Discussion on the paper by R. Langheim and W.J. Bartz: "The significance of the effective viscosity in instationary loaded journal bearings"

problem makes it impractical, especially for bearings with time-dependent load and speed.

To simplify the analysis, the authors considered a constant temperature and an averaged shear stress, corresponding to the bearing specific load over the bearing area, while the viscosity varied with the external load, i.e. the crank angle. Regarding these assumptions, the discusser has some doubts as to their validity, especially in highly loaded bearings of internal combustion engines. Indeed, the pressure is a coordinate function and the shear rate as well. Hence, considering the viscosity and shear stress as constant over the bearing area raises the question of how these values should be determined in order to obtain the best approximation. The problem is even more complicated since the largest viscosity variations with both temperature and shear rate occur across the film thickness, a fact which is not mentioned in the paper. Comparisons with available data show that the method proposed by the authors is appropriate; however, more experimental evidence should be welcome.

Thermohydrodynamic theory shows that a constant (effective) viscosity correctly chosen may provide satisfactory results. However, different viscosity values should be used for load or friction calculations (*A1*). Since, at the present time, friction assessment is an important element in bearing evaluation, we believe that the current problem should be also examined from this point of view.

No matter how the viscosity is calculated, the authors' idea of considering its variation with the crank angle is fertile and provides accurate results and a simple method of calculation. Their data show that non-Newtonian lubricants exhibit large viscosity variations and need special attention. The paper is a significant contribution to the calculation of unsteadily loaded bearings and the authors are to be congratulated on their work in the field.

REFERENCE

(*A1*) Ezzat, H. A. and Rohde, S. M., "A Study of the Thermohydrodynamic Performance of Finite Slider Bearings." *J. Lubr. Tech.*, **95,** July (1973).

DISCUSSION

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As soon as local pressure effects on viscosity come into the picture, Reynolds' equation is not linear in the pressure any longer, which means that the discussed solution methods cannot be applied. This can be avoided by substituting

$$\frac{1}{\eta}\,\mathrm{grad}\,p = \frac{1}{\eta_i}\,\mathrm{grad}\,q$$

where q is the so-called reduced pressure, and η_i the dynamic viscosity under isoviscous conditions. Under low pressure conditions (below 1000 bar), the piezoviscous behavior is represented quite accurately by the Barus equation (*B1*):

$$\eta = \eta_i \exp(\alpha p)$$

which means that, see (*B2*)

$$q = \frac{1}{\alpha}\{1 - \exp(\alpha p)\}$$

This definition of q will allow for application of all discussed methods of solution for a piezoviscous lubricant according to Barus. It should be noted that Reynolds' cavitation boundary conditions can easily be taken into account:

$$p = 0 \qquad \rightarrow q = 0$$
$$\mathrm{grad}\,p = 0 \rightarrow \mathrm{grad}\,q = 0$$

It is possible to generalize this transformation for the Kuss relation, as shown by Blok (*B3*). In this case α^* should be used instead of α, which is defined as

$$[\alpha^*]^{-1} = \int_0^\infty \frac{\eta_i}{\eta}\,dp$$

$$= \sqrt{\frac{\pi}{4\beta}}\,e^{\alpha^2/4\beta}\left\{1 - \frac{2}{\sqrt{\pi}}\sum_{k=0}^{\infty}\frac{(-1)^k(\alpha\sqrt{1/(4\beta)})^{2k+1}}{k!\quad(2k+1)}\right\}$$

Using this transformation, there is no need to turn for aid to the average film pressure, and the effect of piezoviscous lubricants is studied more carefully.

It is difficult to make an accurate estimate of θ_{eff}, which amounts to 74°C in this study. Figure 1 shows that an error of only 5°C in θ_{eff} will result in a 20 percent change in η_o, which is the same order of magnitude as shear rate effects on η_{eff} for the non-Newtonian oil, see Fig. 11. So, if some uncertainty concerning the operating temperature arises, this effect will easily outplay G_{eff}. What is the advantage of the authors' refinement in this case?

As the effect of shear rate on viscosity can be processed quite easily through the known eccentricity, including this effect will not add that much time to the normal execution time for isoviscous lubricants. Can the authors give some idea of computing times and time step sizes? And which solution method is used to march from one journal position to the next (a "time" step of 5° crank angle rotation looks pretty coarse)?

The designer will be very interested in the areas where the minimum film thickness becomes very low, to where the eccentricity ratio approaches 1. Hence, the discusser disagrees with the authors' opinion that higher values of the eccentricity ratio are unimportant. Although it seems not likely that metallic contact will occur under the condition of Fig. 21, the non-Newtonian oil is no improvement from this point of view. It might be that other aspects, like cooling capacity (oil flow), will favor the non-Newtonian lubricant. Have the authors considered these aspects in their calculations?

It seems that a more or less arbitrary choice of G_{eff} correlates well with experimental results under stationary conditions. For example, cavitation effects are not taken into account when deriving the formula for G_{eff}. Do the authors have some evidence why this concept also applies to dynamically loaded bearings?

The theoretical results for a non-Newtonian fluid are compared with calculations on a Newtonian fluid. It is uncertain whether the former results are an improvement of the latter or not, because the proposed method does not show much subtlety, and differences on itself cannot be the proof. Therefore, experimental evidence seems to be indispensible. The authors intend to do this. A report on their experimental findings will be welcomed by many researchers in the area of dynamically loaded bearings.

REFERENCES

(B1) Barus, C., "Isothermals, Isopiestics and Isometrics relative to Viscosity." *Amer. J. Sci.*, **45**, 266, pp 87–96 Feb. (1893).

(B2) Dowson, D. and Higginson, G. R., *Elastohydrodynamic Lubrication*, Pergamon Press, Oxford, 1977.

(B3) Blok, H., "Inverse Problems in Hydrodynamic Lubrication and Design Directives for Lubricated Flexible Surfaces." *Proc. Intl. Symp. Lubr. and Wear*, Houston 1963, D. Muster and B. Sternlicht (eds.), McCutchan Publishing Corporation, 1965.

AUTHORS' CLOSURE

We would like to thank the discussers for their comments on our paper. Of course we do agree with Dr. Tipei's statement that our approach to solve the complex viscosity problem in nonstationary loaded journal bearings contains some simplifying assumptions.

In order to describe the behavior of Newtonian and non-Newtonian oils, e.g. regarding the journal displacement loci, we defined effective factors of temperature, pressure, and shear rate, resulting in a so-called effective viscosity.

Indeed, the effective pressure is an averaged value—based on the instantaneous value of specific load—and the effective shear rate as well, because this value describes the vectorial sum of the velocity components of flow in circumferential and axial direction. But both data, effective pressure and shear rate, are calculated step by step of crank angle within the whole cycle of load. Thus, the effective viscosity, the basis of displacement calculations, varies not only with the external load, but also with the shear stress at each time. In the discussion of our paper, this point may be misunderstood.

The approach considering the factors effecting the temperature, pressure, and shear rate have proved to be satisfactory for stationary loaded bearings. Some of these results were presented at the ASLE/ASME Conference at San Francisco. We are now trying to apply this approach to nonstationary loaded bearings as well.

Of course, the validity of the simplifying assumptions must be confirmed experimentally. Preliminary results recently attained show a fairly good correlation between calculated and measured data.