Keywords: lubrication; import substitution; resource; wheel flange; friction; friction modifier; tribotechnics; tribology; transport; dents

Vladimir SHAPOVALOV, Alexander LUBYAGOV, Pavel KHARLAMOV*
Rostov State Transport University
2 Rostovskogo Strelkovogo Polka Narodnogo Opolcheniya Sq., 344038, Rostov-on-Don, Russia
**Corresponding author*. E-mail: kcharlamov@yandex.ru

APPLICATION OF TRIBOLOGY THEORETICAL BASES FOR WORKING OUT OF RESOURCE-SAVING SYSTEMS ON RAILWAY TRANSPORTATION

Summary. In this article we consider the increase of the resource of wheelsets of cars and locomotives. We give general data on present research in the field of tribotechnical systems, and offer alternative variants of development of domestic tribotechnical systems for railway transportation, which can be useful to replace foreign systems. The systems capable of increasing the reliability of a railway branch are described.

Theoretical and research papers on the system «railway track and rolling stock» allow improving a variety of technical, economic and ecological indicators of railway transportation performance [1]. RSTU scientists have carried out the theoretical basics of an amplitude-phase-frequency analysis of essential-nonlinear dynamic processes. These processes take place in mechanical systems with friction units [2-4] with the subsequent synthesis of frictional systems with optimum tribotechnical and dynamic parameters. Moreover, our researchers have developed methods of physical and mathematical modelling and dynamic monitoring of nonlinear mechanical systems [3]. It has allowed the creation of a powerful experimental base with a unique laboratory complex for modelling tests of the systems «railway track and rolling stock» with various types of traction and trailing-rolling stock. Experimental results have been obtained both in laboratory and under natural conditions. Their accuracy is proved by adjusting the methods of different-scaled, and physical and mathematical modelling [5-8]. The findings reveal ample opportunities for the efficient control of frictional contacts of the «wheel and rail» subsystem; its reliability and efficiency impacts the following values: trailing-loading, braking distance, noise level and vibrations, resource of wheelsets and permanent way elements, and reliability and efficiency of the power-drive gear of the traction-rolling stock. Auxiliary systems are no less important as they provide necessary modes of contact under certain service conditions (wheel and rail). For example, hump retarders on hump-yards and modules of anti-slide bar systems on unpowered hump-yards, switch elements, rail locks for bascule bridges with a central elevating part, devices of «wheel and rail» contact modifying both in curves and on straight lengths of a track, and parameters of rail gauge in small radius curves [7-10].

It is established that bilateral flat wheels, dents and scratches appear on operating surfaces of car wheels, and their numbers grow with time. This process is connected with the low efficiency of rail lubrication performed by locomotives and rail-oiler cars of the non-contacting type. During their performance, grease is supplied on a side-face of the railhead; it can be squeezed out or dissipated by wind on the traction surface and lubricate it. During train-braking on oily rails, the friction moment on the contact area «brake pad and wheel» exceeds the friction moment on the contact area «wheel and rail». The increased sliding friction of a wheel on the rail eventually forms bilateral flat wheels and activates adhesive bonds on the wheel and rail contact area. Thus, conditions of athermal and thermal seizure are created, which lead to the formation of dents and scratches on the surface of the wheel-rolling circle. All this causes a problem of intensive wheel-flange wear, wheel-tread wear, bilateral flat wheels, and also causes the formation of dents and scratches on the surface of the wheel-rolling circle. In order to eliminate this problem, it is necessary to equip freight cars with a combined system of modifying operating surfaces of wheels. It would provide the frictional modifier feed (FMF) on the roll surface and the antifrictional modifier feed (AMF) on wheel flanges of freight cars. The equipment of one car costs 12,000 roubles, the pay-off period is up to 6 months. The system is introduced by RSTU experts and «TTT» Co Ltd., and can be delivered to consumers on a contract basis.

The friction drag of wheel flanges of the railway rolling stock on a side face of the railhead is the reason for the intensive wear process of wheel flanges of all trains, lateral rail wear and for up to 10% of traction power losses. RSTU scientists and experts from RZhD plc. have developed a highly effective technology of rotaprint and contact lubrication of wheel flanges of the rolling stock with solid greases (SG). The given technology (Fig. 1) was called railhead and wheel flange lubrication (RHWFL) because the greased wheel flanges of a rolling stock lubricate a side-face of the railhead when they interact with it.

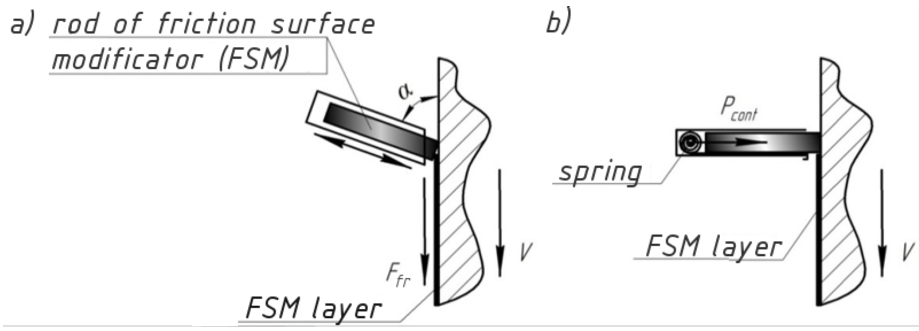


Fig. 1. The scheme of contact-rotaprint modification of friction surfaces: a) drive gear on the base of servoeffect; b) conventional drive gear

The given lubrication technology allows us to obtain an eight- to tenfold decrease in the intensity of the wear process of wheel flanges and a side-face of the railhead; it considerably saves fuel and energy resources on traction. According to minutes № TSTech-388/pr (dated 15.06.2011) in the Department of Technical policy of «RZhD» plc., approved by Gapanovich V.A. (the senior vice-president of «RZhD» plc.), the RHWFL-RAPS (GRS-RAPS) technology has been recognised as the most effective of existing technologies. According to the policy, the fleet of road engines are to be equipped with onboard railhead lubrications RHWFL-20.07 and the fleet of shunting diesel locomotives of the North Caucasian railway are to be equipped with onboard railhead lubrications RHWFL. According to the minutes, the points of the enacting clause have been executed in full by RSTU, the documentation for new locomotives («Ermak», 2ES5, 2ES6, 2ES10, EP2K, 2ES4, 2Te25v/i, EP1v/i, TEP70v/i, TEM7v/i, TEM-18v/i, 2TE116U rail buses RA-2) has been prepared and approved.

Also, tests of railhead lubrication have been conducted on the Multiple-unit rolling stock (MURS) (depot Mineralnye Vody). Positive results have been received on ED9m №164. On October 15th, 2014, RHWFL was implemented. Such a contact-rotaprint method of lubrication is much more effective than the remote (spray-type) method of grease-feeding offered by «REBSZentralschmiertechnikGmbH». This technology practically does not differ from the technology of automatic wheel flange lubrication, which is proved inefficient. It caused RZhD plc. financial losses of billions of roubles and has been rejected. Thus, the technology developed by RSTU is a vivid example of import substitution of foreign technologies, process equipment and consumable material. It is a more advanced, economical and ecologically friendly domestic method.

The management of RZhD plc. has approved the concept of development of lubrication technologies and modifying of traction surface of wheels of locomotives. It provides equipment to the fleet of locomotives with systems of wheel-flange lubrication. Experts of RSTU are ready to put these concepts into practice, delivering a sufficient number of RHWFL system and lubricant rods RAPS, RAPS-NANOTEH on the network of RZhD plc.

Increasing the size and stability of tractive power of locomotives is a key issue in increasing the efficiency of a railway branch, which also contributed to the above-mentioned concept. To increase traction effort, one can apply a traffic plan of a train with two locomotives, located ahead and behind the train formation, and use quartz sand to provide friction. The possible mismatch of traction efforts at bank engine application leads to an increase of resistance to train movement; it creates additional efforts in the contact area «wheel flange and rail» and increases the intensity of the cross-section creep forces as well as the intensity of the wear process of wheels and rails. Application of sand, which is an active abrasive, leads to a sharp growth in the wear process of wheels and rails, and also to losses of up to 5% of traction power. These losses are caused by the energy spent on destroying particles of sand which get under the wheels. On long slopes, sand feeding causes ballast oversanding, which reduces the overhaul life of a railway track. A single refuelling of a locomotive with sand provides a round trip of no longer than 1,500 km, though round trips of 8,000 km are usually necessary.

Nowadays, independent (axle-based) control of the process of realisation of traction force is necessary. Main locomotives 2ES5, 2ES6, 2ES10, EP2K, 2ES4, 2TE25v/i, EP1v/i, TEP70v/i, TEM7 v/i, TEM-18 v/i, 2TE116U realise the traction force, because they increase the capacity of traction engines at various sliding speeds of wheelsets. These speeds can exceed the maximum traction effort. Energy dissipation into heat leads to a temperature rise within the contact area of the wheel and rail. It causes a drop in the adhesive coefficient (tractive effort), and also a sharp increase in the wear process of the wheels of the locomotive.

The given problems are solved by the technology, which lets locomotive wheels steer frictional contact [6-9]. The onboard system of automatic check and control (SACC), installed on the locomotive, contains devices for feeding of briquettes of frictional modifiers of friction surface (FMFS). This system predicts the approach of a marginal level of slippage in order to switch the modifying system before modes of realisation of traction force will be excluded at an increased level of sliding velocity. Devices for feeding of briquettes of FMFS with the SACC are installed on all wheelsets of the locomotive, which provide independent (axle-based) steering of power units.

The core of the given technology is a scheme of contact-rotaprint modification of the traction surface by a lubricant with anisotropic properties. The scheme is applied for realisation of a maximum level of tractive effort (longitudinal creep forces) during rolling motion with 2-5% frictional sliding. The grease plays a part of the third body (the modifier of friction surface); it allows realising of the adhesive coefficient at a rate of 0.3÷0.5. Given 100% slippage, there is anisotropy in properties of the material of the modifier of the friction surface; in this case, the friction factor falls to a level of 0.12÷0.15, which leads to a 3-5 times drop in cross-section creep force. By reducing resistance forces against the locomotive movement, arising while overcoming cross-section creep forces, we can cut power consumption [2, 8, 9]. Fig. 2 and 3 give an example of FSMA.

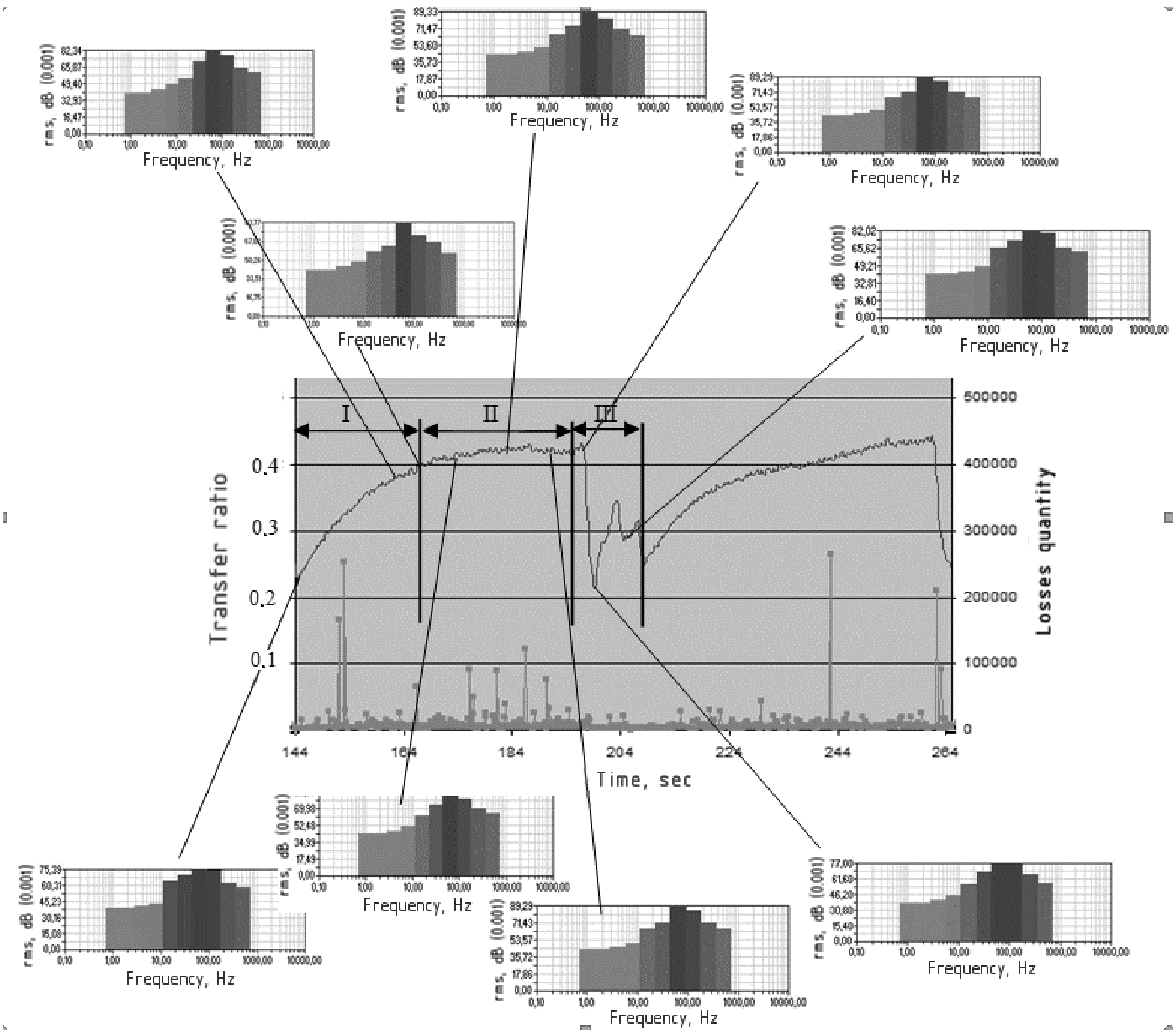


Fig. 2. Application of FSMA to tractive effort increase: I - area of spraying, II – area of work, III - area of cleaning of friction surface

This solution allows increasing the tractive effort due to the maintenance of optimum sliding velocities of axes of wheelsets; it improves the conditions of moving locomotive bogies in curves because of the drop in cross-section creep forces. Applying FMFS with anisotropic properties, we can lower the probability of development of fatigue cracks in the wheel material by «curing» them in the very beginning, which increases the wheelset resource.

During the supervision of physical models [2], we provide the identity of the following:
(a) frequencies and the basic forms of fluctuations of weights of mechanical systems,
(b) frequencies and forms of fluctuations in micro- and macroroughnesses,
(c) pressures,
(d) speeds of relative slippage of friction surfaces,
(e) characteristic types of wear processes of friction surfaces of models and natural objects.

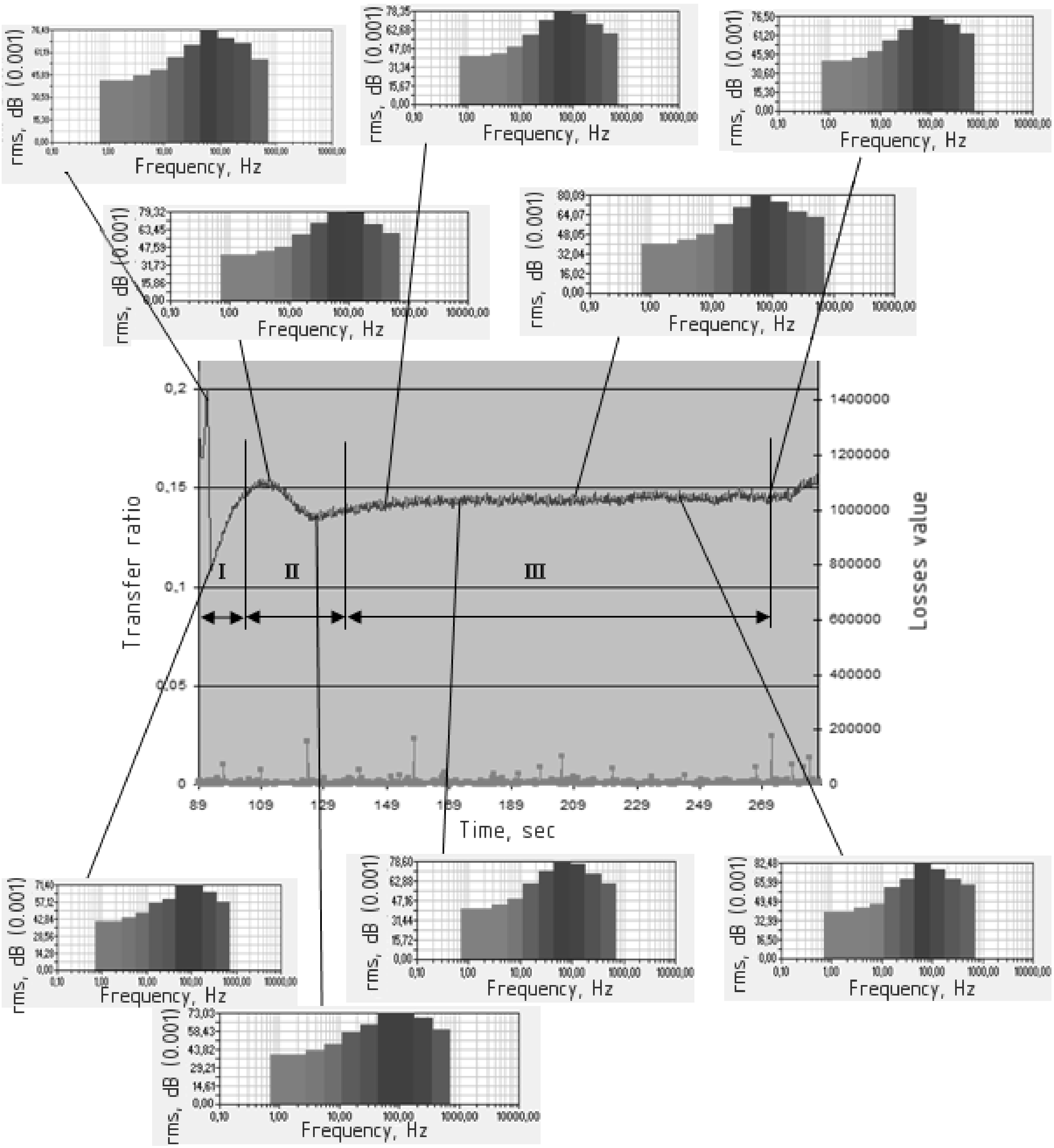


Fig. 3. Application of FSMA as a grease: I - area of spraying, II - area of distribution of material, III - area of work

For this purpose we enter a model of real frictional contact into the dynamic model of a quasi-linear mechanical subsystem. Its dynamic characteristics can be defined on the basis of representation of contact interaction forces in the co-ordinates of a status that can be measured. On the basis of the modelling experiment we can analyze the tribocharacteristics of natural friction units. We take into account the interference of the processes taking place in mechanical and frictional subsystems, which allows us to advance the existing methods of experimental research of friction processes on physical models. At the given research stage, we record target tribotechnical characteristics, and simultaneously carry out «*not destroying control*» of the mechanical system and its frictional subsystems. It is performed by recording and analysing the amplitude and phase-frequency characteristics in a demanded frequency range, which is defined by the following: the maximum value of one of the partial frequencies, parameters of micro- and macroroughnesses of surfaces of rubbing bodies, firmware and a class of the problems to be solved.

The complex friction factor of frictional contact is defined by a complex function of amplitude and phase-frequency characteristics of the system as the relation of the mutual tribospectrum in tangential and normal directions to the autotribospectrum of normal contact influence (its real part characterises elastic-inertial properties, and its imaginary part characterises dissipative properties) [2, 6, 8, 9]:

$$W(i\omega) = \frac{S_{yx}(i\omega)}{S_{xx}(\omega)} = \frac{S_y(\omega)\cdot S_x(-\omega)}{\left|S_x(\omega)\right|^2} = A(\omega)\,e^{i\varphi(\omega)} = P(\omega) + iQ(\omega), \qquad (1)$$

where S_{xx} (i ω) is the autospectral function of normal influence on frictional contact taking into the account the uncontrollable power noise revolting stationary movements of the system;

S_{yx} (i ω) is the mutual spectral function of tangential and normal interaction taking into consideration uncontrollable power noise, properties of triboconditions of frictional contact and the external conditions influencing the system;

A (ω) is the module of the complex drive factor (the *amplitude and phase-frequency characteristic* shows how the investigated friction unit passes the amplitude of a signal of various frequencies as it passes through the system), $A(\omega) = \left|W(i\omega)\right| = \sqrt{P^2(\omega) + Q^2(\omega)}$;

φ (ω) is a phase of the vector of a complex drive factor (the *amplitude and phase-frequency characteristic* shows phase shifts that the system brings on various frequencies in relation to the initial phase of the signal) $\varphi(\omega) = arctg\left(Q(\omega)/P(\omega)\right)$;

P (ω) is *the valid frequency characteristic*, dependent on the real part of the complex friction factor on frequency; it also characterises a conservative (elastic-inertial) component of friction process $P(\omega) = \mathrm{Re}\{W(i\omega)\} = A(\omega)\cdot\cos[\varphi(\omega)]$;

Q (ω) is the *imaginary frequency characteristic*, dependent on the imaginary part of the complex friction factor on frequency; it also characterises the *dissipative properties* of the tribosystem $Q(\omega) = \mathrm{Im}\{W(i\omega)\} = A(\omega)\cdot\sin[\varphi(\omega)]$.

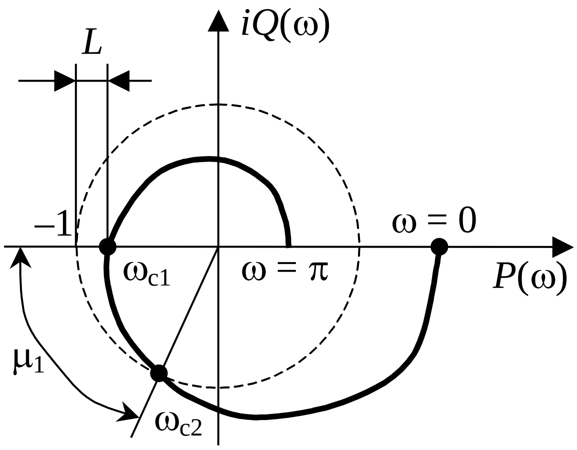


Fig. 4. Illustration of the stability factor on amplitude and phase

To solve the above-stated problems of dynamic monitoring of frictional systems, we offer an estimation method for the status of the tribosystem according to the analysis of integrated estimations [8, 9]. It is a stability factor of amplitude *L* and phase of amplitude and phase-frequency characteristics μ_1 (Fig. 4); it definitely characterises the variety of states of the mechanical system. This variety displays the properties of frictional subsystems, as in the case of both steady and non-steady trajectories of movements, when frictional self-oscillations [2] develop in the mechanical system. It can be called out by the following conditions:

(a) excess on the module of an inertial component of elastic properties of frictional interaction. As a result, in some frequency range borders, the actual area of contact tends to zero; it reduces the traffic safety of transport systems (it is fixed by an integrated estimation of loss of stability on amplitude);

(b) coincidence of frequencies of external influence with one of the frequencies of own fluctuations (there is a resonance of mechanical and (or) frictional subsystems). Consequently, values of inertial and dissipative components of frictional interaction increase, and we can note stability losses on amplitude and (or) on a phase;

(c) action of so-called «negative friction» (the system loses stability on a phase). Amplitude and phase-frequency characteristics on the complex plane get concentric representation that leads to an increase in inertial forces as well as development of stability loss on a phase, and then – on amplitude (Fig. 5).

The vector of inertial forces changes its direction, increasing the actual contact area with a subsequent dissipation increase. It leads to the drop of inertial forces, the increase of friction forces, and to a full stop of the transport system (Fig. 6).

The offered method will allow for providing the optimum level of sliding velocity which corresponds to the maximum level of tractive effort of the locomotive. Thus, it provides an increase in the resource of wheelsets due to the drop in intensity of the wear process of the surface of the wheel rolling circle. It can be carried out by grease plating, «curing» of fatigue microcracks on the friction surface of the wheels (Tab. 1) and by eliminating the phenomenon of thermal and athermal seizure, accompanied by jumps of the friction factor. It is possible to decrease or to expel frictional self-oscillations in the power-drive gear of the locomotive, to increase reliability and durability of its elements.

Application of friction surface modifiers with anisotropic properties (FSMA) obviates the need to use sand in order to increase tractive efforts and eliminates all negative consequences from its action in the contact area. They are as follows:

- traction capacity losses of up to 5%; the power is spent on destroying the particles of sand by the rolling stock wheels;
- losses of up to 7% due to the decrease of cross-section creep forces;

- intensive abrasive wear process of wheels and rails;
- restriction of round-trips of locomotives;
- ballast section oversanding, and consequent reduction of interrepair cycles of high-speed train service, etc.

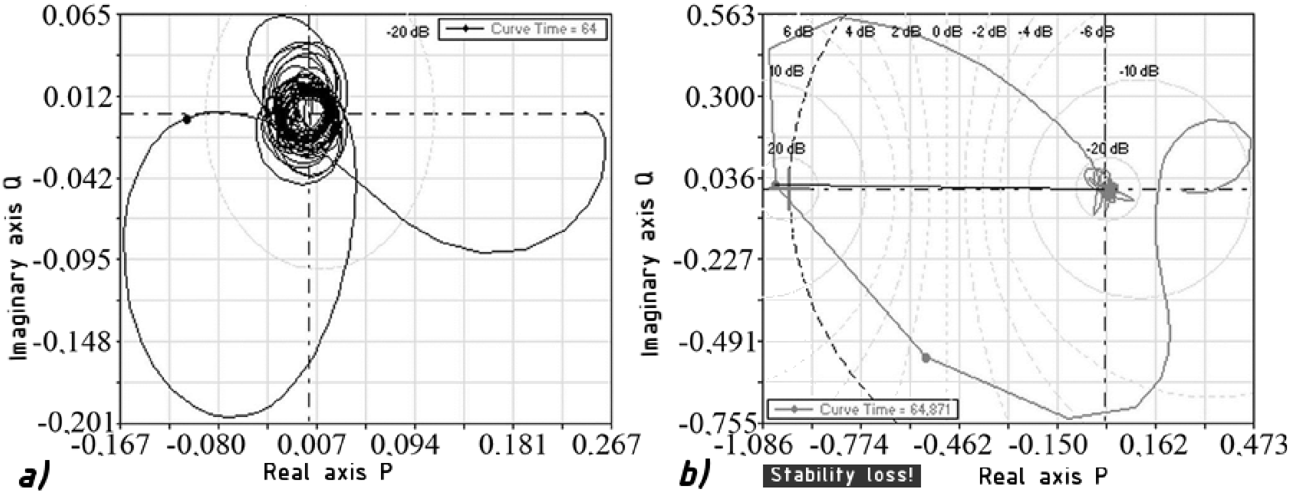


Fig. 5. Amplitude and phase-frequency characteristic of tribosystem instability: a - development of frictional jumping; b - stability losses on amplitude (an inertial component)

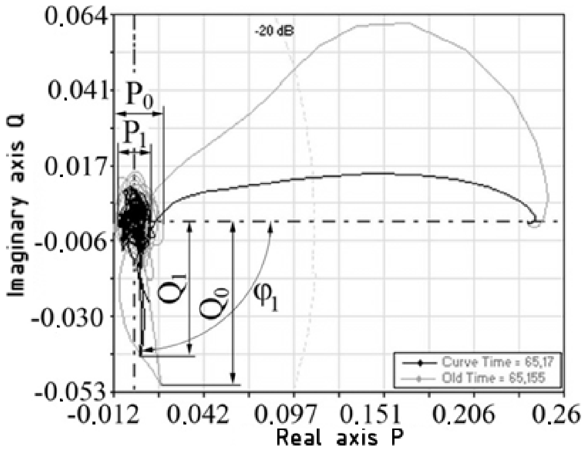


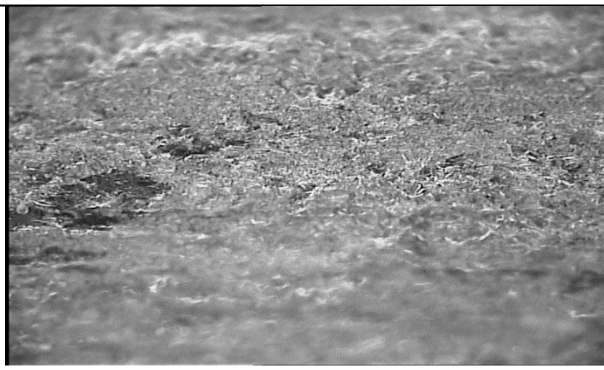
Fig. 6. Amplitude and phase-frequency characteristics at vanishing of sliding velocity

Thus, one can organise the technology of steering processes taking place in the frictional contact of a locomotive wheel with a rail on the basis of CPB, phase - and the amplitude and phase-frequency analysis of elastic-dissipative processes of rolling friction with skidding of locomotive wheels on a rail.

Traditional application of sand feeding allows using tractive effort at an adhesion coefficient level of no more than $f_a = 0.31$. Application of FSMA provides the use of tractive effort at an adhesion coefficient level of no less than $f_a = 0.35$. Besides, in comparison with an applied method of increase in tractive effort by sand feeding, our model can increase round-trips by up to 7,000 km and more, and also reduce the level of amplitude of frictional self-oscillations by 5-10 times.

Table 1

State of friction surfaces

Before application of FSMA (friction surface modifier with anisotropic properties)	
	
After application of FSMA	
	

References

1. Шаповалов, В.В. & Сладковский, А. & Эркенов, А.Ч. Актуальные задачи современной триботехники и пути их решения. *Известия высших учебных заведений (сер. Машиностроение)*. 2015. №1. С. 64-75. [In Russian: Shapovalov, V.V. & Sladkowski, A. & Erkenov, A.Ch. Topical problems of modern tribotechnics and ways of their solution. *Journal of Higher Educational Institutions (Machine building)*. 2015. No. 1. P. 64-75].
2. Пат. № 2517946 РФ. *Способ динамического мониторинга фрикционных мобильных систем*. Шаповалов, В.В. & Озябкин, А.Л. & Харламов, П.В. & и др. № 2517946; заявл. 05.04.2012; опубл. 10.06.2014, Бюл. № 16; приоритет 05.04.2012, № 2012113329/28. [In Russian: Patent № 2517946 of the Russian Federations. *A method of dynamic monitoring of frictional mobile systems*. Shapovalov, V.V. & Ozjabkin, A.L. & Kharlamov, P.V. & etc. No. 2517946. Appl. 05.04.2012. Publ. 10.06.2014. Bull. No. 16. Priority 05.04.2012. No. 2012113329/28].
3. Greenwood, J.A. & Williamson, J.B.P. Contact of Nominally Flat Surfaces. *Proc. Roy. Soc. Ser. A.* 1966. Vol. 295. No. 1442. P. 300-319.
4. Yang, Y.C. & Chu, S.S. & Chang, W.J. & Wu, T.S. Estimation of Heat Flux and Temperature Distributions in a Composite Strip and Homogeneous Foundation. *Int. Commun. Heat Mass Tran*. 2010 (37). No. 5. P. 495-500.
5. Ciavarella, M. & Johansson, L. & Afferrante, L. & Klarbring, A. & Barber, J.R. Interaction of Thermal Contact Resistance and Frictional Heating in Thermoelastic Stability. *Int. J. Sol. Struct*. 2003. Vol. 40. P. 5583-5597.

6. Mao, J.-J. & Ke L.-L. & Wang, Y.-S. Thermoelastic contact instability of a functionally graded layer and a homogeneous half-plane. *Int. J. Solids Struct.* 2014. Vol. 51. No. 23-24. P. 3962–3972.
7. Glaeske, H.-J. & Prudnikov, A.P. & Skórnik, K.A. *Operational Calculus and Related Topics*. Chapman and Hall/CRC. 2006.
8. Afferrante, L. & Ciavarella. M. Thermo-Elastic Dynamic Instability (TEDI)-a review of recent results. *J. Eng. Math.* 2008. Vol. 61. No. 2. P. 285–300.
9. Шаповалов, В.В. & Эркенов, А.Ч. & Щербак, П.Н. & Озябкин, А.Л. & Фейзов, Э.Э. Физико-математическое моделирование нелинейных фрикционных система. *Известия высших учебных заведений. Технические науки.* 2014. №6. С.77-82. [In Russian: Shapovalov, V.V. & Erkenov, A.Ch. & Scherbak, P.N. & Ozjabkin, A.L. & Fejzov, E.E. Physical and mathematical modelling of nonlinear frictional systems. *Proceedings of higher educational institutions. Engineering science.* 2014. No. 6. P. 77-82].

Received 22.01.2016; accepted in revised form 22.05.2017