CONCEPT FOR INTERPRETATION AND ASSESSMENT OF SLIDE BEARINGS OPERATION IN DIESEL ENGINES IN PROBABILISTIC APPROACH

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Abstract

The paper provides a proposal of interpretation that valuates operations, which (just like operation of Hamilton and Maupertius shown in the classical mechanics and operation resulting from changes of body momentum) is considered as a physical quantity with: joule-second [joule x second] as a unit of measure. It presents suggestion of a quantitative interpretation of operation of a slide journal bearing, in which energetic interactions proceed at determined time. It has been here motivated that when the suggested interpretation for slide bearing operation in which energy conversions proceed, is accepted the operation can be a carrier of information about states of the systems so, it can become a diagnostic signal. Moreover, an original method of operation analysis and assessment for a slide journal bearing has been herein presented with regards to its reliability and safety. Possibilities of applying this method for the process of taking the rational operating decisions have been shown, too. The homogeneous process of Poison has been applied in order to prove usability of operation in such interpretation. This process has enabled construction of a model of the course of getting-worse operation for a bearing while the operation time goes by. Therefore, the model is a random process of homogenous and independent gains in energy lost due to friction and slide bearing wear.

***Keywords**: friction heat, operation, friction energy, slide bearing, friction work*

1. Introduction

Operation of a slide journal bearing in a diesel or turbine engine is analyzed here as operation of a tribological system consisting of [2, 6]:

- pin, being an element moving toward a bearing bushing inside which is placed,
- bearing bushing, being an element toward which a pin moves,
- convergent lubricating film (oil wedge), being an indirect element formed between a pin and bearing bushing during operation.

Between these elements there are strictly determined relations which undergo changes as the surface layers characteristics of pin and bearing bushings and also lubricating oil characteristics change. The changes depend on operating conditions of bearings, particularly on their load. Thus, journal bearings of diesel engines may be considered as tribological systems of which operation will be troubled by external load dependant on tasks being performed by engines inside which they are installed and on external conditions in which the tasks are performed [2, 6, 9, 10].

Consequence of the troubles is bearings wear which proceed in different ways. Because of huge load on the bearings, it is essential to determine the wear of top layers of the cooperating surfaces, after prior determination of values of heat energy, friction force and friction work [11]. During operation of slide journal bearings there may occur different kinds of friction. Mixed friction occurring while starting and stopping diesel engines, is particularly unfavourable. At this friction, the greater part of kinetic energy of bearing pins is converted in the form of work (friction work) into heat energy. A part of heat energy produced in this way is carried away out of the bearing with lubricating oil flowing through the bearing and due to radiation. However, a part of the energy cause energy increase within inner surface layers of cooperating elements what affect reducing their resistance to wear. Depending on the course of kinetic energy dissipation the bearing operates in different way. Depending on this operation the bearing wear will proceed at different speed. Hence, there is a need of tending to work out a method for assessing operation of tribological systems of this kind. Such assessment is indispensable for taking rational decisions in the phases of designing and operating of the mentioned systems.

Operation of diesel engine slide bearing as a tribological system should be rationally controlled and this requires proper interaction to the friction process inside a slide bearing. The control should consist in minimizing friction parameters to obtain the effect that friction energy (E_T) is not an amount higher than demanded, so $E_T \leq E_{TW}$ at time t indispensable to perform the task by a diesel engine enclosing bearings. Such control enables minimizing effects of friction, like bearing wear. Demonstration of this concern requires prior formulation of the assessment problem for operation of diesel engine slide journal bearing.

2. Formulating the problem of assessment of journal bearing operation

Slide journal bearing operation is possible in case of producing inside them a resultant force occurring as a result of hydrodynamic pressure. The force is a bearing response to external load on condition that it finds itself at static equilibrium. Thus, it characterizes the bearing capacity. Slide journal bearing capacity (just like thrust bearing capacity) depends essentially on ability of carrying away the inside-released heat. From this reason technical diagnosis on the bearings is based on measures of lubricating oil temperature and bearing metal temperature in at least one characteristic point. Bearing capacity undergoes changes dependently on torque transmitted in a diesel engine as well as changes of physical and chemical characteristics of lubricating oil. That is why the lubricating oil should be considered as an inseparable element of the bearing. Loss of required characteristics of lubricating oil (like oil body, lubricating ability, base number, etc) must be treated as a failure and bearing having such oil – disable for operation.

During bearing operation the lubricating oil undergoes coagulation [6]. This causes increase of its temperature. The reason is that in the process of oil coagulation the work done by internal friction in oil is fully exchangeable into heat. Energy transferred in the form of work and then in the form of heat may be considerable. In case of large-size and high-speed bearings (used in turbines) flux of heat released under friction (friction force) may reach a value of even a few megawatts [6] at the capacity of even 7 MPa [2] in case of proper selection of bearing materials and lubrication system. The flux is carried away from bearing mainly with the oil and through bearing elements forming an oil clearance. Heat absorbance by oil causes increase of its temperature and reduction of its body. Moreover, heat is cumulated in bearing metal elements (pin and bushing). That causes thermal deformation of them and change in geometry of the bearing oil clearance. This is accompanied by considerable changes of mechanical load (which ex. in case of diesel engines causes that pressure gain rate $\varphi p_{śr}$ > 0,7 MPa/1° OWK [9,10]), pin rotational speed and also getting-worse physical and chemical characteristics of lubricating oil may lead to quick increase of friction energy E_T and faster wear of bearing.

From the considerations above follows that the energy generated in bearing under friction (E_T) is a part of energy delivered to this, occurred as the result of friction work (L_T) being a form of energy conversion. The work is fully exchangeable inside a bearing into friction heat (Q_T). Friction energy as well as friction work and friction heat increase as bearing wear becomes greater. During task performance by a diesel engine the friction energy (action, heat) of its slide journal bearings (as a physical quantity) can take different values that may be classified into one of the two below ranges of values:

- required, lower than boundary ones,
- admissible (boundary) ones.

In this connection we can assume that the required friction energy (E_{TW}) is generated in a slide journal bearing (finding itself in full ability state). Statement ex. during diagnostic investigations that friction energy generated in a bearing is of at least admissible (boundary) value or bigger, so that its friction energy is admissible energy (E_{TD}), carries information that the bearing should be recognized as disable. However, assessment that a bearing is able or disable to perform a task by a diesel engine cannot be limited only to finding whether the E_{TW} energy or E_{TD} energy is generated in the bearing. Duration of emission E_{TW} should be estimated additionally. The time should be equal at least to the required time (t_W), so time indispensable to perform a task by a diesel engine. Such a task in a formal aspect may be interpreted as follows:

$$Z = \langle D_z , W , t \rangle , \tag{1}$$

where:

Z - task to perform,
D_Z - such diesel engine operation (including bearing operation) which make performance of the task Z possible,
W - conditions in which the task Z is to be performed,
t - time of the task Z performance.

Thus, analyzing the operation of slide journal bearings, in order to asses their ability to perform a given task Z, a value of friction energy (work, heat) should be determined and time at which E_{TW} or L_{TW} or Q_{TW} can be obtained, should be estimated at the same time. That means the possibility of equating the bearing operation to a physical quantity having the following interpretation:

$$D = E_T t \equiv L_T t \equiv Q_T t , \tag{2}$$

where:

D - bearing operation,
E_T - bearing friction energy,
L_T - bearing friction work,
Q_T - bearing friction heat,
t - bearing operation time.

Such interpretation of operation is a physical quantity with a *joule-second* as a unit of measure.

3. Solving the problem of assessment of journal bearing operation

Law of conservation of energy, according to which the difference between energy delivered to a bearing and energy transmitted to the surroundings is equal to internal energy cumulated in the bearing [6, 11], is in force during operation of the bearings.

Friction energy, one of mechanical energy forms, is fully exchangeable (in the form of friction) into heat energy. This energy generated during bearing operation in strictly defined conditions, can be considered as its ability to carry out the friction work (L_T) [6, 12, 14]. This work as a kind of conversion of energy transmitted through the bearing can be determined on the basis of the following dependence:

$$L_T = M_T \alpha = M_T \omega t = 2\pi M_T n t , \tag{3}$$

where:

L_T - friction action on the α angular path,

M_T - moment of friction,
α - angle of pin rotation towards a bearing brushing,
ω - angular velocity,
t - time of pin rotation,
n - pin rotational speed towards a bearing bushing.

From the presented above considerations and dependences (2) and (3) follows that bearing operation in time interval $[t_0, t_n]$ can be expressed by the equation:

$$D = \int_{t_0}^{t_n} M_T \, \omega t \, dt \, . \tag{4}$$

In order to determine global losses of friction (friction work L_T or friction power N_T first, and friction work next) of a slide bearing there can be applied known dependences that enable determining shearing stresses on a surface of any fluid component and resulting from them friction forces (tangential resistances). The losses are possible to be defined after determining friction forces occurring directly at movable surfaces (of a pin) [6].

For symmetrical distribution of oil shearing stresses being directly at the surface of rotating pin along a bearing width, the moment of friction can be expressed by the formula [6]:

$$M_T = T_{\psi 1} R = 2R \int_0^{L/2} \int_{\psi_1}^{\psi_2} \tau_{\psi 1} \, dz \, R \, d\psi \, , \tag{5}$$

where:
T - friction force along angular coordinate at pin surface,
R - pin radius,
L - bearing width,
Ψ - angular (circumferential) coordinate, Ψ= x/R,
τ - tension.

Thus, friction work (3) can be determined as follows:

$$L_T = M_T \omega t = T_{\psi 1} R \, \omega t \, . \tag{6}$$

Thus, bearing operation, in accordance with the dependence (4) and formula (6) can be determined as follows:

$$D = \int_{t_0}^{t_n} T_{\psi 1} R \, \omega t \, dt \, . \tag{7}$$

Processes of exchanging mechanical operation (occurred as a result of overcoming oil coagulation resistances) into heat and appearing in consequence the heat energy in oil clearance can be described with energy equations [1, 6, 11]. Further considerations may be developed by applying general dependences defining friction work or friction power [6, 12, 13, 15]. However, the sense of interpretation of operation presented by the formulas (2), (4) and (7) will remain the same.

Bearing operation in the presented approach may be considered as:

a) demanded operation (D_W) that is indispensable to perform a task Z by a diesel engine inside which the bearing is installed,
b) possible operation (D_M) that can be done by a bearing finding itself in given technical state,

lubricated with oil of defined physical and chemical characteristics.

We can assume that each bearing operation is possible operation (D_M) if generated inside friction energy (E_{TM}) and associated with it the friction work (L_{TM}) or its equivalent, the friction heat (Q_{TM}) attain at most a boundary value after the lapse of time t. Demanded operation of a bearing (D_W) is when generated inside friction energy (E_{TW}), so also friction work (L_{TW}) or friction heat (Q_{TW}) attain required values (adequately to operating conditions for a bearing, its technical state and physical and chemical characteristics of oil used for lubricating) at time (t_W) demanded to perform the task Z (1). Thus, we can assume that each bearing finding itself in state of ability (is able to perform a task Z) when:

$$D_W < D_M \,. \tag{8}$$

In this case the maximal possible operation is the boundary operation. The possible boundary operation can be expressed by the formula:

$$D_{MG} = L_{TG}\, t \,, \tag{9}$$

where:

D_{MG} - maximal possible operation,
L_{TG} - boundary friction work so work at which galling of a bearing is possible.

The bearing can correctly work (operate) according to the dependence (8) when $t_M \geq t_W$, when at the same time $L_{TM} \geq L_{TW}$. This means that because of practical aspects this general case must be considered in the following alternatives:

1) $t_M = t_W$, if simultaneously $L_{TM} = L_{TW}$
2) $t_M = t_W$, if simultaneously $L_{TM} > L_{TW}$
3) $t_M > t_W$, if simultaneously $L_{TM} = L_{TW}$
4) $t_M > t_W$, if simultaneously $L_{TM} > L_{TW}$

In the case when:

$$D_W > D_M \,, \tag{10}$$

The assumption should be made that a bearing is failed and the diesel engine in which the bearing is installed is not able to perform the task Z.

For modelling changes of friction energy or friction work or friction heat a homogenous process of Poison can be applied [3, 4, 5, 7].The process enables presentation of the following interpretation of the process of friction work (L_T) growing by a constant elementary value e_T: *from the moment of initiation of the process of bearing operation (ex. t = 0) to the moment of the first record taken by a measuring device of an event A meaning increase of friction work L_T by the value $\Delta L_T = e_T$, every task can be performed by the bearing*. Further operation of the bearing during performance of a task by diesel engine in which the bearing is installed, causes, with time going by, occurrence of successive, recorded by a measuring device, increases of work value L_T by successive the same values e_T. Thus, in case of the cumulated number B_t of occurred events A, described with homogenous process of Poison, recorded to time t, the total growth of work L_T by values $\Delta L_T = e_T$ to time t can be presented by the dependence [3]:

$$P(B_t = k) = \frac{(\lambda t)^k}{k!} \exp(-\lambda t)\,; \quad k = 1,2,\ldots,n\,, \tag{11}$$

where:

λ - constant value (λ = idem), interpreted as a rate of the work L_T growth by the same values e_T, recorded during investigation, $\lambda > 0$.

Expected value and variation of the process of growing the events *a* number and so growing the work L_T by successively recorded e values, may be presented as follows:

$$E(B_t) = \lambda t\ ; \quad D^2(B_t) = \lambda t\ . \tag{12}$$

Considering the fact that a new bearing (if $t = 0$) generates the lowest friction energy E_T and due to this the friction work L_T is the least, the mathematical dependence showing the work growth with going time t can be expressed with the formula:

$$L_T(t) = \begin{cases} L_{T\min} & \text{dla } t = 0 \\ L_{T\min} + e_T \lambda t \pm e_T \sqrt{\lambda t} & \text{dla } t > 0 \end{cases} . \tag{13}$$

Graphic interpretation of the dependence (13) has been presented below in Fig. 1.

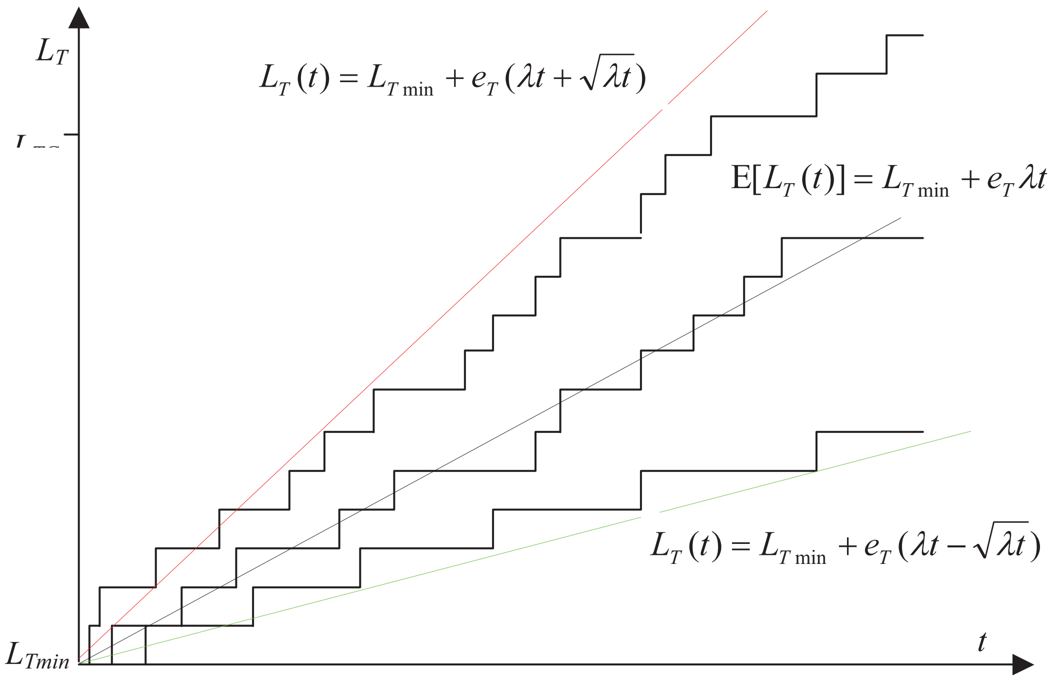

Fig. 1. Graphic interpretation of growth of friction work for a bearing, controlled by the process of Poison: LT – friction work, E(LT) – expected value of friction work, eT – quantum by which the work LT undergoes a change

From the formula (13) follows that friction work L_T, which may be performed by the bearing, can be determined for any moment t, and from the formula (11) – that the probability of occurring such growth of work L_T is possible for estimation. Thus, the probability P(B_t = k, k = 1, 2, …, n) determined with the formula (11), can be accepted as a bearing operation reliability index. Wear of a bearing as a result of friction can be considered in a similar way [7].

4. Final conclusions

In the presented above proposal operation of a slide journal bearing is considered as friction energy E_T, generated by the bearing in determined time t in the form of friction work L_T. From this reason the operation of a slide journal bearing has been equated to a physical quantity which can be expressed with a number value and a unit of measure: [joule-second]. Direct effect of such interpretation is friction energy generated by the bearing and time at which this energy is or may be emitted. Friction energy (and also friction work or friction heat) and time are quantities characterizing the bearing operation uniquely. Such understood operation may be accepted as a quantity characterizing directly a technical state of the bearing. The higher wear of the bearing and/or the worse physical and chemical, characteristics of lubricating oil in determined conditions and determined time, the higher the value of such understood operation as a result of growing generated friction energy, so also friction work and friction heat. In order to determine a range of getting worse operation of a bearing, a stochastic model of growing friction work (L_T) has been applied in the form of a random process with the same (constant) intervals, homogenous and independent gains, that is a homogenous process of Poison.

Operation of a bearing, in the presented version, has also this advantage that it can be tested by doing precise measures and afterwards expressed in the form of:

- a number with a unit of measure (formula 4 or 7),
- a graph as a area of operation (Fig.1).

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