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Elastohydrodynamic Lubrication of Elliptical Contacts

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ELASTOHYDRODYNAMIC LUBRICATION OF
ELLIPtical CONTACTS

Summary

The emphasis of the first part of the lecture is on fully flooded, elastohydro-
dynamically lubricated, elliptical con-
tacts. A fully flooded conjunction is one in
which the film thickness is not signifi-
cantly changed when the amount of lubri-
cant is increased. The relevant equations
used in the elastohydrodynamic lubrication
(EHL) of elliptical contacts are briefly
described. The most important practical
aspect of the elastohydrodynamic theory is
the determination of the minimum film
thickness within the contact. The main-
tenance of a fluid film of adequate
magnitude is an essential feature of the
correct operation of lubricated machine
elements. The results to be presented
show the influence of contact geometry on
minimum film thickness as expressed by the
ellipticity parameter and the dimension-
less speed, load, and materials param-
ters. Film thickness equations are
developed for materials of high elastic
modulus, such as metal, and for materials
of low elastic modulus, such as rubber.

The solutions for materials of high
elastic modulus are sometimes referred to
as "hard EHL," and the solutions for
materials of low elastic modulus as "soft
EHL." In addition to the film thickness
equations that are developed, plots of
pressure and film thickness are pre-

sent ed. These theoretical solutions for
film thickness have all the essential
features of previously reported experi-
mental observations based on optical
interferometry.

In the second part of the lecture a
theoretical study of the influence of
lubricant starvation on film thickness and
pressure in hard and soft elliptical
elastohydrodynamic contacts is presented.

From the results for both hard and soft
EHL contacts a simple and important dimen-
sionless inlet boundary distance is speci-
fied. This inlet boundary defines whether
a fully flooded or a starved condition
exists in the contact. It is also found
that the film thickness for a starved
condition can be written in dimensionless
terms as a function of the inlet distance
parameter and the film thickness for a
fully flooded condition. Contour plor's of
pressure and film thickness in and around
the contact are shown for fully flooded
and starved conditions. The theoretical
findings are compared directly with re-

sults obtained experimentally.

1. Introduction

Elastohydrodynamic lubrication is a
form of fluid-film lubrication where
elastic deformation of bearing surfaces
becomes significant. It is usually asso-
ciated with highly stressed machine com-
ponents of low conformity, such as gears and
rolling-element bearings. This lubri-
cation mechanism is also encountered with
soft bearing materials, such as rubber
seals and tires. The common factor in
these applications is that local elastic
deflection of the solids provides
coherent fluid films and thus asperity
interaction is prevented.

Historically, elastohydrodynamic
lubrication may be viewed as one of the
major developments in the field of
tribology in the twentieth century. It
not only revealed the existence of a
previously unsuspected regime of lubrica-
tion in highly stressed and nonconformal
machine elements, such as gears and
rolling-element bearings, but it brought
order to the understanding of the complete
spectrum of lubrication ranging from
boundary to hydrodynamic.

2. Conformal and Nonconformal Surfaces

Hydrodynamic lubrication is generally
characterized by surfaces that are confor-
mal. That is, the surfaces fit snugly
into each other with a high degree of
geometrical conformity, so that the load
is carried over a relatively large area.
Furthermore the load-carrying surface area
remains essentially constant while the
load is increased. Fluid-film journal and
slider bearings exhibit conformal sur-
faces. In journal bearings the radial
clearance between the shaft and the bear-
ing is typically one-thousandth of the
shaft diameter; in slider bearings the
inclination of the bearing surface to the
runner is typically one part in a thousand.

Many machine elements have contacting
surfaces that do not conform to each other
even well. The full burden of the load
must then be carried by a very small con-
tact area. In general the contact areas
between nonconformal surfaces enlarge
considerably with increasing load but are
still small compared with the contact
areas between conformal surfaces. Some
examples of these nonconformal surfaces
are mating gear teeth, cams and followers,
and rolling-element bearings.

The load per unit area in conformal
bearings is relatively low, typically only
1 MN/m² and seldom over 5 MN/m². By
contrast, the load per unit area in non-
conformal contacts, such as those that
exist in ball bearings, will generally
exceed 700 MN/m², even at modest applied
loads. These high pressures result in
elastic deformation of materials such that
the elliptical contact areas are formed
for oil film generation and load support.
The significance of the high contact pressures is that they result in a considerable increase in fluid viscosity. Inasmuch as viscosity is a measure of a fluid's resistance to flow, this increase greatly enhances the lubricant's ability to support load without being squeezed out of the contact zone.

The undeformed geometry of contacting solids can be represented in general terms by two ellipsoids. The two solids with different radii of curvature in a pair of principal planes (x and y) passing through the contact between the solids make contact at a single point under the condition of zero applied load. Such a condition is called point contact and is shown in Figure 1, where the radii of curvature are denoted by r's. It is assumed throughout the lecture that convex surfaces, as shown in Figure 1, exhibit positive curvature and concave surfaces, negative curvature. Therefore, if the center of curvature lies within the solid, the radius of curvature is positive; if the center of curvature lies outside the solid, the radius of curvature is negative. It is important to note that if coordinates x and y are chosen such that

\[ \frac{1}{r_{ax}} + \frac{1}{r_{bx}} > \frac{1}{r_{ay}} + \frac{1}{r_{by}} \]  

coordinate x then determines the direction of the semiminor axis of the contact area when a load is applied and y, the direction of the semimajor axis.

### 3. Relevant Equations

The relevant equations used in elastohydrodynamic lubrication of elliptical contacts are as follows:

**Lubrication equation (Reynolds equation)**

\[ \frac{\partial}{\partial x} \left( \frac{\sigma h^3}{n} \right) + \frac{\partial}{\partial y} \left( \frac{\sigma h^3}{n} \right) = 12u \frac{\partial h}{\partial x} (\nu h) \]

where

\[ u = \frac{u_a + u_b}{2} \]

**Viscosity variation**

\[ n = n_0 e^{ap} \]

where \( n_0 \) is the coefficient of absolute or dynamic viscosity at atmospheric pressure and \( a \) is the pressure-viscosity coefficient of the fluid.

**Density variation (for mineral oils)**

\[ \rho = \rho_0 \left( 1 + \frac{0.01 p}{1 + 1.7 \gamma p} \right) \]

where \( \rho_0 \) is the density at atmospheric conditions.

### Elasticity equation

\[ w = \frac{2}{E_i} \iint_A \frac{p(x,y)}{\sqrt{(x-x_1)^2 + (y-y_1)^2}} \, dA \]

where

\[ E_i = \frac{2}{\left( \frac{1 - v_a^2}{E_a} + \frac{1 - v_b^2}{E_b} \right)} \]

**Film thickness equation**

\[ h = h_0 + S(x,y) + w(x,y) \]

where

\[ h_0 = \frac{1}{R_x} + \frac{1}{R_y} \]

The problem is to calculate the pressure distribution in the contact and at the same time allow for the effects that this pressure will have on the properties of the fluid and on the geometry of the elastic solids. The solution will also provide the shape of the lubricant film, particularly the minimum clearance between the solids. A detailed description of the elasticity model used is given in Dowson and Hamrock (1976), and the complete EHL theory is given in Hamrock and Dowson (1976).

### 4. Dimensionless Grouping

The variables resulting from the isothermal elliptical contact theory developed in Hamrock and Dowson (1976) are:

- \( E' \) effective elastic modulus, N/m²
- \( F \) normal applied load, N
- \( h \) film thickness, m
- \( R_x \) effective radius in x (motion) direction, m
- \( R_y \) effective radius in y (transverse) direction, m
- \( u \) mean surface velocity in x direction, m/s
- \( a \) pressure-viscosity coefficient of fluid, m²/N
- \( n_0 \) atmospheric viscosity, N s/m²

From these variables the following five dimensionless groupings were established:

**Dimensionless film thickness**

\[ H = \frac{h}{R_x} \]

**Ellipticity parameter**

\[ k = \frac{a}{b} = 1.03 \left( \frac{R_y}{R_x} \right)^{0.64} \]
Browe and Hamrock (1977) used a linear regression by the method of least squares to obtain the simplified equations given in equation (11). That is, for given sets of data \( \{k_s, R_s/G_s(1/n)\} \\
J = 1, 2, ..., n \), a power fit using a linear regression by the method of least squares resulted in obtaining equation (11). To obtain the simplified equations given in equation (11), that is, for given sets of data \( \{k_s, R_s/G_s(1/n)\} \\
J = 1, 2, ..., n \), a power fit using a linear regression by the method of least squares resulted in obtaining equation (11). Dimensionless load parameter

\[
W = \frac{F}{E^*R^*X}
\]

Dimensionless speed parameter

\[
U = \frac{u}{E^*R^*X}
\]

Dimensionless material parameter

\[
\sigma = \frac{k}{\sigma^*}
\]

The dimensionless film thickness can thus be written as a function of the other four parameters

\[
H = f(k, U, W, \sigma)
\]

The influence of the dimensionless parameters \( k, U, W, \) and \( \sigma \) on minimum film thickness \( H_{\text{min}} \) is presented later for both hard and soft contacts.

The set of dimensionless groups \( \{k, U, W, \sigma\} \) is a useful collection of parameters for evaluating the results presented in this lecture. It is also comparable to the set of dimensionless parameters used in the initial elastic hydrodynamic analysis of line contacts, and it has the merit that the physical significance of each term is readily apparent. However, a number of authors, for example, Ros (1980) and Yeshe (1980), have noted that this set of dimensionless groups can be reduced by one parameter without any loss of generality.

5. Fully Flooded Hard-Lip Results

By using the numerical procedures outlined in Hamrock and Dowson (1976), the influence of the ellipticity parameter and the dimensionless speed, load, and materials parameters on minimum film thickness has been investigated for hard-lip, fully flooded contacts (Hamrock and Dowson, 1976). The ellipticity parameter \( k \) was varied from 1 (a ball-on-plate configuration) to 8 (a configuration approaching a rectangular contact). The dimensionless speed \( U \) was varied over a range of nearly two orders of magnitude, and the dimensionless load parameter \( W \) over a range of one order of magnitude. Situations equivalent to using solid materials of bronze, steel, and silicon nitride and lubricants of paraffinic and naphthenic oils were considered in an investigation of the role of the dimensionless materials parameter \( \sigma \). The 34 cases used to generate the minimum-film-thickness formula are given in table 1. In the table \( H_{\text{min}} \) corresponds to the minimum film thickness obtained from the Hertzian contact theory given in Hamrock and Dowson (1976). The minimum-film thickness formula obtained from a least-squares fit of the data was first given in Hamrock and Dowson (1976) and is given here as

\[
H_{\text{min}} = 3.03 \times 10^{-4} \cdot 0.0080 \cdot 0.49 \cdot 0.073 (1 - e^{-0.68})
\]

In table 1 \( H_{\text{min}} \) is the minimum film thickness obtained from equation (11). The percentage difference between \( H_{\text{min}} \) and \( H_{\text{min}} \) is expressed by

\[
\beta = \frac{H_{\text{min}} - H_{\text{min}}}{H_{\text{min}}} \times 100
\]

In table 1 the values of \( \beta \) are within 5%.

A representative contour plot of dimensionless pressure is shown in figure 2 for \( k = 1.25, U = 0.10630^{11}, W = 0.11110^{6}, \) and \( \sigma = 388.2 \); in this figure and in figure 3, the * symbol indicates the center of the Hertzian contact zone. The dimensionless representation of the \( x \) and \( y \) coordinates causes the actual Hertzian contact ellipse to be a circle regardless of the value of the ellipticity parameter. The Hertzian contact circle is shown by asterisks. On the figure is a key showing the contour labels and each corresponding value of dimensionless pressure. The inlet region is to the left and the exit region is to the right. The pressure gradient at the exit end of the conjunct is much larger than that in the inlet region. In figure 2 a pressure spike is visible at the exit of the contact.

Contour plots of film thickness are shown in figure 3 for \( k = 1.25, U = 0.10630^{11}, W = 0.11110^{6}, \) and \( \sigma = 388.2 \); in this figure two minimum-film-thickness regions occur in well-defined side lobes that follow, and are close to, the edge of the Hertzian contact ellipse. These results reproduce all the essential features of previously reported experimental observations based on optical interferometry (Cameron and Gohar, 1990).

The variation of pressure and film thickness in the direction of rolling quite close to the \( x \)-axis near the midplane of the conjunct is shown in figure 4 for three values of \( k \). The values of the dimensionless load, materials, and ellipticity parameters were held constant at \( k = 0, W = 0.73310^{6}, \) and \( \sigma = 388.2 \). In figure 4(a) the dashed line corresponds to the Hertzian pressure distribution. This figure shows that the pressure at any location in the inlet region as the speed increases, a result that is also consistent with the elastohydrodynamic theory for line or rectangular contacts, furthermore, as the speed decreases, the height of the pressure spike decreases and
the hydrodynamic pressures gradually approach the semielliptical form of the Hertzian contact stresses. Note that the location of the pressure spike moves downstream toward the edge of the Hertzian contact ellipse as the speed decreases.

For nominal line or rectangular contacts Dowson and Higginson (1966) showed results similar to those in figure 4(a).

The typical elastohydrodynamic film shape with an essentially parallel section in the central region is shown in figure 4(b). There is little sign of a reentrant region in this case, except perhaps at the lowest speed. Also, there is a considerable change in the film thickness as the dimensionless speed is changed, as indicated by equation (16). This illustrates most clearly the dominant effect of the dimensionless speed parameter \( \Omega \) on the minimum film thickness in elastohydrodynamic contacts.

The variation of pressure and film thickness in the direction of motion along a line close to the midplane of the conjunction is shown in figure 5 for three values of dimensionless load parameter \( N \). The values of the dimensionless speed, materials, and ellipticity parameters were held fixed at \( \Omega = 0.66, \) \( \beta = 45^\circ, \) and \( k = 0.5 \). Note from figure 4 that the pressure at any location in the inlet region falls as the load increases. For the highest load \( N = 1.108 \times 10^3 \), figure 4(b), the film thickness rises between the central region and the outlet restriction. This reentrant effect is attributed to lubricant compressibility. Note also that at \( N = 0.538 \times 10^3 \) the film thickness is slightly smaller than at \( N = 1.108 \times 10^3 \). This somewhat curious result is linked to the fact that the location of the minimum film thickness also changes drastically over this load range. At the lower load the minimum film thickness is located on the midplane of the conjunction downstream from the center of the contact; at the higher load it moves to the side lobes as described earlier.

6. Fully Flooded Soft-EHL Results

The earlier studies of elastohydrodynamic lubrication of conjunctions of elliptical form are applied to the particular and interesting situation exhibited by materials of low elastic modulus (soft EHL). The procedure used in obtaining the soft-EHL results is given in Hamrock and Dawson (1976). The ellipticity parameter was varied from \( 1 \) (a ball-on-plate configuration) to \( 1 \) (a configuration approaching a nominal line or rectangular contact). The dimensionless speed and load parameters were varied by one order of magnitude. Seventeen different cases used to generate the minimum film thickness formula are given in table II. In the table \( \Omega_{\text{min}} \) corresponds to the minimum film thickness obtained from applying the EHL elliptical contact theory given in Hamrock and Dawson (1976) to the soft-EHL contacts. The minimum film thickness formula obtained from least squares fit of the data was first given in Hamrock and Dawson (1976) and is given here as

\[
\Omega_{\text{min}} = 7.43 \left[ 0.66 - 0.21 (1 - 0.86 e^{0.3k}) \right]
\]

In table II \( \Omega_{\text{min}} \) is the minimum film thickness obtained from equation (18). The percentage difference between \( \Omega_{\text{min}} \) and \( \Omega_{\text{min}} \) is expressed by \( \Omega_{\text{err}} \), given in equation (19). The values of \( \Omega_{\text{err}} \) in table II are within the range \( 0 \) to 3 percent.

It is interesting to compare the equation for materials of low elastic modulus (soft EHL), eq. (18) with the corresponding equation for materials of high elastic modulus (hard EHL) given in equation (19). The powers of \( k \) in equations (18) and (19) are similar, but the power of \( \Omega \) is much more significant for low elastic modulus materials. The expression showing the effect of the ellipticity parameter is of exponential form in both equations, but with different constants.

A major difference between equations (18) and (19) is the absence of material parameters in the expression for low-elastic modulus materials. There are two reasons for this. One is the negligible effect of pressure on the viscosity of the lubricating fluid, and the other is the way in which the value of elasticity is simply and automatically incorporated into the prediction of conjugation behavior through an increase in the size of the Hertzian contact zone corresponding to changes in load. As a check on the validity of this, case 9 of table II was repeated with the material changed from nitrile to silicone rubber. The results of this change are recorded as case 1' in table II. The dimensionless minimum film thickness calculated from the full numerical solution to the elastohydrodynamic contact theory was \( 18.85 \times 10^3 \), and the dimensionless minimum film thickness predicted from equation (18) turned out to be \( 12.58 \times 10^3 \). This clearly indicates a lack of dependence of the minimum film thickness for low-elastic modulus materials on the materials parameters.

The variation of the ratio \( \Omega_{\text{min}}/\Omega_{\text{min}} \), shown in figure 6, where \( \Omega_{\text{min}} \) is the minimum film thickness for rectangular contacts, with the ellipticity parameter \( k \) for both high- and low-elastic modulus materials. If it is assumed that the minimum film thickness obtained from the elastohydrodynamic analysis of elliptical contacts can only be obtained to an accuracy of 3 percent, we find that the ratio \( \Omega_{\text{min}}/\Omega_{\text{min}} \) approaches the limiting...
value at \( k = 5 \) for high-elastic-modulus materials. For low-elastic-modulus materials the ratio approaches the limiting value more slowly, but it is reasonable to state that the rectangular-contact solution will give a very good prediction of the minimum film thickness for conjunctions in which \( k \) exceeds about 11.

7. Fully Flooded - Starved Boundary

The computing area in and around the Hertzian contact is shown in figure 7. In this figure the coordinate \( X \) is made dimensionless with respect to the semimajor axis \( a \) of the contact ellipse, and the coordinate \( Y \) is made dimensionless with respect to the semimajor axis \( a \) of the contact ellipse. The ellipticity parameter \( k \) is defined as the semimajor axis divided by the semimajor axis of the contact ellipse \((k = a/b)\). Because of the dimensionless form of the coordinates \( X \) and \( Y \) the Hertzian contact ellipse becomes a Hertzian circle regardless of the value of \( k \). This Hertzian contact circle is shown in figure 7 with a radius of unity. The edges of the computing area, where the pressure is assumed to be ambient, are also denoted. In this figure the dimensionless inlet distance \( m^* \), which is equal to the dimensionless distance from the center of the Hertzian contact zone to the inlet edge of the computing area, is shown. Lubricant starvation can be studied by simply changing the dimensionless inlet distance \( m^* \). A fully flooded condition is said to exist when the dimensionless inlet distance ceases to influence the minimum film thickness to any significant extent.

The value at which the minimum film thickness first starts to change when \( m^* \) is gradually reduced from a fully flooded condition is called the fully flooded - starved boundary position and is denoted by \( m^* \). Therefore lubricant starvation was studied by using the basic elastohydrodynamic lubrication elliptical contact theory developed earlier in the lecture and by observing how reducing the dimensionless inlet distance affected the basic features of the conjunction. The next two sections make extensive use of the work presented by Hamrock and Dowson (1977a) and Hamrock and Dowson (1979).

8. Starved Hard-EHL Results

Table III shows how changing the dimensionless inlet distance affected the dimensionless minimum film thickness for three groups of dimensionless load and speed parameters. All the data presented in this section are for hard-EHL contacts that have a materials parameter \( G \) fixed at 40.5 and the ellipticity parameter, at \( 6 \). It can be seen from table III that, as the dimensionless inlet distance \( m^* \) decreases, the dimensionless minimum film thickness \( H_{\min}^* \) also decreases.

Table IV shows how the three groups of dimensionless speed and load parameters considered affected the location of the dimensionless inlet boundary distance \( m^* \). Also given in this table are the corresponding values of dimensionless central and minimum film thickness for the fully flooded condition as obtained by interpolating the numerical values. The value of the dimensionless inlet boundary position \( m^* \) shown in table IV was obtained by using the data from table III when the following equation was satisfied:

\[
\frac{H_{\min}^*}{H_{\min}} = \left( \frac{m^* - 1}{m^* - 1} \right) = 0.03 \tag{19}
\]

The value of 0.03 was used in equation (19) since it was ascertained that the data in table III were accurate to only \( \pm 3\) percent.

The general form of the equation that describes how the dimensionless inlet distance at the fully flooded - starved boundary \( m^* \) varies with the geometry and central film thickness of an elliptical elastohydrodynamic conjunction is given as

\[
m^* - 1 = A^* \left( \frac{R_a}{b} \right)^{B^*} \left( \frac{H_{\min}}{H_{\min}} \right)^{B^*} \tag{20}
\]

The right side of equation (20) is similar in form to the equations given by Wolteridge, et al. (1971) and Meedeven, et al. (1971). By applying a least squares power fit to the data obtained from table III can write

\[
m^* = 1 + 3.34 \left[ \left( \frac{R_a}{b} \right)^{0.06} \right] \tag{21}
\]

A fully flooded condition exists when \( m^* > m^* \), and a starved condition exists when \( m^* < m^* \).

Having clearly established the limiting location of the inlet boundary for the fully flooded conditions (eq. (21)) we can develop an equation defining the dimensionless film thickness for elliptical conjunctions operating under starved lubrication conditions. The ratio between the dimensionless minimum film thickness in starved and fully flooded conditions can be expressed in general form as

\[
\frac{H_{\min,S}}{H_{\min,F}} = \left( \frac{m^* - 1}{m^* - 1} \right) \tag{22}
\]

Table V shows how the ratio of the dimensionless inlet distance parameter to the fully flooded - starved boundary \((m - 1)/(m^* - 1)\) affects the ratio of minimum film thickness in the starved and fully flooded conditions \( H_{\min,S}/H_{\min,F} \). A least-squares power curve fit to the 10 pairs of data points
The application of optical interferometry allows the film thickness through the conjunction to be determined experimentally. An example of the interference pattern for a starved, elastically-hydrodynamically lubricated conjunction is shown in figure 10, which was kindly supplied by Sanborn from the work he reported in 1969. This technique produces information of great clarity and beauty. The film shape of the lubricated conjunction revealed by the experimental results shown in figure 10 compares quite well in qualitative terms with the theoretical results shown in figure 9(c).

9. Starved Soft-EHL Results

By using the theory and numerical procedure mentioned earlier in the lecture, we can investigate the influence of lubricant starvation on minimum film thickness in starved, elliptical, elastohydrodynamic conjunctions for low-elastic-modulus materials (soft EHL). Lubricant starvation is studied by simply moving the inlet boundary closer to the center of the conjunction, as described in the previous section.

Table VI shows how the dimensionless inlet distance affects the dimensionless film thickness for three groups of dimensionless load and speed parameters. For all the results presented in this section the dimensionless materials parameter $b$ was fixed at 0.427, and the ellipticity parameter $k$ was fixed at 0.6. The results shown in table VI clearly indicate the adverse effect of lubricant starvation in the sense that, as the dimensionless inlet distance increases, the dimensionless minimum film thickness also decreases.

Table VII shows how the three groups of dimensionless speed and load parameters affect the limiting location of the dimensionless critical inlet boundary distance $m^*$. Also given in this table are corresponding values of the dimensionless minimum film thickness for the fully flooded condition, as obtained by interpolating the numerical values. By making use of table VI and following the procedure outlined in the previous section, we can write the critical dimensionless inlet boundary distance at which starvation becomes important for low-elastic-modulus materials as

$$m^* = 1 + 1.07 \left( \frac{b}{h_{min}} \right) \left[ \frac{x}{b} \right]^{0.25}$$

where $h_{min}$ is obtained from the fully flooded soft-EHL results in equation (18).

Table VIII shows how $m^*$ affects the ratio of minimum film thickness in the starved and fully flooded conditions $H_{min,starved}/H_{min,fully flooded}$. The dimensionless minimum film thickness for a starved condition
for low elastic modulus materials can thus be written as

$$\frac{h_{min}}{h_{min}} = \left(\frac{m - 1}{m^* - 1}\right)^{0.22}$$

(25)

Therefore, whenever $$m < m^*$$, where $$m^*$$ is defined by equation (24), a lubricant starvation condition exists. When this is true, the dimensionless minimum film thickness is expressed by equation (25). If $$m > m^*$$, a fully flooded condition exists, and the expression for the dimensionless minimum film thickness for a fully flooded condition $$h_{\text{min}}$$ for materials of low elastic modulus is given in equation (18).

10. References


Figure 3. - Contour plot of dimensionless film thickness, \( k = 1, 2, 3; W = 1.10 \times 10^{-4}, 6 \times 10^{-4}, 1.2 \times 10^{-3} \), and \( W = 1.0 \times 10^{-3} \).

Figure 4. - Variation of dimensionless pressure and film thickness on \( x \)-axis for three values of dimensionless load parameter. The value of \( y \) is held near axial center of contact.

Figure 5. - Variation of dimensionless pressure and film thickness on \( x \)-axis for three values of dimensionless load parameter. The value of \( y \) is held near axial center of contact.

Figure 6. - Effect of ellipticity parameter on ratio of dimensionless minimum film thickness to dimensionless minimum film thickness for a line contact, for EHL high- and low-elastic-modulus analyses.
Figure A. Contour plots of dimensionless pressure for dimensionless inlet distances $H$ of 1, 2, and 1.25 and for group I of Table III.

Figure B. - Interference pattern for a starved elastohydrodynamic lubricated conjunction. (From Sanborn, 1969.)
### Table I. Data Showing Effect of Ellipticity, Load, Speed, and Material Parameters on Minimum Film Thickness for Hard on Soft Contacts

| Case | Ellipticity parameter, $k$ | Dimensionless load parameter, $N$ | Dimensionless speed parameter, $U$ | Dimensionless material parameter, $G$ | Minimum film thickness, $H_{min}$ (nm) | Difference between Min. and Load, $\%$ | Ellipticity
|------|---------------------------|----------------------------------|-----------------------------------|-----------------------------------|----------------------------------|-----------------------------------|--------|
| 1    | 1                        | 0.1024 x 10$^{-4}$               | 0.1483 x 10$^{-11}$               | 4.872                            | 3.94 x 10$^{-10}$               | 5.42 $\%$                         | Ellipticity
| 2    | 2                        | 1.024 x 10$^{-4}$               | 1.483 x 10$^{-11}$               | 4.872                            | 3.94 x 10$^{-10}$               | 5.42 $\%$                         | Ellipticity
| 3    | 3                        | 1.024 x 10$^{-4}$               | 1.483 x 10$^{-11}$               | 4.872                            | 3.94 x 10$^{-10}$               | 5.42 $\%$                         | Ellipticity
| 4    | 4                        | 1.024 x 10$^{-4}$               | 1.483 x 10$^{-11}$               | 4.872                            | 3.94 x 10$^{-10}$               | 5.42 $\%$                         | Ellipticity
| 5    | 5                        | 1.024 x 10$^{-4}$               | 1.483 x 10$^{-11}$               | 4.872                            | 3.94 x 10$^{-10}$               | 5.42 $\%$                         | Ellipticity
| 6    | 6                        | 1.024 x 10$^{-4}$               | 1.483 x 10$^{-11}$               | 4.872                            | 3.94 x 10$^{-10}$               | 5.42 $\%$                         | Ellipticity
| 7    | 7                        | 1.024 x 10$^{-4}$               | 1.483 x 10$^{-11}$               | 4.872                            | 3.94 x 10$^{-10}$               | 5.42 $\%$                         | Ellipticity

### Table II. Datashowing Effect of Ellipticity, Load, Speed, and Material Parameters on Minimum Film Thickness for Soft on Soft Contacts

| Case | Ellipticity parameter, $k$ | Dimensionless load parameter, $N$ | Dimensionless speed parameter, $U$ | Dimensionless material parameter, $G$ | Minimum film thickness, $H_{min}$ (nm) | Difference between Min. and Load, $\%$ | Ellipticity
|------|---------------------------|----------------------------------|-----------------------------------|-----------------------------------|----------------------------------|-----------------------------------|--------|
| 1    | 1                        | 0.442 x 10$^{-3}$               | 0.12 x 10$^{-3}$                 | 0.4276                            | 0.4276                           | 0.4276 $\%$                         | Ellipticity
| 2    | 2                        | 0.442 x 10$^{-3}$               | 0.12 x 10$^{-3}$                 | 0.4276                            | 0.4276                           | 0.4276 $\%$                         | Ellipticity
| 3    | 3                        | 0.442 x 10$^{-3}$               | 0.12 x 10$^{-3}$                 | 0.4276                            | 0.4276                           | 0.4276 $\%$                         | Ellipticity
| 4    | 4                        | 0.442 x 10$^{-3}$               | 0.12 x 10$^{-3}$                 | 0.4276                            | 0.4276                           | 0.4276 $\%$                         | Ellipticity
| 5    | 5                        | 0.442 x 10$^{-3}$               | 0.12 x 10$^{-3}$                 | 0.4276                            | 0.4276                           | 0.4276 $\%$                         | Ellipticity
| 6    | 6                        | 0.442 x 10$^{-3}$               | 0.12 x 10$^{-3}$                 | 0.4276                            | 0.4276                           | 0.4276 $\%$                         | Ellipticity

-10-
### TABLE III - EFFECT OF STARVATION ON MINIMUM FILM THICKNESS FOR HARD-EHL CONTACTS

<table>
<thead>
<tr>
<th>Dimensionless Inlet Distance, W</th>
<th>Load Parameter, W</th>
<th>Speed Parameter, U</th>
<th>Minimum Film Thickness, H_{min}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3686 \times 10^{-6}</td>
<td>0.7371 \times 10^{-6}</td>
<td>0.7371 \times 10^{-6}</td>
<td>29.73 \times 10^{-6}</td>
</tr>
<tr>
<td>0.3686 \times 10^{-6}</td>
<td>0.7371 \times 10^{-6}</td>
<td>0.7371 \times 10^{-6}</td>
<td>61.32 \times 10^{-6}</td>
</tr>
<tr>
<td>0.3686 \times 10^{-6}</td>
<td>0.7371 \times 10^{-6}</td>
<td>0.7371 \times 10^{-6}</td>
<td>61.70 \times 10^{-6}</td>
</tr>
<tr>
<td>0.3686 \times 10^{-6}</td>
<td>0.7371 \times 10^{-6}</td>
<td>0.7371 \times 10^{-6}</td>
<td>57.60 \times 10^{-6}</td>
</tr>
<tr>
<td>0.3686 \times 10^{-6}</td>
<td>0.7371 \times 10^{-6}</td>
<td>0.7371 \times 10^{-6}</td>
<td>39.91 \times 10^{-6}</td>
</tr>
<tr>
<td>0.3686 \times 10^{-6}</td>
<td>0.7371 \times 10^{-6}</td>
<td>0.7371 \times 10^{-6}</td>
<td>27.90 \times 10^{-6}</td>
</tr>
</tbody>
</table>

### TABLE VI - EFFECT OF STARVATION ON FILM THICKNESS FOR SOFT-EHL CONTACTS

<table>
<thead>
<tr>
<th>Dimensionless Inlet Distance, W</th>
<th>Load Parameter, W</th>
<th>Speed Parameter, U</th>
<th>Minimum Film Thickness, H_{min}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4405 \times 10^{-6}</td>
<td>0.2202 \times 10^{-6}</td>
<td>0.5139 \times 10^{-6}</td>
<td>13.51 \times 10^{-6}</td>
</tr>
<tr>
<td>0.4405 \times 10^{-6}</td>
<td>0.2202 \times 10^{-6}</td>
<td>0.5139 \times 10^{-6}</td>
<td>24.78 \times 10^{-6}</td>
</tr>
<tr>
<td>0.4405 \times 10^{-6}</td>
<td>0.2202 \times 10^{-6}</td>
<td>0.5139 \times 10^{-6}</td>
<td>40.72 \times 10^{-6}</td>
</tr>
<tr>
<td>0.4405 \times 10^{-6}</td>
<td>0.2202 \times 10^{-6}</td>
<td>0.5139 \times 10^{-6}</td>
<td>61.70 \times 10^{-6}</td>
</tr>
<tr>
<td>0.4405 \times 10^{-6}</td>
<td>0.2202 \times 10^{-6}</td>
<td>0.5139 \times 10^{-6}</td>
<td>24.78 \times 10^{-6}</td>
</tr>
</tbody>
</table>

### TABLE VIII - EFFECT OF INLET DISTANCE ON MINIMUM FILM-THICKNESS RATIO FOR SOFT-EHL CONTACTS

<table>
<thead>
<tr>
<th>Dimensionless Inlet Distance, W</th>
<th>Ratio of Minimum Film Thicknesses for Starved and Flooded Conditions, ( \frac{H_{min}^{starved}}{H_{min}^{flooded}} )</th>
<th>Critical Inlet Boundary Parameter, ( \delta_{min} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4405 \times 10^{-6}</td>
<td>0.485 \times 10^{-6}</td>
<td>1.041 \times 10^{-6}</td>
</tr>
<tr>
<td>0.2202 \times 10^{-6}</td>
<td>2.202 \times 10^{-6}</td>
<td>2.202 \times 10^{-6}</td>
</tr>
<tr>
<td>0.5139 \times 10^{-6}</td>
<td>4.51 \times 10^{-6}</td>
<td>4.51 \times 10^{-6}</td>
</tr>
</tbody>
</table>

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