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Prediction of wear in grease-lubricated oscillatory journal bearings via energy-based approach

A.B. Aghdam, M.M. Khonsari*

Department of Mechanical and Industrial Engineering, Louisiana State University, 2508 Patrick Taylor Hall, Baton Rouge, LA 70803, USA

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ABSTRACT

An energy-based approach is proposed for prediction and analysis of wear in grease-lubricated oscillatory journal bearings. The methodology relies on measurement or estimation of the temperature rise in the sliding system. Experimental tests are conducted to examine the relationship between the wear rate, power dissipation and temperature rise. An important property of the tribo-system is identified as the wear-energy dissipation (WED) coefficient. The relationship between the frictional energy and temperature also yields the power dissipation-temperature rise (PTR) coefficient for the tribo-system. The proposed methodology is shown to be capable of predicting the wear rate under a wide range of loading conditions.

1. Introduction

Many engineering mechanisms and machinery components rely on journal bearings for their operation. Most journal bearings can operate for long periods of time under ideal operating conditions. Such conditions, however, only prevail under full hydrodynamic lubrication (HL) regime wherein a continuous lubricant film, with sufficient thickness, separates the journal and the bearing surfaces. Nevertheless, there exist many applications – such as piston-pin contact in internal combustion engines, articulating pin-joint assemblies in robotic arms, and earth-moving machinery – in which the bearing operates under boundary or mixed lubrication due to the oscillatory nature of the contact which disrupts formation of a sufficient lubrication film. In the absence of a lubricant film to fully separate the contacting surfaces, direct solid-to-solid contact inevitably ensues rendering the journal bearing highly prone to wear.

Occurrence of wear in journal bearings can largely, and often adversely, influence their performance. Wear defects can reduce the stability, dynamic performance and load-carrying capacity of journal bearings through misalignment and changes in the clearance and friction coefficient [1–5]. The progressive nature of wear, particularly under mixed or boundary lubrication regime, ultimately leads to failure of the bearing due to excessive loss of material. Therefore, to avoid such costly consequences, it is highly desirable to predict the loss of material in journal bearings that operate under oscillatory motion.

There exist volumes of archival publications dedicated to quantification of wear under boundary or mixed lubrication condition [6–23]. Examination of these studies indicates a preponderance of wear prediction methodologies that involve numerous physical and geometrical parameters with limitations to applicability to only specific sets of operating conditions. Such studies notwithstanding, the industry is in want of a robust predictive methodology that can be readily employed in a wide range of applications. In fact, the sheer number of physical parameters that are often required for successful application of the theoretical models can limit their utility in practical applications. The situation becomes far more complex for oscillatory configuration where the contact parameters and the attendant underlying processes are subject to continuous variations. More convenient methodologies are, therefore, desirable to facilitate quantification of wear even under such complex sliding conditions.

The pursuit of developing alternative approaches for prediction of wear has led many researchers to identify the frictional energy dissipation as a unique characteristic parameter in the analysis of contacting components. Matveeskey [24], in 1965, was perhaps among the first to recognize a correlation between the frictional energy dissipation and wear. Numerous research studies [25–48] that followed have unanimously verified the existence of a fairly linear correlation between the amount of frictional energy

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* Corresponding author. Tel.: +1 225 578 9192.
E-mail address: Khonsari@me.lsu.edu (M.M. Khonsari).

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Nomenclature

C	clearance between the shaft and bearing (mm)
E	modulus of elasticity (GPa)
f	oscillation frequency (Hz)
h_f	thermal convection coefficient on free surfaces (W/m^2 K)
h_t	thermal convection coefficient on the tapered section of the shaft (W/m^{2}K)
h_b	thermal convection coefficient inside the bearing (W/m^2 K)
k	thermal conductivity (W/m K)
L	length of the bearing (mm)
l_1, l_2, l_3, l_4	lengths of the linkages of the crank-rocker mechanism (mm)
N	normal load (N)
N_s	speed of the shaft in unidirectional rotation (rev/s)
P_d	average value of the power dissipation during the steady state (W)
$p(\theta, z)$	contact pressure distribution (MPa)
$q(\theta, z)$	total frictional heat flux generated at the contact interface (W/m^2)
R	radius of the shaft (mm)
S_g	grease-Sommerfeld number
t	time (s)
T	temperature (°C)
T_∞	ambient temperature (°C)
ΔT_1, ΔT_2, ΔT_3, ΔT_4	temperature rise pertaining to measurement points 1, 2, 3 and 4 (°C)
$\dot{w}_{av}$	average wear rate (mm^3/s)
r, θ, z	cylindrical coordinates
η_{BO}	dynamic viscosity of the base oil for the grease (Pa s)
θ_2, θ_3, θ_4	angular positions of the linkages in the crank-rocker mechanism (rad)
θ_{amp}	oscillation amplitude (deg)
μ	mean friction coefficient
ν	Poisson's ratio
ξ	heat partitioning factor
ψ_T	power dissipation-temperature rise coefficient (J/K)
ψ_w	wear-energy dissipation coefficient (mm^3/J)
Ω_b	convection surfaces inside the bearing in the finite element model
Ω_f	free convection surfaces in the finite element model
Ω_s	symmetry surfaces in the finite element model
Ω_t	surface of the shaft's tapered section in the finite element model
$\omega(t)$	periodic function of the oscillatory speed of the output arm in the crank rocker mechanism (rad/s)
ω_2	rotational speed of the input arm in the crank-rocker mechanism (rad/s)

dissipated in the contact interface and the resulting wear volume. The particular advantage associated with the application of energy approach lies in the fact that it brings in the effect of different sliding parameters, such as speed, friction, and normal force, into a single parameter.

With regard to the case of oscillatory journal bearings, there appears to be a particular need for application of the energy approach. Experimental measurements made in previous studies [49–51], indeed, reveal continuous transitions of the lubrication regime between the boundary and the mixed type due to changes in both the magnitude and the direction of the sliding speed. Periodic variations of the friction coefficient are also observed as a further consequence of the transitions of lubrication regime. The energy approach can, therefore, be employed to integrate the effects of such variations into a single parameter, i.e. the frictional energy dissipation.

While the energy approach has been recognized by many as a powerful tool for analysis of wear [52], the dissipated energy, in and of itself, does not significantly facilitate the prediction of wear in practice. In fact, direct estimation of the dissipated energy requires the knowledge or measurement of the sliding speed and the friction force and, as such, is encumbered with the same difficulties associated with measurement of these parameters. Measurement of the dissipated energy can be carried out by means of alternative techniques such as thermal energy dissipation or measurement of the temperature rise. The dissipation of the frictional energy, in the absence of hydrodynamic effects, can be assumed to occur mostly within the contacting bodies. In many sliding configurations, this energy is primarily converted into heat which, in turn, results in contact temperature rise [53–56]. Recent experimental results obtained under unidirectional and reciprocating dry sliding [25,26] confirm the presence of a linear correlation between the frictional power dissipation and the amount of temperature rise in the vicinity of contact. Theoretical models developed by Tian and Kennedy [57] also suggest a similar correlation between the frictional heat dissipation and the nominal contact temperature rise.

According to the recent findings mentioned above, an alternative wear prediction and monitoring methodology is proposed that entails measurement of the contact temperature rise in order to estimate the frictional energy dissipation, and to predict wear. The present study seeks to extend and explore the utility of this technique to the case of oscillatory journal bearings operating under mixed or boundary lubricated regime. To this end, a series of laboratory wear tests are performed on a grease-lubricated and heavily loaded journal bearing. The experiments are designed to cover a relatively wide range of loading conditions. Results are presented and discussed in detail in order to ascertain the relationship between the system's frictional power dissipation, temperature rise and wear rate. Finite element (FE) analysis is also performed, as part of the proposed methodology, to identify the system's thermal behavior. Based on the results obtained in this study, a simple, yet practical, wear prediction methodology is proposed.

2. Experiments

2.1. *Test apparatus and measurements*

A tribometer designed by Lewis Research (Model LRI-8H) is utilized to conduct the wear tests. Fig. 1 shows a schematic view of the apparatus. The drive mechanism consists of an electro-motor with a maximum speed of 2700 RPM. The oscillatory motion is produced by means of a crank-rocker mechanism which connects the motor to the shaft. The oscillation amplitude can be adjusted by changing the length of crank and rocker arms. The assembly of the shaft and bearing inside the housing is illustrated in Fig. 2. The journal shaft (6) is tapered at one end where it is rigidly affixed to a supporting base and the drive mechanism. This type of fixture results in a shaft that deforms akin to a cantilever beam. According to the experimental setup the normal load is applied to the housing block (4). The housing (3) sits inside the housing block and is supported by two bearings to allow it to freely rotate inside the housing block. The housing is attached to the friction sensor (1) via two connecting rods and a ball joint (2), but is otherwise free to rotate inside the housing block about the axis of rotation.