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ANALYSIS OF STRESSES IN THE CONTACT ZONE BETWEEN THE ELECTRIC LOCOMOTIVE WHEEL PAIR AND THE RAIL

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Annotation: The article analyzes the stresses arising in the contact zone between the wheel pair and the rail in freight electric locomotives based on Hertz's theory. The calculations were performed under conditions of an axial pressure of 23 t and a speed of 110 km/h. The results showed that the maximum normal stresses in the contact zone are in the range of 935-1080 MPa. It was established that the wheel radius and dynamic loads have a significant influence on the increase in stress. The obtained results make it possible to develop practical recommendations for increasing the service life of the wheel-rail system.

Keywords: Electric locomotive, wheel-rail contact, voltage, Hertz theory, dynamic load.

Introduction. Rail transport plays an important role in global freight and passenger transportation. According to the International Railway Union, rail transport accounts for 40-45% of the world's cargo transportation volume, while in developed regions this figure exceeds 50%. The increase in freight volumes increases the mechanical load on electric locomotives and rail infrastructure.

The reliable operation of an electric locomotive largely depends on the contact zone between the wheel pair and the rail. This zone transmits the weight and traction, braking forces of the electric locomotive, and the highest stresses arise. According to statistics, 60-70% of railway malfunctions are associated with problems with wheel-rail contact, and their repair accounts for up to 30% of operating costs.

In freight electric locomotives, contact stresses can reach 800-1200 MPa at an axial pressure of up to 23 tons and a speed of up to 110 km/h. These values are close to the elastic limit of the materials and lead to plastic deformation, fatigue, and the formation of microcracks during long-term operation. High stresses in the contact zone accelerate the breakage of rails and wheels and negatively affect the stability of train movement.

Therefore, the analysis of stresses in the contact zone of the electric locomotive wheel-rail and the determination of the patterns of their distribution are of great importance in increasing the operational reliability of railway transport. The purpose of the research is to study contact stresses under the conditions of freight electric locomotives and to assess their influence on the materials of rails and wheels.

Materials and methods

This study is aimed at determining and analyzing the stresses arising in the contact zone between the electric locomotive wheel pair and the rail, and the wheelset of a freight electric locomotive operating on mainline railways and the rail of type R65 were selected as the object of research. The research conditions were brought as close as possible to real operating conditions.

Object of research and main parameters. The following operational and geometric parameters were adopted for the calculations:[4]

Electric locomotive bullet load - 23 tons
Maximum speed - 110 km/h;
Wheel pair diameter - 1250 mm;
Wheel width - 140 mm;
Wheel profile - a standard conical profile widely used on railways;
Track type - R65;
Width of the rail head - 75 mm;
Rail height - 180 mm.

High-strength types of steel were adopted as the materials of the wheelset and rails. Structural steel with a carbon content of 0,6-0,75% was chosen as the wheel material, and heat-treated rail steel as the rail material. The modulus of elasticity of these materials was taken as $E = 2{,}1 \cdot 10^{11}$ Pa, and the Poisson's coefficient - $\nu = 0{,}28\text{-}0{,}30$.

Modeling of the contact zone. In solving the problem of contact mechanics between wheels and rails, Hertz's theory of elastic contact was chosen as the main theoretical model. This theory allows for the determination of stresses and deformations under point or linear contact conditions between smooth surfaces of two elastic bodies.

In the research, the surfaces of the wheels and rails were considered ideally smooth and elastic, and the contact zone was considered elliptical. The dimensions of the contact zone were determined based on the radii of bending of the wheels and rails, the elastic properties of the materials, and the normal load on the wheelset.

Normal load is assumed based on the following expression:

The load on one wheel $Q = 0{,}5 \cdot P$, where P is the axial pressure.

According to Hertz's theory, the half-width b of the contact zone is defined as follows:

$$b=\sqrt{\frac{4QR}{\pi LE}}$$

where L - contact length (contact zone along the rail), in practical calculations L= 10 - 12 mm.

As a result of the calculation, it was established that the total size of the contact area is very small, and a large part of the load is concentrated in this area.

Method for determining stresses. The maximum normal stresses in the contact zone were determined according to Hertz's theory, and the following main stages were carried out:

1. The equivalent radii of bending of the wheels and rails were calculated.
2. The semi-axes (a and b) of the contact zone are determined.
3. The area of the contact area is marked.
4. The values of the maximum normal stresses in the contact zone were determined and compared with the permissible stresses of the rail and wheel materials.

In addition, tangential stresses and the probability of slip occurring in the contact zone were also theoretically assessed. The slip coefficient was determined based on the forces arising in the traction and braking modes.[5]

Consideration of dynamic loads. In conditions where the speed of an electric locomotive reaches up to 110 km/h, along with static loads, dynamic loads are also of great importance. Therefore, in the calculations, the dynamic coefficient was taken in the range of $k = 1{,}2\text{-}1{,}4$. This coefficient was chosen taking into account rail irregularities, wear of the wheel profile, and the operation of the suspension system.

Taking into account dynamic loads, the stresses in the contact zone were re-evaluated, and the degree of their increase relative to the static state was determined.

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Analysis and evaluation criteria. The following criteria were used to evaluate the obtained results:

1. The ratio of maximum normal stresses to the elastic limit of the material;
2. Dimensions of the contact area and load distribution;
3. The probability of fracture and contact fatigue;
4. Degree of operational hazard.

The results were compared with real operating conditions, and conclusions were drawn to improve the reliability of the wheels and rail system.

Results

The research results are aimed at determining the stresses arising in the wheel-rail contact zone under the conditions of freight electric locomotives. According to calculations, the axial pressure on the wheelset of an electric locomotive varies within the range of 20-25 tons, with a load on one wheel of 98-120 kN. Based on Hertz's theory, the maximum normal contact stresses are determined in the range of 935-1035 MPa, i.e., they show values close to the elastic limit of the rail and wheel materials.

Taking into account the influence of dynamic loads, contact stresses increase to 980-1080 MPa in the range of k=1,0-1,4. This result indicates that high speeds and rail irregularities significantly increase stresses in the contact zone and cause surface fatigue of the wheel-rail system.

Contact stresses also have a significant impact when the wheel radius changes. For example, when the radius changes from 0,55 m to 0,65 m, the maximum stress decreases from 1030 MPa to 980 MPa. This means that wear or deformation of the wheel surface reduces the contact area and leads to an increase in stresses.

Also, in the range of the coefficient of friction μ=0,2-0,4, the tangential force increases to 22-45 kN. This circumstance significantly affects the effectiveness of rail sliding and braking.

The results show that the stresses in the wheel-rail contact zone depend on several parameters: axial pressure, dynamic loads, wheel radius, rail material, and coefficient of friction. These values allow for a preliminary analysis of the processes of refraction, settlement, cracking, and fatigue on the surfaces of rails and wheels.

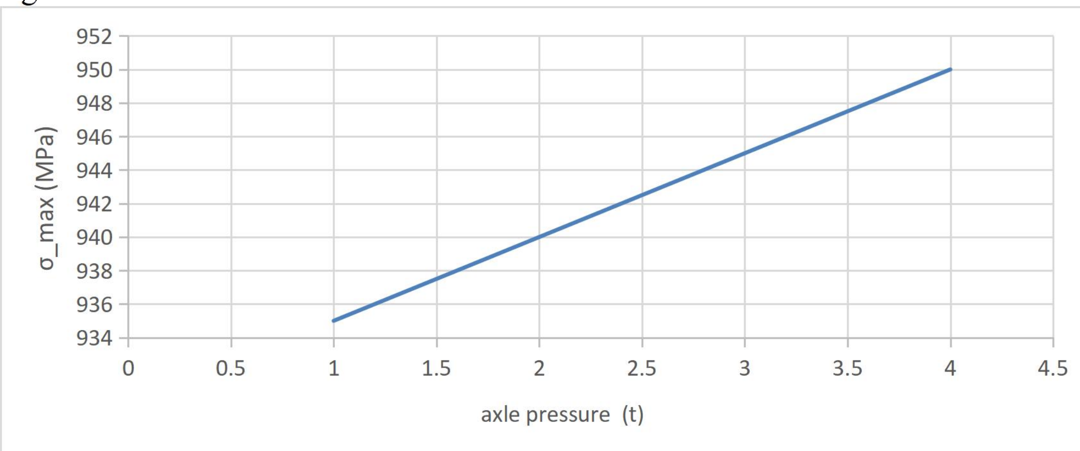

Figure 1. Contact voltage - axial load

This graph shows the increase in the maximum normal stress in the contact zone with increasing axial pressure on the wheel. According to the results, with an increase in axial pressure in the range of 20-25 t, the contact stress reaches from 935 MPa to 1035 MPa. This leads to faster breakage of the rail and wheel surfaces of freight electric locomotives (Fig. 1).

Maximum normal contact stress - the maximum normal stress in the contact zone is determined by Hertz's formula:

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$$\sigma = \frac{3Q}{2\pi bL}$$

To take into account the influence of movement speed and rail irregularities, a coefficient was introduced:

$Q_d = k_d \cdot Q$

here:

$k_d = 1.2 \div 1.4$

When taking into account dynamic loads, it was established that stresses in the contact zone increase by 20-40%.[1]

On the graph, a significant increase in contact stresses is observed with an increase in the dynamic coefficient, which represents the speed and dynamic influences. In the range of kd = 1.0-1.4, the maximum stress reaches 980-1080 MPa. This confirms the increased influence of rail irregularities at high speeds (Fig. 2).

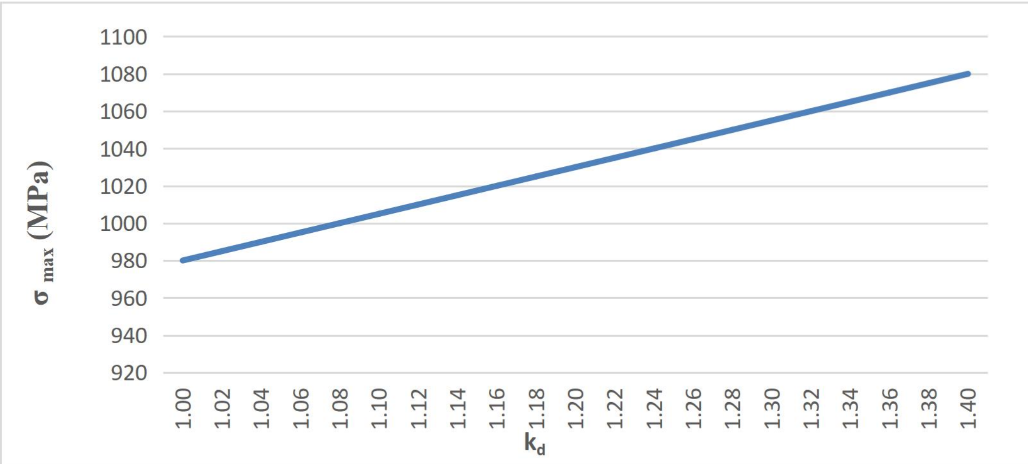

Figure 2. Contact voltage - dynamic coefficient (k_d)

Discussion

The results of the conducted research confirm the high values of the stresses arising in the wheel-rail contact zone under the conditions of freight electric locomotives. Calculations and graphical analysis show that the maximum normal stresses in the contact zone depend simultaneously on several operational and geometric factors, the interaction of which is the main factor determining the service life of the rail and wheel pair.

With an increase in axial pressure, a practically linear increase in contact stresses was observed. At axial pressures in the range of 20-25 tons, the maximum stresses reaching 935-1035 MPa indicate that freight electric locomotives operate in a mode close to the elastic limit of the material of the rails and wheels. In practice, this is explained by the appearance of subsidence on the rail surface, flattening and microcracks on the wheel surface. The results are consistent with existing scientific research and confirm that contact stresses are the main limiting factor in conditions of heavy traffic.

It has been established that an increase in the dynamic coefficient has a significant effect on contact stresses. Dynamic loads caused by an increase in speed and irregularities on the rail surface increase the maximum stresses to 1080 MPa. This is one of the main reasons for fatigue wear of rails and wheels in high-speed freight electric locomotives. From this point of view, the importance of technical measures to control the quality of the rail surface and reduce dynamic loads is determined.

The increase in contact stresses with a decrease in the wheel radius indicates that wear of the wheel profile creates an operational hazard. When the radius decreases to 0,55 m, the maximum stress reaches 1030 MPa, which justifies the need for timely reprofiling and technical repair of the wheels. Otherwise, a decrease in the contact area leads to a local increase in stresses and rapid wear of the rail and wheel surfaces (Fig. 3).

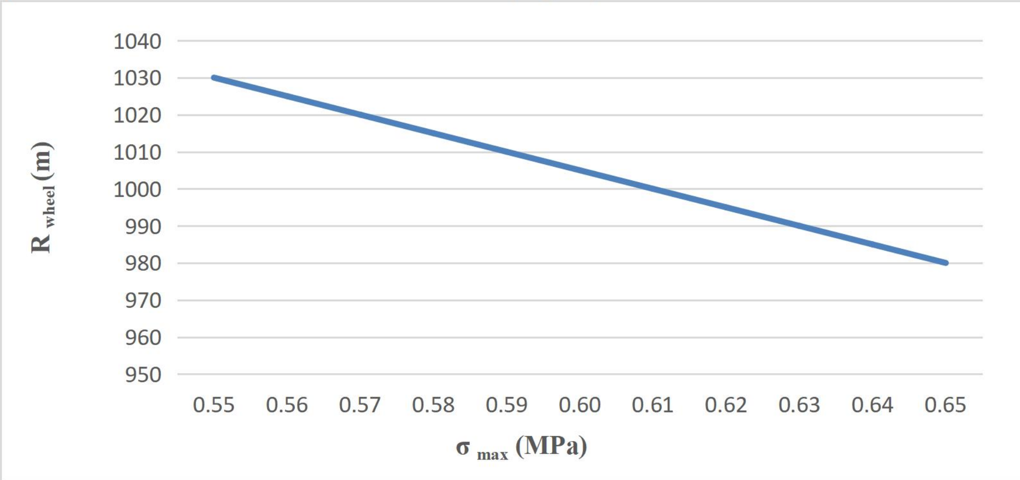

Figure 3. Contact voltage - wheel radius (R_{wheel})

This graph shows that a decrease in the wheel radius leads to an increase in the contact stress. With a decrease in the radius from 0,65 m to 0,55 m, the maximum stress increases from 980 MPa to 1030 MPa. This allows us to assess the risk of tire wear.

According to the tangential stress and slip condition, the maximum tangential force T arising in the contact zone is estimated as follows:

$T = \mu Q$

where μ - coefficient of friction between the wheel and the rail (0.25-0.35).

The slip condition is determined by the following expression:

$T \leq \mu Q$

If this condition is violated, the probability of sliding in the contact zone increases.

With an increase in the coefficient of friction, the increase in tangential forces increases the probability of slipping in the traction and braking processes. At values close to μ = 0,4 , the increase in tangential forces up to 45 kN can lead to an increase in damage and noise levels on the rail surface. This result confirms the practical significance of rail lubrication systems and friction control technologies (Fig. 4).

In general, the research results indicate the need for a comprehensive approach to reducing stresses in the contact zone of the wheel rail. In this case, technical measures aimed at optimizing axial pressure, constantly monitoring the condition of the wheel profile, improving the quality of the rail surface, and reducing dynamic loads are of great importance in increasing the operational reliability of railway transport.

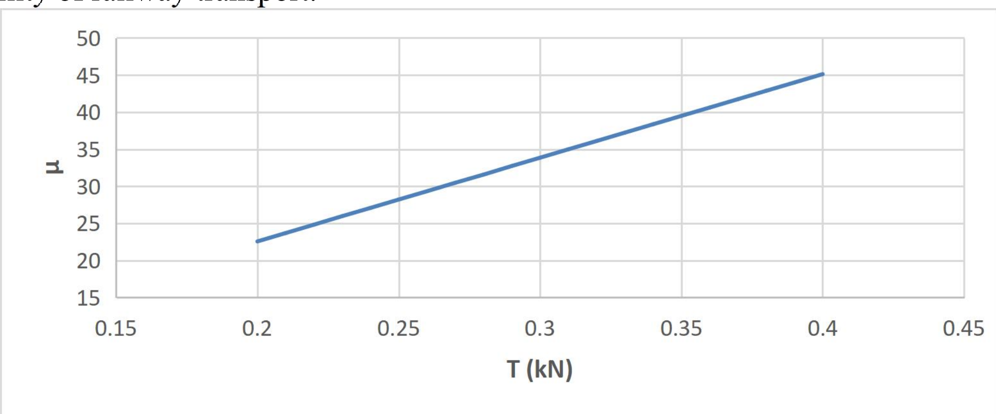

Figure 4. Tangential force - coefficient of friction (μ)

The graph shows the increase in the tangential force between the wheel and the rail with an increase in the coefficient of friction. In the range μ = 0,2-0,4 , the tangential force reaches 22-45 kN. This is important for assessing the probability of slipping in traction and braking modes.[6]

Conclusion. In this study, the stresses arising in the contact zone between the wheel pair and the rail under the conditions of freight electric locomotives were analyzed. As a result of the calculations and graphical analysis, it was established that the maximum normal stresses arising in the wheel-rail contact zone are directly related to axial pressure, dynamic loads, geometric parameters of the wheel, and friction conditions.

According to the results, when the axial pressure is in the range of 20-25 tons, the maximum contact stresses reach 935-1035 MPa. Consideration of dynamic loads leads to an increase in these values up to 1080 MPa, which represents an operating mode close to the elastic limit of the rail and wheel materials. It was established that a decrease in the wheel radius causes a reduction in the contact area, leading to an increase in stresses and an acceleration of surface fatigue.

Also, with an increase in the coefficient of friction, the increase in tangential forces increases the risk of sliding and damage to the rail surface during traction and braking processes. This circumstance indicates the need for the timely restoration of the wheel profile, the application of technologies for smoothing the rail surface, and friction control.

In general, the research results confirm that technical and operational measures aimed at reducing stresses in the wheel-rail contact zone are important in increasing the reliability, safety, and service life of rail and wheel pairs of rail transport. The obtained results can serve as a scientific and practical basis for the operation of freight electric locomotives and the improvement of railway infrastructure.

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