Optimization of dynamically loaded nonlinear technical systems

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Abstract. Modeling and simulation technologies play an important role in the operation, diagnosis of the current state and prediction of changes in various mechanical systems. The most effective approach for the study of nonlinear friction systems is the use of the method of physical and mathematical modeling, which is based on the construction of a mathematical model of a quasi-linear subsystem of a machine or mechanism and the creation of a physical model of a substantially nonlinear friction subsystem. Fundamentally new approaches have been developed to solve the problems of optimization, increasing the efficiency and competitiveness of nonlinear technical systems using the example of the wheel-rail tribosystem. Proposed technology of metal cladding of locomotive wheel band and implementation of anisotropy of friction coupling provide significant increase of efficiency of "wheel-rail" tribosystem.

1. Introduction

Almost all technical systems use friction units, such as gearing, rolling and sliding bearings, brakes, frictional vibration dampers, friction gears of the wheel-rail, wheel-road surface, belt and chain drives, spline joints, etc. Comprising only 5–8% of the total weight of a technical system, friction units largely determine its main technical and economic characteristics, such as reliability, efficiency, economic indicators, etc. In turn, the output parameters of friction units (friction coefficient and its stability, wear and tear of working surfaces and their intensity, etc.) depend on more than forty interrelated parameters and factors in a complex and nonlinear way. There are the following ones among these factors: the temperature of the contacting bodies and their temperature gradients; temperature pattern displayed in a thin tribolayer; normal and tangential mechanical strains in contacting materials and their gradients; actual contact areas and coefficients of mutual overlap; relative sliding and rolling speeds; type of movement; environment; the nature of contacting lubricants; micro- and macrogeometry of the contacting surfaces; the nature of the film on the friction surfaces; design features of friction units; dynamic characteristics of quasilinear mechanical subsystems, including friction units, as well as tribospectral characteristics of frictional interaction, and many more.

Obtaining a mathematical model of a nonlinear friction system and nonlinear frictional processes in the form of regression equations leads to a violation of the principle of inapplicability of the superposition method for the nonlinear system study, as well as to an increase in the number of mathematical models. It might occur as a result of variation of just five factors out of 40 while the rest is “unaccounted”. It must be admitted that it is unrealistic to obtain such amount of information; as it
has been mentioned above, the models themselves would be incorrect due to the use of the superposition method [1-6].

2. Method for increasing the friction systems efficiency

The most effective approach for the study of nonlinear friction systems is the method of physical and mathematical modeling. It is based on the construction of a mathematical model of a quasilinear subsystem of a machine or mechanism in the form of an equivalent dynamic model performed at a selected scale (or scales when using n-variant modeling). Further, a model (or models) of the friction unit is (are) attached to that dynamic model. At the same time, the model provides a given level of correlation coefficients of the main dynamic characteristics of the full-scale and model quasi-linear subsystems. Tribospectral characteristics of the full-scale and model friction subsystems are also provided.

This approach was used to solve a number of optimization problems for nonlinear technical systems. For example, by order of JSC Russian Railways, according to a business agreement, there was optimization of the geometric parameters of the railway track in small radius curves. The use of the method of physical and mathematical modeling and a unique model of the friction system “track – rolling stock” helped to reduce significantly the time of work performance and to develop recommendations for optimizing the geometry of the rail track. It allows obtaining an economic effect on the road network of JSC Russian Railways of about 3 billion rubles. A grant "Improving the wear resistance and durability of heavily loaded friction units of vehicles, machines and mechanisms by forming an antifriction layer of surface nanostructures on the tribocontact and providing dynamic control over the technical state of the tribosystem" was received for this purpose. In the process of solving the tasks of this grant, this approach has been chosen as the basis for creating a method for monitoring spline joints of the anti-torque rotor drive of the Mi-26 helicopter, as well as for obtaining options for studying the effectiveness of the developed measures to increase the reliability and durability of spline joint elements.

Technological progress is impossible without innovative developments, discoveries and inventions. One of such developments is a patent for invention RU No. 2674899 "Method for increasing the efficiency of friction systems" [7]. This method is based on a fundamental research in the field of mechanics of contact frictional interaction and tribology, as well as contact interaction of solids.

One of the technical solutions made on the basis of the patent "Method for increasing the efficiency of friction systems" is the technology, technological equipment and consumables for increasing the tractive effort of the locomotive and the wheel sets resource. The theoretical basis of this technology is the anisotropy of frictional bonds formed by thermal metal cladding (TMC) of the working surfaces of the wheels (WSW) of locomotives (rolling circle surfaces and wheel flanges) [8].

As it is shown in multi-purpose studies of WSW thermal cladding with metals, their hardness is lower than the hardness of the WSW rim metal, the maximum effect of increasing the traction force of the locomotive (energy efficiency) and increasing the wheel sets resource is provided by the use of TMC technology where special aluminum alloys are used as consumables. Application of a thin aluminum layer on the traction surface of the rolling circle of a locomotive wheel provides 20–30% increase in the longitudinal friction forces (Figure 1). The increase in tractive effort is connected with a high rate formation of the aluminum adhesive component (in particular, the developed compounding of aluminum alloys), as well as a low level of limiting values of tangential $\tau$ and normal $\sigma$ strain components [9-14]. The combination of these physical and mechanical characteristics is provided in the mode of rolling friction with slipping, at a sliding speed $V_{sl} < 3\%$, the mode of preliminary displacement with a friction coefficient (adhesion) equal to $f_{rr.adhesion} \geq 0.4$, practically approaching the coefficient of static friction $f_{static} \geq 0.5$. 

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The adhesion friction coefficient drops to 0.18–0.2 level in the following modes: in the mode of action of the forces of transverse creep (locomotive movement across the axis of the track); fitting into curved sections of the track, and movement along a sinusoid (lateral vibrations when overcoming a wind load, as well as while driving with a banking engine) if there is a layer of an aluminum alloy with an optimized formula (Al-M) on the surface of the wheel rolling circle. This decrease is explained by an increase in heat generation in proportion to an n times increase of the sliding speed approximately:

\[ n = \frac{v_{lateral}}{v_{longitud}} = \frac{100\%}{2.5\%} = 40\% \]

Accordingly, the flash point at the tops of the contacting microroughnesses of the wheel and rail increases. An increase in the flash point is connected with a k-fold increase in the energy released during friction, which is equal to the following:

\[ N_{longitud} = F_{fr} \times v_{sl}^{longitud}; \]
\[ N_{lateral} = F_{fr} \times v_{sl}^{lateral}; \]
\[ k = \frac{F_{fr} \times v_{lateral}^{sl}}{F_{fr} \times v_{longitud}^{sl}} \approx n \approx 40. \]

A decrease in the level of the friction coefficient during the lateral movement of the locomotive is also connected with a 100% decrease in the adhesive component during sliding, and a decrease in the contact time of micro- and macro-irregularities. In this case, the rupture rate of single friction contacts is higher than the rate of formation of adhesive bonds between them. Thus, the use of the TMC of the wheel rolling circle surface makes it possible to increase the tractive effort of the locomotive by 20–30%, and to reduce the wear and tear (rolling) rate of the wheel by 5–7 times. In the case of using the TMC technology, the calculation of traction energy losses is also made according to the following formula:

\[ \Delta F_{long} = \sum F_{long} - F'_{long} \]
\[ \Delta F_{long} = t g (45 - \alpha / 2) \times F_{lateral} \approx 5\% \]
Thus, the use of technology of thermal metal cladding reduces the level of traction energy losses in the presence of lateral creep forces by approximately several times. As it was mentioned above, when using the TMC for wear protection of the working surfaces of the flange, one can obtain additional tractive effort due to the frictional connection \( P \) of the surfaces of the flange and the side surface of the rail head. This two-point state of interaction of the locomotive wheel with the rail occurs when the locomotive fits into the curves, and when the required tractive effort increases significantly to compensate for the additional resistance of the trailed rolling stock when it moves in curved track sections. It also happens under wind load when moving with a banking engine. The traction force scheme is shown in Figure 2.

The possibility of existence of this traction two-point contact is associated with practically equal sliding speeds of the wheel relative to the rail at points 1; 2 and the absence of the output of the traction force curve at point 2 on the horizontal sections of the traction characteristic page Fig. 4.

3. Realization of traction force for point-to-point contact

 Issues related to the wear and tear of the wheel sets flanges have always been and do remain relevant. Reducing the wear rate of the working surfaces of the wheels flanges to the level and below the level of the wear rate of the surfaces of the rolling circles makes it possible to reduce the number of wheel turning due to the "thin" flange and, accordingly, to increase the number of turns on the "rolling" of the tread. The latest technological scheme helps to reduce turning costs by 3–4 times and increase the resource of wheel sets by 4–5 times. Traditionally, the solution to problems associated with reducing the wear rate of the wheel sets flanges was carried out by supplying consistent antifriction lubricants to the contact zone of the wheel flange with the rail. However, the positive effect of lubrication of the wheel flanges is accompanied by negative consequences, such as oiling of the rolling stock and elements of the permanent way, getting of the rolling circle of the locomotive wheels into the contact zone and, as a consequence, the appearance of two-sided "flat wheels".

 As a result of complex theoretical experimental studies, a technological scheme was developed to protect the working surfaces of the wheel flanges from wear by applying a protective metal film on them. This solution is based on a slight excess of the sliding speed of the working surface of the flange relative to the rail (no more than 0.2%) (Figure 3, point 2) compared to the sliding speed of the rolling surface of the tread.
Figure 3. Scheme of contact of a railway wheel with a rail: a) one-point contact, b) two-point contact

Thus, in the two-point contact, an additional frictional connection is created, which helps to increase the tractive effort of the locomotive by 20–25% when driving in a traction mode (Figure 4).

Figure 4. Dependence of the adhesion coefficient on the sliding speed for a two-point contact

Currently, there are two schemes for lubricating locomotive wheel set flanges with solid anti-friction materials: driven and non-driven.

Figure 5. Shows diagrams and photos of drive lubricators
In some cases, for example, with limited geometrical spaces for the installation of flange lubrication systems (FLS) or grease rail lubrication systems (GRLS) or the need to provide a long service life with a single refueling, non-powered structures are the best option to protect against wear of flanges.

The scheme for calculating the values arising in the contact zone of lubricating rods (briquettes) or metal-clad rods is presented below.

Figure 6. Scheme for calculating the action of forces in the contact zone of the lubricating rods

4. Conclusion
The considered technology, technological equipment and consumables (optimized aluminum alloy) can significantly improve the technical, economic and ecological characteristics of the friction subsystem “locomotive wheel – rail”, as well as the entire system “track – rolling stock”. Thermal metal cladding of the working surfaces of the wheel tread of the locomotive and use of the anisotropy of the Al-Fe friction bond allows the following:

- 5–6-fold reduction of the level of traction energy losses associated with the lateral creep forces when the locomotive moves in a pushing mode, when overcoming the wind load, and when moving in curved track sections;
- a possibility of turning locomotive wheel set treads due to such a defect as rolling along the rolling circle of a wheel set of a tread. Compared to turning due to a defect in the limiting value for the thickness of the flange, it ensures 3–4-fold reduction of the cost for the measures for turning locomotive wheel treads;
- thermal metal cladding of the rolling circle surface of the wheel tread of a locomotive wheel helps to increase the trailer load by 20–25% by increasing the adhesion coefficient from 0.27 in case of the frictional coupling of the wheel to the rail in the traditional form Fe-Fe to 0.45 – 0.5 when the Fe-Al friction bond is applied;
- thermal metal cladding with an optimized aluminum alloy of the working (frictional) surface of the wheel flange allows increasing the draw pull by 15–20% in the presence of unbalanced acceleration. It compensates for the resistance forces during the movement of the locomotive (for example, the forces of resistance to the movement of the rolling stock as a "carriage" in curved track sections);
- thermal metal cladding of the working surfaces of the wheel tread of the locomotive allows excluding (reduction) of using sand as an activator of the adhesion coefficient. It excludes the phenomenon of oversanding the ballast prism of the railway track and, as a result, 1.5–1.8-fold increase in the interrepair time; it also reduces the expenses of traction energy by 2–3%.
• the application of the technology of thermal metal cladding helps to increase the mileage of a locomotive from 1.5 thousand km with its one-time servicing to 8–10 thousand km when filling it with briquettes of the TMC modifier.

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