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Increase of energy efficiency and competitiveness of mechanical systems on the basis of anisotropy of nonlinear frictional bonds

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Abstract. Interaction dynamics of contacting micro- and macroroughnesses of friction surfaces defines the main tribocharacteristics: friction factor, a wear-out type, its intensity, coefficient of energy efficiency of all the system. Reliability and energy efficiency of mechanical systems substantially depend on reliability and energy efficiency of their friction units. In their turn, reliability and energy efficiency of friction units are defined by interaction of the dynamic processes happening in frictional and mechanical subsystems.

Introduction

The authors have developed novel ways of increase of energy efficiency and competitiveness of mechanical systems with friction units on the basis of available theoretical and experimental data in the field of dynamic processes of friction, properties of friction surfaces, analyses and their development. This work has been carried out according to a novel approach to the solution of problems on research and optimisation of nonlinear frictional systems, namely: on the basis of methods of non-uniformly scaled physical and mathematical modelling of nonlinear frictional systems, tribospectral identification of processes of friction, their amplitude and phase-frequency CPB analysis, division of elastic-dissipative and strongly nonlinear processes happening in frictional contact into material and imaginary components, with determination of their dependence on frequencies of external and internal dynamic influence.

Purpose

Ultimate purposes of the given researches are the following: definition of real values of triboparametres taking into account the interference of dynamic processes happening in subsystems of real machines and mechanisms with friction units; synthesis of optimum frictional systems; development and perfection of methods of dynamic monitoring of mechanical frictional systems. For the solution of the above-named problems there have

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been created modernised unique laboratory complexes, data-acquisition equipment and social program resources [1].

Methods

The above-named approaches have allowed performing the following tasks: we investigated processes of friction taking into account their elastic and dissipative nature; by distinguishing the information on dissipative and conservative components of frictional interaction, we estimated current value of coefficient of energy efficiency of machine and mechanism on timely basis; we diagnosed a status of frictional systems and predicted its change taking into account dynamic external influence and strongly nonlinear processes of formation of elastic-dissipative links, and also their adhesive and deformative nature. The given techniques and analyses have allowed us to do the following: to carry out dynamic monitoring of frictional systems with the use of unique known and new information technologies, to solve optimisation problems of applied mechanics, problems of dynamics, strength, efficiency, durability, resource increase, ecological cleanliness, reliability and safety of mechanical systems with friction units. The given methods and techniques have allowed us to execute effective monitoring of frictional systems (FS) without breaking technological processes (the so-called nondestructive testing). Application of amplitude and phase-frequency CPB analysis of FS status allows us to expand unboundedly the number of information channels with division of data about dissipative and conservative components of dynamic processes happening in the system and subsystems [2].

Practically all mechanical systems with friction units are strongly nonlinear, and they should be also described by nonlinear models with acceptable deviations of real calculation data. You can linearize frequency transfer function in particular a mechanical subsystem with the minimum deviations of calculation results from real ones, by criterion of minimum of dispersion of a target signal of the Dirac delta function [2].

The minimum dispersion of a target dynamic signal is provided with polynomials that have numerator order m and denominator n; thus, the minimum dispersion of a pulse signal is provided.

The result of the analysis of amplitude and phase-frequency characteristics (APFC) is possibility of stability check of internal space of statuses of the system and value of complex friction factor operating in the zone of friction of tested samples:

$$f(j\omega) = W(j\omega) = A(\omega)\, e^{j\psi} = U(\omega) + jV(\omega) \tag{1}$$

where $A(\omega) = |f(i\omega)|$ is the amplitude-frequency characteristic of a friction factor $\psi(\omega) = \arg f(i\omega)$ is the phase-frequency characteristic of a friction factor; $U(\omega) = \mathrm{Re} f(i\omega)$ the material frequency characteristic of a friction factor $V(\omega) = \mathrm{Im} f(i\omega)$ is the imaginary frequency characteristic of a friction factor[3-9].

Observing stability of space of condition in the system, and having current values of a frequency transfer function (analogue of a friction factor),we can identify processes in the nonlinear frictional system by means of the data array analysis on amplitude and phase-frequency characteristics (APFC) of frictional interaction of experimental samples. Tests were carried out for interaction of a wheel of the locomotive on a rail with sliding; we also examined friction modes of rollingwith zero sliding, and also at movement in a slipping mode at 100 % slippage of rollingsurface of a wheel on a railhead.

To determine the moment of rupture of frictional bonds we carried out tests withthe following parameters. Testing of dynamic process has been carried out on the apparatus fordetermination of the actual area of contact, given normal loading NM =0.408 kN (static loading of a wheel on rail NO = 235 kN, the relation of the linear sizes of wheels of the locomotive and the scale factor of normal loading) and rolling speeds of wheels of model VM = 0.1 m/s, object of research V0 = 2.4 m/s = 8.64 km/h.

Analyzing the results of hodographofamplitude and phase-frequency characteristics (APFC), we can record the moment of rupture of frictional bonds and an exit from a mode of preliminary offset of contact of micro-and macroroughnesses of a wheel and a rail. Thus, there is a change of ratio of imaginary and material components of complex factors of adhesion of a wheel with a rail. Analyzing Nyquist hodograph, we can draw a conclusion that at the increased friction factors (adhesion factors) of a wheel with a rail the largestpartof APFC hodograph is established in the zone of high frequencies [3-9]. Change of a ratio of imaginary and dissipative components of complex adhesion factor is connected with rupture of frictional bonds, and it is characterized by increase in dissipative component of contact energy. It leads to deformation of APFC schedule in a direction of an imaginary axis approximately on 30 %. Sharp failure of adhesion is connected with redistribution of energy of forces of frictional interaction of a wheel with a rail.

For creation steering of the signal that switches on the drive system of activators of adhesion, a special system can be used that allows defining the moment of rupture of frictional bonds of a wheel with a rail (i.e. we can predict this moment), by analyzing correlation between signals of contact interaction of a wheel and a rail in tangential and normal directions [10].

During physical and mathematical modelling we did the calculation of scale factors of transition (SFT) for the accepted model and life model concerning the set scale factor of circular ruggedness CC. For this purpose we used the program realising algorithm of the solution of the linear equations with n unknown quantities. The findings of the calculation are shown in the table below [10].

Table 1. The findings of calculation of critical parameters of the model of friction unit.

Parameter	Dimension in SI system	Similarity criterion, = idem	Scale conversion factor	The recalculation formula from original to model
Heat-transferfactor, θ	W / (m^2*K)	Basic parameter	$C_\sigma = C_C^0 = 1$	$(\sigma)_M = (\sigma)_H$
Loading,N	N	Basic parameter	$C_N = C_C^2$	$(N)_M = \frac{(N)_H}{C_C^2}$
Rolling speed, V	m/s	Basic parameter	$C_V = C_C$	$(V)_M = \frac{(V)_H}{C_C}$
Linear rigidity C_ℓ ,N	N/m	Basic parameter	Basic parameter C_c is set at model operation as an experiment result	
Vibrational frequency, k	Hz	$\pi_k = \frac{kN}{VC}$	$C_k = C_C^0 = 1$	$(k)_M = (k)_H$
Contact pressure, q	Pa	$\pi_q = \frac{qN}{C^2}$	$C_q = 1$	$(q)_M = (q)_H$
Temperature gradient,	K/m	$\pi_{\Delta\Theta} = \frac{\Delta\Theta\sigma N^2}{VC^3}$	$C_{\Delta\Theta} = 1$	$(\Delta\Theta)_M = (\Delta\Theta)_H$
Moment of inertia, J	kg*m^2	$\pi_J = \frac{JV^2C^3}{N^4}$	$C_J = C_C^3$	$(J)_M = \frac{(J)_H}{C_C^3}$
Damping,	N*s/m	$\pi_\beta = \frac{\beta V}{N}$	$C_\beta = C_C$	$(\beta)_M = \frac{(\beta)_H}{C_C}$
Hardness, HB	Pa	$\pi_{HB} = \frac{HB \cdot N}{C^2}$	$C_{HB} = 1$	$(HB)_M = (HB)_H$
Coefficient of elasticity, E	Pa	$\pi_E = \frac{EN}{C^2}$	$C_E = 1$	$(E)_M = (E)_H$
Friction time,	s	$\pi_\tau = \frac{\tau VC}{N}$	$C_\tau = 1$	$(\tau)_M = (\tau)_H$
Friction track, L	m	$\pi_L = \frac{LC}{N}$	$C_L = C_C$	$(L)_M = \frac{(L)_H}{C_C}$

Friction area, S	м^2	$\pi_S = \frac{SC^2}{N^2}$	$C_S = C_C^2$	$(S)_M = \frac{(S)_H}{C_C^2}$
Frictional force, F	N	$\pi_F = \frac{F}{N}$	$C_F = C_C^2$	$(F)_M = \frac{(F)_H}{C_C^2}$
Weight wear, U	kg/m^3	$\pi_U = \frac{UNV^2}{C^2}$	$C_U = C_C^{-2}$	$(U)_M = \frac{(U)_H}{C_C^{-2}}$
Heat capacity, c	J / K	$\pi_c = \frac{cVC^3}{\sigma N^3}$	$C_c = C_C^2$	$(c)_M = \frac{(c)_H}{C_C^2}$
Amplitude of deformation and connections, A	m	$\pi_A = \frac{AC}{N}$	$C_A = 1$	$(A)_M = (A)_H$

For example, we will show deducing of similarity of non-basic parameter criterion of temperature gradient in matrix. Then we will check the received result [11].

Using the main determinant of system D0, we will unite every parameter with basic, N, V, C. For this purposeone by one we replace a line with parameters, N, V, C in the lines with parameter dimensions for which the criterion of similarity is defined. For each parameter we will receive four determinants. Then we will deduce similarity criteria.

The temperature gradient criterion is [ΔΘ] = [$M^0\ L^{-1}\ T^0\Theta^1$].

Determinants calculation is as follows:

$$D_1 = \begin{array}{c|cccc|} \Delta\Theta & 0 & -1 & 0 & 1 \\ N & 1 & 1 & -2 & 0 \\ V & 0 & 1 & -1 & 0 \\ C & 1 & 0 & -2 & 0 \end{array} = 1; \quad \alpha_1 = \frac{D_1}{D_0} = \frac{1}{-1} = -1,$$

$$D_2 = \begin{array}{c|cccc|} \sigma & 1 & 0 & -3 & -1 \\ \Delta\Theta & 0 & -1 & 0 & 1 \\ V & 0 & 1 & -1 & 0 \\ C & 1 & 0 & -2 & 0 \end{array} = 2; \quad \alpha_2 = \frac{D_2}{D_0} = \frac{2}{-1} = -2,$$

$$D_3 = \begin{array}{c|cccc|} \sigma & 1 & 0 & -3 & -1 \\ N & 1 & 1 & -2 & 0 \\ \Delta\Theta & 0 & -1 & 0 & 1 \\ C & 1 & 0 & -2 & 0 \end{array} = -1; \quad \alpha_3 = \frac{D_3}{D_0} = \frac{-1}{-1} = 1,$$

$$D_4 = \begin{array}{c|cccc|} \sigma & 1 & 0 & -3 & -1 \\ N & 1 & 1 & -2 & 0 \\ V & 0 & 1 & -1 & 0 \\ \Delta\Theta & 0 & -1 & 0 & 1 \end{array} = -3; \quad \alpha_4 = \frac{D_4}{D_0} = \frac{-3}{-1} = 3.$$

The similarity criterion for temperature gradient parameter $\Delta\Theta$ will look like the following.

$$\pi_{\Delta\Theta} = \frac{\Delta\Theta}{\sigma^{\alpha_1} \cdot N^{\alpha_2} \cdot V^{\alpha_3} \cdot C^{\alpha_4}} = idem \ \pi_{\Delta\Theta} = \frac{\Delta\Theta}{\sigma^{-1} \cdot N^{-2} \cdot V \cdot C^3} = 1$$

then $\pi_{\Delta\Theta} = \frac{\Delta\Theta \cdot \sigma \cdot N^2}{V \cdot C^3} = idem$.

Let us check it $\pi_{\Delta\Theta} = \frac{M^0L^{-1}T^0\Theta^1 \cdot M^1L^0T^{-3}\Theta^{-1} \cdot M^2L^2T^{-4}\Theta^0}{M^0L^1T^{-1}\Theta^0 \cdot M^3L^0T^{-6}\Theta^0} = 1$

Amplitude criterion of connections deformation is [A] = [$M^0\ L^1\ T^0\Delta\Theta^0$].

Determinants calculation is as follows:

$$D_1 = \begin{array}{c|cccc|} A & 0 & 1 & 0 & 0 \\ N & 1 & 1 & -2 & 0 \\ V & 0 & 1 & -1 & 0 \\ C & 1 & 0 & -2 & 0 \end{array} = 0; \quad \alpha_1 = \frac{D_1}{D_0} = \frac{0}{-1} = 0,$$

$$D_2 = \begin{array}{c|cccc|} \sigma & 1 & 0 & -3 & -1 \\ A & 0 & 1 & 0 & 0 \\ V & 0 & 1 & -1 & 0 \\ C & 1 & 0 & -2 & 0 \end{array} = -1; \quad \alpha_2 = \frac{D_2}{D_0} = \frac{-1}{-1} = 1,$$

$$D_3 = \begin{array}{c|cccc|} \sigma & 1 & 0 & -3 & -1 \\ N & 1 & 1 & -2 & 0 \\ A & 0 & 1 & 0 & 0 \\ C & 1 & 0 & -2 & 0 \end{array} = 0; \quad \alpha_3 = \frac{D_3}{D_0} = \frac{0}{-1} = 0,$$

$$D_4 = \begin{array}{c|cccc|} \sigma & 1 & 0 & -3 & -1 \\ N & 1 & 1 & -2 & 0 \\ V & 0 & 1 & -1 & 0 \\ A & 0 & 1 & 0 & 0 \end{array} = 1; \quad \alpha_4 = \frac{D_4}{D_0} = \frac{1}{-1} = -1.$$

The similarity criterion for amplitude parameter of connections deformation A will look like the following:

$$\pi_A = \frac{A}{\sigma^{\alpha_1} \cdot N^{\alpha_2} \cdot V^{\alpha_3} \cdot C^{\alpha_4}} = idem \text{ or } \pi_A = \frac{A}{\sigma^0 \cdot N^1 \cdot V^0 \cdot C^{-1}} = 1 \text{ then } \pi_A = \frac{A \cdot C}{N} = idem .$$

Let us check it $\pi_A = \frac{M^0 L^1 T^0 \Theta^0 \cdot M^1 L^0 T^{-2} \Theta^0}{M^1 L^1 T^{-2} \Theta^0} = 1$, which confirms stability of microgeometry ofsurfaces during modelling and natural researches. Similarly all other parameters of friction process that are accepted for modeling are connected with basic parameters. The similarity equation which has united the received criteria consists of 14 criteria, as according to Buckingham theorem it should be equal to the number of parameters minus four basic ones:

$$I = f\left(\begin{array}{l} \frac{kN}{VC}, \frac{qN}{C^2}, \frac{\Delta\Theta\sigma N^2}{VC^3}, \frac{JV^2C^3}{N^4}, \frac{\beta V}{N}, \frac{HB \cdot N}{C^2}, \\ \frac{EN}{C^2}, \frac{\tau VC}{N}, \frac{LC}{N}, \frac{SC^2}{N^2}, \frac{F}{N}, \frac{UNV^2}{C^2}, \frac{cVC^3}{\sigma N^3}, \frac{AC}{N} \end{array} \right) \quad (2)$$

The received similarity criteria comprising the criterion equation (2) demand experimental check. This fact depends upon their quite limited application. Beside experimental check, it is possible to make comparison of the received criteria with «standard» ones, which have been repeatedly approved in researches of friction and wear processes, and also in other areas of engineering. [1]The criteria (see Table 1) are received as dependences of the modelled quantity on the parameters accepted as basic ones, that is from quantities, making the greatest impact on the investigated process. Accordingly, change of basic parameters will change the received criteria as well. However, as the practice shows, similar changes are not reflected in «standard» criteria if selection of basic parameters and modelling are made correctly [12, 14].

Conclusion

During work performance State Standard Specification draftsforresearch of friction processes were created. They will allow having the actual information on friction processes taking into account real values of a friction factor varying from zero to ∞.

On the basis of usage of anisotropy of frictional bondssome specific optimization problems have been solved. There have been created the following:

1. Ahighly effective, reliable and competitive automatic gear box for power transmissions of land transport systems;
2. Frictional plate materials (FPM) for increase ofeffectiveness of a «wheel-rail» system based on the chemical anisotropy of frictional bonds;
3. Technology of formation of protective films of plating antifrictional material (PAM) on operating surfaces of the open (closed) friction units;the system of automatic dispensing PAM on the basis of anisotropy of properties ofthermoplastic bases;
4. Technology of selective suppression of amplitudes of frictional oscillations in the open and closed friction units based on frictional bonds properties anisotropy and variation of elastic-dissipative components.

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