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SLIDING BEARING DIAGNOSTICS

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Abstract: An explanation of electrophysical sounding method using for sliding bearing diagnostics at a boundary friction is given. Electrical circuits and a sliding bearing diagnostic way, where the control analysis of a boundary lubricant layer (BLL) thickness is realized indirectly in accordance with contact resistance parameters are developed. The sliding bearing greasing state is defined according to installed threshold values in advance which achievement defines it operating regime.

Keywords: sliding bearing; boundary lubricant layer; contact resistance.

1. INTRODUCTION

The diagnosing problem of a sliding bearing boundary greasing regime, containing a shaft and an insert, for example, in the internal-combustion engine of the all-purpose power unit (APPU) at its loading in operating conditions is actual [1]. As a result of increasing the internal-combustion engine (ICE) augmented ratings show increased requirements to operational properties of engine oils, therefore creation of the way, allowing to control a state and properties of a boundary lubricant layer (BLL), is rather necessary and actual.

The increasing of ICE load and high-speed operational parameters, especially in a high-augmented rating (GOST (state standard specification) 17479.1–2015) shows increased requirements to lubricant layers of nanometer thickness, i.e. to boundary lubricant layers (BLL). The state BLL is a complex value, defined by its structural changes and causes many measured tribotechnical parameters (strength, antifriction, antiscuff, thermooxidative stability etc.) which in the aggregate define operational properties of lubricants.

In connection with quality debasement of outputting lubricants the problem of their quality estimation is actual. The quality analysis of lubricants in service is carried out on 15 physical and chemical parameters (GOST 8581–78), basic of which are: kinematic viscosity, flash and chilling temperature, mass fraction of water and mechanical impurities, alkaline number, sulfonate ash content etc. The properties of a lubricated layers research by the laboratory methods [2, 3]. The complex estimation of lubricants operational properties is carried out at bench tests on drive axles, various installations and internal-combustion engines, and also at field tests. The user of lubricants is interested, as a rule, the quality, instead of the viscosity class and operational properties which define necessary, but not sufficient conditions of oil using in the real installation. Sufficient conditions are not declared in the certificate at lubricants manufacture, and those real lubricants parameters which define a sliding bearing state at load and high-speed using conditions, especially in the moment start-stop of the internal-combustion engine or the forced acceleration in real-time.

The aim of the work is an estimation of operational properties and thermooxidative stability of oil for its replacement periods definition, and sliding bearing diagnostics in accordance with a state of a boundary lubricant layer for a raising of the control reliability and a mode control of operation in real time.

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2. EXPERIMENTAL TECHNIQUE

BLL thickness and a presence of films between the shaft and the insert define operational oil properties. The roller was located in a tray with investigated oil before a test operation. Hydraulic oils of one operational class according to the 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) ware subjects of inquiry.

A value of contact resistance R_c between the shaft and the insert, measured according to the four-wire circuit (figure 1) [4–6] has been chosen in the capacity of measured sliding bearing greasing diagnostic state parameter at boundary friction. It is caused by that a value of contact resistance R_c correlates with a BLL thickness, and also reflects physical, frictional and chemical processes proceeding on a boundary surface of interfaced bodies [7].

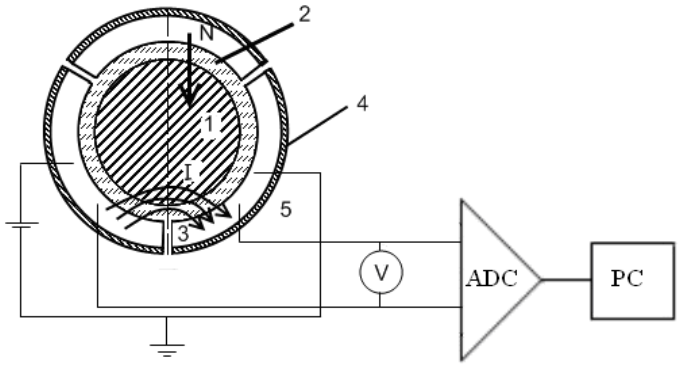


Figure 1. The electrophysical sounding circuit of the sliding bearing (1 – shaft, 2 – grease, 3 – insert, 4 – insert insulation, 5 – bearings body).

An experimental data analysis of contact resistance values at step load increasing has allowed us to mark out four boundary operating modes of the sliding bearing, connected with its greasing condition (figure 2):

– hydrodynamic regime – between the shaft and the sliding bearing is a "thick" enough polymolecular layer of lubricant;

– regime of a boundary friction: a polymolecular layer of greasing is between the shaft and the sliding bearing, a tunnel electrical conduction is realized between the shaft and the support (figure 2);

– preemergency operation: the bearing is in a regime of boundary friction with conservation of several monomolecular BLL. The tunnel conduction occurs (figure 2);

– critical behavior: conservation of minimum possible thickness is ≈ 0,3 nm of monomolecular BLL with the greatest possible lapped face of actual contact;

– support destruction: a BLL absence, testifying about a "dry" metal contact with an oxide films destruction between the shaft and the sliding bearing, which is accompanied by a scoring and a seizure of mated surfaces (figure 2).

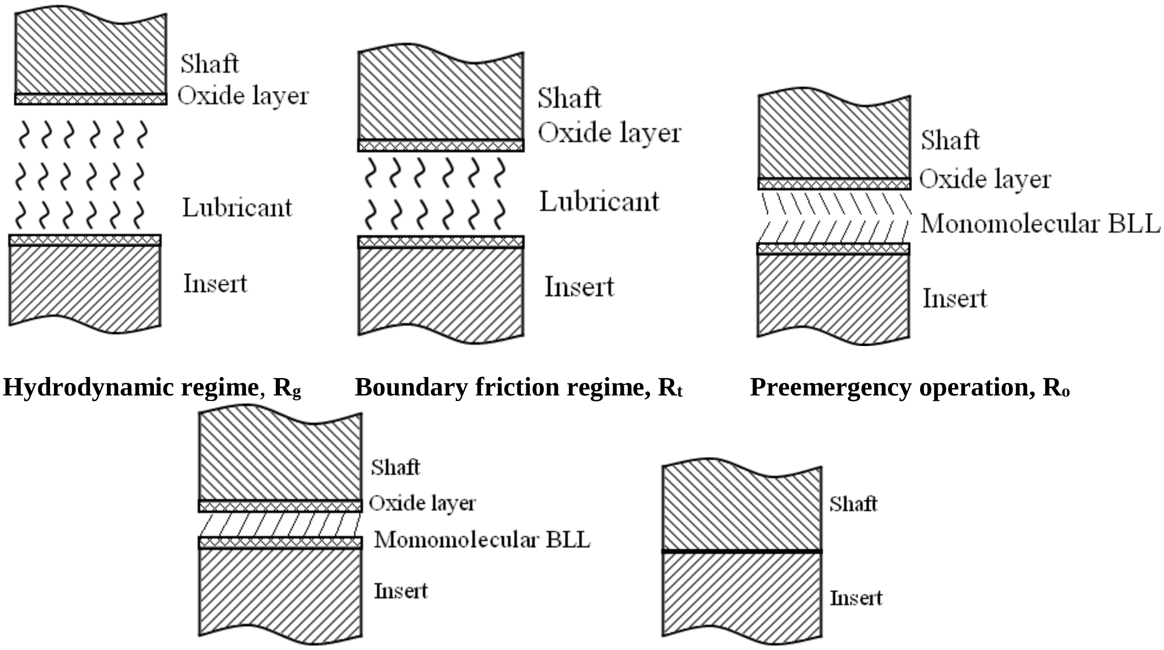
3. RESULTS AND DISCUSSION

A relationship of recording contact R_c to threshold values (R_g, R_t, R_o, R_{cr}, R_s) characterizes greasing condition of conjugate bodies. Using of the developed invariant test to rolling bearings [8] and sliding bearings allows to develop a way of condition control greasing. The test is based on comparison of measured contact resistance R_c value and theoretically counted threshold values of contact resistance R_g, R_t, R_o, R_{cr}, R_s characterizing sliding bearing operating modes, examined above.

Electrical conductivity per unit area σ and contact resistances R_g and R_t values, matching to sliding bearing hydrodynamic and boundary operating modes and differing by various thickness values of lubricant layer *d*, are calculated by the formulas [9] (1) and (2).

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

where: e – a charge of electron, m – a mass of electron, h – Planck's constant, φ – an effective work of electron, d – a distance between the electrodes.



Hydrodynamic regime, $\mathbf{R_g}$ **Boundary friction regime,** $\mathbf{R_t}$ **Preemergency operation,** $\mathbf{R_o}$

Critical behavior, $\mathbf{R_{cr}}$ **Destruction,** $\mathbf{R_s}$

Figure 2. Sliding bearing operating modes.

The simplified expression for calculation of a tunnel contact resistance is given [5] (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 – an effective work of electron liberation;

d – a boundary lubricant layer thickness (BLL).

An effective work of electron liberation φ at BLL thicknesses less than 1.5 nm is 2.025 eV, and at 2.0–3.0 nm is 1.8 eV [5].

The measurements of film thickness (d ≈ 1–2 nm) supported by results of X-ray electron spectroscopy [10] and calculation of the value of module Young for chemisorbed layer formed with grease LGBH–2 (E ≈ 1.4 GPa) [11].

The contact resistance R_o value, installing a boundary line of a contact metal resistance with taking into account presence of oxide films and matching to an emergency bearing operation, we counted by formula [4] (3):

$$R_o = \sigma/\pi a^2, \quad (3)$$

where σ is specific sheet resistance, a is an actual contact spot radius.

In view of the fact that a specific sheet resistance value, defining from reference data, can differ considerably for really used contact surfaces of materials with various process technology (cementation, nitriding, etc.), the contact resistance R_o value, matching to metal contact, taking into account a presence of oxide films, it is necessary to measure in statics at a loading bearing under a dead load in absence of lubricant.

A contraction resistance R_s value, installing boundary line of a contact metal resistance, taking into account mechanical properties of materials from which the bearing is made, it is necessary to count the actual contact spot (*a*) radius and the real contact area (S) for the concrete bearing circuit, proceeding from relationships of the classical Hertz theory (4).

The contact spot radius is estimated from relationships for elastic (4) deformation of bodies, it is defining by a loading value, mechanical properties of bodies and their geometrical sizes [12]:

$$a=1{,}11(Nr/E^*)^{1/3}, \qquad (4)$$

where N is a loading, r is an effective radius of conjugate bodies; E* is effective elastic modulus of conjugate bodies.

A criteria application assumes the following operations procedure: in the beginning we calculate criterion values R_s, R_g, R_t, R_o theoretically, then we record a contact resistance value R_c in bearing service. Further, by means of comparison recorded value R_c and calculated criterion values the conclusion about a sliding bearing state is made [11]:

at $R_c > R_g$ the bearing is in hydrodynamic friction regime;
at $R_c \approx R_g$ the bearing moves from a hydrodynamic friction to a boundary friction regime;
at $\mathbf{R_c} \approx \mathbf{R_t}$ the bearing is in a boundary friction regime at sliding bearing operation;
at $\mathbf{R_c} \leq \mathbf{R_o}$ the bearing is in a preemergency operation with a minimal BLL thickness and a possible metal contact on real contact spots;
at $R_c \approx R_s$ a critical destruction behavior of sliding bearing occurs.

Model tests on BLL formation and destruction kinetics, with using of the friction test machine CMT–1 with step loading increasing have been made for criteria tryout. The roller – segment circuit was used in the experiment, where the roller (Ст 45) modeled the shaft, and the segment (Ст 45) modeled the bearing insert. A linear speed of roller rotation made 0.5 m/s, the segment area made $2\cdot10^{-4}$ m^2.

Segment and rollers surfaces ware ground and polished preliminary to an average arithmetical deviation of surface profile $R_a \approx 0.04$ microns. Loading changed over the range ≈ 20–1200 N. Volume temperature in a friction zone was recorded with the thermocouple placed on distance $2\cdot10^{-3}$ m from a segment contact surface. Four-wire electric circuit was used at voltage on open contacts ≈ 50 mV for a measurement of contact resistance R_c [5].

We measured in the experiment course a contact resistance R_c value at a step loading and we recorded kinetics of its changing during 300 s for each loading value, that was necessary for stabilization of the physical and chemical processes proceeding in BLL [13]. Measured value R_c was compared with counted threshold values R_s, R_{cr}, R_o, R_t, R_g, and the bearing greasing regime was defined.

The figure 3 represents dependences of contact resistance R_c and a friction coefficient *f* from loading N, dashed lines show obtained threshold values of contact resistances. The figure 3 visualizes a correlation between a dependence of friction coefficient from loading and a measured value of contact resistance R_c. The test subject was hydraulic oil of goods delivery МГЕ–46В (ТУ 38.001347–00).

We accept a boundary lubricant layer thickness, matching to transition from a hydrodynamic friction to a boundary friction regime 2.0 nm, and the boundary lubricant layer thickness matching to a monomolecular lubricant layer of the minimum thickness 1 nm for investigated oil.

We have counted threshold values R_g, R_t, R_o, R_{cr}, R_s theoretically and we have received R_g= 166722 Ohm, R_t= 5 Ohm, R_o= 0.1 Ohm, R_{cr} = 0.04 Ohm, R_s = 0.001 Ohm.

We measured the contact resistance R_c at the segment step loading on a roller for investigated oil and we recorded its changing kinetics within 300 s on each loading step. We compared the readout R_c with counted threshold values R_g, R_t, R_o, R_{cr}, R_s (figure 3). It is necessary to note, that the value R_g has not been attained at experimentation, as in field of loadings implemented on the friction test machine CMT–1, a boundary friction regime comes at once.

Following results (figure 3) were obtained for hydraulic oil of goods delivery, brand МГЕ–46В. A measured value R_c = 33 Ohm was for loading 200 N.

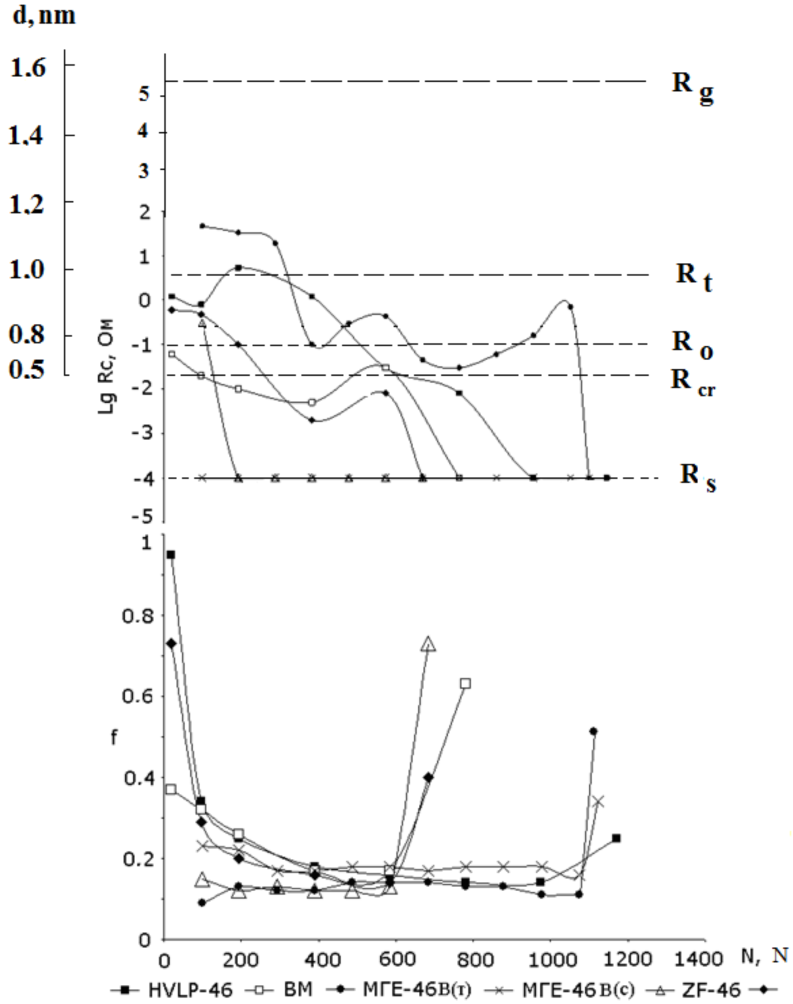


Figure 3. Dependence of contact resistance R_c and a friction coefficient from loading.

We have compared the obtained value with calculated threshold values and as $R_t < R_c < R_g$ (5 Ohm <33 Ohm <166722 Ohm), we concludes, that the bearing is in a boundary friction regime, the BLL thickness makes more than 1 nm, i.e. is in a normal regime of bearing operation.

A measured value R_c = 5 Ohm is for loading 350 N. We have compared the obtained value with calculated threshold values and as $R_c = R_t$ (5.2 Ohm = 5 Ohm), we conclude, that the bearing is in a boundary friction regime, the BLL thickness makes 1 nm, i.e. is in a normal regime of bearing operation.

A measured value R_c = 0.43 Ohm is for loading 600 N. We have compared the obtained value with calculated threshold values and as $R_o < R_c < R_t$ (0.2 Ohm < 0.43 Ohm < 5 Ohm), we conclude, that the bearing is in a boundary friction regime, the BLL thickness is less than 1 nm, but BLL keeps the integrity.

A measured value R_c = 0.2 Ohm is for loading 650 N. We have compared the obtained value with calculated threshold values and as $R_c = R_o$ (0.2 Ohm ≈ 0.1 Ohm), we conclude, that the bearing goes in the preemergency operation, at which there is a destruction of a boundary lubricant layer and an appearance of electric conduction through actual metal contact spots with taking into account oxide films.

A measured value R_c = 0.03 Ohm is for loading 800 N. We have compared the obtained value with calculated threshold values and as $R_s < R_c < R_{cr}$ (0,001 Ohm < 0,04 Ohm < 0.1 Ohm), we conclude, that the bearing is in an emergency operating regime, at which there is a destruction of the boundary lubricant layer monomolecular component and a dominance of metal contact spots.

A measured value R_c = 0.0001 Ohm is for loading 1120 N. We have compared the obtained value with calculated threshold values and as $R_c = R_s$ (0.0001 Ohm), we conclude, that the mated surfaces seizure regime of sliding bearing occurs.

We used in the capacity of tested oils turbine oil ТП–22С and gear oil ТАД–17и also. The given oils have wide practical application at turbine operation in RUE «Gomelenergo» and in transmission assemblies of fodder- and grain-harvesting techniques made by JSC "Gomselmash".

We installed as a test result, that predicted theoretically contact resistance criterion levels, describing sliding bearing greasing state, have found the practical evidence completely. In case of the dry metal contact shaft (Ст 45) and the bronze insert (БрОЦС–5–5–5) voltage drop between them made ≈ 0.1 mV. We installed experimentally, that voltage drop decreasing to ≈ 2–3 mV means the BLL monomolecular component destruction, presented as turbine, and gear oils, at step loading increasing. We noted mated surfaces seizure and engine electrical seizure, turning the shaft after an achievement of given critical value R_{cr}. The last was accompanied by uneven decreasing of recorded contact resistance to contraction resistance.

4. CONCLUSION

Thus, the substantiation of an electrophysical sounding method using for sliding bearing diagnostics on a boundary lubricant layer state is given. The way to control a sliding bearing boundary greasing regime is developed, for example, crankshaft journal of the internal-combustion engine (ICE) at its loading in operating conditions, and also to estimate an incoming control or engine oils quality. The mentioned diagnostic way allows to define an incoming control of oils quality (hydraulic, turbine, motor), to estimate their antifrictional, antiscuff, and operational properties, to operate this work at an early stage before the coming of sliding bearing critical, emergency operating regimes. The developed way has a big practical value as on its basis the device which carries out a quality control of used engine oil in the internal-combustion engine is created in real time. This device using will allow the driver, for example, in an automobile production to carry out not only a quality control of buying engine oil in the market, but also to replace it in terms of its thermal-oxidative capacity in due time.

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