

FILM THICKNESS FOR DIFFERENT REGIMES OF FLUID-FILM LUBRICATION

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FILM THICKNESS FOR DIFFERENT REGIMES OF FLUID-FILM LUBRICATION

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There are a number of reasonably well-defined regimes within the full range of conditions of fluid-film lubrication of elliptical contacts. Each regime has characteristics determined by the operating conditions and the properties of the material.

The type of lubrication of a particular contact is influenced by two major physical effects: the elastic deformation of the solids under an applied load, and the increase in fluid viscosity with pressure. Therefore it is possible to have four main regimes of fluid-film lubrication, depending on the magnitude of these effects and on their importance. These four regimes are defined as

(1) Isoviscous-rigid: In this regime the magnitude of the elastic deformation of the surfaces is an insignificant part of the thickness of the fluid film separating them, and the maximum pressure in the contact is too low to increase fluid viscosity significantly. This form of lubrication is typically encountered in circular-arc thrust bearing pads; in industrial coating processes in which paint, emulsion, or protective coatings are applied to sheet or film materials passing between rollers; and in very lightly loaded rolling bearings.

(2) Viscous-rigid: If the pressure within the contact is sufficiently high to increase the fluid viscosity significantly within the contact, it may be necessary to consider the pressure-viscosity characteristics of the lubricant while assuming that the solids remain rigid. For the latter part of this assumption to be valid it is necessary that the deformation of the surfaces remain an insignificant part of the fluid-film thickness. This form of lubrication may be encountered on roller end-guide flanges, in contacts in moderately loaded cylindrical tapered rollers, and between some piston rings and cylinder liners.

(3) Isoviscous-elastic: In this regime the elastic deformation of the solids is a significant part of the thickness of the fluid film separating them, but the pressure within the contact is quite low and insufficient to cause any substantial increase in viscosity. This situation arises with materials of low elastic modulus (soft EHL), and it is a form of lubrication that may be encountered in seals, human joints, tires, and elastomeric-material machine elements.

(4) Viscous-elastic: In fully developed elastohydrodynamic lubrication the elastic deformation of the solids is often a significant part of the thickness of the fluid film separating them, and the pressure within the contact is high enough to cause a significant increase in the viscosity of the lubricant within the contact. This form of lubrication is typically encountered in ball and roller bearings, gears, and cams.

Several authors - Moes (1965-66), Theyse (1966), Archard (1968), Greenwood (1969), Johnson (1970), and Hooke (1977) - have contributed solutions for the film thickness in the four lubrication regimes, but their results have been confined largely to rectangular contacts. The essential difference between these contributions is the way in which the parameters

were made dimensionless. In this lecture the film thickness is defined for the four fluid-film lubrication regimes just described for conjunctions ranging from circular to rectangular. The film thickness equations for the respective lubrication regimes come from theoretical studies on elastohydrodynamic and hydrodynamic lubrication of elliptical conjunctions by the author. The results are valid for isothermal, fully flooded conjunctions. In addition to the film thickness equations for the various conditions a map is presented of the lubrication regimes, with film thickness contours being represented on a log-log grid of the viscosity and elasticity parameters for three values of the ellipticity parameter. This lecture draws extensively from the work of Hamrock and Dowson (1979).

DIMENSIONLESS GROUPING

Representation of the results of elastohydrodynamic theory for elliptical contacts in lectures 2 and 3 in terms of the dimensionless groups (H , U , W , G , k) has been particularly helpful since the physical explanation of conjunction behavior can readily be associated with each set of numerical results. However, several authors have noted that this dimensionless group can be reduced by one parameter - without any loss of generality - by using dimensionless analysis. The film thickness contours for the four fluid-film lubrication regimes can be conveniently represented graphically by the fewest parameters, even though the physical meaning of each composite parameter requires careful consideration.

Johnson (1970) has pointed out that the behavior distinguishing the four lubrication regimes can be characterized by three quantities, each having the dimensions of pressure:

- (1) The reduced pressure parameter q_f , a measure of the fluid pressure generated by an isoviscous lubricant when elastic deformation is neglected
- (2) The inverse pressure-viscosity coefficient $1/\alpha$, a measure of the change of viscosity with pressure
- (3) The maximum Hertzian pressure p_{max} , the maximum pressure of a dry elastic contact

Although Johnson (1970) does not consider elliptical contacts, he does state what the nondimensional parameters for such configurations should be.

Dimensionless film parameter:

$$\hat{H} = H \left(\frac{W}{U} \right)^2 \quad (1)$$

Dimensionless viscosity parameter:

$$g_V = \alpha q_f = \frac{6W^3}{U^2} \quad (2)$$

Dimensionless elasticity parameter:

$$g_E = \frac{1}{\pi} \left(\frac{3}{2} \right)^{1/3} \left(\frac{q_f}{p_{max}} \right) = \frac{W^{8/3}}{U^2}$$

The ellipticity parameter k remains as discussed in lectures 2 and 3. Therefore the reduced dimensionless group is (H, g_V, g_E, k) .

ISOVISCIOUS-RIGID REGIME

The influence of conjunction geometry on the isothermal hydrodynamic film separating two rigid solids was investigated by Brewe, et al. (1979) for fully flooded, isoviscous conditions. The effect of geometry on the film thickness was determined by varying the radius ratio R_y/R_x from 1 (a circular configuration) to 36 (a configuration approaching a rectangular contact). The film thickness was varied over two orders of magnitude for conditions representative of steel solids separated by a paraffinic mineral oil. It was found that the computed minimum film thickness had the same speed, viscosity, and load dependence as the classical Kapitza (1955) solution. However, when the Reynolds cavitation boundary condition - $ap/\partial n = 0$ and $p = 0$ at the cavitation boundary, where n represents the normal coordinate to the cavitation boundary - was introduced, an additional geometrical effect emerged. Therefore from Brewe, et al. (1979) the dimensionless minimum, or central, film thickness parameter for the isoviscous-rigid lubrication regime can be written as

$$(\hat{H}_{\min})_{IR} = (\hat{H}_c)_{IR} = 128 \alpha_a \lambda_b^2 \left[0.131 \tan^{-1} \left(\frac{\alpha_a}{2} \right) + 1.683 \right]^2 \quad (4)$$

where

$$\alpha_a = \frac{R_y}{R_x} = \left(\frac{k}{1.03} \right)^{1/0.64} \quad (5)$$

$$\lambda_b = \left(1 + \frac{2}{3\alpha_a} \right)^{-1} \quad (6)$$

In equation (4) the dimensionless film thickness parameter \hat{H} is shown to be strictly a function of the geometry of the contact R_y/R_x .

VISCOUS-RIGID REGIME

Blok (1952) has shown that the minimum film thickness for the viscous-rigid lubrication regime in a rectangular contact can be expressed as

$$h_{\min} = h_c = 1.66 \left(\alpha^2 n_0^2 u^2 R_x \right)^{1/3} \quad (7)$$

By taking account of the ellipticity of the conjunction under consideration equation (7) can be rewritten as

$$h_{\min} = h_c = 1.66 \left(\alpha^2 n_0^2 u^2 R_x \right)^{1/3} (1 - e^{-0.68k}) \quad (8)$$

The absence of an applied-load term in equation (8) should be noted. When expressed in terms of the dimensionless parameters of equations (1) and (2), this can be written as

$$(\hat{H}_{min})_{VR} = (\hat{H}_c)_{VR} = 1.66 g_V^{2/3} (1 - e^{-0.68k}) \quad (9)$$

Note the absence of the dimensionless elasticity parameter g_E in equation (9).

ISOVISCIOUS-ELASTIC REGIME

The influence of the ellipticity parameter k and the dimensionless speed U , load W , and materials G parameters on the minimum, or central, film thicknesses was investigated theoretically for the isoviscous-elastic (soft EHL) regime, and the results have been presented in lecture 2. The ellipticity parameter was varied from 1 (a circular configuration) to 12 (a configuration approaching a rectangular contact). The dimensionless speed and load parameters were each varied by one order of magnitude. Seventeen cases were considered in obtaining the dimensionless minimum-film-thickness equation

$$H_{min} = 7.43 U^{0.65} W^{-0.21} (1 - 0.85 e^{-0.31k}) \quad (10)$$

From equations (1) and (3) the general form of the dimensionless minimum-film-thickness parameter for the isoviscous-elastic lubrication regime can be expressed as

$$\hat{H}_{min} = A g_E^c (1 - 0.85 e^{-0.31k}) \quad (11)$$

where A and c are constants to be determined. From equations (1) and (3) we can write equation (11) as

$$H_{min} = A U^{2-2c} W^{(8/3c)-2} (1 - 0.85 e^{-0.31k}) \quad (12)$$

Comparing equation (10) with (12) gives $c = 0.67$. Substituting this into equation (11) while solving for A gives

$$A = \frac{\hat{H}_{min}}{g_E^{0.67} (1 - 0.85 e^{-0.31k})} \quad (13)$$

The arithmetic mean for A based on the 17 cases considered in lecture 2 is 8.70, with a standard deviation of ± 0.05 . Therefore the dimensionless minimum-film-thickness parameter for the isoviscous-elastic lubrication regime can be written as

$$(\hat{H}_{min})_{IE} = 8.70 g_E^{0.67} (1 - 0.85 e^{-0.31k})$$

With a similar approach the dimensionless central-film-thickness parameter for the isoviscous-elastic lubrication regime can be written as

$$(\hat{H}_c)_{IE} = 11.15 g_E^{0.67} (1 - 0.72 e^{-0.28k}) \quad (15)$$

VISCOUS-ELASTIC REGIME

In lecture 2 for hard EHL contacts the influence of the ellipticity parameter and the dimensionless speed, load, and materials parameters on the minimum and central film thicknesses was investigated theoretically for the viscous-elastic regime. The ellipticity parameter was varied from 1 to 8, the dimensionless speed parameter was varied over nearly two orders of magnitude, and the dimensionless load parameter was varied over one order of magnitude. Conditions corresponding to the use of solid materials of bronze, steel, and silicon nitride and lubricants of paraffinic and naphthenic oils were considered in obtaining the exponent on the dimensionless materials parameter. Thirty-four cases were used in obtaining the following dimensionless minimum-film-thickness formula:

$$H_{min} = 3.63 U^{0.68} G^{0.49} W^{-0.073} (1 - e^{-0.68k}) \quad (16)$$

The general form of the dimensionless minimum-film-thickness parameter for the viscous-elastic lubrication regime can be written as

$$\hat{H}_{min} = B g_V^d g_E^f (1 - e^{-0.68k}) \quad (17)$$

where B, d, and f are constants to be determined. From equations (1), (2), and (3) we can write (17) as

$$H_{min} = B G^d U^{2-2d-2f} W^{-2+3d+(8f/3)} (1 - e^{-0.68k}) \quad (18)$$

Comparing equation (16) with (18) gives $d = 0.49$ and $f = 0.17$. Substituting these values into equation (17) while solving for B gives

$$B = \frac{\hat{H}_{min}}{g_V^{0.49} g_E^{0.17} (1 - e^{-0.68k})} \quad (19)$$

For the 34 cases considered in lecture 2 for the derivation of equation (16) the arithmetic mean for B was 3.42, with a standard deviation of ± 0.03 . Therefore the dimensionless minimum-film-thickness parameter for the viscous-elastic lubrication regime can be written as

$$(\hat{H}_{min})_{VE} = 3.42 g_V^{0.49} g_E^{0.17} (1 - e^{-0.68k}) \quad (20)$$

An interesting observation to make in comparing equations (9), (14), and (20) is that in each case the sum of the exponents on g_V and g_E is close to the value of $2/3$ required for complete dimensional representation of these three lubrication regimes: viscous-rigid, isoviscous-elastic, and viscous-elastic.

By adopting a similar approach to that outlined here the dimensionless central-film-thickness parameter for the viscous-elastic lubrication regime can be written as

$$(\hat{H}_c)_{VE} = 3.01 g_V^{0.25} g_E^{0.13} (1 - 0.01 e^{-0.13k})$$

PROCEDURE FOR MAPPING THE DIFFERENT LUBRICATION REGIMES

Having expressed the dimensionless minimum-film-thickness parameters for the four fluid-film lubrication regimes in equations (4), (9), (14), and (20), we used these equations to develop a map of the lubrication regimes in the form of dimensionless minimum-film-thickness-parameter contours. These maps are shown in figures 1 to 3 on a log-log grid of the dimensionless viscosity and elasticity parameters for ellipticity parameters of 1, 3, and 6, respectively. The procedure used to obtain these figures was as follows:

(1) For a given value of the ellipticity parameter $(\hat{H}_{min})_{IR}$ was calculated from equation (4).

(2) For a value of $\hat{H}_{min} > (\hat{H}_{min})_{IR}$ and the value of k chosen in step 1, the dimensionless viscosity parameter was calculated from equation (9) as

$$g_V = \left[\frac{\hat{H}_{min}}{1.66(1 - e^{-0.68k})} \right]^{3/2} \quad (22)$$

This established the dimensionless minimum-film-thickness-parameter contours \hat{H}_{min} as a function of g_V for a given value of k in the viscous-rigid regime.

(3) For the values of k selected in step 1, \hat{H}_{min} selected in step 2, and g_V obtained from equation (22), the dimensionless elasticity parameter was calculated from the following equation, which was derived from equation (20):

$$g_E = \left[\frac{\hat{H}_{min}}{3.42 g_V^{0.49} (1 - e^{-0.68k})} \right]^{1/0.17} \quad (23)$$

This established the boundary between the viscous-rigid and viscous-elastic regimes and enabled contours of \hat{H}_{min} to be drawn in the viscous-elastic regime as functions of g_V and g_E for given values of k .

(4) For the values of k and \hat{H}_{min} chosen in steps 1 and 2 the dimensionless elasticity parameter was calculated from the following equation, obtained by rearranging equation (14):

$$g_E = \left[\frac{\hat{H}_{min}}{8.70(1 - 0.85 e^{-0.31k})} \right]^{1/0.67} \quad (24)$$

This established the dimensionless minimum-film-thickness-parameter contour \hat{H}_{min} as a function of g_E for a given value of k in the isoviscous-elastic lubrication regime.

(5) For the values of k and \hat{H}_{min} selected in steps 1 and 2 and the value of g_E obtained from equation (24), the viscosity parameter was calculated from the following equation:

$$g_V = \left[\frac{\hat{H}_{min}}{3.42 g_E^{0.17} (1 - e^{-0.68k})} \right]^{1/0.49} \quad (25)$$

This established the isoviscous-elastic and viscous-elastic boundaries for the particular values of k and \hat{H}_{min} chosen in steps 1 and 2.

(6) At this point, for particular values k and \hat{H}_{min} , the contours were drawn through the viscous-rigid, viscous-elastic, and isoviscous-elastic regimes. A new value of \hat{H}_{min} was then selected, and the new contour was constructed by returning to step 2. This procedure was continued until an adequate number of contours had been generated. A similar procedure was followed for the range of k values considered.

CONTOUR PLOTS

The maps of the lubrication regimes shown in figures 1 to 3 were generated by following the procedure outlined in the previous section. The contours of the dimensionless minimum-film-thickness parameter were plotted on a log-log grid of the dimensionless viscosity parameter and the dimensionless elasticity parameter for ellipticity parameters of 1, 3, and 6. The four lubrication regimes are clearly shown in these figures. The smallest \hat{H}_{min} contour considered in each case represents the values obtained from equation (4), and this forms a boundary to the isoviscous-rigid region. The value of \hat{H}_{min} on the isoviscous-rigid boundary increases as k increases.

By using figures 1 to 3 for given values of the parameters k , g_V , and g_E , the fluid-film lubrication regime in which any elliptical conjunction is operating can be ascertained and the approximate value of \hat{H}_{min} determined. When the lubrication regime is known, a more accurate value of \hat{H}_{min} can be obtained by using the appropriate dimensionless minimum-film-thickness-parameter equation.

A three-dimensional view of the surfaces developed by using constant values of \hat{H}_{min} (500, 2000, and 6000) is shown in figure 4. The coordinates in this figure are g_E , g_V , and k . The four fluid-film lubrication regimes are clearly shown. This figure not only defines the regimes of fluid-film lubrication clearly for elliptical contacts, but it also indicates in a single illustration how the parameters g_V , g_E , and k influence the dimensionless minimum-film-thickness parameter.

CONCLUDING REMARKS

Relationships for the dimensionless minimum-film-thickness parameter equations for the four lubrication regimes found in elliptical contacts have been developed and expressed as

(1) Isoviscous-rigid regime:

$$(\hat{H}_{\min})_{IR} = (\hat{H}_C)_{IR} = 128 \alpha_a \lambda_b^2 \left[0.131 \tan^{-1} \left(\frac{\alpha_a}{2} \right) + 1.683 \right]^2$$

where

$$\alpha_a = \frac{R_y}{R_x} = \left(\frac{k}{1.03} \right)^{1/0.64}$$

$$\lambda_b = \left(1 + \frac{2}{3\alpha_a} \right)^{-1}$$

(2) Viscous-rigid regime:

$$(\hat{H}_{\min})_{VR} = 1.66 g_V^{2/3} (1 - e^{-0.68k})$$

(3) Isoviscous-elastic regime:

$$(\hat{H}_{\min})_{IE} = 8.70 g_E^{0.67} (1 - 0.85 e^{-0.31k})$$

(4) Viscous-elastic regime:

$$(\hat{H}_{\min})_{VE} = 3.42 g_V^{0.49} g_E^{0.17} (1 - e^{-0.68k})$$

The relative importance of the influence of pressure on elastic distortion and lubricant viscosity is the factor that distinguishes these regimes for a given conjunction geometry.

In addition, these equations have been used to develop maps of the lubrication regimes by plotting film thickness contours on a log-log grid of the viscosity and elasticity parameters for three values of the ellipticity parameter. These results present a complete theoretical film-thickness-parameter solution for elliptical contacts in the four lubrication regimes. The results are particularly useful in initial investigations of many practical lubrication problems involving elliptical conjunctions.

APPENDIX - SYMBOLS

E	modulus of elasticity, N/m ²
E'	effective elastic modulus, $2 / \left[\frac{1 - \nu_a^2}{E_a} + \frac{1 - \nu_b^2}{E_b} \right]$, N/m ²
F	normal applied load, N
G	dimensionless materials parameter, $\alpha E'$
H	dimensionless film thickness, h/R_x
\hat{H}	dimensionless film thickness, $H \left(\frac{W}{U} \right)^2 = \frac{F^2 h}{u^2 \eta_0^2 R_x^3}$
h	film thickness, m
k	ellipticity parameter, $1.03 (R_y/R_x)^{0.64}$
P_{max}	maximum Hertzian pressure, N/m ²
q_f	reduced pressure parameter, N/m ²
R	effective radius, m
r	radius of curvature, m
U	dimensionless speed parameter, $\eta_0 u / E' R_x$
u	mean surface velocity in direction of motion, m/s
W	dimensionless load parameter, $F / E' R_x^2$
α	pressure-viscosity coefficient of lubricant, m ² /N
η_0	viscosity at atmospheric pressure, N-s/m ²
ν	Poisson's ratio
λ_b	Archard-Cowking side-leakage factor, $[1 + (2/3\alpha_a)]^{-1}$

Subscripts:

a	solid a
b	solid b
c	central
E	elastic
I	isoviscous
min	minimum
R	rigid
V	viscous
x,y	in x and y directions, respectively

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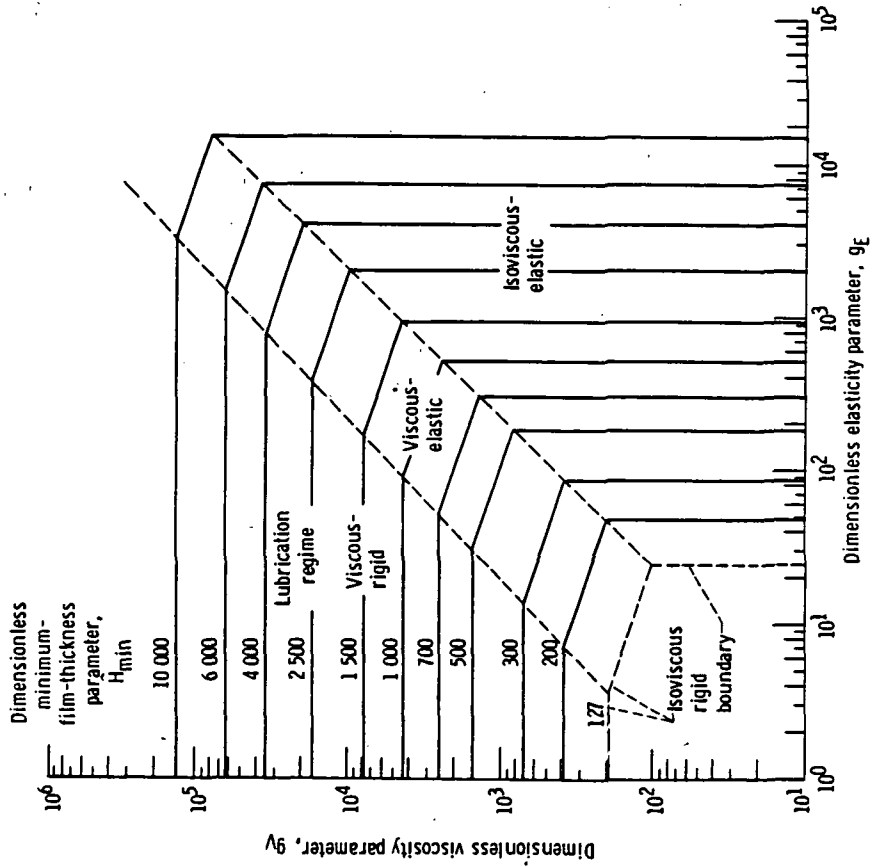


Figure 1. - Map of lubrication regimes for ellipticity parameter k of 1.

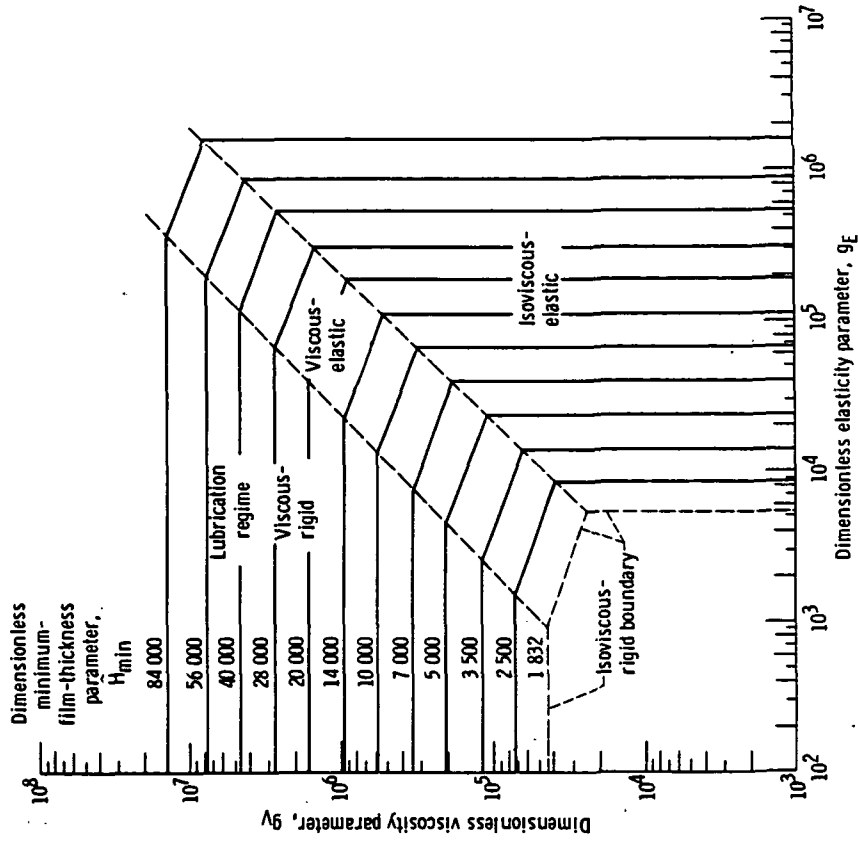


Figure 2. - Map of lubrication regimes for ellipticity parameter k of 3.

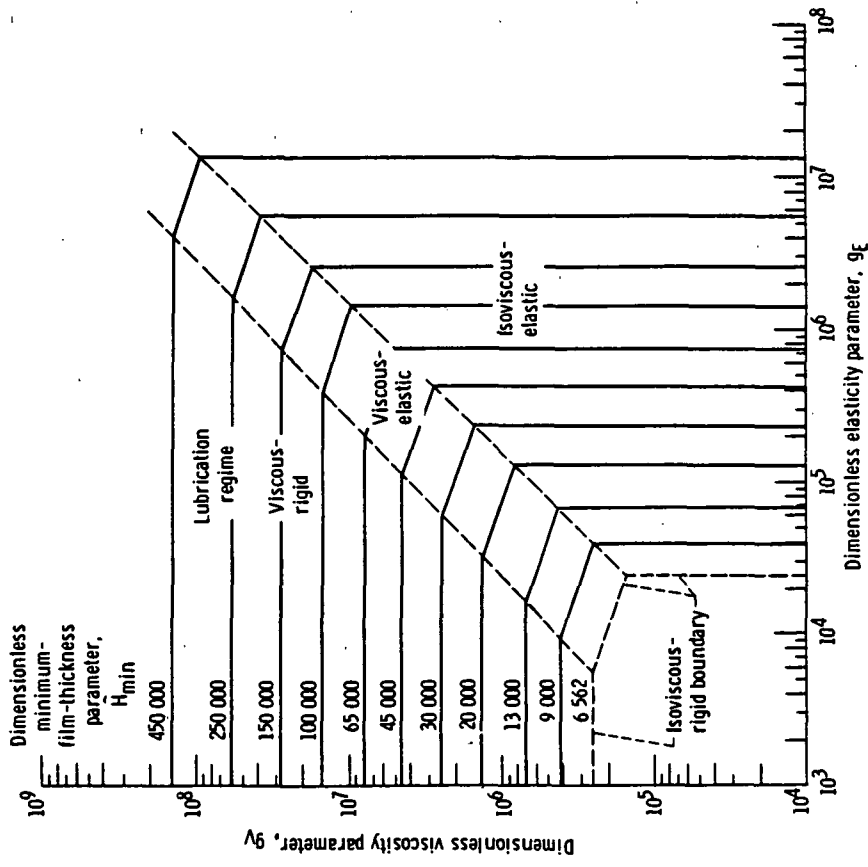


Figure 3. - Map of lubrication regimes for ellipticity parameter k of 6.

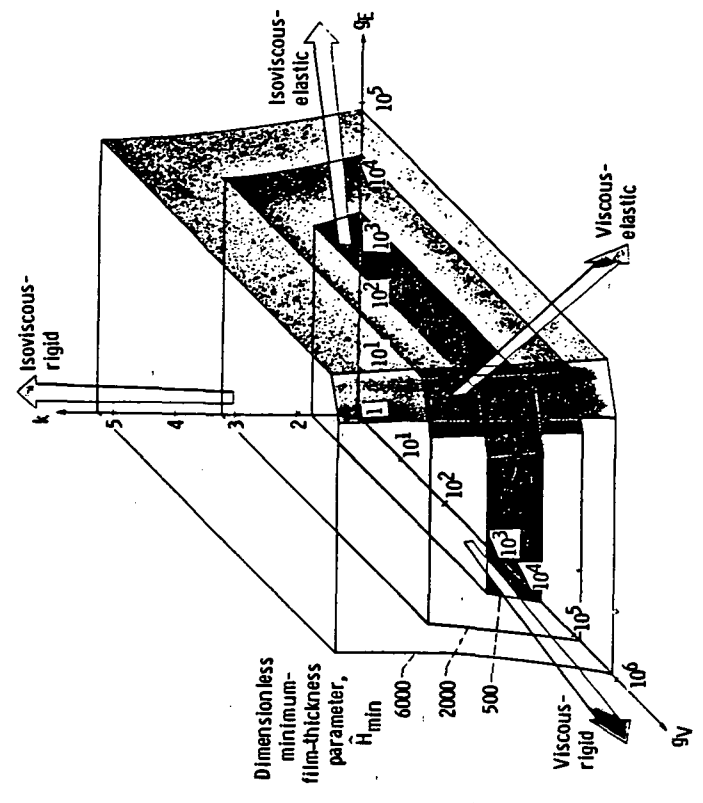


Figure 4. - Surfaces for constant values of dimensionless minimum-film-thickness parameter.

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16. Abstract <p>In this lecture the film thickness equations are provided for four fluid-film lubrication regimes found in elliptical contacts. These regimes are isoviscous-rigid; viscous-rigid; elastohydrodynamic lubrication of low-elastic-modulus materials (soft EHL), or isoviscous-elastic; and elastohydrodynamic lubrication of high-elastic-modulus materials (hard EHL), or viscous-elastic. The influence or lack of influence of elastic and viscous effects is the factor that distinguishes these regimes. Film thickness equations for the four lubrication regimes are stated, and the results are presented as a map of the lubrication regimes, with film thickness contours on a log-log grid of the viscosity and elasticity for three values of the ellipticity parameter.</p>			
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