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DISCUSSION

T. E. Tallian[2] Y. P. Chiu[3] W. Crecelius[4] and J. I. McCool[5]

The authors address an important problem in rolling bearing lubrication: that of starved EHD lubrication. The principles of calculating film thickness for starved lubrication have been well expounded in the references cited by the authors and also by one of the discussers [15].[6] The calculation of tractions under starved condition is not as broadly documented in the literature, although one of the discussers [16] has published on the subject. The author's presentation of a simple calculation for this effect is, accordingly, very welcome.

The discussers' laboratory has recently (May 1975) completed preparation and documentation of a bearing dynamics analysis package [17] (primarily aimed at high-speed *ball* bearings) which incorporates the results of [15] and [16], and contains solutions to the same problem. (See also [18] for the relation of this model to that of Archard and Baglin.) The program package comprises modules defining the following friction contributions:

(*a*) EHD traction due to sliding in the plateau

(*b*) HD traction in the inlet due to rolling and to sliding, taking starvation into account

(*c*) Asperity traction in the Hertz contacts, as a function of film thickness/roughness ratio

(*d*) HD or EHD traction in the cage/ball contacts

(*e*) HD traction at the cage/land interface

(*f*) Bulk churning losses in the lubricant as the ball/cage assembly plows through a lubricant-laden atmosphere.

Experiments have been conducted with ball bearings at high speed, with jet lubrication, through-race circulating oil lubrication and mist. They confirm the authors' findings that reduction of lubricant mass in the bearing reduces losses greatly. Mist lubrication tests under conditions where no starvation is predicted, yield strong evidence that much of the reduction of losses encountered when switching from circulating oil to mist is due to the elimination of the major bulk churning losses. However, our computer predictions agree with those of the authors that a reduction of meniscus distance at the contact inlets, further reduces losses and—most importantly—that there is an optimum range of meniscus distances—or inlet oil layer thicknesses—yielding low friction but essentially undiminished film thickness.

It is instructive to look beyond the ring contact losses to the total loss distribution in the bearing, (and Table 1 provides a brief excerpt of computer predictions of this distribution.) The *total* losses are most dramatically reduced by curtailing the density ratio of oil/air in the bearing cavity (first three lines). Second most effective in reducing losses is inlet oil layer reduction on the *outer ring* (last three lines). Under the conditions examined, a similar improvement on the *inner ring* is prevented by the predominance of asperity friction at the lower ratios of film thickness/roughness prevailing at this contact. The cage/ball losses are of comparable order to the losses at ring contacts. Design changes to minimize these are possible, but were not explored in these computations.

[2] Vice-President, Technology Services.
[3] Research Scientist.
[4] Senior Researcher.
[5] Supervisor, Physics Laboratory, SKF Industries, Inc., King of Prussia, Pa.
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Table 1 Losses in 125 mm bore angular contact ball bearing run with MIL-L-7808C ester at 10,000 rpm and 4.4 kN axial load. Free contact angle 24.5°

% Oil/Air in brg. cavity	Inlet oil layer μm	EHD Film thickness/roughness ratio: Outer ring	EHD Film thickness/roughness ratio: Inner ring	Friction losses, watts: Outer ring contacts	Inner ring contacts	Cage/ball contacts	Cage/land contact	Bulk churning	Total (rounded)
2.5	10	4.1	1.4	457	576	69	142	2220	3470
1.0	10	4.1	1.4	446	558	13	141	899	2060
0.1	10	4.1	1.4	448	556	<0.1	141	91	1240
2.5	1	4.1	1.4	274	442	69	142	2220	3150
2.5	0.5	4.1	1.4	215	402	69	142	2220	3050
2.5	0.1	2.7	1.2	75	350	69	142	2220	2860

L. D. Wedeven[7]

The authors have considered the effect of starvation on rolling friction in addition to film thickness, and have concentrated mostly on the aspects of rolling friction. It is of interest to note the similarities and differences between the effect of starvation on rolling friction and film thickness.

Rolling friction and film thickness are both associated with the pressure generation within the inlet region. Therefore, a starved inlet region, as measured by S_i or H_1 would be expected to influence rolling friction and film thickness in a similar way. This can be seen by comparing the authors' theoretical rolling friction results of Fig. 4 with the theoretical film thickness results obtained for point contacts as shown in Fig. 10 (see discussion of [11] by L. D. Wedeven). Fig. 10 shows the dimensionless film thickness (h_0/R) plotted against a speed-viscosity parameter ($\alpha\mu_0 u/R$) for constant values of inlet boundary location (S/R). Both rolling friction and film thickness show a decreasing dependence on speed and viscosity as the degree of starvation increases.

While rolling friction and film thickness are both associated with the amount of pressure generated in the inlet region, they are by nature quite different. Rolling friction is also a function of the location of the inlet pressure with respect to the line of centers. Thus, it is found that rolling friction increases with load while film thickness decreases with load. In addition, rolling friction becomes sensitive to the degree of starvation sooner than film thickness as shown in Fig. 2. This makes it desirable to establish an optimum degree of starvation to minimize rolling friction without reducing film thickness beyond an acceptable level.

In practice the optimum degree of starvation is difficult to establish as well as maintain. The supply and distribution of lubricant within a bearing is a function of many force fields such as centrifugal force, gravity, windage, surface tension, and pressure fields generated between moving surfaces. Many of these are velocity dependent. Thus, it is frequently found that as bearing speed increases the degree of starvation increases (i.e., S_i or H_1 become smaller) which can lead to a situation where film thickness and rolling friction decrease with speed. This may explain why the slopes of the experimental curves in Fig. 7(b) are lower than the theoretical curves where H_1 is held constant.

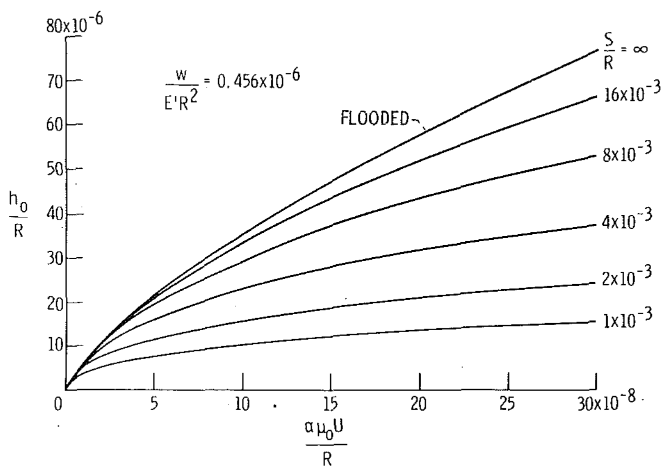

Fig. 10 Effect of speed-viscosity parameter on film thickness for constant degrees of starvation

It is very difficult to determine the actual degree of starvation that occurs within a bearing. If it can be assumed, as the authors have done, that $t_S = t_R$ then an accurate measurement of t_R can be used to determine the degree of starvation (ψ or β^*) as a function of flow rate. In this regard it would be helpful if the authors could give an order-of-magnitude analysis of the other sources of viscous tractions within the bearing.

The authors have shown that rolling friction (t_R) decreases with starvation. It has recently been shown by Wedeven [19] and Baglin and Archard [20] that sliding friction (t_S) can increase with starvation. This is important in connection with high-speed, lightly loaded bearings where skidding may be a problem. The effects of starvation on t_R and t_S are both in a favorable direction to reduce skidding. Have the authors observed this in their experiments?

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Author's Closure

The authors would like to thank the discussers for their interesting contributions to the paper.

An estimate of the sources of friction torque in the bearings under test, based on reference [8], provides the following:

(a)	Viscous friction at the roller/track contacts	70%
(b)	Viscous friction at the cage/track contacts	10%
(c)	Viscous friction at the roller/cage contacts	9%
(d)	Oil churning	10%
(e)	Other causes, such as elastic hysterisis in rollers and tracks, abrasive wear, etc.	1%

The contribution at the roller/track contacts is dominant in this estimate, and represents the conditions thought to exist under modest lubrication conditions. Table 1, presented by Tallian et al., suggests that oil churning can dominate under some conditions, even when inlet oil films are small. The authors have difficulty visualizing how these conditions might arise in practice and look forward to definitions of the operating conditions under which this effect becomes apparent.

A simple consideration of continuity of lubricant flow in the bearing assembly suggests that oil film thicknesses at the inner contacts are always less than those at the outer track contacts, and this is in broad agreement with the findings of Tallian et al., although the quoted EHD film thickness/roughness ratios differ rather more than would be expected from consideration of flow continuity.

As Fig. 7 shows, the values of the starvation factor at which the experimental results were obtained indicates severe starvation conditions at the contacts in the test bearings.

Under these conditions, no cage or roller slip was observed. It may be that running under starvation conditions could inhibit skidding in some applications, possibly running at a steady speed when accelerating forces were absent.

[7] NASA Lewis Research Center, Cleveland, Ohio.

[8] Numbers 19–20 in brackets designate Additional References at end of discussion.