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Lubrication Fundamentals

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SUMMARY

A lubricant is any substance that is used to reduce friction and wear and to provide smooth running and a satisfactory life for machine components. This section deals with lubrication fundamentals and, in particular, defines the various lubrication mechanisms: hydrodynamic, elastohydrodynamic, mixed, boundary, and extreme pressure. Before the various lubrication mechanisms are presented, it is desirable to define conformal and nonconformal surfaces.

CONFORMAL AND NONCONFORMAL SURFACES

Hydrodynamic lubrication is generally characterized by surfaces that are conformal. 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 surfaces. In journal bearings the radial clearance between the shaft and bearing 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 very well. The full burden of the load must then be carried by a very small contact 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/m^2 and seldom over 7 MN/m^2 . By contrast, the load per unit area in nonconformal contacts, such as those that exist in ball bearings, will generally exceed 700 MN/m^2 , even at modest applied loads. These high pressures result in elastic deformation of the bearing 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 within the contact area. 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.

Figure 1 illustrates the two distinctly different geometries. On the left is a typical journal bearing; on the right is a rolling-element bearing. A universal characteristic of the journal bearing - and other sliding-surface bearings such as pad thrust bearings - is a high degree of conformity between the surfaces, relatively large effective contact areas, and low unit loading. In contrast, as mentioned earlier, the rolling-element bearing has poor conformity between surfaces, very small contact areas, and very high unit loads.

HYDRODYNAMIC LUBRICATION

Fluid-film lubrication occurs when the lubricant film is sufficiently thick to prevent the opposing solids from coming into contact. This condition is often referred to as the ideal form of lubrication since it provides low friction and a high resistance to wear. The lubrication of the contact is governed by the bulk physical properties of the lubricant, notably viscosity; and the frictional characteristics arise purely from the shearing of the viscous lubricant. The characteristics of hydrodynamic lubrication are illustrated in figure 2. The pressure developed in the oil film of hydrodynamically lubricated bearings is due to two factors:

(1) The geometry of the moving surfaces produces a convergent wedge of the liquid.

(2) The liquid is viscous which results in a resistance to flow.

The lubricant films are normally many times thicker than the surface roughness. The physical properties of the lubricant dictate contact behavior. The film thickness normally exceeds 10^{-6} m. The effect of the surface finish can be related to the film thickness by the following equation:

$$\Lambda = \frac{h}{\sqrt{f_a^2 + f_b^2}}$$

where

h film thickness
 f_a, f_b rms surface finish of solids a and b

Therefore the film parameter Λ is a ratio of the film thickness to the composite rms. For hydrodynamic lubrication the film parameter is in excess of 10 and may even rise to 100. Films of this thickness are clearly insensitive to chemical action in surface layers of molecular proportions.

ELASTOHYDRODYNAMIC LUBRICATION

Elastohydrodynamic lubrication is a form of fluid-film lubrication where elastic deformation of the bearing surfaces becomes significant. It is usually associated with highly stressed machine components of low conformity, such as gears and rolling-element bearings. Besides the elastic effect there is a viscous effect, that is, for example, at a pressure of 700 MN/m^2 (which is moderate since the pressure can be as high as 2100 MN/m^2) the viscosity may be increased 10 000-fold. The liquid entering the gap between the gear teeth is trapped between the surfaces, and at the high pressures existing in the contact region, behaves virtually like a solid separating layer.

Figure 3 demonstrates the contact effects found in elastohydrodynamic lubrication. As the contacts approach, lubricant is forced from between them because of the hydrodynamic effect. This flow is resisted by viscous forces, and there is an accompanying pressure rise that, in turn, raises the viscosity of the trapped lubricant. As the pressure increases, the surfaces deform elastically. The increased pressure resulting from the contact interaction represents load support by the contacts through the fluid film. Elastohydrodynamic lubrication normally occurs in contacts where the film thickness is in the range $10^{-7} \text{ m} < h \leq 10^{-6} \text{ m}$ and the film parameter

is in the range $3 < \Lambda < 10$. The characteristics of elastohydrodynamic lubrication are illustrated in figure 4.

The elastohydrodynamic lubrication mechanism is also encountered with soft bearing materials, such as elastomeric seals and rubber tires. The common factors in these applications are that the local elastic deformation of the solids provides coherent fluid film and that contact of asperities (high points on the surface) is largely prevented. Another feature of the elastohydrodynamic lubrication of low-elastic-modulus materials is the negligible effect of the relatively low pressures on viscosity of the lubricating fluid.

BOUNDARY LUBRICATION

If in a lubricated contact the pressures become too high, the running speeds too low, or the surface roughness too great, penetration of the lubricant film will occur. Contact will take place between the asperities. The friction will rise and, more importantly, wear will take place. Adding a small quantity of a certain active organic compound to the lubricating oil can extend the life of machine elements. These additives are present in small quantities (<1 percent). They function because they form low shear strength surface films that are strongly attached to the metal surfaces. Although they are generally only one or two molecules thick, they are able to prevent metal-to-metal contact.

Some boundary lubricants are long-chain molecules with an active end group, typically an alcohol, an amine, or a fatty acid. When such a material, dissolved in a mineral oil, meets a metal or other solid surface, the active end group attaches itself to the solid and gradually builds up a surface layer. The surface films vary in thickness from 5×10^{-9} to 10^{-8} m, and the film parameter Λ is less than unity ($\Lambda < 1$).

MIXED-FILM LUBRICATION

The behavior of the conjunction in a mixed-film lubrication regime is governed by a combination of boundary and hydrodynamic or elastohydrodynamic effects. Some asperity contact may occur. Interaction takes place between one or more molecular layers of boundary lubricating films. A partial fluid-film lubrication action develops in the bulk of the space between the solids. The film thickness in a mixed-film lubrication contact is less than 10^{-8} m and greater than 10^{-6} m. The film parameter Λ is normally between 1 and 4.

Figure 5 illustrates the film conditions existing in fluid film, mixed-film, and boundary lubrication. The surfaces shown are greatly distorted for purposes of illustration. To scale, real surfaces would appear as gently rolling hills rather than sharp peaks.

The variation of the coefficient of friction μ with the film parameter Λ is shown in figure 6. In this figure the approximate locations of the various lubrication regimes already discussed are shown. This figure shows that, as the film parameter Λ increases, there is initially a decrease in the coefficient of friction in the elastohydrodynamic regime and then an increase in the coefficient of friction in the hydrodynamic regime.

EXTREME-PRESSURE LUBRICATION

The best boundary lubricants cease to be effective above 200° to 250° C because the softening or melting point of the surface film is exceeded. If surfaces are to operate under more severe conditions, other types of lubricants must be used. Extreme-pressure (EP) lubricants usually consist of a small quantity of an EP additive in a lubricating oil. The most widely used additives for this purpose contain phosphorus, chlorine, and sulfur. In general these materials function by reacting with the surface to form a surface film that prevents metal-to-metal contact at high temperatures. If, in addition, the surface film formed has a low shear strength, it will not only protect the surface, but it will also give a low coefficient of friction. A word of caution - although EP additives function by reacting with the surface, they must not be too reactive or chemical corrosion may be more troublesome than friction and wear.

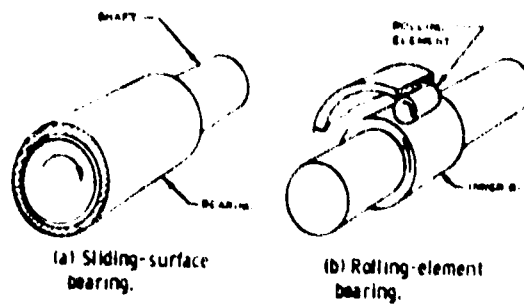


Figure 1. - Comparative bearing geometries.

CONFORMAL CONTACT
HYDRODYNAMIC LUBRICATION
(1880'S, REYNOLDS, TOWER)

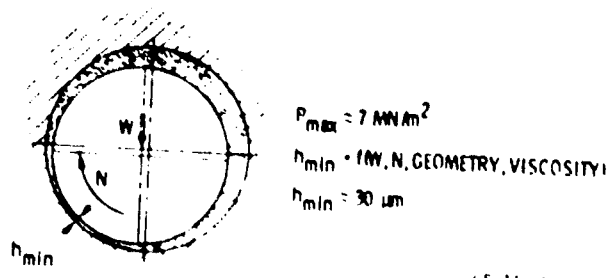


Figure 2. - Hydrodynamic lubrication.

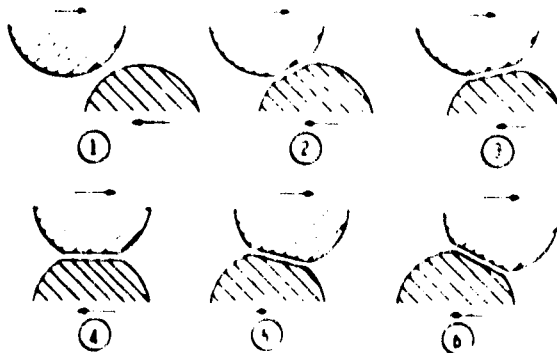


Figure 3. - Model illustrating contact interaction.

NONCONFORMAL CONTACT
ELASTO-HYDRODYNAMIC
LUBRICATION
LONDOS, PETRUSEVICH, GRUBINI

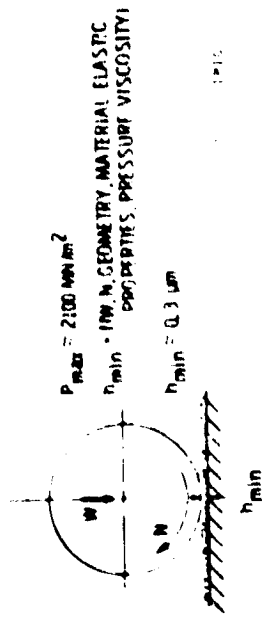


Figure 4 - Elastohydrodynamic lubrication

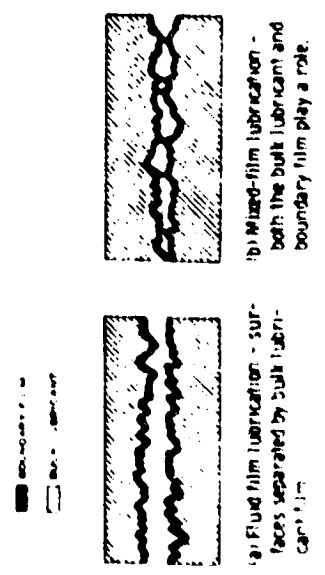


Figure 5 - Illustration of conditions existing in fluid film, mixed-film, and boundary lubrication regimes.

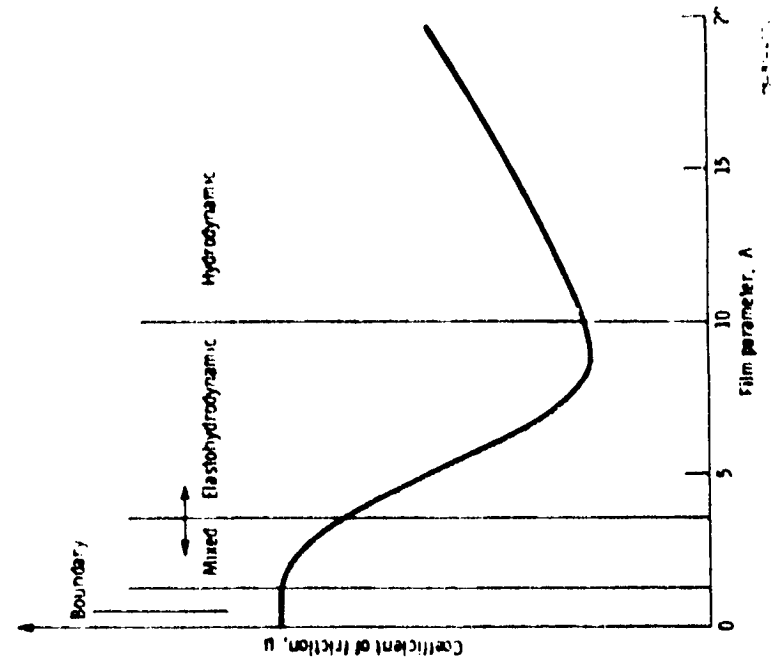


Figure 6 - Variation of coefficient of friction with film parameter.