The tractive force transmitted across the thin lubricant film of a concentrated contact is a very interesting aspect of the elastohydrodynamic lubrication problem. The authors' design of an advanced disk machine and their careful investigation of EHD traction characteristics at high speeds and high loads are most commendable.

The authors have used the disk machine as a viscometer by adjusting the constants in the viscosity equation for the lubricant to ensure that the analytically predicted traction curve will match the experimentally determined curve at a specific set of values of the operating parameters. The authors are well aware of the danger in this type of correlation that the analytical and experimental tractive forces will agree only at those values of the parameters at which the fit was performed. Figs. 11, 12, and 13 show the predicted values of tractive force diverging from the experimental values as the rolling speed is changed.

I suggest that the authors need to readjust one of the viscosity equation constants can be explained by the failure of the lubricant viscosity to respond to the rapid changes of pressure encountered in passing through the EHD contact area. The time required for the lubricant to reach a state of equilibrium following an applied pressure step and, consequently, the compression of the lubricant never reaches the equilibrium state corresponding to the peak pressure. Therefore the viscosity will have a value less than the value measured under equilibrium conditions. An increase in the rolling speed reduces the residence time of the lubricant in the contact zone, resulting in an even lower value for the viscosity attained by the lubricant, and a consequent decrease in the effective viscosity.

Recently, G. Harrison and I have analyzed the time-dependent viscosity response to pressure. We propose a simple model for the volume creep of a liquid following the application of a pressure step and use this model to determine the dependence on rolling speed of the traction coefficient between highly loaded rolling contacts. Good agreement has been obtained with experimental results at rolling speeds above 50 in/sec. Figs. 17 and 18 are results from our study of a synthetic parafinic lubricant. These two graphs provide a quick and simple method of determining the variation of the effective viscosity with rolling speed for a given value of maximum pressure. Although the rheological properties of 5P4E polyphenyl ether differ significantly from the fluid of our study, the graphs qualitatively explain the authors' results. At a peak Hertzian pressure of 120,000 psi and rolling speeds of 900, 1360, and 1820 in/sec, the graphs predict the effective viscosities will have a ratio of 1.67/1.26/1.00.

I hope that inclusion of the compressional viscoelastic effect in the authors' analysis might help bring our understanding of elastohydrodynamic traction characteristics closer to experimental experience.

W. O. Winer and D. M. Sanborn

The authors present a very interesting set of data. Their equipment appears to have the potential for contributing much more data that will help in the general understanding of edh traction.

The authors acknowledge possible differences in lubricants which are referred to by the same name in their discussion of the use of the Midwest polyphenyl ether viscosity data. It would be very useful, for future reference, if they would include a table with as much physical property data as possible for the material actually used in these experiments. The use of the Midwest data at all is probably not necessary, however, since the "extrapolated" portion of the curve in Fig. 15 appears not to be dependent on the low pressure-viscosity characteristics. In addition, the authors state, "Predicted tractions should be relatively insensitive to the shape of the lower portion of the viscosity curve and should be determined by the 'high pressure line' shown in Fig. 15."

The authors have shown, Fig. 14, that the experimental data cannot be predicted using measured pressure-viscosity-temperature relations of the form of equation (2). The experimental traction data are then used, however, to obtain a derived set of pressure-viscosity-temperature constants which will enable the same equation (2) to reasonably interpolate within the observed traction data. If the functional relation (equation (2)) describes the lubricant characteristics, but not the traction behavior, why should an interpolation method based on this function be any better than linear, logarithmic, or some other type of interpolation?

Since Kannel and Bell, in addition to our own investigations,
have shown that film thickness and, therefore, derived traction coefficients are much more dependent on load than current eld theory predicts, it would be more meaningful to use experimentally determined film thickness values in predicting traction. It is not clear how the film thickness values used in deriving traction coefficients in this paper were obtained.

Authors' Closure

The authors wish to thank each discussor for his contribution in clarifying the main points of this work. We are sorry that Archard has had difficulties in obtaining some of the references and suggest that interested persons write: Defense Documentation Center, Alexandria, Va. 22314 for copies of the works listed. Accession numbers are usually required and are as follows:

AD 73774 for reference [3]
AD 877708 for reference [9]
AD 70752 for reference [12]

A full set of traction data for a MIL-L-7808 over a wide range of loads, speeds, and temperatures has been recorded since the submission of this report and are included in reference [12].

As mentioned by Dr. Archard, the support bearing torque was plotted on the graphs while the disks were unloaded and can be observed not to coincide with the symmetry points of the full traction curves of the original data plots. The purpose for plotting the support bearing torque was to show that it did not vary over the slip range plotted. The advantage of plotting the full traction curve over negative as well as positive slips is that the support bearing load effect (although found to be small) is biased out when the data is doubly folded across the pure rolling speed of the abrasion and the ordinate line defined by the midpoints of the two traction peaks obtained.

Over twenty thermocouples in and around the fully flooded contact zone were recorded during every data gathering period on the disk rig. As well as monitoring the inlet fluid temperature, thermocouples which slid on the disc provided evidence that the temperature on the inlet side of the contact zone was always within 2 deg of the noted test temperature. Reference [3] contains full details on the temperature stability of the system.

As noted, ceiling tractions were not obtained in the present work and could, as mentioned by Dr. Archard, be fluid dependent. Curves plotted in Fig. 19 are submitted from our most recent work [12] to demonstrate that the traction characteristics of two fluids with similar conventional properties (viscosity and pressure viscosity at moderate pressure coefficients) under identical load and slip conditions can be significantly different. Viscosity was matched by running the two fluids at different temperatures. It is apparent from the plot that the traction dependence of fluids is a strong function of some parameter or parameters which are not usually measured on most fluids today. Perhaps the answers to this perplexing situation are a combination of such parameters as:

1. Local viscosity-temperature changes at high pressures,
2. Solidification or other non-Newtonian rheological property,
3. "Boundary" films mentioned by Pein and Trachman, or
4. Viscosity time dependent effects.

It was interesting to note that Trachman's comments on the effective viscosities correspond qualitatively to the apparent viscosity values determined in the paper. Although the fluids compared are different, it is the authors' belief that the time-dependent viscosity response of a complex organic fluid is a basic parameter which (if determined on a wide variety of fluids) may serve to explain some of the anomalous behaviors observed in traction data. Recent measurements of such time dependence have been made by two of the authors [13] on the MIL-L-7808 fluid sighted above. Refinements of the technique used are planned for the near future.

The authors would like to thank Drs. Winer and Sanborn for their comments and will try to answer them in the order that they appear in the discussion.

Most of the physical property data for the polyphenyl ether under consideration is given in reference [2]. The viscosity-pressure-temperature relationship obtained from the data in reference [2] were used in obtaining the "low pressure" viscosity lines used in computing film thickness. As stated in the paper, the high pressure lines were determined from measured traction and not direct viscometric data. The point that the authors wish to make is that these lines although not derived from viscometric data are not in conflict with the data and are quite useful in predicting tractions in good agreement with experimental measurements. The authors feel that in the absence of a complete traction theory based on a full rheological model for the lubricant it is far better to use a quasi-empirical "effective viscosity" approach involving three empirical constants (α*, ω*, and β*) as opposed to using an interpolation technique requiring hundreds of data points over a range of loads, slip rates and rolling speeds to estimate tractions.

At the time the traction data presented in this paper were obtained, we did not have film thickness measurements for the polyphenyl ether used. Film thickness calculations were obtained with the use of the elastohydrodynamic performance program presented in reference [9] which was based upon solutions to the thermal elastohydrodynamic problem obtained by Cheng as described in reference [14].

In closing, the authors agree fully with Dr. Archard's belief that a more complete set of traction data for a wide variety of fluids, in use today, should be obtained under full elastohydrodynamic conditions.

Additional References