

Chapter 2

Classification of Non-circular Journal Bearings

The chapter presents the reasons towards the development of non-circular journal-bearing profiles and classification of such profiles. The chapter also presents the basic mechanism of operation on which non-circular journal bearing works. In the last section of the chapter, the different regime of lubrication which may occur in various types of bearing has also been presented.

2.1 Circular Journal Bearing

The basic configuration of the circular journal bearing consists of a journal that rotates relative to the bearing which is also known as bush (Fig. 2.1). Efficient operation of such bearing requires the presence of a lubricant in the clearance space between the journal and the bush. In hydrodynamic lubrication, it is assumed that the fluid does not slip at the interface with the bearing and journal surface. There exists a velocity gradient over the thickness of the fluid, which depends upon the relative movement of bearing surfaces. There will be no pressure generation if the bearing surfaces are parallel or concentric, which means bearing could support any bearing load. However, if the surfaces are at a slight angle, the resulting lubrication fluid velocity gradients will be such that generation of pressure results from the wedging action of the bearing surfaces and on the same concept hydrodynamic lubrication depends.

The operation of hydrodynamic lubrication in journal bearings has been illustrated in Fig. 2.2. Before the rotation commences, i.e. at rest, the shaft rests on the bearing surface. When the journal starts to rotate, it will climb the bearing surface gradually as the speed is further increased; it will then force the lubricant into the wedge-shaped region. When more and more lubricant is forced into a wedge-shaped clearance space, the shaft moves up the bore until an equilibrium condition is reached, and now, the shaft is supported on a wedge of lubricant. The moving

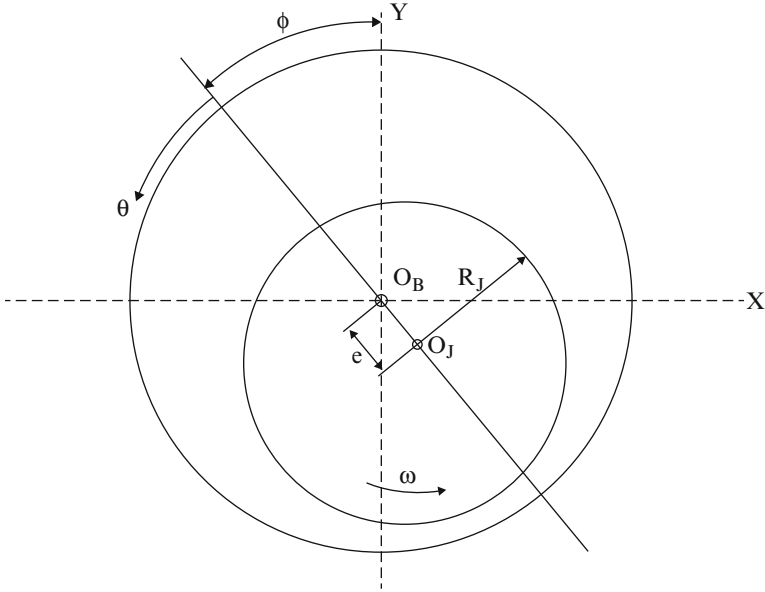


Fig. 2.1 Schematic of circular journal bearing

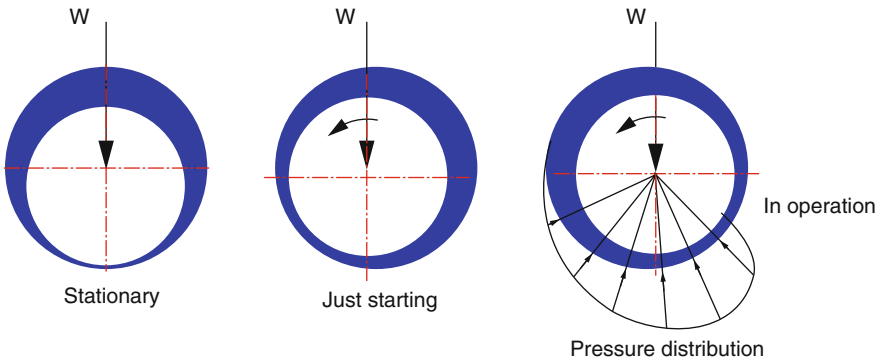


Fig. 2.2 Schematic of operation of hydrodynamic lubrication in journal bearing

surfaces are then held apart by the pressure generated within the fluid film. Journal bearings are designed such that, at normal operating conditions, the continuously generated fluid pressure supports the load with no contact between the bearing surfaces. This operating condition is known as thick film or fluid film lubrication and results in a very low operating friction.

On the other hand, if the lubricant film is insufficient between the relatively moving parts, it may lead to surface contact and the phenomenon is normally known as boundary lubrication. This occurs at rotation start-up, a slow speed operation or if the load is too heavy. This regime results in bearing wear and a relatively high

friction value. If a bearing is to be operated under boundary lubricating conditions, special lubricants must be used. Among hydrodynamic bearings, circular journal bearing is the most familiar and widely used bearing. Simple form of this bearing offers many advantages in its manufacturing as well as in its performance. However, the circular journal bearings operating at high speed encounter instability problems of whirl and whip. Instability may damage not only the bearings, but also the complete machine.

Moreover, these bearings usually experience a considerable variation in temperature due to viscous heat dissipation. This significantly affects the bearing performance as lubricant viscosity is a strong function of temperature. Furthermore, excessive rise in temperature can cause oxidation of the lubricant and, consequently, lead to failure of the bearing. Pressure also influences the viscosity of the lubricant to certain extent. Usually viscosity increases exponentially as the pressure increases, which in turn increases the load capacity of the journal bearing. Researchers have studied the behaviour of circular journal bearing by adopting various numerical approaches to simulate the performance in accordance with the real conditions.

2.2 Non-circular Journal Bearing

It has been reported in the literature that the temperature rise is quite high in circular journal bearings as they operate with single active oil film. This resulted in the development of bearings with non-circular profile, which operate with more than one active oil film. This feature accounts for the superior stiffness, damping, and reduced temperature in the oil film as compared to the circular journal bearings. Almost all the non-circular journal bearing geometries enhance the shaft stability, and under proper conditions, this will also reduce power losses and increase oil flow (as compared to an inscribed circular bearing), thus reducing the oil film temperature. Among non-circular journal bearings, offset-halves, elliptical, lemon bore, and three-lobe configurations are the most common.

The offset-halves journal bearing has been commonly used as a lobed bearing in which two lobes are obtained by orthogonally displacing the two halves of a cylindrical bearing. Offset-halves journal bearings (Fig. 2.3) find applications in gear boxes connecting turbine and generator for the power generation industries. They can also be used where primary directions of force, constant direction of rotation are found or high bearing load capacity, long service life, high stiffness, and damping values are the main features under concentration. If the unit is operated at full power, such requirements can also be met by lemon bore bearings. Lemon bore bearing is a variation of the plain bearing where bearing clearance is reduced in one direction and this bearing has a lower load-carrying capacity than the plain bearings, but is more susceptible to oil whirl at high speeds (Chauhan 2011). However, equipment must often be operated at lower performance levels, particularly in the times of reduced current needs. It is precisely under these conditions that lemon bore bearings may provide unstable conditions, which may require equipment shutdown to

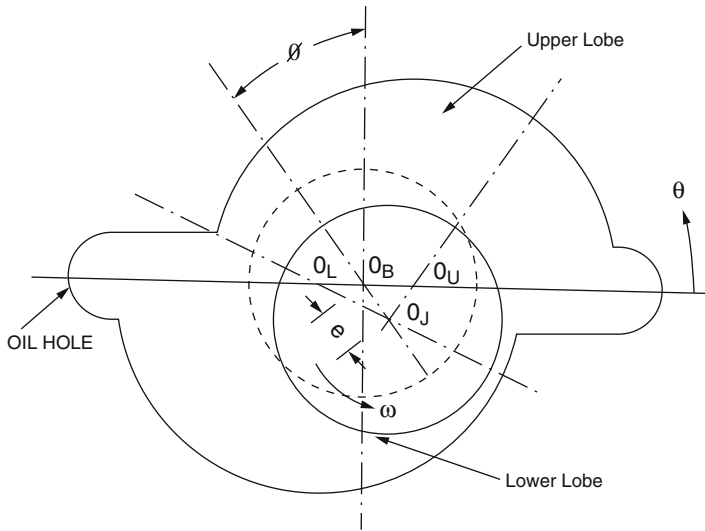


Fig. 2.3 Schematic diagram of offset-halves journal bearing

avoid damage. Offset-halves journal bearings have the durability equal to lemon bore bearings, while the bearings have good stiffness and damping properties which enables light loads while bearing runs at high speeds. The same bearing profile also offers the advantage of a long, minimally convergent inlet gap, which results in high load capacity for it. Also, the externally applied force and compression resulting from the horizontal displacement of bearing halves accurately holds the shaft in the lubricant film. This effect produces excellent characteristics such as elastic rigidity and damping by the oil film. Thus, the offset-halves journal bearings prove to be technical alternative to conventional lemon bore bearings (Chauhan and Sehgal 2008).

The elliptical journal bearings (Fig. 2.4) are commonly used in turbo-sets of small and medium ratings, steam turbines, and generators. The so-called elliptical journal bearing is actually not elliptic in cross-section but is usually made up of two circular arcs whose centers are displaced along a common vertical straight line from the centre of the bearing. The same bearing has also been referred as two-lobe journal bearing by some researchers. The bearing so produced has a large clearance in the horizontal or split direction and a smaller clearance in the vertical direction. Elliptical journal bearings are slightly more stable toward the oil whip than the cylindrical bearings. In addition to this, elliptical journal bearing runs cooler than a cylindrical bearing because of the larger horizontal clearance for the same vertical clearance. Some other non-circular journal bearing configurations; Three-lobe journal bearing (symmetrical and asymmetrical, Fig. 2.5), Elliptical journal bearing (profile is elliptic in cross-section, Fig. 2.6), and orthogonally displaced journal bearing (vertical offset, Fig. 2.7); have also been shown below.

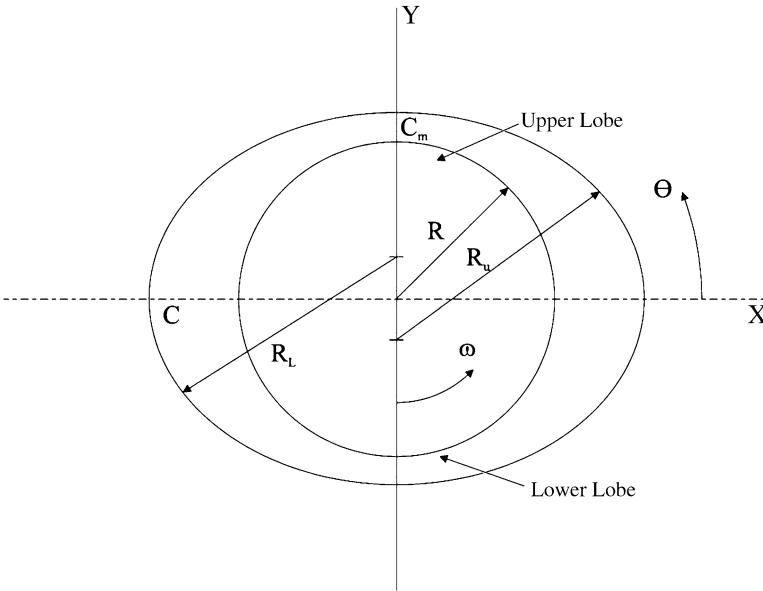
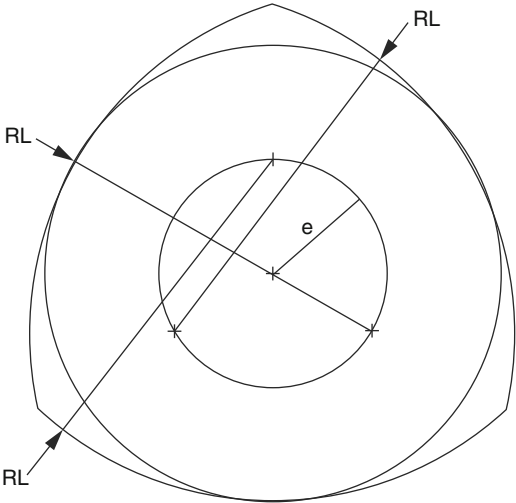


Fig. 2.4 Schematic diagram of elliptical journal bearing (two-lobe)

Fig. 2.5 Symmetrical three-lobe bearing



2.3 Methods of Analysis

In earlier works, the bearing performance parameters have been computed by solving the Reynolds equation only. Over the years, many researchers have proposed number of mathematical models. A more realistic thermohydrodynamic

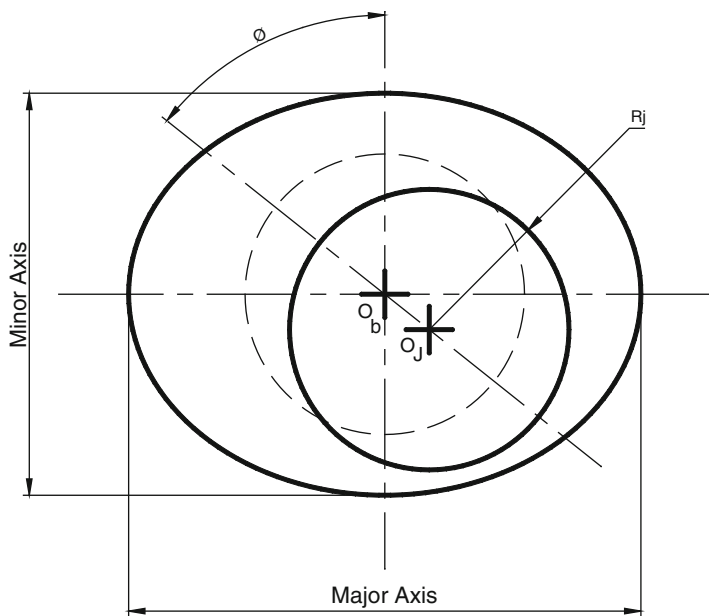


Fig. 2.6 Truly elliptical journal bearing

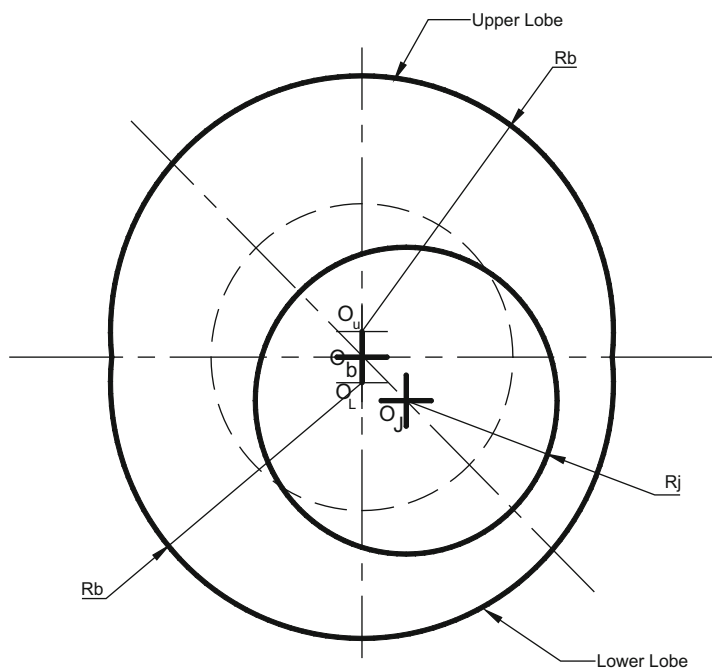


Fig. 2.7 Orthogonally displaced journal bearing

(*THD*) model for bearing analysis has been developed which treats the viscosity as a function of both the temperature and pressure. Moreover, it also considers the variation of temperature across the film thickness and through the bounding solids (housing and Journal). The thermohydrodynamic model also presents coupled solutions of governing equations by incorporating appropriate boundary conditions and considering the heat conduction across the bearing surfaces. Even the importance of *THD* studies in hydrodynamic bearings can be justified by looking at the large volumes of research papers that are being published by researchers using various models.

The theoretical investigations have been carried out into the performance of hydrodynamic journal bearing by adopting various methods, which are classified in two categories as (Kumar 2007):

1. Methods which comprise a full numerical treatment of temperature variation across the lubrication film thickness in energy equation using Finite Difference Method (FDM) or Finite Element Method (FEM).
2. Methods which incorporate polynomial approximation to evaluate the transverse temperature variation in the lubrication film thickness.

Both approaches mentioned can be used for the analysis of hydrodynamic bearings and have certain merits. The first approach is relatively accurate at the expense of computational speed and time, whereas the second is relatively fast at the expense of accuracy.

However, in recent years, the analysis works for the journal bearings have been carried out using various available simulation softwares like COMSOL, ANSYS, etc. The simulation softwares carry out the analysis in real conditions and thus the results obtained are littler higher than those obtained by above-mentioned two methods of analysis.

2.4 Regimes of Lubrication

From the ages, it is a known fact that lubrication reduces the friction between sliding surfaces by filling the surface cavities and making the surfaces smoother and such action of lubricant is known as lubrication. In other words, lubrication is a process by which the friction and wear rates in a moving contact are reduced by using suitable lubricant. Lubricant is a substance introduced between relatively moving parts to reduce friction ($\mu = 0.1-0.0001$) and wear rate. Most lubricants are some type of fluid such as mineral and synthetic oils etc.; however, there are some solid lubricants, e.g. gold, silver, polymers, etc. Almost every relatively moving component in an assembly requires lubricant. Liquid lubricants can be brought into a converging contact due to rotation and pressure generation between the bodies; they can lower the temperature of interacting surfaces and remove contaminants. Liquid lubricants can be mixed with other chemicals to provide additional properties (i.e. corrosion resistance, surface active layers, etc.).

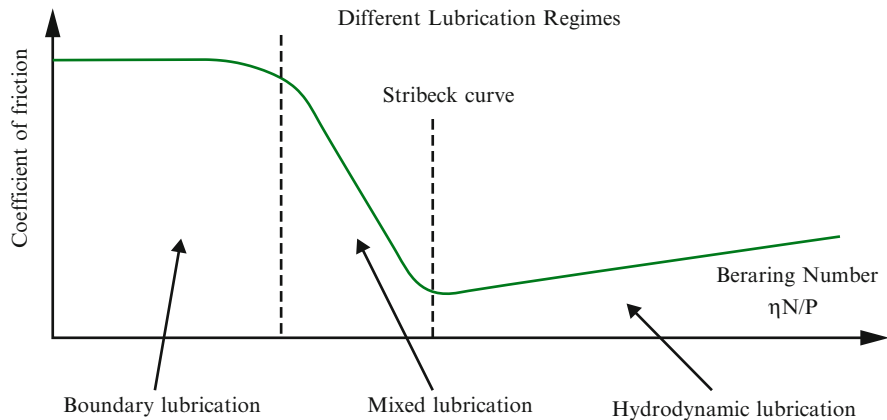


Fig. 2.8 Different regimes of lubrication

Four different forms of lubrication can be identified for self-pressure-generating lubricated contacts: (1) Hydrodynamic, (2) Elastohydrodynamic, (3) Partial or mixed, (4) Boundary. Different regimes of lubrication can be shown (Fig. 2.8) using Stribeck's curve (Stachowiak and Batchelor 1993) available in most literature dealing lubrication.

The Stribeck's curve presented is for a hypothetical fluid lubricated bearing system presents friction coefficient as a function of sliding speed, fluid viscosity and unit load. Three lubrication mechanisms; boundary, mixed, and hydrodynamic lubrications; have been marked on this plot. This plot defines the stability of lubrication. Say the operator is operating to the right of minimum friction and an increase in lubricant temperature happens which causes decrease in viscosity and hence a smaller value of bearing number. The coefficient of friction decreases, not as much as heat is generated in shearing the lubricant, and consequently lubricant temperature drops. Thus, the region to the right of the minimum defines stable lubrication because variations in this side are self-correcting. To the left of line, a decrease in viscosity would increase the friction. As temperature rise would increase, the viscosity would be reduced still more. The result would be compounded and the region represents unstable lubrication and load sharing.

2.4.1 *Hydrodynamic or Full Film Lubrication*

Hydrodynamic or full film lubrication is the condition when the load-carrying surfaces are separated by a relatively thick film of lubricant. This is a stable regime of lubrication and metal-to-metal contact does not occur during the steady state operation of the bearing. The lubricant pressure is self-generated by the moving surfaces drawing the lubricant into the wedge formed by the bounding surfaces at a high enough velocity to generate the pressure to completely separate the surfaces

and support the applied load. The coefficient of friction is lower than with boundary-layer lubrication. In hydrodynamic lubrication, the following characteristics can be outlined:

1. With increase in load, the fluid film thickness at the point of minimum thickness decreases.
2. In this lubrication, the pressure within the fluid mass increases when the applied load decreases the film thickness.
3. Pressure within the fluid mass is highest at some point approaching minimum clearance and lowest at the point of maximum clearance.
4. Viscosity of the oil increases as the pressure increases. Also, film thickness increases with the use of more viscous oils.
5. Fluid friction increases as the viscosity of the lubricant becomes high.

2.4.2 Elastohydrodynamic Lubrication

Elastohydrodynamic lubrication is the condition that occurs when a lubricant is introduced between surfaces that are in rolling contact, such as ball and rolling element bearings. In this lubrication regime, the load is sufficiently high enough for the surfaces to elastically deform during the hydrodynamic action.

2.4.3 Partial or Mixed Lubrication

Partial or mixed lubrication regime deals with the condition when the speed is low, the load is high, or the temperature is sufficiently large to significantly reduce lubricant viscosity—when any of these conditions occur, the tallest asperities of the bounding surfaces will protrude through the film and occasionally come in contact.

2.4.4 Boundary Lubrication

Boundary Lubrication term was coined by English Biologist Sir Hardy in 1922. He quoted that “Very thin adsorbed layers, about 10 Å thick, were sufficient to cause two glass surfaces to slide over each other”. The layer of lubricant separates sliding surfaces, i.e. no direct contact of the sliding parts. This situation is required for many applications, such as steel gears, piston-rings, and metal-working tools, to prevent severe wear or high coefficients of friction and seizure. The physical and chemical properties of thin surface films are of significant importance, while the properties of the bulk fluid lubricant are insignificant.

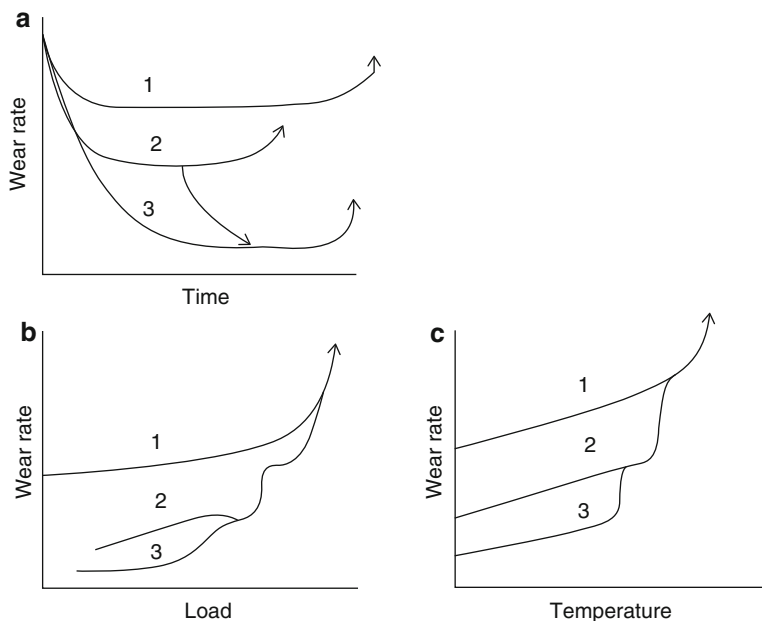


Fig. 2.9 Comparative study among dry (1), boundary (2), and hydrodynamic (3) lubrication mechanisms (a) Wear rate vs time, (b) Wear rate vs load, (c) Wear rate vs temperature ([E-Learning courses from IITs/IISC NEPTel](#))

2.4.5 Mechanisms of Boundary Lubrication

Physisorption: is the classical form of adsorption. Molecules of adsorbate may attach or detach from a surface without any irreversible changes to the surface or the adsorbate.

Chemisorption: It is an irreversible or partially irreversible form of adsorption which involves some degree of chemical bonding between adsorbate and substance.

To understand lubrication in all respect, a comparative study among dry, boundary lubricated, and fluid film lubricated has been discussed here and is shown in Fig. 2.9 [E-Learning courses from IITs/IISC NEPTel](#). From the Fig. 2.9, one can observe that as the time increases, wear rate decreases and remain constant up to certain time, then increases for dry lubrication. For boundary lubrication, the wear rate decreases up to certain time, then decreases or increases depending on the improvement in surface smoothness. If surface smoothness occurs, boundary lubrication turns out to be fluid film lubrication which means wear rate decreases, otherwise wear rate increases. For fluid film lubrication, wear rate drastically decreases, then remain constant up to certain limit and then increases. Also, for dry lubrication, as the load increases wear rate increases. For boundary lubrication, wear rate increases and the rate of increase in wear rate is lesser than the dry lubrication. For fluid film lubrication also, wear rate increases, but rate of increase in wear rate is

initially lower. Same process does occur with increase in the temperature. It should also be noticed that the wear rate increases for all three lubrication mechanisms with increase in temperature. One of the common elements in all machines is spur gear. Spur gear generally operates under boundary lubrication regime.

2.4.6 Hydrostatic Lubrication

In this mechanism of lubrication, the bearing surfaces are fully separated by a lubricating film of liquid or gas. The medium of lubrication is forced between the surfaces by an external source of pressure. A complete fluid film is present even at zero sliding speed as long as a continuous supply of pressurized lubricant is maintained. There is complete absence of sticking friction. Hydrostatic bearings can support very large masses and allow them to be moved from their stationary with the use of minimal force.

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