external forces acting in one of the main planes of this beam, its axis is bent in the same plane. In this case, the beams sections are not only progressively displaced, but also turn round [11]. Neglecting shear deformations, we can assume that the angle of rotation of the beam cross-section equals to the angle between the tangent drawn to the curved axis beam in this section and the non-deformed beam axis, i. e. the angle of rotation of the axis of the beam in this section.

From the physical fundamental of the bending phenomenon, it follows that the curved axis of the continuous beam must be continuous and smooth (without kinks) curve. In this case, the deformation of a particular section of the beam is determined by the curvature of its elastic line, that is, the curvature of the axis of the beam.

Taking into account the hard landing of the wheels in a wheel pair on the axle, turning its corresponding sections during bending should lead to corresponding turns of the wheels fixed on it. The magnitudes of these turns determine the additional (elastic or inelastic) displacements of the points of contact of the wheels with the rails in the transverse to axis of the rail track when the wheel pair is subjected to static and dynamic loads during the movement of vehicle.

2. Research Results

When rail vehicles are moving in a track, the safety of this movement and acceptable levels of force and wear processes of interaction between the running gear and the rails should be ensured. The showing of these processes is influenced by a significant number of factors. The main ones are the construction and condition of the crew and the rail track, as well as the speed of movement. They largely determine the level of dynamic loads in curves and in straight sections of rail gauge.

It is known that even insignificant transverse slippage at the points of contact of wheels with rails can significantly affect the conditions of their contact and the parameters of force interaction [10]. Therefore, it is necessary to estimate the magnitudes of these additional displacements and the possibility of their influence on the processes occurring in the contact of the wheels with the rails.

As calculations [11, 22] show, the axial moment of inertia of the wheel section relative to the perpendicular axis to the plane passing through the axis of the wheel pair is approximately three orders of magnitude greater than the corresponding axial moment of inertia of the wheelset axis. Therefore, the bending deformations of the wheel itself in this plane under the action of the system of loads under consideration can be neglected. At the same time, we believe that the possible displacement of the point of contact of the wheel with the rail in the across of the rail track at bending the axis of the wheel pair will depend primarily on the angle of rotation of the cross-section of the axis of the wheelset in which the wheel is mounted.

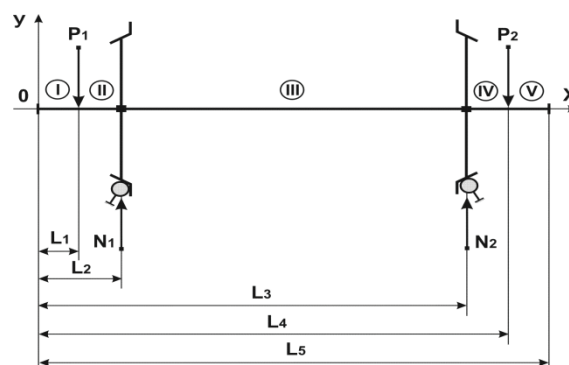


Fig. 2 A design scheme

With a simplified solution of the problem, we take the following assumptions: the axis of the wheelset is considered as a straight beam with a constant cross-section with a diameter d ; the influence of the mounted wheels on the shape of the curve of bending of the axis of the wheelset is not taken into account, the distributed application of loads to the axis of the wheelset is replaced by the single force. The design scheme of the wheelset with the vertical loads acting on it is shown in Fig. 2. We consider a rectangular x - y coordinate system with the origin in the point O on the left side of the wheelset axis. With an uniform distribution of the acting vertical loads on the necks of the axis

($P_1 = P_0/2, P_2 = P_0/2$), normal reactions from the side of the rails are $N_1 = P_0/2, N_2 = P_0/2$.

For determination of the displacements of the axis sections, it is necessary to obtain equations relating the values of the angles of rotation and deflection of the beam sections with the x coordinate along the axis length. These equations can be obtained by integrating the known basic differential equation of the curved axis of a beam [11]:

$$\frac{d^2 y}{dx^2} = \frac{M(x)}{E \cdot J_z}. \quad (1)$$

Taking into account the accepted assumptions for the beam of a constant cross-section $E \cdot J_z = const.$, after integration, we obtain the equation for determining the angles of rotation of sections of a beam:

$$\frac{dy}{dx} = \phi(x) = \int \frac{M(x)}{E \cdot J_z} \cdot dx + C = \frac{1}{E \cdot J_z} \int M(x) \cdot dx + C. \quad (2)$$

After double integration, we obtain the equation of the elastic line (the equation of the deflections of sections the axle) in the following form:

$$y(x) = \frac{1}{E \cdot J_z} \int \phi(x) \cdot dx + C \cdot x + D. \quad (3)$$

For this, it is necessary to write it in a general form of equations of bending moments $M(x)$ as a function of the coordinate x of the beam cross-section for the others sections of the beam under consideration (Fig. 2):

$$\begin{aligned} M^I(x) &= 0; \\ M^{II}(x) &= -P_1 \cdot (x - L_1); \\ M^{III}(x) &= -P_1 \cdot (x - L_1) + N_1 \cdot (x - L_2); \\ M^{IV}(x) &= -P_1 \cdot (x - L_1) + N_1 \cdot (x - L_2) + N_2 \cdot (x - L_3); \\ M^V(x) &= -P_1 \cdot (x - L_1) + N_1 \cdot (x - L_2) + N_2 \cdot (x - L_3) - P_2 \cdot (x - L_4). \end{aligned} \quad (4)$$

Then expressions (4) are substituted into Eqs. (2)-(3) and integrated. Since the expressions of bending moments for segments $I - V$ are different, the equations of the elastic line are also different in these segments. Therefore, the integration of equations (4) must be performed separately for each segment. The integration constants C and D for each segments of the beam can be determined from the boundary conditions, for example: $y^{II}(L_2) = y^{III}(L_2) = 0$, $y^{III}(L_3) = y^{IV}(L_3) = 0$, $\phi^{II}(L_2) = \phi^{III}(L_2)$, $\phi^{III}(L_3) = \phi^{IV}(L_3)$ etc.

Determining the displacements for beams having several segments can be quite laborious, since for n segments the number of arbitrary constants (C and D) increases to $2 \cdot n$. To reduce the computational work, we use the method of initial parameters [3-5], which allows for any number of segments of the beam to provide a solution for finding only two constants – deflection and rotation angles of a section at the origin:

$$C = \phi(x=0) = \phi_0; \quad D = y(x=0) = y_0, \quad (5)$$

where, ϕ_0, y_0 – are angles of rotation and deflection of the beam section at the origin.

Using the Clebsch method, we integrate equations (2) and (3) on all selected segments of the axis of the wheelset without opening the brackets. The universal equations of the method of initial parameters in relation to our problem are:

$$M(x) = \sum_i M_i + \sum_i F_i \cdot \frac{(x - L_{F_i})^1}{1!}; \quad (6)$$

$$\phi(x) = \phi_0 + \frac{1}{E \cdot J_z} \cdot \left[\sum_i M_i \cdot \frac{(x - L_{M_i})^1}{1!} + \sum_i F_i \cdot \frac{(x - L_{F_i})^2}{2!} \right]; \quad (7)$$

$$y(x) = y_0 + \phi_0 \cdot x + \frac{1}{E \cdot J_z} \cdot \left[\sum_i M_i \cdot \frac{(x - L_{M_i})^2}{2!} + \sum_i F_i \cdot \frac{(x - L_{F_i})^3}{3!} \right], \quad (8)$$

where L_{F_i}, L_{M_i} are coordinates of sections in which the corresponding forces are applied, bending the axis of the wheelset.

Having determined the integration constants y_0 and ϕ_0 from the boundary conditions, using dependencies (7),

(8), we can create graphs characterizing the bending of the axis of the wheelset and calculate the angular and linear deformations of the axis in the sections of interest.

Fig. 3 shows the example of graphs characterizing the angles of rotation of the cross-sections $\vartheta(x)$ and deflections of the axis of the wheelset $y(x)$ with the axis diameter $d = 0.17$ m under the influence of the vertical loads applied to the journals of the axis $P_0/2$.

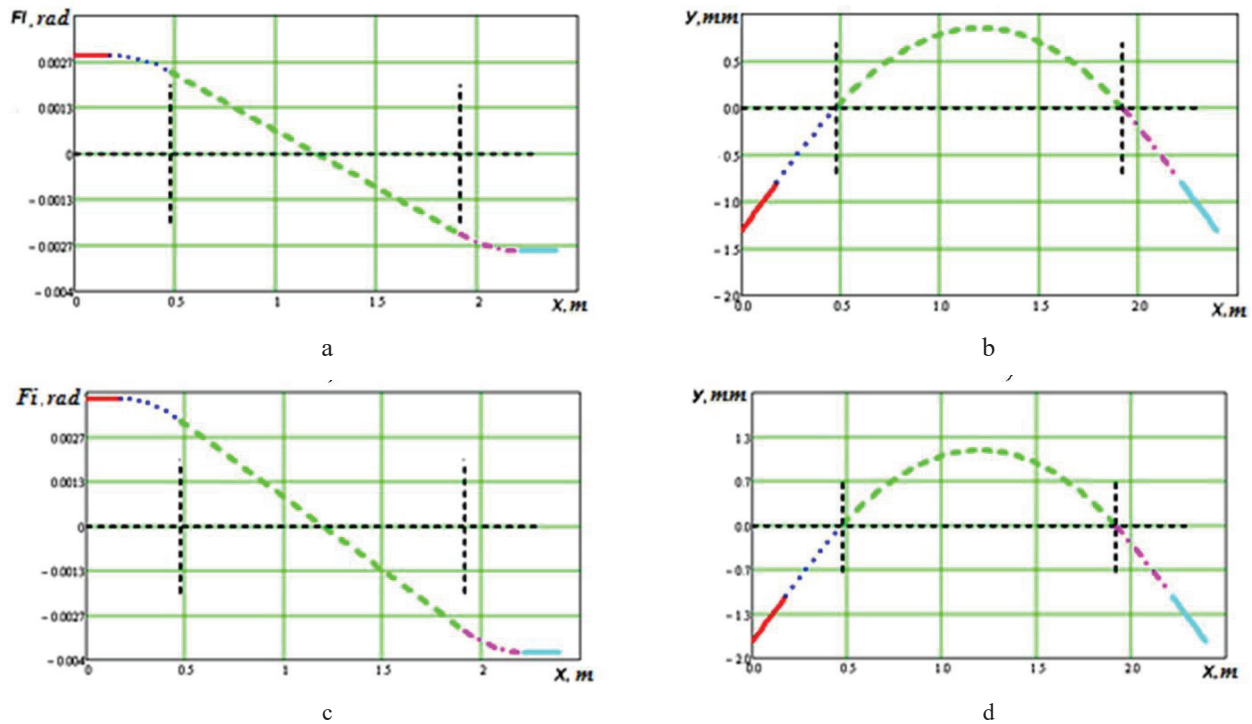


Fig. 3 Graphs of dependencies of $\vartheta(x)$ and $y(x)$ for bending of the wheelset: a – dependence of $\vartheta(x)$ for $P_0/2 = 90$ kN; b – dependence of $y(x)$ for $P_0/2 = 90$ kN; c – dependence of $\vartheta(x)$ for $P_0/2 = 120$ kN; d – dependence of $y(x)$ for $P_0/2 = 120$ kN

Analysis of the results of the calculations shows the following. Under the existing loading scheme of the wheelset with the static vertical loads in the range from 90 to 120 kN, the angles of rotation of the axle sections in which the wheels are rigidly fixed, can be from 0.0024 to 0.0032 rad for proposed initial conditions (positive angles of rotation of the sections, we think the angles when turning sections of counterclockwise). Corresponding to these angles of rotation, possible additional displacements of the points of the contact of each wheel with the rail in the direction perpendicular to the longitudinal axis of the rail track can be from 1.12 to 1.49 mm.

The main geometrical parameters of wheelsets are strictly regulated in terms of movement safety. Therefore, for example, the distance between the inner edges of the wheel flanges in the wheelsets intended for movement on the 1,520 mm rail track with speeds up to $120 \text{ km} \cdot \text{h}^{-1}$ should be $1,440 \pm 3$ mm [1]. However, the results of calculations described above show, that only due to the shortcomings of the existing loading circuit of a traditional wheelset with the static vertical loads, the distance between the wheels of the wheelset during crew movement in operation can decrease about 3 mm and taking into account the influence of dynamic processes and more. Under the influence of intensive dynamic processes, this value can be much higher.

It can be assumed that the noted possibility of additional transverse wheel slippage along the rails, due to the traditional design of the wheelset, during the movement of rail vehicles the negative effects on the processes of wear of the wheels and rails, significantly intensifying them. Therefore, for example, the presence of cyclic bending of the axis of the wheelset with the traditional loading pattern determines the uneven wear of the liners of the motor-axial bearings along their length. To avoid this, the inner surface of these liners is in the form of a hyperbola [27].

This structural disadvantage of the traditional driving wheelset, in addition to the intensification of wear processes in the contact of wheels with rails, should also have a negative impact on the implementation of traction and braking efforts by increasing the level of transverse slippage of the wheels along the rails, especially with a sufficiently high intensity of spatial oscillations of the railroad rail vehicle upper structure.

Summarizing the above, it can be noted that the traditional design of a wheelset of rail vehicles with a rigid wheel attachment to the axle has a significant drawback associated with the transmission of vertical loads on the wheels from the upper structure eccentrically (that is, not in those sections where the wheels are mounted on the axle). This causes deformations of the bending of the axis of the wheelset and the additional transverse movement of the points of the contact of the wheels and rails relatively to the rails during the movement of a rail vehicle.

One of the ways to eliminate this drawback is to change the load scheme of the wheels vertical loadings.

Obviously, this is only possible, if the traditional design of a wheelset is changed and the traditional axis is abandoned [1, 2, 10, 29, 31]. Fig. 4 shows some load schemes for such wheelsets (pairs of wheels).

It should be noted that the use of wheelsets (pairs wheel) of such design schemes allows to eliminate another significant drawback of traditional wheelset designs. It is associated with the high torsion stiffness of the axes of such structures, which does not allow relative rotation of the wheels relative to each other. The rigid coupling of the wheels of the wheelset in the torsion direction causes increased slippage along the rails when moving in curved sections of the track, and also limits the speed of steady movement of rail vehicles in straight sections of tracks.

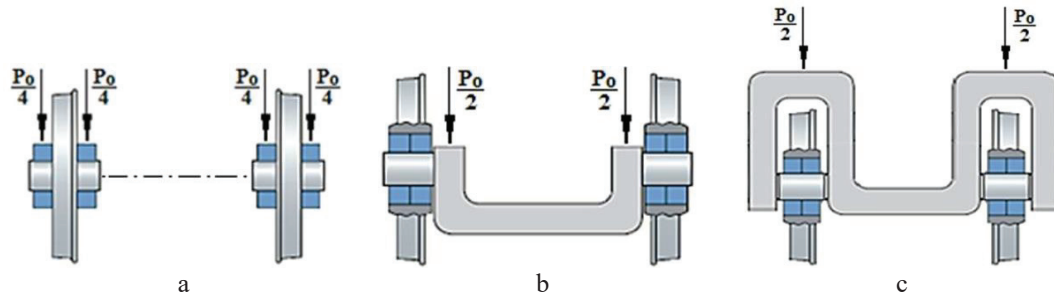


Fig. 4 Schemes of wheelsets with a rotational transfer of vertical loads from the upper structure to the wheels

However, studies show that wheelsets with IRW in accordance with the schemes of Fig. 4 are not centred in the rail gauge. In this regard, there is a long contact of the flange of one of the wheels and the rail and an increased level of their wear and resistance to movement [4, 5, 10, 30, 31]. Therefore, designs of running gears with independently rotating wheels are mainly used in urban rail vehicles with low floors, where the wear of the wheel flanges is low due to low speed and low axle load [2, 31]. In the case of the use of such structures on the magistral rail transport, it is necessary to take additional measures to ensure the self-centering of such wheelsets in the rail gauge [13, 14, 28]. For example, Talgo running gears, are being successfully used for several decades thanks to the original concept of the direction of wheelsets on a rail track [29].

A certain reduction in slipping of wheel flanges on rails can be achieved by improving the design schemes of the wheels themselves. Some from them provide the possibility of independent rotation of their support and guide surfaces [21, 26].

Structures that provide limited possibility for independent rotation of the wheels in the wheel pair relative to each other through the use of innovative axle structures and wheel attachment assemblies on it [2, 6, 18] are also being investigated.

One of the most currently developed areas of research in improving the dynamics of rail vehicles with IRW, reducing wheel and rail wear and resistance of movement is the use of mechatronic systems to control the position of wheelsets with IRW in a rail track in the horizontal direction. The results of numerous theoretical and experimental studies [6, 7, 23] confirm the effectiveness of this approach.

3. Conclusions

One of the significant drawbacks of traditional wheelsets of rail vehicles is that in operation, elastic deformations of the bending of her axis arise. They are due to the displacement of the points of application of vertical loads from the upper structure from the sections of the axis of the wheelset in which the wheels are mounted.

One of the ways to eliminate this drawback is to change the load scheme of the wheels with the vertical loads. Obviously it is possible only when changing the traditional design of the wheelset (abandoning its traditional axis and using IRW). In addition, the use of wheel pairs (pair wheels) with IRW eliminates another significant disadvantage of traditional wheel sets. It is associated with the high torsion stiffness of the axes of such structures. It does not allow the wheels to rotate relative to each other and causes their increased slippage along the rails when moving in curved sections of the track, and also limits the speed of steady movement of rail vehicles in straight.

However, when using wheel pairs with IRW, they are not centred in the track gauge. At the same time, there is a long contacting of the flange of one of the wheels with the rail and an increased level of their wear.

The most effective improvement of the dynamics of rail vehicles with IRW and reduction of wear of wheels and rails is possible through the use of mechatronic systems to control the position of wheelsets in the track gauge.

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