Nondestructive testing of sliding bearings

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Abstract**—** *A validation of electro-physical probing method usage is given for a sliding bearings diagnostic at a boundary friction. Electric circuits and a way of sliding bearings diagnostic, where an analysis of a boundary lubricating layer (BLL) thickness control is carried out on contact resistance parameters indirectly. A sliding bearing lubricating state is defined on previously installed threshold values which achievement defines its running regime.*

Keywords— boundary lubrication layer, contact resistance, diagnostic, criteria, phenomenological model.

I. INTRODUCTION

A diagnosing task of a boundary lubricating sliding bearing mode, containing a shaft and an insert, in the internal-combustion engine (ICE), for example, of all-purpose power unit (APU) at its loading under operating conditions is actual. As a result of forced operations ICE increasing in operation modes, increased requirements are laying claim to engine oils operational properties, therefore creation of the way, allowing to control the state and properties of a boundary lubricating layer (BLL), is rather necessary and actual [1].

The service load and high-speed ICE parameters increasing especially in a high-forced mode (GOST 17479.1-2015) are laying increased requirements to nanometer lubricating layers thickness, i.e. to boundary lubricating layers (BLL). BLL state is a complex value defined by its structural changes and causing many measured tribotechnical parameters (strength, antifrictional, antiscuff, thermo-oxidative stability etc.) which are defined operational properties of lubricating material (LM) in aggregate.

In connection with a degradation of producing LM a problem of their quality assessment is actual. Moreover, before machinery producers is a nagging problem of import on domestic oils replacement with an optimum combination price and quality. On-stream, LM quality analysis is carry out on 15 physical and chemical parameters (GOST 8581-78), basic of which are kinematic viscosity, flash and chilling temperature, a mass fraction of water and mechanical impurities, alkali neutralization number, sulfonate ash content etc. Operational LM properties complex estimation is carried out at benchmark test on driving axles, different installations and internal-combustion engines and also field test [2]. Usually a LM user is interesting in its quality, but not a viscosity class and operational properties which define necessary, but not sufficient service oil conditions in specific installation. Under sufficient conditions we understand not that it is declared in the certificate at LM production, but those real LM characteristics, which define a sliding bearing state at specific load and speed service modes, especially during the moment of ICE start and stop or the forced acceleration in real time.

The work purpose is an estimation of operational properties and thermooxidative oil stability for its replacement age definition, and sliding bearing diagnostic on a boundary lubricating layer state to raise control reliability and its operation modes management in real time.

The method based on registration of a point contact conductivity parameters, was successfully applied by Bowden, Tabor [3], W. H. Abbot [4, 5], M. Antler [6, 7], J. F. Archard [8] for frictional behavior of "dry" materials used in electric contacts to research. Anti-wear properties of noble metals: platinum, gold, silver and their alloys were studied generally. It is installed, that in the absence of lubricants and comparatively low contact pressures the electric current passing promotes wear rising, acceleration of adsorbed films formation and chemical reactions passage on a surface. The results gained by them had qualitative character in the main, without a quantitative estimation of thickness and boundary lubrication continuity.

II. EXPERIMENTAL TECHNIQUE

In the general case conductivity through the molecular scale contact gap can be carried out by means of tunnel effect, thermionic and intrinsic conduction substance of an intermediate layer. The contraction resistance theory and thermionic conductivity are observed in this work [9]. The quantum-mechanical tunnel effect theory in metal-dielectric-metal system is observed for the first time in Sommerfeld and Bethe works [10], concerning to idealized square potential barrier, and has gained further development in the work [9].

In the presence a continuous flash lubricating layer *d* of nanometric thickness in a contact zone, its specific conductance is defined by tunnel conductivity generally [9, 10]:

$$\sigma_{\text{specific}} = \frac{e^2}{h^2 \cdot d}\sqrt{2 \cdot m \cdot \varphi}\,\exp\left(-\frac{4\pi d}{h}\sqrt{2 \cdot m\varphi}\right) \quad (1)$$

where e is an electron charge, m is an electron mass, h is a Planck constant, φ is an electron liberation work, d is an electrode spacing.

Mathematical factors calculation in an expression (1), where *d* is measured in nms (nanometers), and the electron liberation work in eV allows to simplify the expression (1) and to write down it in the form (2):

$$R_t = \left(\frac{10^{-14} d}{a^2 \varphi^{1/2}}\right)\exp\left(10{,}24\varphi^{1/2} d\right) \quad (2)$$

where φ is an effective electron liberation work, *a* is a contact point radius, *d* is lubricating layer thickness.

In the general case conductivity through the molecular scale contact gap can be carried out by means of tunnel effect, thermionic and intrinsic conduction substance of an intermediate layer. The dependence conductivity analysis from temperature has shown that at temperature tests to ≈ 300^{o} C thermionic and intrinsic conduction in a boundary lubrication rate it is possible to neglect [11]. The experimental data analysis can be carried out, using the theory of tunnel conductivity and the contraction theory, for a contour ground with an indissoluble lubricant layer which thickness is up to ≈ 3 nm [11].

R. Holm studied electric current passage processes in case of point and multiple contacts of conjugate objects. In a basis of voltage drop measuring on a searched object, having unknown contact resistance R_c a 4-wiring circuit (figure 1) [9] has been accepted.

E is a current source, R_1 is calibrating resistance; R_2 is a resistance box; R_c is contact resistance; V is a voltmeter; ADT is an analog digital transducer; PC is a personal computer.

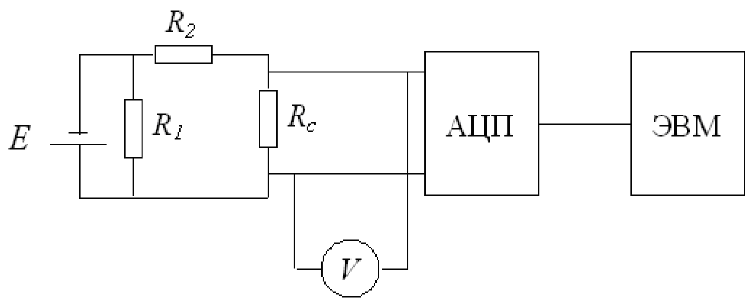


FIGURE 1. 4-WIRING CIRCUIT OF CONTACT RESISTANCE REGISTRATION.

Conjugate objects greasing point contact state analysis with using of all possible alternatives, given in the figure 1, namely: metallic; mixed or cluster and sieve; indissoluble lubricant layer was carried out in the beginning. Each alternative has its type, the electric conduction value accordingly and it is calculated on the basis of matching mathematical expressions [12]. It is necessary to calculate an actual contact point radius for a quantitative estimation of BLL nanometer thickness. The contact point radius is estimated on the basis of Hertz theory relationships for objects elastic (3) deformations; it is defined by loading value, objects' mechanical properties and their geometrical sizes [12]:

$$a=1.11(NR/E^*)^{1/3} \quad (3)$$

where N is a loading, r is conjugate objects effective radius; E* is an effective conjugate objects elastic modulus. At calculation of BLL thickness it is necessary to consider also, that an effective electron liberation work φ at BLL thickness less than 1.5 nm is 2.025 eV, and at 2.0–3.0 nm is 1.8 eV [11, 12].

An effective elastic modulus E* and a radius R are calculated from correlations (4) and (5) [13].

$$1/E^* = (1-\nu_1^2)/E_1 + (1-\nu_2^2)/E_2 \quad (4)$$

where E_1 and E_2 are elastic modulus, and ν_1 and ν_2 are both conjugate objects Poisson's ratios. At contact of two spheres with radiuses R_1 and R_2, an effective radius R, using for a calculation, is defined from correlation [13]:

$$\frac{1}{R} = \frac{1}{R_1} \pm \frac{1}{R_2} \tag{5}$$

where R_1 and R_2 are conjugate objects radiuses, we take the sign plus (+) at convex objects contact, and the sign minus (-) at the cylinder and the matching cylindrical cavity contact [13]. The roller width made ≈ 0.01 m. As a roller and a segment are executed from one material, steel 45, and a ball from steel ШХ 15, we considered an effective module value equal to the elastic steel modulus value ($E \approx 2.6 \cdot 10^{11}$ Pa). The calculated effective radius *R* for the circuit roller-sphere makes $3.45 \cdot 10^{-3}$ m.

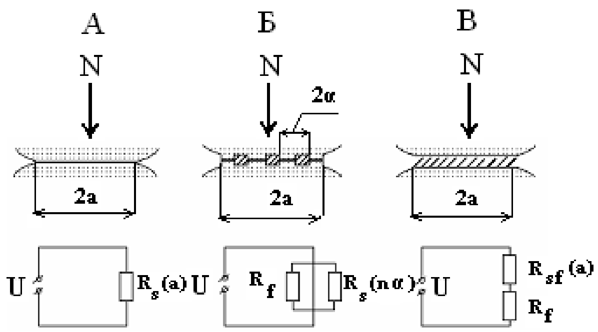
Parameters calculation contact (table 1) data with a theory of Hertz correlation using are given in table 1 [14].

TABLE 1
CONTACT PARAMETERS CALCULATION FOR THE CIRCUIT DESIGN ROLLER-SEGMENT (/), ROLLER-PLANE (/) AND ROLLER-SPHERE

N, H	a $*10^{-6}$, m	p_{cp}, MPa	R_s, mOm	$R_{ок}$, mOm	R_c, mOm
20	155/ 15.7/ 71	6.5/ 64/ 1300	1/ 9.6/ 2.1	0.3/ 3.2/ 63	1.3/ 12.8/ 65
100	346/ 35/ 122	14.5/ 143/ 2100	0.4/ 4.3/ 1.2	0.1/ 1.4/ 21.4	0.5/ 5.7/ 22.6
200	490/ 49.5/ 154	20.4/ 202/ 2700	0.3/ 3/ 0.9	0.1/ 1/ 13.5	0.4/ 4/ 14.4
400	693/ 70/ 194	28.9/ 286/ 3400	0.2/ 2.1/ 0.8	0.07/ 0.7/ 8.5	0.7/ 2.8/ 9.3
600	849/ 85.7/ 222	35.3/ 350/ 3900	0.18/ 1.8/ 0.7	0.06/ 0.6/ 6.5	0.24/ 2.4/ 7.2
800	980/ 99/ 244	40.8/ 404/ 4300	0.15/ 1.5/ 0.6	0.05/ 0.5/ 5.4	0.20/ 2.0/ 6
1000	1100/ 111/ 263	45.7/ 452/ 4600	0.14/ 1.4/ 0.57	0.04/ 0.45/ 4.6	0.18/ 1.9/ 5.2
1200	1200/ 121/ 279	50.0/ 495/ 4900	0.13/ 1.2/ 0.54	0.04/ 0.04/ 4.1	0.17/ 1.2/ 4.6
1400	1300/ 131/ 294	54.0/ 535/ 5200	0.12/ 1.15/ 0.51	0.04/ 0.04/ 3.7	0.16/ 1.2/ 4.2
1600	1390/ 140/ 307	57.7/ 571/ 5400	0.11/ 1.1/ 0.49	0.04/ 0.04/ 3.4	0.15/ 1.1/ 3.9
1800	1470/ 149/ 319	61.2/ 606/ 5600	0.10/ 1/ 0.47	0.03/ 0.03/ 3.1	0.13/ 1.1/ 3.6
2000	1550/ 157/ 331	64.5/ 639/ 5800	0.10/ 1/ 0.45	0.03/ 0.03/ 2.9	0.13/ 1/ 3.4

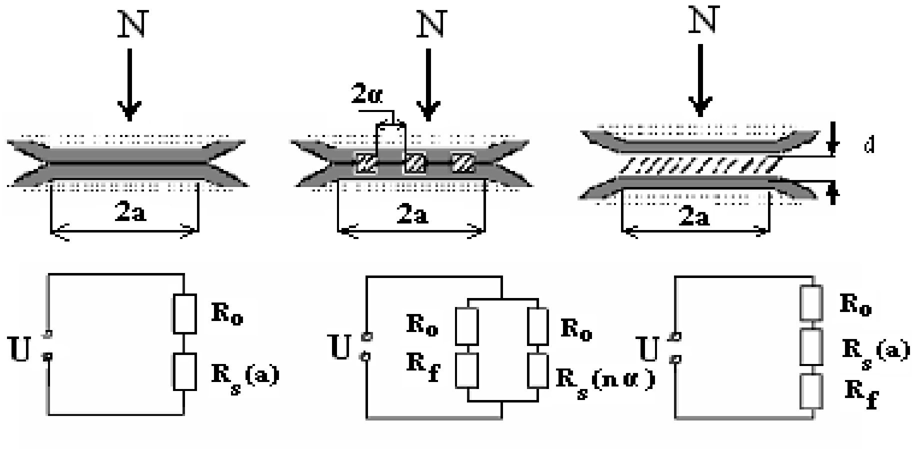
**** Notes. The real contact point radius (a), the actual average (p_{cp}) value, the contact contraction resistance (R_s), the oxide film ($R_{ок}$) and the recorded contact resistance (R_c) value. In each column row three figures are given through the slash. The first figure matches for the circuit roller-segment, the second figure matches for the circuit roller-plane and the third figure matches for the roller-sphere circuit.***

Lubricated contact interfaces models are given in the figure 2.



$$А)\ R_s = \rho/2a;\ Б)\ R_s = \rho/2n\alpha;\ В)\ R_t = \frac{10^{-14}\, d}{a^2 (\varphi)^{1/2}} \exp(10{,}24\ (\varphi)^{1/2} d)$$

OXIDIZED METAL



$$R_f = \sigma/\pi \cdot a^2 \qquad \rho_f = \sigma/d$$

FIGURE 2. LUBRICATED CONTACT INTERFACES MODELS

The passage from point to multiple contact at oils scoring resistance analysis of the various nature and functionality (hydraulic, motor, transmission, geared) was carried out with the flow-chart using, given in the figure 3.

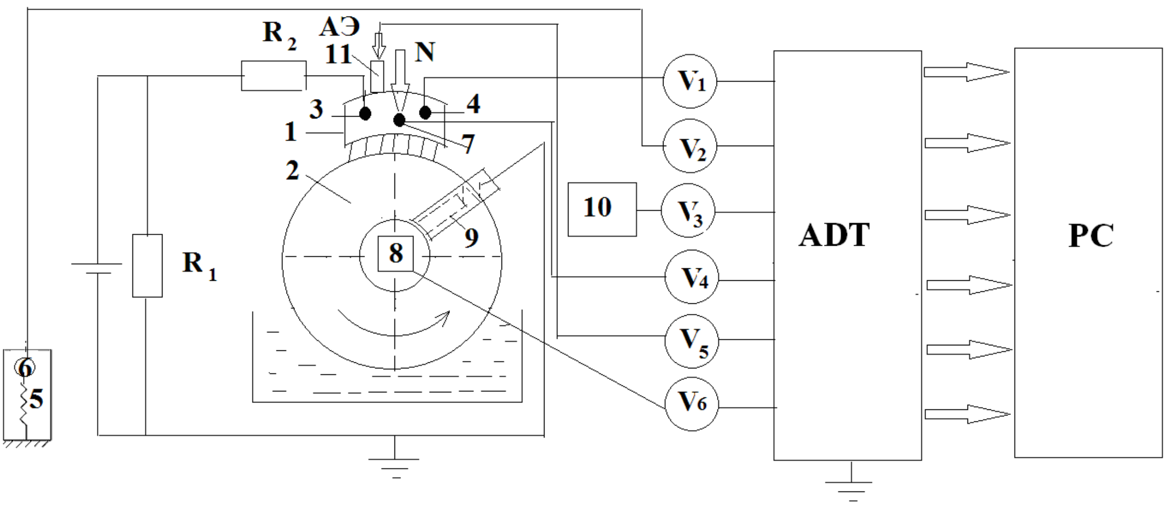


FIGURE 3. Flow chart device, where 1 is a backplate in a segment form; 2 is a mobile electrode in a roller form; 3 are current electrodes; 4 are potential electrodes; 5 is a load node; 6 is a load cell; 7 is a thermocouple; 8 is an inductive sensor for a friction torque measurement; 9 is spring-loaded copper-graphite brush; 10 is a drive with a velocity sensor; 11 is an acoustic emission sensor; ADT is an analog digital transducer; PC is a personal computer.

III. RESULTS AND DISCUSSION

A recorded contact resistance value (R_c) at experiment execution is equal to the contraction resistance sum R_s and oxide film $R_{ок}$. Calculated resistance values are given in the table 1. It is necessary to note, that the average contact pressure codomain changed within: 6.5 – 64.5 MPa – for the circuit roller-segment; 64 – 639 MPa – for the circuit roller-plane; 1.3 – 5.8 GPa – for the circuit roller-sphere.

Recorded contact resistance decreasing in experiment to level values characteristic for contraction resistance (Rs), given in the table 1, means BLL destruction on real contact points and presence of "dry" metal contact with a subsequent mating surfaces of the roller and the segment gripping.

In works [15, 16] operating modes at a step radial loading rolling bearings depending on a lubrication condition and structure of a steel surface are experimentally defined. It is shown, that the one cycle time period of a metal surface reinforcement and destruction is in many aspects defined by high-speed loading conditions [17], physical and chemical lubricant nature [17] and, as consequence, BLL tribological properties and structural changes kinetics accumulation [18-20]. The most typical sliding bearings and rolling bearings diagnostics difference is that at loading on the shaft increasing or in a turbine start and stop period or the forced ICE power increasing a regime with an aggravation at which hydrodynamic, and then a boundary lubricant layer destruction are accompanied by catastrophic jamming and the sliding bearing destruction with all consequences can occur in result.

The calculation analysis dependence on tunnel resistance (R_t), and BLL nanometric thickness, and a real contact area shows, that at loading increasing by two orders the actual contact area changes by one order, and the contribution from the BLL thickness in calculated value Rt increases by ten orders [21]. The basic contribution in the tunnel resistance calculated value is brought the BLL thickness, but not the real contact area, that allows estimating mechanical and frictional properties of boundary lubricant layers (BLL) at elastic contact interacting of conjugate objects at their relative movement. The last has defined a possibility to use an electrophysical probing method for an antiscuff various functionality oils properties estimation: motor [22], transmission [14], hydraulic [23], geared [21], etc.

Modeling tests on BLL formation and destruction kinetics, with friction machine CMT-1 using with step load increment have been made for criterion development. The circuit roller-segment was used in the experiment where the roller (Cт 45) modeled the shaft, and the segment (Cт 45) modeled the support insert. Linear roller rotational velocity made 0.5 m/s, the segment area was $2\cdot10^{-4}$ m^2.

Let's instance antiscuff and operational properties of hydraulic oils features estimation (figure 4) [23]. The roller was located in a tray with analyzed oil before a test operation. One operational class hydraulic oils were test subjects on classification API: ZF-46 (ТУ 0253-014-44918199-2005); МГЕ-46В (ТУ 38.001347-2000); HVLP-46 (ТУ 0253-028-44918199-2006); HLP-46 (ТУ 38.301-41-180-2001).

The contact resistance value R_c between the shaft and the insert, measured on the four-wire circuit (figure 1) [9] has been chosen as measured sliding bearing lubrication parameter state at a boundary friction diagnostic. It is caused by that the BLL thickness estimation is carried out on contact resistance R_c value indirectly.

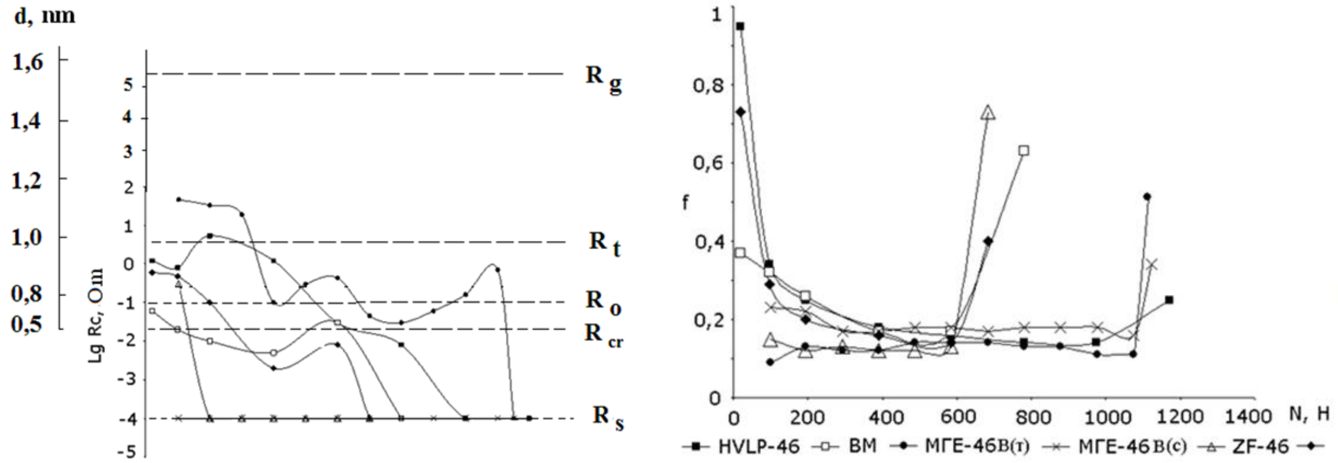


FIGURE 4 – A contact resistance (R_c) and a friction factor (f) on loading (N) dependence.

The estimation results generalization of antiscuff oils durability various functionality (motor, transmission, hydraulic, geared, etc.) by influence on them external load and high-speed factors are presented in the figure 5. It is experimentally installed, that a boundary lubricant layer [24] presented, for example, by engine oil, and metal conjugate objects surfaces of the tribosystem under some load and high-speed (P, V) factors influence will occupy some equilibrium and stable structural states characterized by certain points (O; A; B; C; D; K) on the circuit (figure 5) [14]. Each structural section surface condition causes a certain contact resistance (R_c) dependence, i.e. each point O, A, B,… will match its average contact resistance (R_c, about; $R_{c,\ A}$; $R_{c,\ B}$; $R_{c,\ C}$; $R_{c,\ D}$; $R_{c,\ K}$) value level. Let there is some minimum load and high-speed influence (for example, a friction knot idling) on an interface which is characterized by O point. Then with electrophysical probing parameters using we will develop diagnostic estimation criterion of lubricants antiscuff properties at step loading which is applied at an estimation of engine oils antiscuff properties. The given complex criterion can be used only at registration, external load and high-speed factors as well as internal tribosystem factors, for example, a contact resistance (R_c), characterizing structural changes of conjugate objects interface.

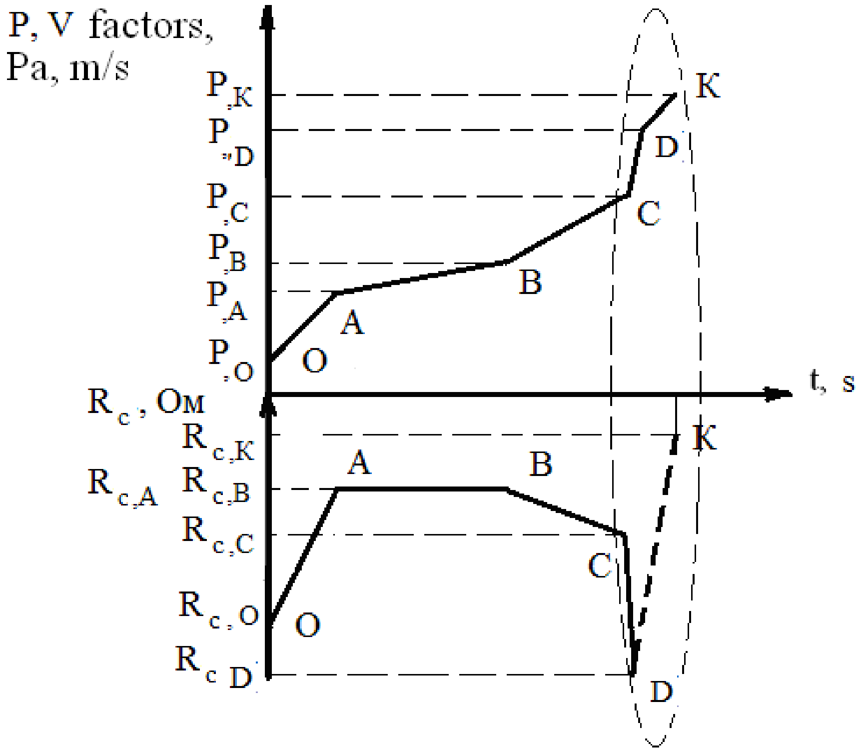


FIGURE 5. An external load and high-speed (P, V) factors on tribosystem depending on a time (t), where structural section surface conditions are characterized by points (O, A, B, C, D, К) with matching to them contact resistance (R_c) levels.

The diagnostic invariant criterion is developed, which does not depend on load and high-speed modes or conjugate objects contact circuit (point, multiple) [14, 25]. The criterion consists in the following:

1. The BLL self-organizing mode occurs in the real pressure to ≈ 35 MPa field and is characterized by connection BLL molecules with a surface transition from a physical adsorption to stronger chemical adsorption. BLL structure change is accompanied by increasing its thickness and, as consequence, rising contact resistance R_c level. The recorded contact resistance (R_c) to an initial metal surface (without lubricant) relation with an oxide film ($R_{ок}$) R_c/R_{ok}>> 1 resistance characterizes the BLL state in which the polymolecular component remains;
2. The BLL dynamic equilibrium mode. In the formation and mechanical destruction chemisorbed layer process occurs dynamic equilibrium in time. The polymolecular BLL component remains in this case, and the layer thickness by reason of its wear decreases a little in comparison with the first mode. The chemisorbed layer modulus can attain the value ≈ 1.4 GPa, that is comparable, on the order value with a rubber elasticity modulus (≈ 5 GPa). Resistance values relation is more than one, i.e. R_c/R_{ok}> 1 for this mode;
3. Physical and chemical processes complex (mechanodestruction, thermodestruction, etc.) causes decreasing values of contact resistance level in view of BLL wearing. In this case it is possible to assume, that a polymolecular BLL component is destroyed, and the monomolecular layer component ≈ 0.5 nm (hydrocarbon molecules cross-section size) remains. In view of the fact that an oxide film contact resistance value is comparable with a tunneling conductance value for the given layer thickness, the resistance values relation becomes about one, i.e. $R_c/R_{ok} \approx 1$;
4. At the friction critical behavior, score forestalling, the monomolecular BLL component is destroyed, that proves by the further contact resistance value decreasing. At the same time, depending on the metals plastic deformation nature, two variants can occur: the intensive surface oxidation accompanied, in the running-in period of surfaces interaction, by contact resistance level by two-three orders increasing, with a subsequent an elastic energy surface layer accumulation and developed dislocation structure formation with the subsequent surface layer destruction; surface layer destruction and a juvenile surface uncovering without preliminary its intensive oxidation. For the given mode recorded contact resistance R_c decreasing to contraction resistance (R_s) values level is characteristic. The recorded contact resistance (R_c)

to contraction resistance (R_s) relation becomes equal about one, i.e. $R_c/R_s \approx 1$. In a knot operating mode occurs, local in a time, the friction surfaces gripping accompanied debris formation in a contact zone and conjugate surfaces separating by them. At the same time, fluctuations R_c level increases sharply to an upper limit measurement (the boundary line is set by electrical circuit and set current source parameters). Friction torque value and temperature increase sharply at this time.

The given criterion can be used for a forecasting conjugate objects surface section lubrication state. The developed criterion is in a basis of control algorithms conjugate metal objects surface section state in working friction knots conditions (rolling and sliding bearings etc.), that is important for diagnostic and management by their operation modes.

Let's instance the developed actuality criterion and the way presented in the article, for a diagnostic internal-combustion engine by "Mercedes" manufactured, type OM 502, operated in composition with a fodder harvester КВК 8060. At a high-cycle spring compression and releasing which end rested against a valve cover, there was a fatigue failure of its end cover and spring releasing. The last has led to engine oil supply in the motor trouble. A lack of liquid-film lubrication rate or a hydrodynamic regime violation has led to a piston flashing in the cylinder, to inserts crank and crankshaft jamming (Figure 6).

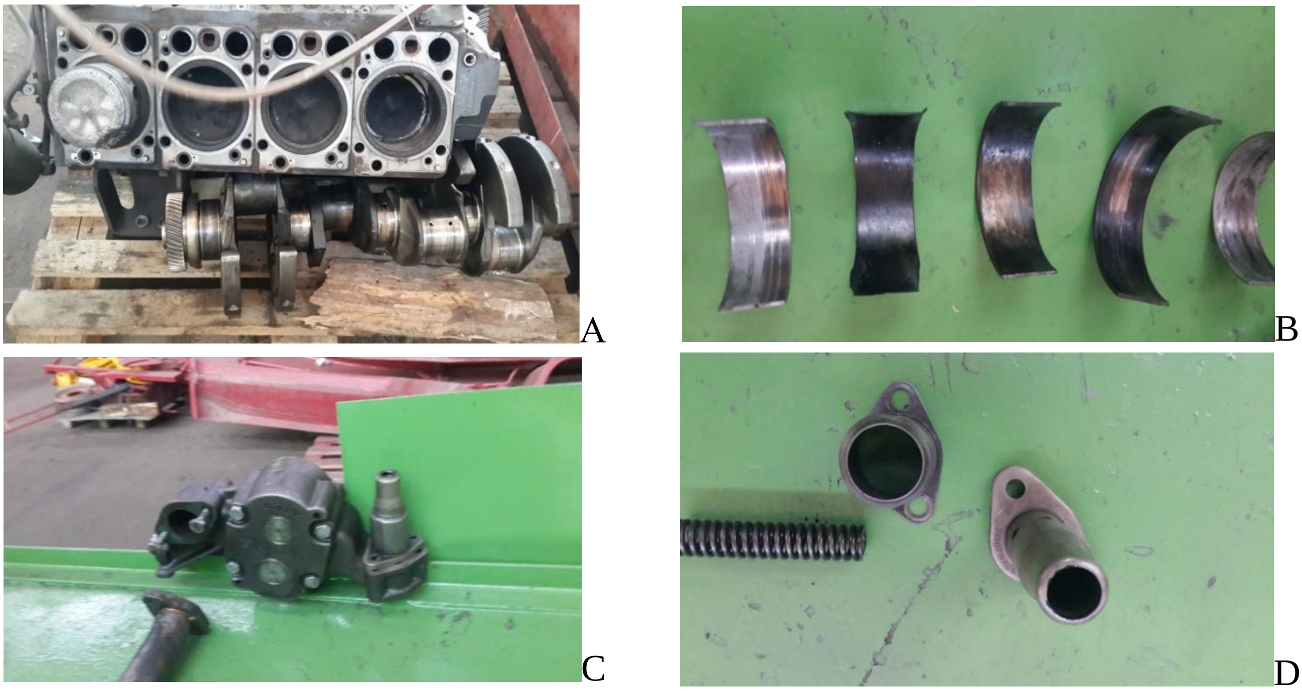
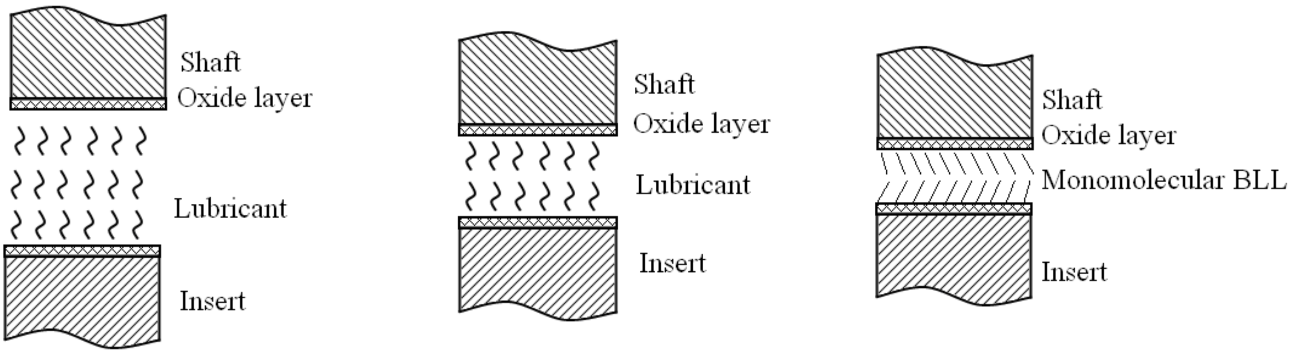


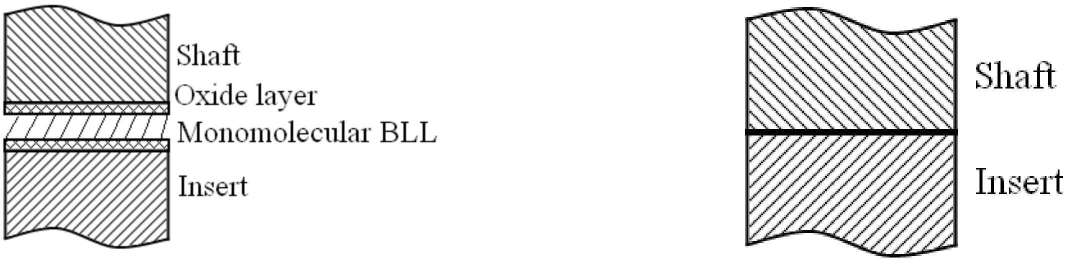
FIGURE 6. An aspect of the jammed engine at its dismantling: A – the system cylinder-piston and the crankshaft with necks (inserts); B – necks or crankshaft inserts; C – the valve controlling oil supply in the engine; D – the valve cover destruction.

An experimental data values analysis of the contact resistance at load step increasing has allowed us to mark out four boundary operating modes of sliding bearings connected with its lubrication state (figure 7) [26]:

- the hydrodynamic regime: a lubricant multilayer [27] between the shaft and the sliding bearing is "enough thick";
- the boundary friction mode: a lubricant multilayer is between the shaft and the sliding bearing and the tunneling electric conductance is realized between the shaft and the bearing;
- the preemergency operation: the bearing is in a boundary friction mode with conservation of several monomolecular BLL. The tunneling conductance occurs;
- the critical behavior: conservation is minimum possible on the thickness BLL monomolecular ≈ 0.3 nm with the maximum possible real contact lapped area;
- the bearing destruction: BLL absence, testifying to "dry" metal contact, with oxide films destruction between the shaft and the sliding bearing which is accompanied by the scoring and conjugate surfaces gripping.



Hydrodynamic regime, Rg Boundary friction mode, Rt Preemergency operation, Ro



Critical behavior, R_{cr} **Destruction, Rs**

FIGURE 7. Sliding bearings operating modes

Comparison of recorded contact R_c value with theoretically counted threshold values R_g, R_t, R_o, R_{cr}, R_s (fig. 4) characterizes conjugate objects lubrication state. The developed invariant test to rolling and sliding bearings using allows elaborating a way of the lubrication state control [14]. The criterion is based on comparison of measured contact resistance R_c value with theoretically counted contact resistance R_g, R_t, R_o, R_{cr}, R_s threshold values characterizing the sliding bearings operating modes observed above.

We measured a contact resistance R_c quantity in the course of experiment at the step loading and we recorded kinetics of its changing during 300 s. for each loading value, that was necessary for stabilization of physical and chemical processes passing in BLL [28]. The measured value R_c was compared with counted threshold values R_s, R_{cr}, R_o, R_t, R_g, and we defined the bearing lubrication mode.

Contact resistance R_c and friction coefficient *f* from loading *N* dependences are presented in the figure 3, received contact resistance threshold values are shown by dashed lines. A correlation between friction coefficient from loading and measured value contact resistance R_c dependence is visually presented in the figure 3. Hydraulic oil of marketable delivery МГЕ-46В (ТС 38.001347-00) was the object of research.

We accept a boundary lubricant layer thickness matching to transition from a hydrodynamic friction to a boundary friction mode – 2.0 nm for testing oil, and the boundary lubricant layer thickness is matching to the monomolecular lubricant minimum thickness layer – 1 nm.

Contact resistances R_g and R_t values, matching to hydrodynamic and boundary sliding bearings operating modes and differing by lubricant layer various values d thickness are calculated with a formula (1).

We counted by formula (6) the contact resistance R_o value, installing the contact resistance boundary line of metal contact with an accounting oxide films presence and corresponding to emergency bearing operation mode:

$$R_o = \sigma/\pi a^2 \qquad (6)$$

where σ is a sheet specific resistance, a is a real contact point radius.

Considering that the sheet resistivity level defined from reference data, can differ considerably for really used contact materials surfaces with various process technology (carburizing, nitriding etc.), the contact resistance R_o value corresponding to metal contact with a glance oxide films presence, it is necessary to measure in a statics at a bearing loading under a dead load in lubricant absence.

We defined R_{cr} experimentally at BLL monomolecular component destruction as it was possibly it to count, but its calculated value will be equal ≈ R_o in signification. We defined the R_{cr} value experimentally at monomolecular BLL component destruction. It is experimentally installed, that a voltage drop decreasing to ≈ 2 – 3 mV means the BLL monomolecular component destruction.

The resistance contraction R_s value installing a contact resistance boundary line of metal contact with a glance mechanical materials properties of which the bearing is made, it is necessary to calculate the radius of a real contact point (*a*) and the actual contact area (*S*) for the specific bearing circuit, proceeding from the classical Hertz theory relationships (7).

$$R_s=\rho/2a \tag{7}$$

where ρ is an electric specific resistance, a is a real contact point radius.

We have theoretically counted threshold values R_g, R_t, R_o, $R_{cr,}$ R_s and have obtained R_g = 166722 Om, R_t = 5 Om, R_o = 0.1 Om, R_{cr} = 0.04 Om, R_s = 0.001 Om (fig. 4).

We measured contact resistance R_c at a step segment loading on a roller for tested oil and recorded kinetics of its change in the course of 300 s. on each loading step. We compared recorded R_c value and counted threshold values R_g, R_t, R_o, R_{cr}, R_s (fugure 4). It is necessary to note, that R_g value at experiment executing has not been attained, as in the loadings field realized on the friction test machine CMT-1, a boundary friction mode become at once.

We are not following results (figure 4) for hydraulic oil marketable delivery of the brand МГЕ-46В. The measured value R_c = 33 Om was for loading 200 N.

We have compared the gained value and counted threshold values and as R_t <R_c <R_g (5 Om <33 Om <166722 Om), we conclude, that the bearing is in a boundary friction mode, the BLL thickness makes more than 1 nm, i.e. is in a normal running regime.

The measured value R_c = 5 Om is for loading 350 N. We have compared the got value and counted threshold values and as R_c = R_t (5.2 Om = 5 Om), we conclude, that the bearing is in a boundary friction mode, the BLL thickness makes 1 nm, i.e. is in a normal running bearing regime.

The measured value R_c = 0.43 Om is for loading 600 N. We have compared the got value and counted threshold values and as R_o <R_c <R_t (0.2 Om <0.43 Om <5 Om), we conclude, that the bearing is in a boundary friction mode, the BLL thickness is less than 1 nm, but BLL keeps its integrity.

The measured value R_c = 0.2 Ohm is for loading 650 N. We have compared the got value and counted threshold values and as R_c = R_o (0.2 Om ≈ 0.1 Om), we conclude, that the bearing passes in the preemergency operation mode at which there is a boundary lubricant layer destruction and an electric conduction appearance through real points of metal contact with a glance of oxide films.

The measured value R_c = 0.03 Om is for loading 800 N. We have compared the got value and counted threshold values and as R_s <R_c <R_{cr} (0.001 Om < 0.04 Om <0.1 Om), we conclude, that the bearing is in an emergency operation mode at which a boundary lubricant layer monomolecular component destruction and points with metal contact predominance occurs.

The measured value R_c = 0.0001 Om is for loading 1120 N. We have compared the got value and counted threshold values and as R_c = R_s (0.0001 Om), we conclude that conjugate surfaces grabbing regime of sliding bearing occurs.

To control developed criteria we created the stand simulating plain bearings work, with recorded parameters output to the computer (figure 8).

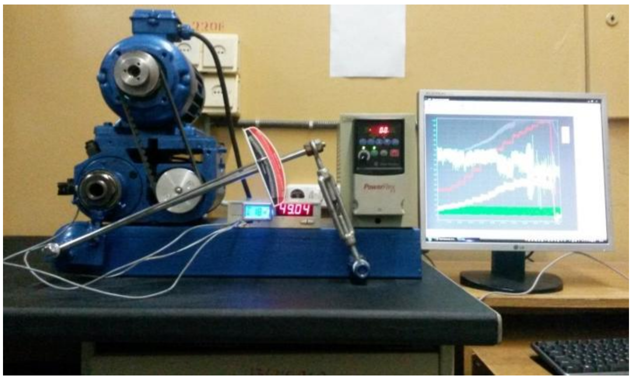


FIGURE 8. Stand to diagnose plain bearings lubrication state

The basic technical features: a test category – friction; loading and force measurement – mechanical; force measurement range – 20... 4000 N; the force dynamometer makes 2 %; the frictional torque type gauge is electronic; a frictional torque error measurement makes 3 %; rpm measurement range is – 15... 3600 min^{-1}; a power consumption is no more than 1 kw; overall dimensions are: 700x450x500 mm; weight is 43 kg.

The stand contains an adjustable electric drive, power expenses measurement device, real frictional unit equipped with a boundary lubricant layer state electrophysical control circuit (hydrodynamic or hydrostatic journal bearing), hydrostation for lubricant supply in frictional units and adjustable loading. The stand circuit is presented in the figure 9.

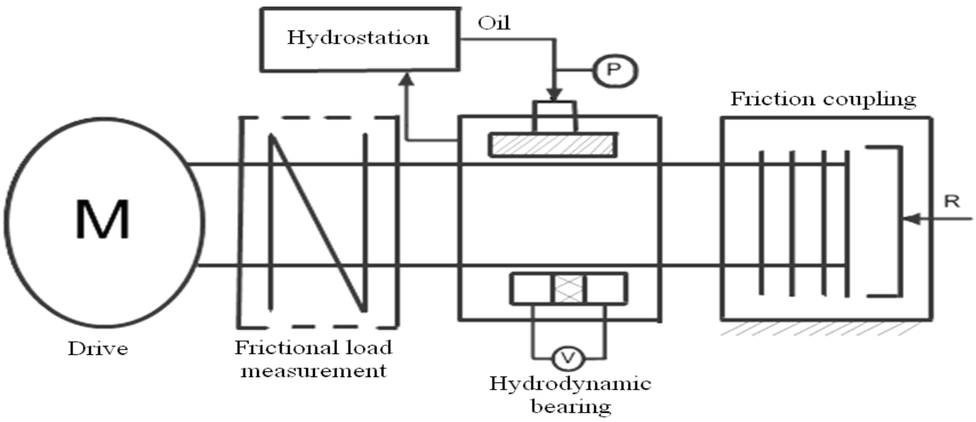


FIGURE 9. Stand circuit for plain bearings diagnostic

One of electrical schematics for voltage drop between the shaft and one of isolated sliding measurement is presented in the figure 10, where N is a loading on the shaft, and I are electric current lines between the shaft and the sliding bearing.

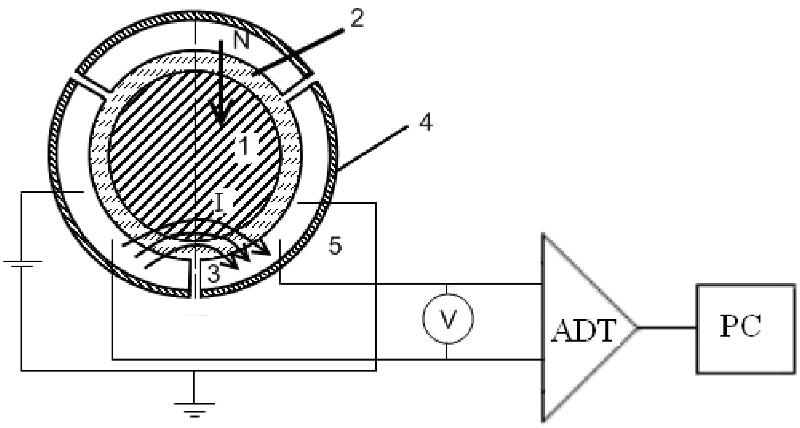


FIGURE 10. Sliding bearing electrophysical probing circuit where 1 is a shaft, 2 is lubricant, 3 is an insert, 4 is an insert isolation, 5 is a bearings case

Another electric circuit for voltage drop between the earthed shaft and one of dielectric isolated sliding bearing measurement is presented in the figure 11.

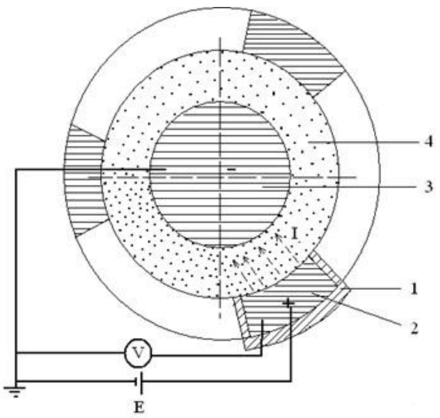


FIGURE 11. Circuit for plain bearing diagnostic on a boundary lubricant layer state, where 1 is dielectric, 2 is a hydrodynamic bearing, 3 is a turbine rotor, 4 is a physical wedge, E is EDS = 50 mV, V is a voltmeter, I are streamlines.

Other circuits for voltage drop between the shaft and sliding bearings measurement are possible also.

We used as tested oils turbine oil ТП-22С and transmission oil ТАД-17и also. These oils have a wide practical application at turbines operation in RUP «Gomelenergo» and in drive train components of fodder and grain harvesters, produced by JSC "Gomselmash". Estimation results of antiscuff and operational oils properties are presented in the figure 12.

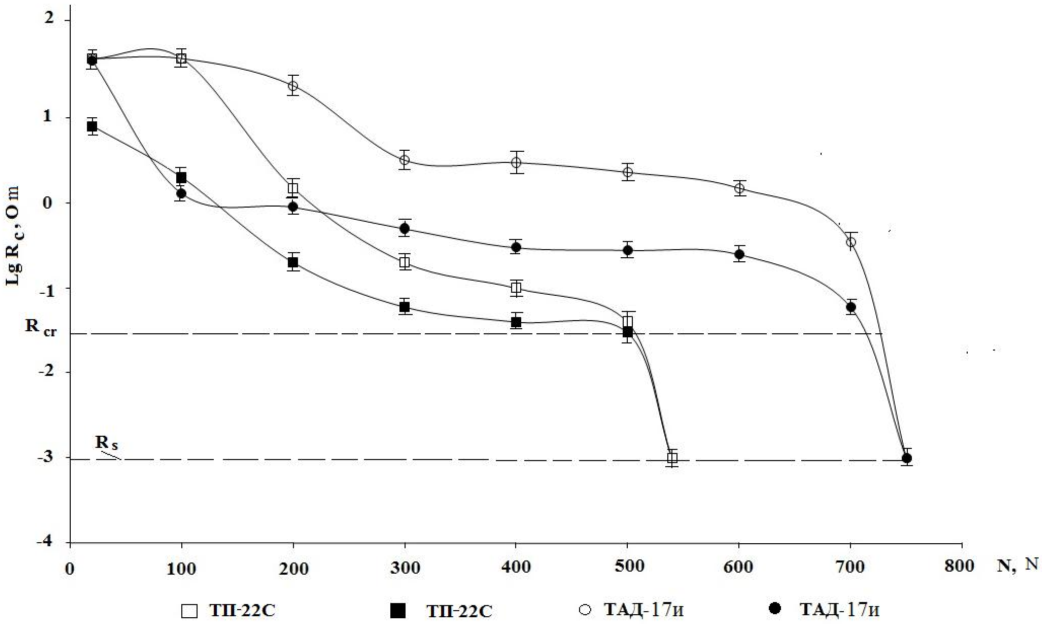


FIGURE 12. Contact resistance on loading for turbine oil ТП-22С and transmission oil ТАД-17и dependence

It is installed as a result of tests, that theoretically prognosticated contact resistance criterion levels defining sliding bearings lubrication state, completely have found practical evidences. In case of the shaft dry metal contact (Ст 45) and the bronze insert or a sliding bearing (БрОЦС-5-5-5) a voltage drop between them made ≈ 0.1 mV. It is experimentally installed at step load increasing, that voltage drop decreasing to ≈ 2 – 3 mV means monomolecular BLL component destruction, presented both turbine, and transmission oils. After achievement the given critical value R_{cr} conjugate surfaces grabbing and an electric motor rotating the shaft jamming were noted. The last was accompanied by spasmodic decreasing of recorded contact resistance to contraction resistance.

IV. CONCLUSION

Electro-physical probing methods using foundation is given for sliding bearings operation modes estimation on BLL state. A calculation dependence analysis of tunnel resistance (R_t) from BLL nanometric thickness and the real contact area shows, that at load increasing by two orders the real contact area changes by one order, and the contribution from a BLL thickness in design value R_t increases by ten orders. The BLL thickness brings a basic contribution in the calculated value tunneling resistance, instead of real contact area that allows to estimate mechanical and frictional properties of boundary lubricant layers (BLL) at elastic contact interacting of conjugate objects at their relative moving.

Electric circuits and methods, allowing estimating BLL operational properties, are developed. This method allows to test BLL formation and destruction kinetics in real sliding bearings direct at their operation.

On the experimental data analysis basis an antifrictional and antiscuff oils and plastic lubricants of a various functional purpose properties estimation (transmission, motor, hydraulic, geared), the recorded contact resistance value relatively to an initial metal surface resistance value or contraction resistance is developed the diagnostic estimation state criterion of metal interface, namely at BLL formation and its self-organizing $R_c/R_{ok}>> 1$ at a dynamic equilibrium between BLL formation and destruction $R_c/R_{ok}> 1$, BLL destruction $R_c/R_{ok} \approx 1$, metal interface destruction $R_c/R_s \approx 1$. The developed criteria are the basis for creating phenomenological models for predicting the state of lubrication of the interface surface of conjugated bodies during rolling and sliding. These criteria are laid in the basis of algorithms for monitoring the state of the interface of conjugated metal bodies under the conditions of rolling and sliding bearings, which is important for the diagnosis and management of their operation modes.

Contact resistance threshold, on which values it is possible to estimate sliding bearings operation modes, connected with its lubrication state, namely, hydrodynamic regime R_g, boundary friction mode R_t with polymolecular BLL conservation, preemergency operation with monomolecular BLL (R_o) conservation, emergency operation mode (R_{cr}) with very thin (≈ 0.3 nm) monomolecular BLL conservation, destruction mode (R_s) are counted. Recorded contact R_c value with theoretically counted threshold values (R_g, R_t, R_o, R_{cr}, R_s) comparison characterizes conjugate objects lubrication state. The proposed way allows to estimate by means of nondestructive testing sliding bearing lubrication state at boundary friction that gives a chance, depending on conjugate surfaces lubrication state to introduce amendments in its operation modes, to define oil replacement age and thus to provide reliability and durability of its work.

Thus, the electro-physical probing method using foundation for sliding bearings diagnostic on the boundary lubricant layer state is given. The way for the boundary sliding bearing lubricant control mode, for example, internal-combustion engine (ICE) crankshaft journal at its loading in operating conditions, and also for an incoming control or engine oils quality estimation is developed. The given diagnostic way allows to make an incoming quality oils inspection (hydraulic, turbine, motor), their antifrictional, antiscuff, and operational properties estimation at an early stage before critical, emergency sliding bearing running, to operate its work mode. The developed way has a big practical importance, as on its basis the device which in real time carries out a quality control of used engine oil in the internal-combustion engine. The given device using, for example, in fodder harvesters will allow to the machine operator to carry out not only a quality control of bought engine oil in the market, but also to do its replacement in due time, on the basis of its thermal-oxidative ability.

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