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POSSIBILITIES OF IMPROVING A RAIL VEHICLE RUNNING SAFETY WITH INDEPENDENTLY ROTATING WHEELS

Summary. This work is focused on the possible ways of improving the running safety of a railway vehicle, which uses IRWs (independently rotating wheels) in a bogie. It discusses the main positive and negative properties of an application of IRWs for a railway vehicle while it is running in a curve. There are evaluated running properties of a railway vehicle in terms of safety for IRWs and a standard wheelset (SW). It is assumed that a wheelset design with IRWs will reduce the risk

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of derailment of a railway vehicle in a curve with a smaller radius because it will be reached a more favourable distribution of decisive forces in the wheel/rail contact. A designed wheelset with IRWs differs from other IRWs designs; in this case, only a flange can rotate independently from a wheel treat surface about the axis of rotation. Further, this research presents an analysis of a friction forces distribution of the friction forces in a contact of a flange and a rail head and a comparison with an SW. The obtained results allow concluding that it is advisable to use the wheels with the perspective wheel design (including independently rotating) to reduce the resistance to movement and improve the running properties of a railway vehicle for safety.

Keywords: rail vehicle; running safety; independently rotating wheels; mathematical calculation

1. INTRODUCTION

Research in the last decades has focused on the design of railway vehicles and their running properties to improve dynamical properties for running safety [1, 2]. It mainly relates to increasing the running speed of railway vehicles, reducing the wear of railway wheelsets and rails and other important facts. However, the factors described above are not only associated with the high speed but, on the contrary, with the low speed of a railway vehicle as well. The risk of derailment of a railway vehicle, a shorter lifetime of its wheels and rails, a higher level of noise and other negative effects also occur while a railway vehicle runs at lower speed and mainly in curves with smaller radii. In such cases, a standard wheelset (SW) of a railway vehicle does not sufficiently meet the demand of the smallest possible angle of attack (it is given by wheelset guidance, etc.). Therefore, longitudinal slippage, as well as the running resistance, arise. The use of IRWs instead of SWs in a bogie for urban railway vehicles (that is. mainly for trams), is one of the possible ways of reducing the described negative effects [3-9].

When IRWs are mounted on a railway vehicle bogie, wheels rotate either as a whole (a flange with a wheel tread surface) or as two parts (a flange rotates independently from a wheel tread surface) about an axis of rotation. Such a technical solution helps to eliminate slippage in the longitudinal direction, which results in reducing running resistance when a railway vehicle runs in curves. Improvements of running behaviours of a railway vehicle with IRWs are mainly [3]:

- reduce wagging at high speeds,
- reduce wear of contact surfaces of a rail and a wheel with a flange,
- improve railway vehicles behaviours related with running in curved sections of a railway track, as it practically eliminates of components the creep forces in the longitudinal direction.

Hence, two wheels of one IRW pair rotate at various speeds. Subsequently, this causes minimal values of creep forces in the longitudinal direction, ensures the moment for controlling the wheelset motion and centres a wheelset in the longitudinal axis of the railway track. On the contrary, the angle of attack of the wheelsets is being increased; therefore, the wear of tread surfaces of the wheels and rails also increase together with the values of the lateral forces. Higher values of the lateral forces lead to higher values of the derailment quotient, which means a higher risk of derailment of a railway vehicle.

2. ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

Relatively, many technical solutions attempt to eliminate the disadvantages of using IRWs in bogies. Some technical solutions include the application of a joint between a wheel and an axle, which has prescribed certain elastic characteristics. The simplest solution is the mounting of a wheel with a flexible element (usually rubber-based elements) to an axle [7]. However, IRWs with rubber elements are not suitable for railway vehicles, which run at higher speeds.

Other technical designs are based on more complicated systems that require using specific components to ensure increasing the torsional flexibility of the axle of a wheelset. The principle of their functionality is that they allow locking the wheels on an axle when a railway vehicle runs on a straight track section, and thus, it behaves as a railway vehicle with SWs. However, when a railway vehicle with this device enters a curve, the device is activated, and it unlocks the wheels, so they can rotate independently on an axle [9]. Pioneers of this approach are believed to be specialists from the MBB Company (Germany). They have developed large studies based on both theoretical backgrounds and experiments. As a regulator, they have applied a clutch working with magnetic powder.

One of the ways of ensuring the optimal interaction of wheels and rails of rail vehicles (with IRWs) to minimise lateral forces together with, is the use of a specialized mechatronic system to monitor the position of a wheelset in the horizontal plane [11-14]. In rail vehicles bogies with radial guidance of wheelsets, the angles of attack of the wheelsets regarding a track when it is running in curves are close to zero. Among the most known bogies with a system ensuring the additional movement of a wheelset in a bogie are those with [15, 16]:

- a system for a self-centring wheelset,
- a system allowing a semi-forced guidance of a wheelset,
- a system allowing a forced guidance of a wheelset.

The results of numerous studies [17-25] have shown an increased propensity of rail vehicles with IRWs to derailment by climbing of the wheel flange on a rail head. The absence of longitudinal creep forces when the IRW moves on a rail means that the friction forces in the wheel/rail contact act entirely in the lateral direction. It results in a risk when the wheel flange can climb on a rail. This risk increases with the decreasing distance of a flange lifting [19, 22]. Furthermore, the results of the research [20] show that the value of the longitudinal forces in the contact of a wheel and a rail directly increases with the value of the Y/Q ratio. This ratio is called the derailment quotient. Hence, the Nadal criterion, which characterizes the conditions where the flange can climb to a rail head, can be softened and this depends on which values the longitudinal forces reach in the contact of a wheel and a rail. The creep forces in the longitudinal direction support the redistribution of the friction forces components in the contact of a wheel and a rail. This decreases the effective friction coefficient and increases the Y/Q ratio, which is required for the derailment of a railway vehicle [23].

Research in this field has demonstrated more or less satisfying results, hence needs further investigation.

In comparison with the IRWs described above, this work is aimed at research relating to the application of IRWs with the perspective wheel design (PWD). This technical design is characterized by a rotating wheel flange relative to the wheel tread surface, which for this work, are IRWs with traditional wheel design (TWD).

Generally, during the moving of a wheel on a rail, contact points of the wheel tread surface and the flange move in a space and they perform a complex spatial movement with a cycloidal trajectory [24]. In the case of the SW with a TWD type, parasitic differential slip arises, as between the geometric parameters of the rolling surfaces of a railway wheel and the kinematic parameters of movement is certain dissonance [25-29]. Thus, the wear intensity of surfaces of a railway wheel and a rail is given by the power of the friction forces. It is more noticeable in the curved sections of a railway track [30-33]. One way of decreasing consumed energy together with wear in curves is to lubricate the contact surfaces. However, this does not adequately solve the problem.

The main objective of this contribution is to present the possibilities of improving a railway vehicle's running properties for safety, which are equipped by the IRW of the PWD type.

3. STATEMENT OF THE MAIN MATERIAL

The distribution of forces, which are important for the evaluation of the risk of derailment of a railway vehicle, is shown in Figure 1. It captures the situation when it begins to climb on a rail head. The individual forces are as follows: R is a general reaction, P_Z is a magnitude of forces in a vertical direction, and Y_G is a magnitude of forces in a horizontal direction.

The following formulations describe the common magnitude of reaction forces in the contact of a flange and a rail head:

$$R = \sqrt{P^2 + Y^2} \quad (1)$$

$$N = R \cdot \sin(\pi - \beta - \varphi_0) \quad (2)$$

$$\varphi_0 = arctg(P/Y) \quad (3)$$

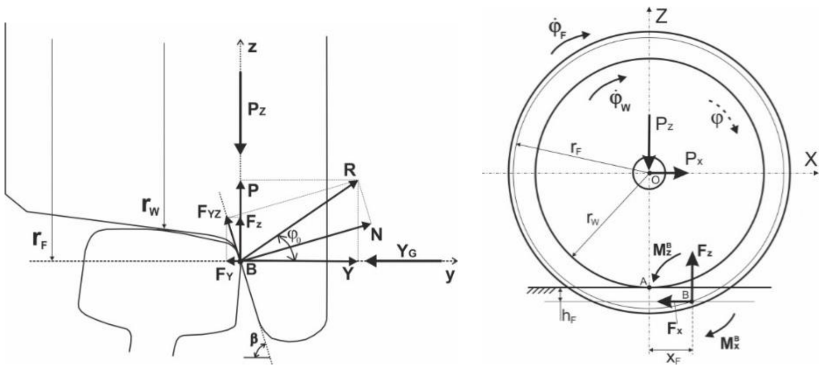

Fig. 1. Distribution of forces in the contact of a flange and a rail head at the moment of climbing: front view (left), side view (right)

The design of a wheelset with the IRWs PWD type allows the flange to rotate relative to the tread surface of the wheel in the given coordinate system; it increases the number of degrees of freedom to the solved mechanical system. Equations of equilibrium of the forces in the z-axis direction and the moments about the B contact point are as follows (Figure 1, right):

$$\sum F_i^Z = 0, \ \sum M_i^B = 0 \quad (4)$$

Where:
$\sum F_i^Z$ - the sum of the forces, which act on the wheel in the axis O_Z direction,
$\sum M_i^B$ - the sum of the moments of the forces about the *B* point.

Then:

$$\sum F_i^Z = Y_Z + F_Z - P_Z = 0 \tag{5}$$

Where:
Y_Z - the component of a reaction of the guiding force Y_G in the vertical direction,
F_Z - the component of the friction force in the contact of the flange and the rail head in the vertical direction,
P_Z - the sum of the forces generated by the wheel gravity and the weight of a railway vehicle corresponding to the wheel.

The process of derailment of the wheel starts at the moment, when the wheel surface (with the PDW type) begins to leave the rail head surface (point *A*). At this moment, the centre of rotation of the wheel moves to point *B* (Figure 1). This sliding movement continues up to the rail head in the O_Z axis direction. This is caused by the component of the reaction Y_Z in the vertical direction, at which, the force Y is the guiding force. The value of the Y_Z force component is given by the formulation:

$$Y_Z > P_Z - F_Z \tag{6}$$

Herein:

$$Y_Z = \frac{Y_G}{\tan\beta} \tag{7}$$

The values of the forces, which are used in formulations 6 and 7, that is, force P_Z and Y_G, are given and they can be changed. Further, the calculation process requires estimating the force F_Z. At the earliest, there have been analysed properties of the movements of the wheels for the TWD type of wheel and the PWD type of wheel for a two-point contact [26-30]. The results of analyses of the TWD type of the railway wheel reveal that the unambiguous determination of the modulus and the direction of the vector of the friction force depends on the geometric characteristics for the contact of the wheel and the rail and the wheel angular speed. However, the railway wheel of PWD type needs to determine the two parameters mentioned above the additional parameter, namely the ratio expressing angular velocity of the tread surface of a wheel and a flange about their mutual axis of rotation. Then, the following formulations can be considered:

$$F_X^i = \mu \cdot N \cdot \cos\delta^i \cdot \cos\chi^i \tag{8}$$

$$F_Y^i = \mu \cdot N \cdot \sin\delta^i \tag{9}$$

$$F_Z^i = \mu \cdot N \cdot \cos\delta^i \cdot \sin\chi^i \tag{10}$$

Index “*i*”, which appears in equations 8 to 10 means, for which wheel design are these forces calculated. The PWD type of a wheel is marked by a “*”.

Formulations for the determination of the parameters δ or δ^* are as follows:

$$\delta = \operatorname{arctg}\left(\frac{\sin\chi}{\operatorname{tg}\beta}\right),\ \chi = \operatorname{arctg}\left(\frac{(r_W + h_F)\cdot \operatorname{tg}\psi \cdot \operatorname{tg}\beta}{h_F}\right) \tag{11}$$

$$\delta^* = \operatorname{arctg}\left(\frac{\sin\chi^*}{\operatorname{tg}\beta}\right),\ \chi^* = \arcsin\left(\frac{(r_W + h_F)\cdot \operatorname{tg}\psi \cdot \operatorname{tg}\beta}{\sqrt{((K_w - 1)\cdot r_W - h_F)^2 + ((r_W + h_F)\cdot \operatorname{tg}\psi \cdot \operatorname{tg}\beta)^2}}\right) \tag{12}$$

where:

$K_W = \dot{\varphi}_W / \dot{\varphi}_F$,

ψ - is the angle of attack of the considered wheel,

β - is the angle, which gives the slope of the flange of a wheel relative to the horizontal plane.

These subsequent formulations enable the calculation of the component of the friction force for both TWD and PWD types of wheels in the vertical direction:

- the TWD type of wheel:

$$F_Z = \mu \cdot N \cdot \cos\delta \cdot \sin\chi = \mu \cdot \sqrt{P_Z^2 + Y_G^2} \cdot \sin(\beta + arctg(P_Z / Y_G)) \cdot \cos\delta \cdot \sin\chi, \tag{13}$$

- the PWD type of wheel:

$$F_Z^* = \mu \cdot N \cdot \cos\delta^* \cdot \sin\chi^* = \mu \cdot \sqrt{P_Z^2 + Y_G^2} \cdot \sin(\beta + arctg(P_Z / Y_G)) \cdot \cos\delta^* \cdot \sin\chi^* \tag{14}$$

Next, condition (6) can be written as:

$$Y_G / tg\beta > P_Z^i - \mu \cdot \sqrt{P_Z^2 + Y_G^2} \cdot \sin(\beta + arctg(P_Z / Y_G)) \cdot \cos\delta^i \cdot \sin\chi^i \tag{15}$$

Now, it is possible to characterize a coefficient of movement stability K_S^i of a wheel regarding derailment:

$$K_S^i = (D - \mu \cdot \sqrt{D^2 + 1} \cdot \sin(\beta + arctg(D)) \cdot \cos\delta^i \cdot \sin\chi^i) \cdot tg\beta \tag{16}$$

where: $D = P_Z / Y_G$.

The wheel begins to climb on the rail head, when the coefficient reaches values lower than 1, that is, $K_S^i < 1$.

Figure 2 depicts the waveform of the calculated values of the K_S^i safety coefficient for a TWD type of wheel and a PWD type of wheel. Curves are determined for the following parameters: ψ = 0.015, K_W = 1.021 and P_Z = 125 kN.

By analysing the graphs shown in Figure 2, we can observe that the value of the coefficient K_S characterizing the margin of stability of the wheels from derailment, when the flange is climbing at the initial stage of this process, depending on the guiding force Y_G magnitude and it is practically the same for railway wheels of both types. Differences in values of the K_S coefficient are determined by the effects of the considered wheel type on the distribution of individual components of the friction force. Particularly, the effect of the component of the friction force in the vertical direction.

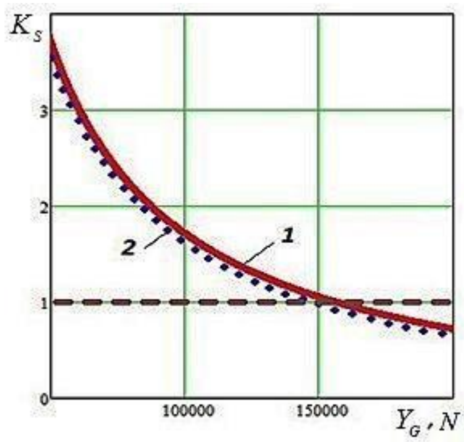

Fig. 2. The waveform of the safety coefficient $K_S = f(Y_G)$: 1 – the TWD of a wheel, 2 – the PWD type of a wheel

In this considered case, the value of this K_S coefficient gives an idea of whether the flange of a railway wheel can climb to a rail head.

The criterion of running safety calculated for the risk of derailment is one of the most important data for railway vehicle running safety [19, 22, 25]. The Nadal criterion (usually marked as K_N) expresses a standard condition from the viewpoint of running stability [31]. Based on this criterion, the demand for running safety given the derailment risk of a railway vehicle must meet the following condition:

$$K_N = K_{Nad} \cdot \left(\frac{G}{V}\right) > \left[K_N\right] \tag{17}$$

where:

K_{Nad} - is the normalized Nadal factor, which reflects the limit of the ratio G/V,

$[K_N]$ - is the limit value for the stability coefficient.

Further:

$$K_{Nad} = \frac{tg\beta - \mu}{1 + \mu \cdot tg\beta} \tag{18}$$

where:
μ - is the friction coefficient of friction between the flange and the rail head.
G - the horizontal force of pressure of the attacking wheel on the rail;
β - the angle of inclination of the generatrix of the wheel flange to the horizontal line;
V - the vertical force of pressure of the attacking wheel on the rail;

The solved task requires modifying the traditional criterion for the evaluation of railway vehicle stability.

It is interesting to determine the friction force magnitude (depicted as F_{YZ}). This force acts in the plane marked as YOZ. Its value is calculated following equations 9 and 10 as follows:

$$\begin{aligned} F_{YZ}^i &= \sqrt{(F_Y^i)^2 + (F_Z^i)^2} = \sqrt{(\mu \cdot N \cdot \sin\delta^i)^2 + (\mu \cdot N \cdot \cos\delta^i \cdot \sin\chi^i)^2} = \\ &= \mu \cdot N \cdot \sqrt{(\sin\delta^i)^2 + (\cos\delta^i \cdot \sin\chi^i)^2}. \end{aligned} \tag{19}$$

Thereafter, the value of the friction coefficient μ_{YZ}^i is determined by the formulation:

$$\mu_{YZ}^i = \mu \cdot \sqrt{(\sin\delta^i)^2 + (\cos\delta^i \cdot \sin\chi^i)^2}. \tag{20}$$

There are certain differences in the values of angles marked as δ^i and χ^i for individual variants of the technical solutions of the designed wheels. Then, the values of the Nadal criterion are calculated as follows:

- for a wheelset with the TWD type:

$$K_N = \frac{tg\beta - \mu \cdot \sqrt{(\sin\delta)^2 + (\cos\delta \cdot \sin\chi)^2}}{1 + \mu \cdot \sqrt{(\sin\delta)^2 + (\cos\delta \cdot \sin\chi)^2} \cdot tg\beta} \cdot \left(\frac{G}{V}\right) > \left[K_N\right] \tag{21}$$

- for a wheelset with the PWD type:

$$K_N^* = \frac{tg\beta - \mu \cdot \sqrt{(\sin\delta^*)^2 + (\cos\delta^* \cdot \sin\chi^*)^2}}{1 + \mu \cdot \sqrt{(\sin\delta^*)^2 + (\cos\delta^* \cdot \sin\chi^*)^2} \cdot tg\beta} \cdot \left(\frac{G}{V}\right) > \left[K_N\right] \tag{22}$$

In the case of the requirement to evaluate the derailment criterion depending on the design of a wheel, the ratio $\Delta K_N = K_N^* / K_N$ is quantified. This ratio is calculated for the same number obtained from the ratio G/V. Figure 3 shows the dependence of the parameter $\Delta K_N = f(\psi, K_W)$.

From the graph, it can be seen that there is a certain range of such operating parameters, for which the reached Nadal criterion values for the wheel with the PWD type are lower in comparison with the Nadal criterion values for the wheel with the TWD type. This is because the design of the wheel influences the friction force distribution in contact with the wheel and the rail.

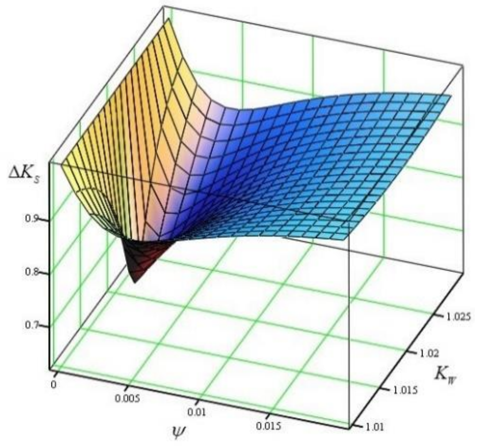

Fig. 3. Dependence graph $\Delta K_N = f(\psi, K_W)$

Figures below (Figures 4 and 5) depict the comparison of the results of the moments calculated for the TWD type as well as the PWD type of a railway wheel for particular parameters as follows: Y_G = 50 kN, K_W = 1.021, P_Z = 125 kN, h_F = 0.01 m, r_W = 0.475 m, μ_r = 0.25.

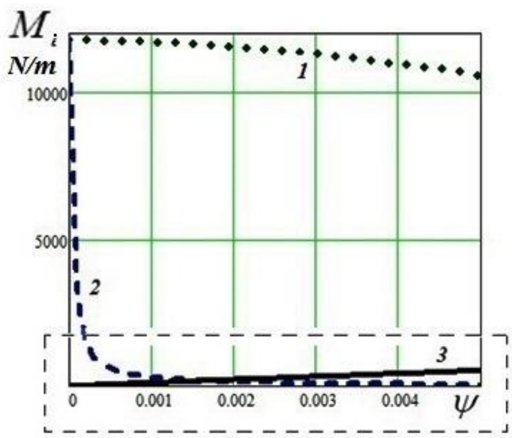

Fig. 4. Graph depicting the dependency of the values of $M_i = f(\psi)$: 1 - M_{X1} = f(ψ) (TWD type of wheel), 2 - $M_{X2} = f(\psi)$ (PWD type of wheel), 3 - $M_Z = f(\psi)$

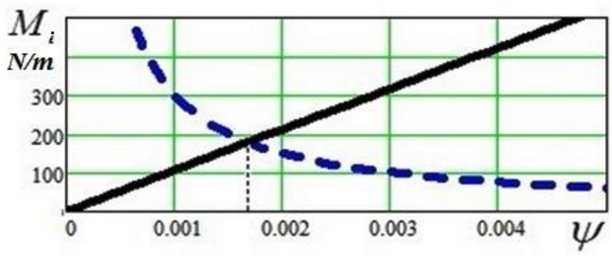

Fig. 5. Detail of the graph depicted in Figure 4

As seen from the graphs depicted in Figures 4 and 5, the value of the moment M_Z is higher than the value of the moment M_X for a railway wheel with the PWD type, although the angle of attack is quite small (that is, for the value of $\psi > 0.0017$ rad or about 0.1°).

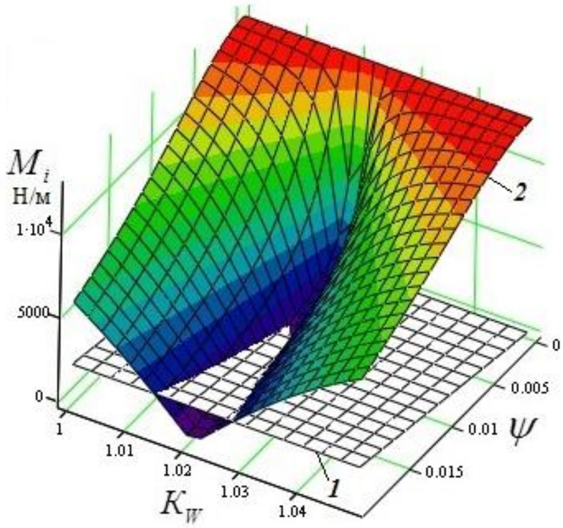

Fig. 6. Dependency graphs $M_i = f(\psi, K_W)$: 1 - $M_Z = f(\psi, K_W)$, 2 - $M_Z = f(\psi, K_W)$

Figure 6 highlights the results of the calculation of the moment M_i for the given parameters for the PWD type of a railway wheel. It can be recognized that the described behaviour of the PDW type of a railway wheel is specific for an obvious range of values K_W.

4. CONCLUSION

The research results revealed interesting findings. Practically, conditions for the beginning of climbing of the wheel flange on a rail head are the same for IRWs with the TWD type and the IRWs with the PWD type. The Nadal criterion was used for the calculation of the derailment factor in this work. This criterion considers the effect of the angle of attack of a wheel as well as the behaviours of the type of IRW. The reached results showed that the calculated values of the modified Nadal criterion are a bit smaller for the PWD type of a wheel in comparison with the considered criterion for the TWD type of a wheel. This is because the design of the railway wheel influences the distribution of the friction forces in contact with the flange and the rail. However, this is not critical for using the PWD of wheels. Performed analyses have determined, in this case, that the angle of attack is higher than $1.7\cdot10^{-4}$ rad, the IRW with the PWD type practically does not roll on a rail. The wheel flange with the PWD type tends to rotate to the opposite side relative to the direction of the wheel in which it moves. Hence, it seems expedient to apply railway wheels with the IRW of the PWD type in a bogie of a railway vehicle with IRWs to improve the running properties for safety.

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