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Experimental verification between the functioning of tribosystems in the conditions of boundary lubrication

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Abstract

The paper presents an experimental test of modeling the limits of stable operation of different structures of tribosystems (robustness criteria) in the conditions of extreme lubrication. The results of the experimental test confirmed the previously concluded conclusion that not all structures of tribosystems lose stability in terms of the coefficient of friction, i.e. the appearance of burrs on the surfaces of the friction. At low values of the coefficient of shape and low values of the quality factor of the tribosystem, the loss of stability occurs due to accelerated wear of materials.

Expressions for calculation of criteria of robustness of tribosystems taking into account speed of change of loading on tribosystem are received. The rate of change of load is taken into account by the coefficients of dynamism, which are obtained taking into account the right-hand side of the differential equation of the dynamics of the functioning of tribosystems. Analysis of the obtained theoretical results on the assessment of the robustness of tribosystems and their comparison with the results of the experiment, suggest that the obtained conditions for stable operation of tribosystems (criteria of robustness) allow theoretically, with error 10,3 - 13,3 %, determine the boundaries of sustainable work.

Criteria for the robustness of the tribosystem by wear rate and friction coefficient should be used in the design of tribosystems.

Key words: tribosystem; stability of tribosystems; burr of friction surfaces; accelerated wear; the stability limit of the tribosystem; robustness of the tribosystem; the robustness range of the tribosystem; criterion of robustness of the tribosystem.

Introduction

Stable operation of tribosystems in the entire load-speed range of operation is the most important characteristic on which the reliability of machines and mechanisms depends. The range of stable operation of tribosystems is predicted at the stage of design development of new machines and is mainly performed on experimental data of previous designs or experimental data of laboratory and bench tests. To implement this approach, it is necessary to ensure the identity of operating conditions and laboratory (bench) tests, which is associated with high material costs during the development of new machines.

The most promising area is the mathematical modeling of the limits of sustainable operation of tribosystems, which will significantly reduce material resources when designing new equipment. The development of such models is based on the theoretical foundations of the stability of technical systems, developed by O.M. Lyapunov, who created a modern theory of stability of motion of mechanical systems determined by a finite number of parameters.

This work is a continuation of the work [1], where the results of theoretical research to determine the limits of sustainable operation of tribosystems. The purpose of this study is to experimentally test the modeling of the limits of stable operation of different structures of tribosystems (robustness criteria) in the conditions of extreme lubrication with the calculation of modeling error.

Literature review

In work [1] the concept of stability of tribosystems is formulated. The stability of the tribosystem is understood as the ability to restore the original mode of operation after the removal of external influences. An important parameter is also the limit of loss of stable operation of the tribosystem, i.e. the magnitude of the load and the sliding speed when there is a burr or accelerated wear. According to the results of theoretical research, the definition of robustness of the tribosystem is formulated. Robust range is a dimensionless quantity that characterizes the range of loads and sliding speeds, taking into account design and technological features, where the mode of wear without damage to friction surfaces.

In work [1] developed criteria for robustness of tribosystems, which, unlike previously known, are not empirical and do not meet a certain type of design or transmission. The criteria are based on the theory of stability of technical systems and can be applied to a large class of structures. The limits of the values of the developed criteria when tribosystems lose stability are theoretically substantiated. Criteria allow to define loss of stability not only on a bully, but also on the beginning of the accelerated wear that will allow to increase forecasting of reliability of tribosystems during designing.

In work [2] Problems in estimating the stability of tribosystems based on the results of analysis of oscillations in the normal and tangential directions of frictional interaction are considered. The authors argue that one of the most effective ways to study nonlinear friction systems is the method of their physical and mathematical modeling. The quasilinear subsystem is described by a system of differentiated equations, according to which an equivalent model of a mechanical subsystem is built. Friction processes are described by criterion equations. According to the offered criterion equations conditions of physical experiment which provide reception of the correct results corresponding to natural conditions are formed. The authors conclude that the use of spectral characteristics can greatly simplify the apparatus of analysis and synthesis of oscillatory processes in a dynamic system on the actual contact spots.

To solve the problems of dynamic monitoring of friction systems and identification of the dynamic state (stability of tribosystems) in the works [3–6] it is proposed to use integrated estimates: dissipation and degree of dissipation in the tribosystem. The first assessment indirectly determines the friction losses, i.e. the dissipative properties of the friction system and the friction process as a dynamic system. The second estimate determines the amount of damping of the friction process as a dynamic connection.

According to the authors [3–6] integrated estimates allow to estimate the ratio of elastic-inertial and dissipative forces of friction interaction, identify mechanisms of loss of stability, conditions of irreversibility in the contact area and formulate a new direction in building systems for dynamic monitoring of friction systems during their operation.

The methodological approach used to analyze the stability of tribosystems and set out in the works [2–6], allows to analyze tribosystems only at the level of actual contact spots, i.e. at the micro level. Methodical approach presented in the work [1], allows you to perform stability analysis at the macro level, taking into account design, technological and operational factors. This approach takes into account the speed of dissipation on the actual contact spots, which is presented in the paper [7].

The analysis of the works devoted to definition of limits of steady functioning of various designs of tribosystems allows to draw a conclusion that at development and substantiation of such criteria it is necessary to consider constructive, technological and operational factors of tribosystems. The geometrical dimensions of tribocouples, physical and mechanical properties of connected materials of triboelements, tribological properties of lubricating medium, roughness of friction surfaces are insufficiently taken into account in the works listed above. The account of the listed factors will allow to extend the received criteria to a wide class of tribosystems and to make such analysis system.

Purpose

The purpose of this study is to experimentally test the modeling of the limits of stable operation of different structures of tribosystems (robustness criteria) in the conditions of maximum lubrication, which are given in [1].

Methods

To substantiate the methodological approach in research, we use the equation of the dynamics of the functioning of the tribosystem, which is given in [8]. The third-order differential equation is written in operator form:

$$\begin{aligned}&(T_1T_2T_3)p^3+(T_1T_2+T_1T_3+T_2T_3)p^2+(T_1+T_2+T_3+K_2K_3T_1)p+K_2K_3+1=\\&=(K_1K_2T_3)p+K_1K_2\end{aligned} \tag{1}$$

p - a differentiation operator that is equivalent to a record d/dt;
T_1, T_2, T_3 – time constants, dimension s;
K_1, K_2, K_3 – gain factors, dimensionless quantities.

Expressions to calculate time constants T_i and gain factors K_i, given in the work [9].

Analysis of the right-hand side of the differential equation shows that the processes of friction and wear in the tribosystem, especially the running-in processes, depend on the first load derivative, i.e. from the load speed. The load speed of the tribosystem can be taken into account by the coefficient of load dynamics, which is proportional to the right part of the differential equation (1):

$$k_d \approx (K_1 K_2 T_3)\frac{dW_i}{dt_l} + K_1 K_2 \,, \tag{2}$$

where the magnitude of the load (external influence during experimental studies) on the tribosystem is determined by expression:

$$W_i = N \cdot v_{sl} \,, J/s, \tag{3}$$

where N – load on the tribosystem, H;
v_{sl} – sliding speed, m/s.
t_l – load change time, s.

With the help of laboratory experimental studies on different structures of tribosystems at different values of the load on the tribosystem and different rates of change of load, an expression was obtained to calculate the coefficient of load dynamics.

When determining the robustness of the tribosystem by the parameter of the coefficient of friction:

$$k_{d(f)} = 0{,}62 \ln\left(\frac{K_1 \cdot K_2 \cdot T_{3(f)}}{t_l}\right), \tag{4}$$

When determining the robustness of the tribosystem by the parameter of wear rate:

$$k_{d(I)} = 0{,}95 \ln\left(\frac{K_1 \cdot K_2 \cdot T_{3(I)}}{t_l}\right), \tag{5}$$

Taking into account the expressions of the coefficients of load dynamics (4) and (5), which were obtained by the results of experimental studies, the formulas for determining the robustness of tribosystems, which are given in [1], we present in the following form.

To determine the robustness of the tribosystem by the coefficient of friction:

$$RR_f = \frac{\left((T_1T_2 + T_1T_{3,f} + T_2T_{3,f}) \times (T_1 + T_2 + T_{3,f} + K_2K_3T_1)\right)}{\left(T_1T_2T_{3,f}K_2K_3 + T_1T_2T_{3,f}\right) \cdot k_{d(f)}} \rangle 1. \tag{6}$$

To determine the robustness of the tribosystem by the wear rate:

$$RR_I = \frac{\left((T_1T_2 + T_1T_{3,I} + T_2T_{3,I}) \times (T_1 + T_2 + T_{3,I} + K_2K_3T_1)\right)}{\left(T_1T_2T_{3,I}K_2K_3 + T_1T_2T_{3,I}\right) \cdot k_{d(I)}} \rangle 1. \tag{7}$$

Criteria for robustness of the tribosystem RR_f and RR_I it is necessary to calculate for each load mode of the operational series of tribosystems, taking into account the rate of change of load. If the value of the criterion is more than one, then the tribosystem operates in a stable range. The greater the value of the criterion of robustness, the greater the margin of steady work.

If the value of the criterion is equal to one - the tribosystem operates on the verge of losing stability. If the value of the criterion is less than one - the tribosystem has lost stability, there is a burr or accelerated wear.

To answer the question of which parameter there was a loss of stability, it is necessary to calculate two criteria: the coefficient of friction, formula (6) and the rate of wear, formula (7). The value of the criterion, which first becomes less than one, answers the question of which parameter there was a loss of stability.

The standard deviation of the values of external influences during experimental research is represented by the formula:

$$S_{W_b} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(W_{b(i)} - W_{b(av)}\right)^2}, \quad (8)$$

where $W_{b(i)}$, $W_{b(av)}$, – the value of the magnitude of the external impact on the tribosystem at which there is a loss of stability (burr or accelerated wear), measured during the experiment and the average value for the number of repetitions *n*. Defined as the product of the load on the tribosystem and the sliding speed according to the formula (3).

The coefficient of variation of measurements of external influence, at which the event of loss of stability of the tribosystem occurs, was determined by the expression:

$$v_{W_b} = \left(\frac{S_{W_b}}{W_{b(av)}}\right) \cdot 100\%. \quad (9)$$

The relative error of modeling the limits of functioning of tribosystems in the conditions of marginal lubrication was determined by expressions:

$$e_{W_b} = \left|\frac{W_{b(ex)} - W_{b(m)}}{W_{b(ex)}}\right| \cdot 100\%, \quad (10)$$

where $W_{b(ex)}$, $W_{b(m)}$, – the value of the value of the external influence on the tribosystem at which there is a loss of stability (burr or accelerated wear), measured during the experiment and the results of modeling.

Experimental studies were performed on a universal friction machine, based on the friction machine 2070 SMT-1, according to the kinematic scheme "ring-ring". The design of the friction machine is presented in the work [10]. The test complex based on friction machines 2070 SMT-1 is presented in fig. 1.

Fig. 1. Experimental equipment based on the friction machine SMT-1

During the tests, the load on the tribosystem was increased at different load speeds: 1 s.; 10 s.; 20 s.

The loss of stability of tribosystems by the coefficient of friction was determined using the value of the moment of friction, which was registered by the friction recorder of the machine 2070 SMT-1. The loss of stability according to the parameter of the beginning of accelerated wear, was determined using the method of acoustic emission. The measuring complex and the method of registration of AE signals are given in the work [11]. To register acoustic radiation from the friction zone, the acoustic emission sensor was installed on a fixed triboelement. During the tests, the event that occurred first was recorded: either an increase in the coefficient of friction and the occurrence of burr; or the beginning of accelerated wear of triboelement materials. According to the results of three repetitions, the mean value of the burr load or the beginning of accelerated wear, the standard deviation of the values of the recorded values during experimental studies, the formula (8), coefficient of variation of measurements of external influence, at which the event of loss of stability of the tribosystem occurs, as a product of load and sliding speed (9), modeling error by the formula (10).

Results

The results of modeling the limits of stable operation of tribosystems and the results of experimental verification are presented in the table 1. The nature of the change in the value of the external influence on the tribosystem at which there is a loss of stability $W_{b(ex)}$ for different designs of tribosystems, which are estimated by the coefficient of form K_f, m^{-1} [12], presented in the first block of the table 1. Experimental studies of the limits of sustainable operation of tribosystems were performed for tribosystem steel 40H + Br.AZh.9-4, lubricating medium E_u= 3,6·10^{14} J/m^3, (motor oil M-10G$_{2к}$, SAE 40, API CC), roughness of friction surfaces: *Ra* = 0,2 micron; *Sm*=0,4 mm. The sliding speed did not change and was equal to υ_{sl} = 0,5 m/s. During the experiment, the values of the form factor of the tribosystem varied K_f = 6,25 - 22,6, m^{-1}. Such values were obtained by changing the values of the friction areas of the fixed triboelement. The following conclusions can be drawn from the presented results. Increasing the values of the shape factor of the tribosystem expands the range of robustness. In this case, the loss of stability of the tribosystem at low values K_f = 6,25 according to the parameter of wear rate, occurs when $W_{b(ex)}$ = 1200 N·m/s, and the parameter of the coefficient of friction $W_{b(ex)}$ = 1750 N·m/s. For the tribosystem with K_f = 12,5 loss of stability occurs at the same values $W_{b(ex)}$ = 1700 N·m/s. For the tribosystem with K_f = 22,6 loss of stability occurs when $W_{b(ex)}$ = 2000 N·m/s by the coefficient of friction. Tribosystems lose stability due to the burr of friction surfaces. The results of experimental studies of changes in the value of the external influence on the tribosystem in which there is a loss of stability when changing the tribological properties of the lubricating medium E_u, are presented in the second block of the table 1. The results are presented for the tribosystem: steel 40H + Br.AZh.9-4; coefficient of forms K_f = 12,5 m^{-1}; roughness of friction surfaces *Ra* = 0,2 micron; *Sm*=0,4 mm. Hydraulic oil was chosen as the changing factor MG - 15V, (E_u= 2,43·10^{14} J/m^3); motor oil M - 10G$_{2к}$, (E_u= 3,6·10^{14} J/m^3); transmission oil TSp - 15K, API GL-4, (E_u= 4,18·10^{14} J/m^3). The sliding speed did not change and was equal to υ_{sl}= 0,5 m/s. Increasing the tribological properties of the lubricating medium from E_u = 2,43·10^{14} J/m^3 to E_u = 4,18·10^{14} J/m^3 contributes to the expansion of the range of robustness of tribosystems, both in terms of wear rate and friction coefficient.

Table 1

The results of checking the error of modeling the range of robustness of different designs of tribosystems

Tribosystem design	$W_{b(m)}$, N·m/s	$W_{b(ex)}$, N·m/s	S_{Wb}, N·m/s	v_{Wb}, %	e_{Wb}, %
40H + Br.AZh.9-4, motor oil M-10G$_{2к}$, E_u= 3,6·10^{14} J/m^3, K_f = 6,25 m^{-1}	1300 *(I)*	1200 *(I)*	200	16,6	8,3
40H + Br.AZh.9-4, motor oil M-10G$_{2к}$, E_u= 3,6·10^{14} J/m^3, K_f = 12,5 m^{-1}	1900	1700 *(I, f)*	300	17,6	11,7
40H + Br.AZh.9-4, motor oil M-10G$_{2к}$, E_u= 3,6·10^{14} J/m^3, K_f = 22,6 m^{-1}	2300	2000 *(f)*	400	20,0	15,0
40H + Br.AZh.9-4, K_f = 12,5 m^{-1}, hydraulic oil MG-15V, (E_u= 2,43·10^{14} J/m^3)	850	1000 *(f)*	200	20,0	15,0
40H + Br.AZh.9-4, K_f = 12,5 м$^{-1}$, motor oil M-10G$_{2к}$, (E_u= 3,6·10^{14} J/m^3)	1900	1700 *(I, f)*	300	17,6	11,7
40H + Br.AZh.9-4, K_f = 12,5 m^{-1}, transmission oil TSp-15K, (E_u= 4,18·10^{14} J/m^3).	2600	2350 *(I)*	350	14,8	10,6
steel 40H+ steel 40H, ($RS_{TS(max)}$ = 326,7; m^{-1}); K_f = 12,5 m^{-1}, motor oil M-10G$_{2к}$, E_u= 3,6·10^{14} J/m^3	1300	1150 *(f)*	250	21,7	13,0
steel 40H+ Br.AZh.9-4, ($RS_{TS(max)}$ = 436,0; 1/m); K_f = 12,5 m^{-1}, motor oil M-10G$_{2к}$, E_u= 3,6·10^{14} J/m^3	1900	1700 *(I, f)*	300	17,6	11,7
steel 40H+ LMcSKA 58-2-2-1-1, ($RS_{TS(max)}$ = 460,9; 1/m), K_f = 12,5 m^{-1}, motor oil M-10G$_{2к}$, E_u= 3,6·10^{14} J/m^3	1950	1800 *(I, f)*	300	16,6	8,3
Tribosystem №1: steel 40H+ steel 40H, ($RS_{TS(max)}$ = 326,7; m^{-1}), K_f = 6,25 m^{-1}, hydraulic oil MG – 15V, (E_u= 2,43·10^{14} J/m^3), Q_0 = 1,12·10^{10} J/m^3.	650	750 *(f)*	150	20,0	13,3
Tribosystem №2: steel 40H+ Br.AZh.9-4, ($RS_{TS(max)}$ = 436,0; 1/m); K_f = 12,5 m^{-1}, motor oil M-10G$_{2к}$, E_u= 3,6·10^{14} J/m^3, Q_0 = 5,5·10^{10} J/m^3.	1900	1700 *(I, f)*	300	17,6	11,7
Tribosystem №3: steel 40X+ LMcSKA 58-2-2-1-1, ($RS_{TS(max)}$ = 460,9; m^{-1}), K_f =14,5, m^{-1}; transmission oil TSp-15K, E_u= 4,18·10^{14} J/m^3, Q_0 = 7,69·10^{10} J/m^3.	3100	2900 *(I)*	350	12,0	10,3

Loss of stability of the tribosystem when using hydraulic oil MG - 15V occurs when loading $W_{b(ex)}$ = 1000 N·m/s, by the coefficient of friction. With increasing tribological properties of the lubricating medium to E_u = 4,18·10^{14} J/m^3 (transmission oil TSp - 15K), the stability limit of the tribosystem increases to values $W_{b(ex)}$ = 2350 N·m/s. Loss of stability occurs according to the parameter of wear rate.

The results of experimental studies of changes in the value of the external influence on the tribosystem in which there is a loss of stability when changing the rheological properties of the structure of bound materials in the tribosystem $RS_{TS(max)}$, [13], presented in the third block of the table 1.

The results are presented for the tribosystem: coefficient form K_f = 12,5 m^{-1}; roughness of friction surfaces Ra = 0,2 micron; Sm=0,4 mm. Lubricating medium - motor oil M – 10$G_{2к}$, (E_u= 3,6·10^{14} J/m^3). The following was chosen as the changing factor: "steel 40H + steel 40H", ($RS_{TS(max)}$ = 326,7; 1/m); "steel 40H + Br.AZh.9-4", ($RS_{TS(max)}$ = 436,0; 1/m); "steel 40H + LMcSKA 58-2-2-1-1", ($RS_{TS(max)}$ = 460,9; 1/m).

Increasing the rheological properties of bound materials in the tribosystem from $RS_{TS(max)}$ = 326,7 m^{-1} to $RS_{TS(max)}$ = 460,9 m^{-1} contributes to the expansion of the range of robustness of tribosystems, both in terms of wear rate and friction coefficient. The following values were obtained for these parameters. When using the tribosystem "steel 40H + steel 40H", burr occurs at $W_{b(ex)}$ = 1150 N·m/s by the coefficient of friction. When using tribosystems with connected materials "steel 40H + Br.AZh.9-4" and "steel 40H + LMcSKA 58-2-2-1-1", loss of stability on the parameter of the coefficient of friction and wear rate does not differ and increases to the value $W_{b(ex)}$ = 1700 - 1800 N·m/s.

The results of experimental studies of changes in the value of the external influence on the tribosystem in which there is a loss of stability when changing all the above factors, which can be taken into account by the value of the quality factor of the tribosystem Q_0, presented in the fourth block of table 1. Determination of the quality factor of the tribosystem is given in the paper [14].

The results are presented for three tribosystems.

1.Tribosystem №1: "steel 40H + steel 40H", ($RS_{TS(max)}$ = 326,7; m^{-1}); K_f =6,25, m^{-1}; lubricating medium E_u= 2,43·10^{14} J/m^3, (MG-15V). Roughness of friction surfaces Ra = 0,2 micron; Sm=0,4 mm. The magnitude of the quality factor of the tribosystem Q_0 = 1,12·10^{10} J/m^3.

2.Tribosystem №2: "steel 40H + Br.AZh.9-4", ($RS_{TS(max)}$ = 436,0; m^{-1}); K_f =12,5, m^{-1}; lubricating medium E_u= 3,6·10^{14} J/m^3, (M-10$G_{2к}$). Roughness of friction surfaces Ra = 0,2 micron; Sm=0,4 mm. The magnitude of the quality factor of the tribosystem Q_0 = 5,5·10^{10} J/m^3.

3.Tribosystem №3: "steel 40H + LMcSKA 58-2-2-1-1", ($RS_{TS(max)}$ = 460,9; m^{-1}); K_f =14,5, m^{-1}; lubricating medium E_u= 4,18·10^{14} J/m^3, (TSp-15K). Roughness of friction surfaces Ra = 0,2 micron; Sm=0,4 mm. The magnitude of the quality factor of the tribosystem Q_0 = 7,69·10^{10} J/m^3.

Increasing the value of the quality factor of the tribosystem, which also takes into account the coefficient of form, tribological properties of lubricating medium, rheological properties of connected materials in the tribosystem, thermal conductivity of materials of movable and fixed triboelements, loading and speed of sliding, from values Q_0 = 1,12·10^{10} J/m^3, (tribosystem №1), to Q_0 = 7,69·10^{10} J/m^3, (tribosystem №3), contributes to the expansion of the range of robustness, both in terms of wear rate and the parameter of the coefficient of friction.

Loss of stability when using the design of the tribosystem №1 occurs at the value of external influences $W_{b(ex)}$ = 750 N·m/s by the coefficient of friction. As the quality factor increases (tribosystem №3), the stability limit of the tribosystem increases to values $W_{b(ex)}$ = 2900 N·m/s by the wear rate parameter.

The results of experimental studies suggest that not all designs of tribosystems lose stability in terms of the coefficient of friction, i.e. after the appearance of burr friction surfaces. There are options when the loss of stability occurs due to accelerated wear of materials.

The experimental data shown in table 1, obtained at the time of loading of the tribosystem equal to 20 s. With this value of the load time, the dynamics coefficients correspond to the minimum values: $k_{d(f)}$=3,42; $k_{d(I)}$=4,37, formulas (4) and (5). When the load time decreases, up to 1 s., the coefficients increase significantly, for example: $k_{d(f)}$=6,4; $k_{d(I)}$=7,38. Figure 1 presents the theoretical dependences of changes in the coefficients of dynamism of different structures of tribosystems on the parameters of the coefficient of friction and wear rate on the value of the load time.

Experimental dependences of the influence of dynamism coefficients on the value of the limit of loss of stability (burr or accelerated wear) are presented in fig..2.

The results of checking the modeling error and the coefficient of variation of the obtained experimental values when changing the magnitude of the external influence on the tribosystem, in which there is a loss of stability of different structures of tribosystems, allow us to draw the following conclusions.

Calculation of the error in determining the limit of stable operation of tribosystems according to the formula (10) when changing the shape factor of tribosystems allows us to say that the error value is equal to e_W= 8,3 - 15,0%, at the coefficient of variation v_W= 16,6 - 20,0%. As follows from the obtained results, increasing the coefficient of shape leads to an increase in modeling error.

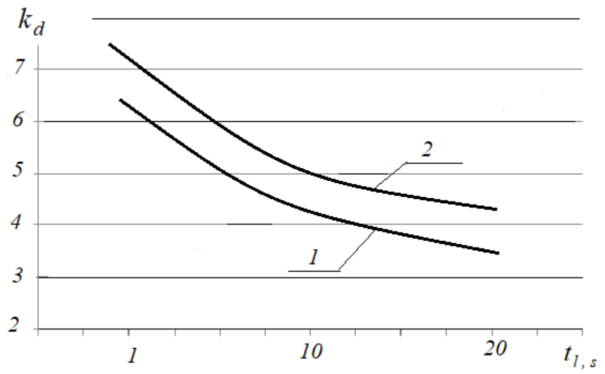

Fig. 2. Dependences of change of coefficients of dynamics of loading k_d different designs of tribosystems from the value of the load time t_l: 1 – by the coefficient of friction; 2 – by the wear rate parameter

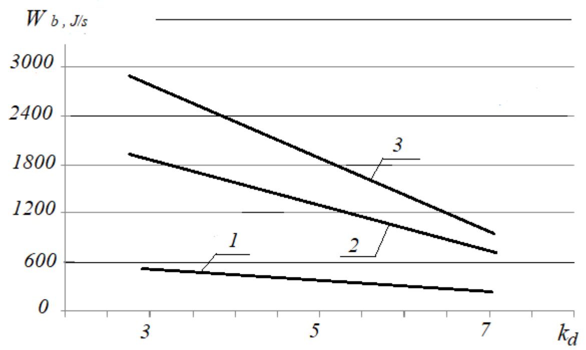

Fig. 3. Dependences of change of size of limit of loss of stability of various designs of tribosystems W_b from the value of the load factors k_d: 1 – tribosystem №1; 2 – tribosystem №2; 3 – tribosystem №3

The calculation of the error in determining the limit of stable operation of tribosystems when changing the tribological properties of the lubricating medium allows us to say, that the value of the simulation error is within e_W= 10,6 - 15,0%, at the coefficient of variation v_W= 14,8 - 20,0%. Greater error is inherent in the use of lubricating media with low values of tribological properties.

Comparison of experimental results with modeling results at change of rheological properties of the connected materials in a tribosystem allows to assert, that the error value is within e_W= 8,3 - 13,0%, at the coefficient of variation v_W= 16, - 21,7%. Greater error is inherent in the use of bonded materials with low values of rheological properties.

Comparison of experimental results with simulation results when changing all the above factors, which can be taken into account by the quality factor of the tribosystem Q_0, allow to state that the value of modeling error is within e_W= 10,3 - 13,3%, at the coefficient of variation v_W= 12, - 20,0%. Greater error is inherent in the use of tribosystems with low quality values.

The introduction of coefficients of dynamism (4) and (5) in the calculated expressions for determining the robustness of tribosystems (6) and (7) reduces the modeling error.

Conclusions

An experimental test of modeling the limits of stable operation of various structures of tribosystems (robustness criteria) in the conditions of maximum lubrication, which were developed in [1]. The results of the experimental test confirmed the previously concluded conclusion that not all structures of tribosystems lose stability in terms of the coefficient of friction, i.e. the appearance of burrs on the surfaces of the friction. At low values of the coefficient of shape and low values of the quality factor of the tribosystem, the loss of stability occurs due to accelerated wear of materials.

Expressions for calculation of criteria of robustness of tribosystems taking into account speed of change of loading on tribosystem are received. The rate of change of load is taken into account by the coefficients of dynamism, which are obtained taking into account the right-hand side of the differential equation of the dynamics of the tribosystems. Analysis of the obtained theoretical results on the assessment of the robustness of tribosystems and their comparison with the results of the experiment, allow us to state that the obtained conditions of stable operation of tribosystems (robustness criteria) in the form of expressions (6) and (7), allow theoretically, with error 10,3 - 13, 3%, define the limits of sustainable work.

Criteria for robustness of the tribosystem by wear rate and friction coefficient should be used in the design of tribosystems. By changing the design and technological parameters of the structure, it is possible to ensure the operation of the tribosystem, which is designed in a given load-speed range without damage and with a margin of safety.

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Войтов А.В. Параметрична ідентифікація математичної моделі функціонування трибосистем в умовах граничного мащення

У роботі представлена експериментальна перевірка моделювання меж стійкого функціонування різних конструкцій трибосистем (критеріїв робастності) в умовах граничного мащення. Результати експериментальної перевірки підтвердили зроблений раніше висновок, що не всі конструкції трибосистем втрачають стійкість за параметром коефіцієнта тертя, тобто по появі задиру поверхонь тертя. При низьких значеннях коефіцієнта форми та низьких значеннях добротності трибосистеми, втрата стійкості настає за прискореним зношуванням матеріалів.

Отримано вирази для розрахунку критеріїв робастності трибосистем з урахуванням швидкості зміни навантаження на трибосистему. Швидкість зміни навантаження враховується коефіцієнтами динамічності, які отримано з урахуванням правої частини диференціального рівняння динаміки функціонування трибосистем. Аналіз отриманих теоретичних результатів з оцінки робастності трибосистем та їх зіставлення з результатами експерименту, дозволяють стверджувати, що отримані умови сталої роботи трибосистем (критерії робастності) дозволяють теоретичним шляхом, з похибкою 10,3 - 13, 3 %, визначити межі стійкої роботи.

Критерії робастності трибосистеми за швидкістю зношування і за коефіцієнтом тертя необхідно застосовувати при проектуванні трибосистем.

Ключові слова: трибосистема; математична модель; диференційне рівняння; параметрична ідентифікація; коефіцієнт посилення; постійна часу; граничне мастило; добротність трибосистеми; швидкість роботи дисипації