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ADDITIONAL ASPECTS OF ELASTOHYDRODYNAMIC LUBRICATION

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ABSTRACT

Professor Cheng is to be congratulated for doing an outstanding job in presenting an up-to-date review of the varying aspects of elastohydrodynamic lubrication. In the present paper I would merely like to add some material which was not covered in Professor Cheng's paper. In particular I would like to present some recent work on elastohydrodynamic lubrication of materials of low elastic modulus as well as work on hydrodynamic lubrication. Both these topics will be applicable for contacts with any ellipticity parameter (ranging from a circular contact to a line contact). These two studies will be combined with some previous work to supply film thickness contours for the different regimes of lubrication as a function of the elasticity and viscosity parameters. From these studies the lubrication regime and the minimum film thickness within the contact can be easily determined.

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INTRODUCTION

Figure 1 points out the difference between hydrodynamic and elastohydrodynamic lubrication (EHL). Hydrodynamic lubrication normally deals with conformal contacts while elastohydrodynamic lubrication deals with nonconformal contacts. Elastohydrodynamic lubrication can be divided into materials of low and high elastic modulus. Note the maximum pressure is three orders of magnitude less for materials of low elastic modulus as compared to that of high elastic modulus. Also, the minimum film thickness is the smallest for EHL of materials of high elastic modulus and next smallest for EHL of materials of low elastic modulus and the largest for hydrodynamic lubrication contacts.

Lubricant in elastohydrodynamic lubrication of high elastic modulus materials enters a typical contact with atmospheric pressure, is subjected to a maximum pressure of approximately 300 000 $lb/in.^2$, traverses a passage one thousand times longer than its height, and is then ejected into the atmosphere within a time span of about 10^{-4} or 10^{-5} second. The viscous character of the fluid while passing through the contact changes drastically, going from an easy flowing liquid to a pseudosolid and back to an easy flowing liquid in less than a fraction of a millisecond.

Lubricant in elastohydrodynamic lubrication of low elastic modulus materials enters a typical contact with atmospheric pressure and is subjected only to a maximum pressure of 3×10^2 psi due to the elastomeric nature of the material. For such materials the distortions are large even with light loads. Another feature of EHL of low elastic materials is the negligible effect of pressure on the viscosity of the lubricating fluid. Therefore the viscous character of the fluid does not change while passing through the contact.

NOMENCLATURE

a	semimajor axis of contact ellipse
b	semiminor axis of contact ellipse
E	modulus of elasticity
E'	$\dfrac{2}{\left(\dfrac{1-\nu_A^2}{E_A} + \dfrac{1-\nu_B^2}{E_B}\right)}$
$\mathcal{E}$	elliptical integral of second kind
F	normal applied load
G	dimensionless material parameter, $\alpha E'$
H	dimensionless film thickness, h/R_x
$\hat{H}$	dimensionless film thickness, $H(W/U)^2$
h	film thickness
k	ellipticity parameter, a/b
m	dimensionless inlet distance
m^*	dimensionless inlet distance at boundary between fully flooded and starved conditions
R	effective radius
r	radius of curvature
U	dimensionless speed parameter, $u\eta_0/E'R_x^2$
u	surface velocity in rolling direction, $(u_A + u_B)/2$

W dimensionless load parameter, $F/E'R_x^2$

α pressure-viscosity constant

β R_y/R_x

η_0 atmospheric viscosity

ν Poisson's ratio

Φ $\left[1 + \frac{2}{3B}\right]^{-1}$

Subscripts:

A solid A

B solid B

E elastic

F fully flooded conjunction

I isoviscous

min minimum

R rigid

S starved conjunction

V viscous

x,y coordinate system

EHL FOR MATERIALS OF LOW ELASTIC MODULUS

The work presented by Professor Cheng related only to materials of high elastic modulus (e.g., steel). The work that I would like to present in this section is for materials of low elastic modulus (e.g., nitrile rubber). Engineering applications in which elastohydrodynamic lubrication is important for low-elastic-modulus materials include seals, human joints, tires, and elastomeric-material machine elements.

The problem of fully flooded line contacts has been solved theoretically for low-elastic-materials by Herrebrugh (1), Dowson and Swales (2), and Boglin and Archard (3). The solutions of references 1 and 2 were obtained numerically and are based on simultaneous solutions of the hydrodynamic and elasticity equations; the analytical solution of reference 3 relied on the assumption of a simplified form for the film shape in the contact region. Biswas and Snidle (4) used the approach of reference 3 to solve the point-contact situation. Reference 5 presents, to the best of the author's knowledge, the first complete numerical solution of the problem of fully flooded isothermal elastohydrodynamic lubrication of elliptical contacts for low-elastic-modulus materials. Reference 6 extends the work of reference 5 by studying the effect of lubricant starvation on pressure and film thickness within the conjunction. This section of the present paper will utilize the work of references 5 and 6.

Reference 5 produces the following dimensionless minimum film thickness for fully flooded elliptical contacts for materials of low elastic modulus

$$\{H_{min,F}\}_{I,E} = 7.43(1 - 0.85\ e^{-0.31\ k})U^{0.65}W^{-0.21} \tag{1}$$

The subscript I,E refers to the isoviscous elastic lubrication condition which is the condition that exists in dealing with materials of low elastic modulus.

It is interesting to compare the equation for materials of low elastic modulus (eq. (1)) with the corresponding equation found in reference 7 for materials of high elastic modulus, namely:

$$\{H_{min,F}\}_{V,E} = 3.63(1 - e^{-0.68\ k})U^{0.68}W^{-0.073}G^{0.49} \tag{2}$$

The powers of U in equations (1) and (2) are quite similar, but the power of W is much more significant for low-elastic-modulus materials. The expressions showing the effect of the ellipticity parameter is of exponential form in both equations, but with quite different constants.

A major difference in equation (1) and (2) is the absence of a material parameter in the expression for the minimum film thickness for low-elastic-modulus materials. The reason for this is the negligible effect of pressure on the viscosity of the lubricating fluid for low-elastic-modulus materials.

When the elliptical contact becomes starved, the dimensionless minimum film thickness for materials of low elastic modulus (6) can be written as

$$\{H_{min,S}\}_{I,E} = \{H_{min,F}\}_{I,E}\left(\frac{m - 1}{m^* - 1}\right)^{0.22} \tag{3}$$

where m is the distance of the inlet miniscus from the center of the contact, and m^* is the inlet distance required for achieving the fully flooded condition. From reference 6 m^* can be expressed as

$$m^* = 1 + 1.07\left[\left(\frac{R_x}{b}\right)^2 \{H_{min,F}\}_{I,E}\right]^{0.16} \tag{4}$$

where b is the semiminor axis of the elliptical contact.

To make it easier to calculate the semiminor axis of the contact ellipse (b), the elliptical integral of the second kind ($\mathcal{E}$), and the ellipticity parameter, the approximate expressions developed in reference 8 will be used and are given below as

$$b = \left[\frac{6\mathcal{E}F}{\pi k E'\left(\frac{1}{R_x} + \frac{1}{R_y}\right)}\right]^{1/3} \tag{5}$$

$$\mathcal{E} = 1 + \frac{3R_x}{5R_y} \tag{6}$$

$$k = 1.03\left(\frac{R_y}{R_x}\right)^{0.64} \tag{7}$$

where

$$\frac{1}{R_x} = \frac{1}{r_{Ax}} + \frac{1}{r_{Bx}} \tag{8}$$

$$\frac{1}{R_y} = \frac{1}{r_{Ay}} + \frac{1}{r_{By}} \tag{9}$$

The approximate expressions (eqs. (5) to (7)) enable one to easily calculate these terms within 3 percent accuracy without resorting to charts or numerical methods.

To explain more fully what happens to the film thickness in going from a fully flooded to a lubricant starvation condition for materials of low elastic modulus, figures 2 and 3 are presented. Figure 2 represents a fully flooded condition and figure 3 a severely starved condition. In these figures the symbol + indicates the center of the Hertzian contact. Because of the way the coordinates are made dimensionless, the actual contact ellipse becomes a Hertzian circle regardless of the ellipticity parameter. The Hertzian contact circle is shown in these figures by asterisks. At the top of these figures the contour label and its corresponding value is given. The inlet region is to the left and the exit region is to the right.

It is observed in these figures that the central portion of the film-thickness contours has become parallel for the severely starved condition (fig. 3). The minimum film thickness area is closer to the exit region for the severely starved condition. Note also that the values of the film thickness contours for the severely starved condition (fig. 3) are much lower than those of the fully flooded condition (fig. 2).

DIMENSIONLESS GROUPING

The dimensionless group {H, U, W, G, and k} used in equations (1) and (2) have served a very useful purpose in aiding the understanding of the results found in references 5 to 7. Several authors (e.g., refs. 9 and 10) have noted that the examination of the dimensionless representation of governing equations shows the above set of dimensionless group can be reduced by one without any loss of generality. Although Johnson's paper (10) does not consider elliptical contacts, it does state what the nondimensional parameters would be, namely:

Dimensionless film thickness

$$\hat{H}_{min} = H_{min} \left(\frac{W}{U}\right)^2 \tag{10}$$

Dimensionless viscosity parameter

$$g_1 = \frac{GW^3}{U^2} \tag{11}$$

Dimensionless elasticity parameter

$$g_3 = \frac{W^{8/3}}{U^2} \tag{12}$$

The ellipticity parameter (k) remains a parameter as discussed in equation (7). Therefore, the reduced dimensionless group is $\{\hat{H}_{min}, g_1, g_3,$ and $k\}$.

FILM THICKNESS IN ELLIPTICAL CONTACTS FOR FOUR LUBRICATION REGIMES

Reference 11 makes use of the reduced dimensionless grouping to give the film thickness equations for four fluid film lubrication regimes found in elliptical contacts. These regimes are distinguishable by the influence or lack of influence of elastic and viscous effects. The film thickness equations for the respective regimes come from earlier theoretical studies on elastohydrodynamic (5 and 7) and hydrodynamic (12) lubrication of conjunctions of elliptical form.

ISOVISCOUS RIGID REGIME

The influence of geometry on the hydrodynamic film separating two rigid solids was investigated in reference 12. It was found that the minimum film thickness had the speed, viscosity, and load dependence as the classical Kapitza (13) solution. However, the incorporation of Reynolds condition resulted in an additional geometry effect. Therefore, from reference 12 the dimensionless minimum film thickness for the isoviscous rigid lubrication regime can be written as

$$\left(\hat{H}_{min}\right)_{I,R} = 128\beta\phi^2\left[1.68 \tan^{-1}\frac{\beta}{2} + 0.13\right]^2 \tag{13}$$

where

$$\beta = \frac{R_y}{R_x} \approx \left(\frac{k}{1.03}\right)^{1/0.64} \tag{14}$$

$$\phi = \left[1 + \frac{2}{3\beta}\right]^{-1} \tag{15}$$

In equation (13) note that the dimensionless film thickness is strictly a function of the geometry of the contact (R_y/R_x).

VISCOUS RIGID REGIME

Making use of Blok (14) while adding a geometry effect for an elliptical contact as discussed in reference 11, the minimum film thickness for the viscous rigid regime can be written as

$$\{\hat{H}_{min}\}_{V,R} = 1.66\ g_1^{2/3}(1 - e^{-0.68\ k}) \qquad (16)$$

ISOVISCOUS ELASTIC REGIME

Expressing equation (1) in terms of the reduced dimensionless group ($\hat{H}_{min}$, g_1, and k) from reference 11 the dimensionless minimum film thickness for the isoviscous elastic regime can be written as

$$\{\hat{H}_{min}\}_{I,E} = 8.70\ g_3^{0.67}(1 - 0.85\ e^{-0.31\ k}) \qquad (17)$$

VISCOUS ELASTIC

Expressing equation (2) in terms of the reduced dimensionless group (H_{min}, g_1, g_3, and k) the minimum film thickness for the viscous elastic regime can be written as

$$\{\hat{H}_{min}\}_{V,E} = 3.45\ g_1^{0.49} g_3^{0.17}(1 - e^{-0.68\ k}) \qquad (18)$$

Having defined the dimensionless minimum film thickness for the four lubrication regimes in equations (13), (16), (17), and (18) these equations were used to develop the dimensionless film thickness contours for the different regimes of lubrication. Reference 11 shows these maps on a log-log grid of dimensionless viscosity parameter and dimensionless elasticity parameter for ellipticity parameters of 1, 2, 3, 4, and 6. Figure 4 shows a sample of these results for an ellipticity parameter of 1. The four lubrication regimes are clearly indicated in this figure. In this figure we see that the transition between the viscous rigid and viscous elastic is nearly smooth whereas the transition from the isoviscous elastic and viscous elastic is not as good. One might speculate that the transition from the isoviscous elastic and viscous elastic might produce slightly lower dimensionless film thicknesses than those in figure 4. Similar results are shown for other ellipticity parameters in reference 11.

Therefore, given an ellipticity parameter (k), the value of the viscosity parameter (g_1), and the elasticity parameter (g_3), one can determine the lubricating regime as well as an approximate value of the dimensionless minimum film thickness. Knowing the lubrication regime a more accurate value of $\hat{H}_{min}$ can be obtained using the appropriate dimensionless minimum film thickness equation (one of the following equations: (13), (16), (17), or (18)).

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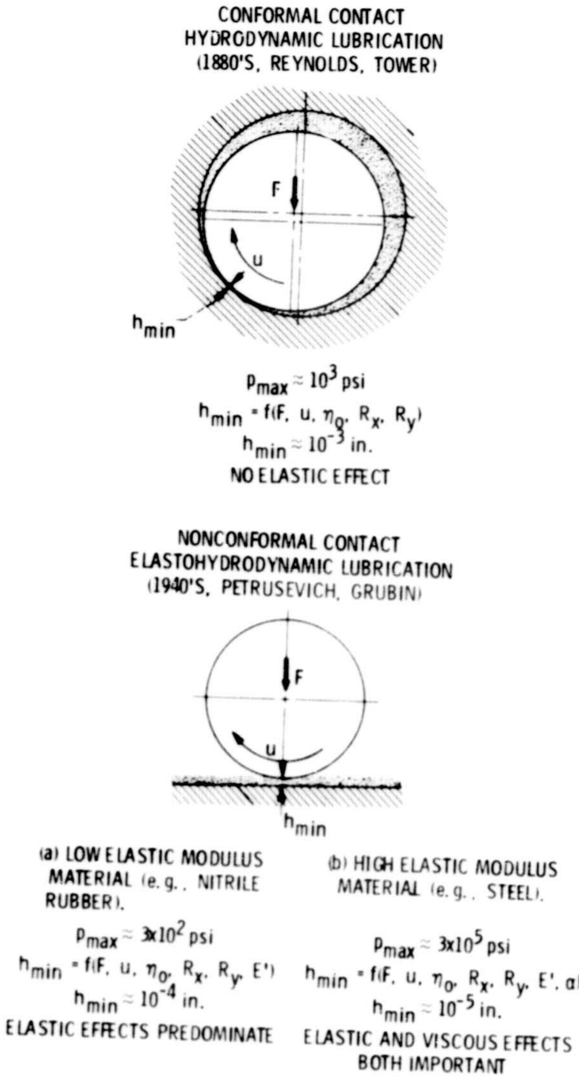

Figure 1. - Hydrodynamic and elastohydrodynamic lubrication.

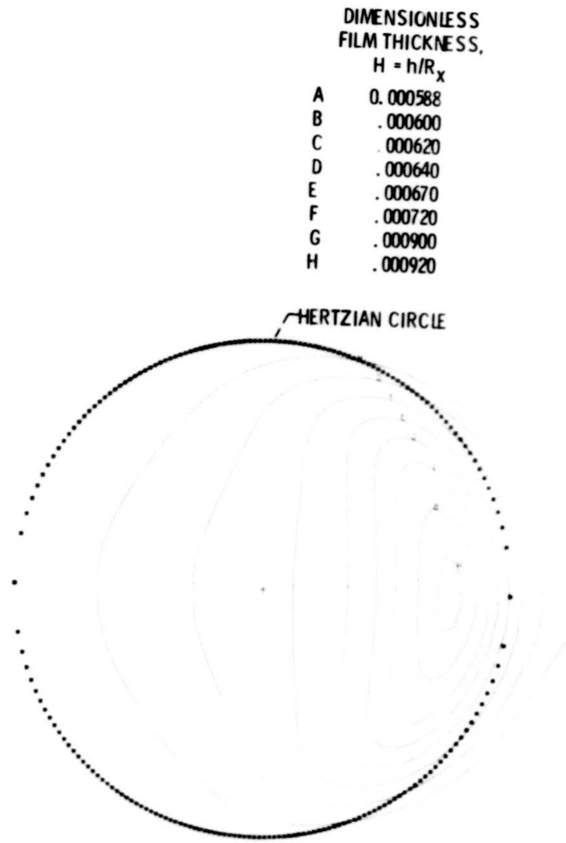

Figure 2. - Contour plot of dimensionless film thickness in a fully flooded conjunction for materials of low elastic modulus.

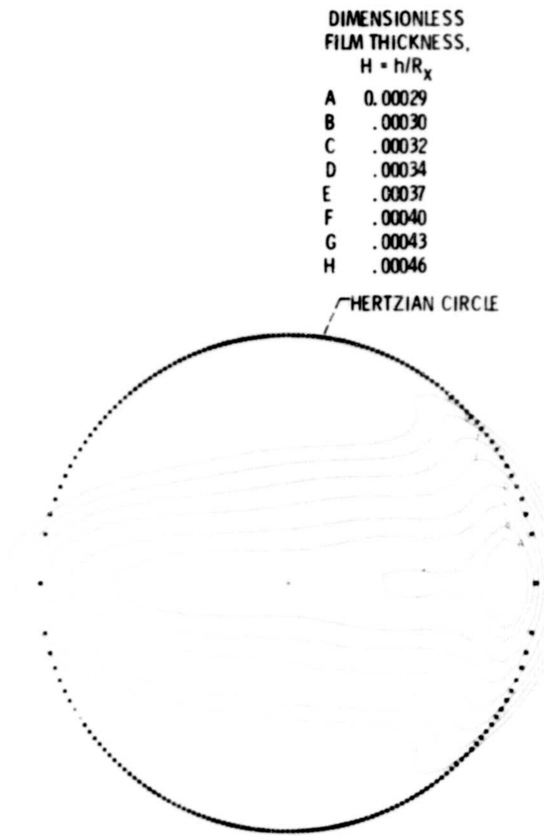

Figure 3. - Contour plot of dimensionless film thickness is a severly starved conjunction for materials of low elastic modulus.

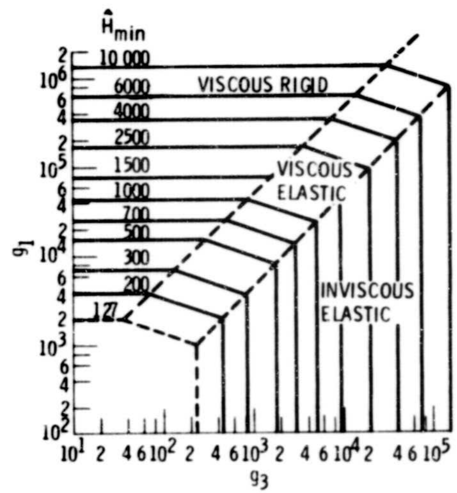

Figure 4. - A map of the regimes of lubrication with dimensionless film thickness ($\hat{H}_{min}$) contours on a log-log grid of the dimensionless viscosity parameter (g_1) and the dimensionless elasticity parameter (g_3) for an ellipticity parameter of one (k = 1).