Machine Design II

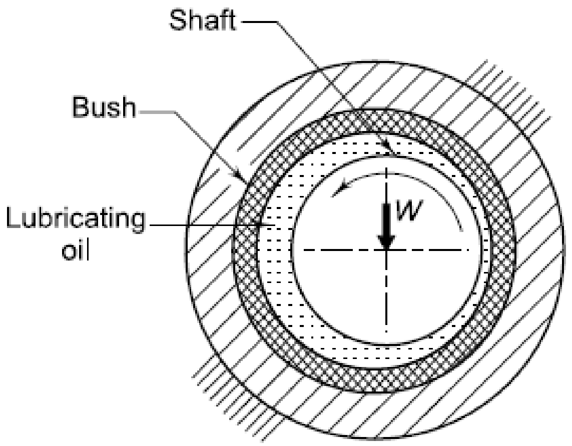
JOURNAL BEARINGS

Bearings

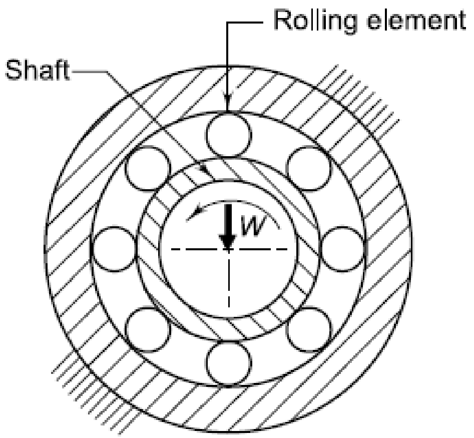
The purpose of a bearing is to support a load, typically applied to a shaft, while allowing relative motion between two elements of a machine.

The term ‘bearing’ typically refers to contacting surfaces through which a load is transmitted. Bearings may roll or slide or do both simultaneously.

The two general classes of bearings are journal bearings, also known as **sliding or plain surface bearings**, and **rolling element bearings**, sometimes also called ball-bearings.



(a) Sliding contact bearing



(b) Rolling contact bearing

Typical Bearing applications

Sliding contact bearings are used in the following applications:

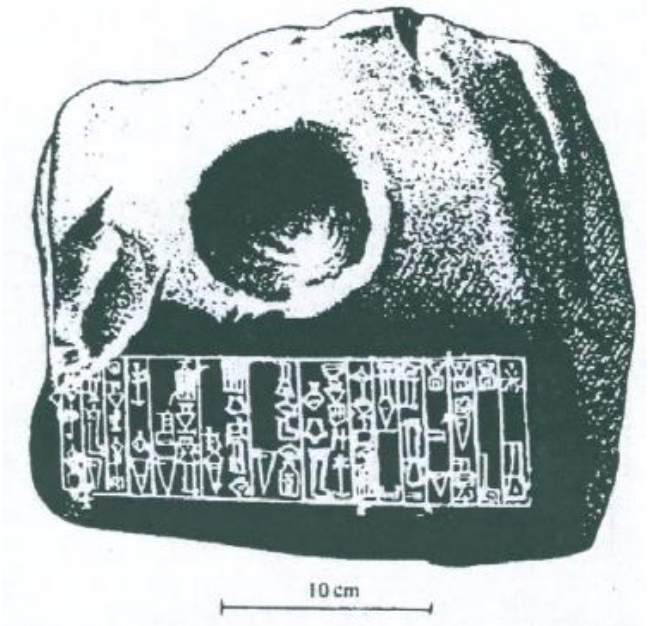
(i) crankshaft bearings in petrol and diesel engines;
(ii) centrifugal pumps;
(iii) large size electric motors;
(iv) steam and gas turbines; and
(v) concrete mixers, rope conveyors and marine installations.

Rolling contact bearings are used in the following applications:

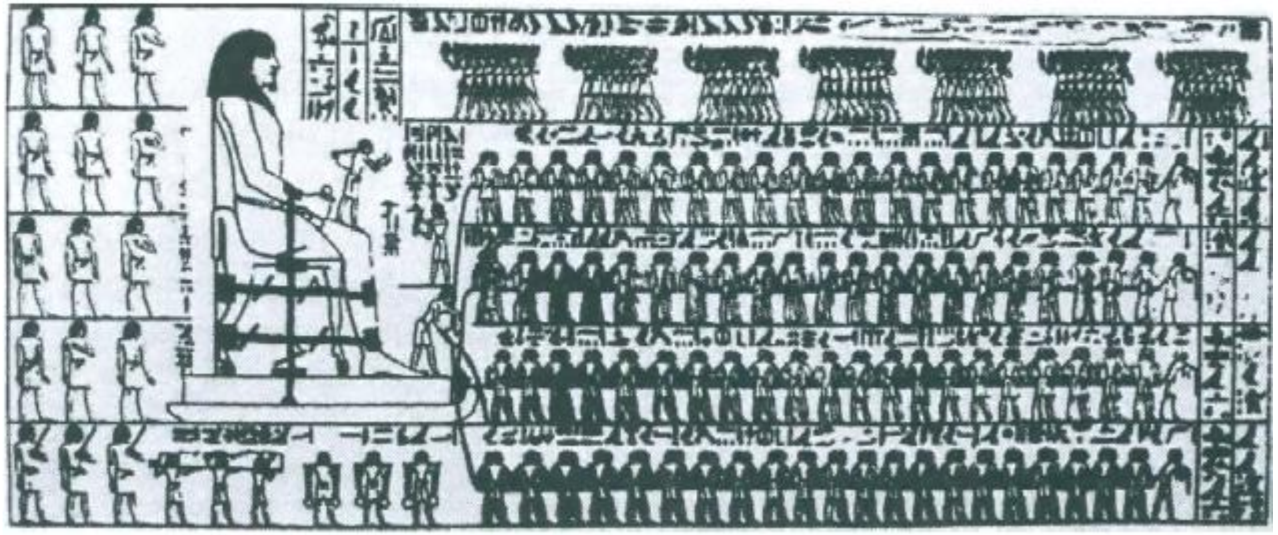
(i) machine tool spindles;
(ii) automobile front and rear axles;
(iii) gear boxes;
(iv) small size electric motors; and
(v) rope sheaves, crane hooks and hoisting drums.

Tribology from antiquity to our times

The name Tribology was created in 1967 and comes from the Greek word Tribein: to rub, and Logos: speech, study or science. It includes the study of lubrication, friction and wear of machine elements.



Lower pivot of door made of stone, dated 2500 B.C., found in Mesopotamia



Transport of a statue, tomb of Tchuti Hetep, El-Bersheh, Egypt, 1800 B.C

Lubrication

Lubrication is the science of reducing friction by application of a suitable substance called lubricant, between the rubbing surfaces of bodies having relative motion.

(i) Liquid lubricants like mineral or vegetable oils
(ii) Semi-solid lubricants like grease
(iii) Solid lubricants like graphite or molybdenum disulphide

(i) to reduce friction
(ii) to reduce or prevent wear
(iii) to carry away heat generated due to friction
(iv) to protect the journal and the bearing from corrosion

Thick film lubrication

Thick film lubrication describes a condition of lubrication, where two surfaces of the bearing in relative motion are completely separated by a film of fluid.

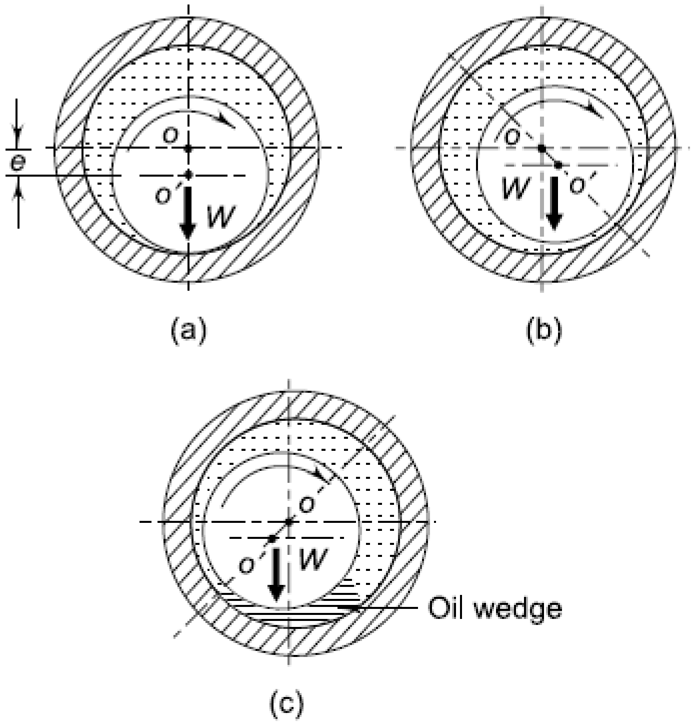
Since there is no contact between the surfaces, the properties of surface, like surface finish, have little or no influence on the performance of the bearing.

The resistance to relative motion arises from the viscous resistance of the fluid. Therefore, the viscosity of the lubricant affects the performance of the bearing.

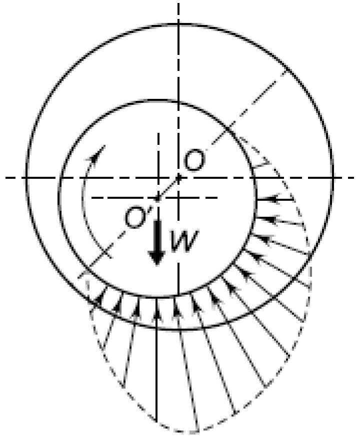
Thick film lubrication is further divided into two groups: hydrodynamic and hydrostatic lubrication.

Hydrodynamic lubrication

Hydrodynamic lubrication is defined as a system of lubrication in which the load-supporting fluid film is created by the shape and relative motion of the sliding surfaces.



Hydrodynamic Lubrication (a) Journal at Rest (b) Journal Starts to Rotate (c) Journal at Full Speed



Pressure Distribution in Hydrodynamic Bearing

A **journal bearing** is a sliding contact bearing working on hydrodynamic lubrication and which supports the load in radial direction.

The portion of the shaft inside the bearing is called **journal** and hence the name 'journal' bearing.

Hydrodynamic lubrication

Hydrodynamic Lubrication

In a hydrodynamically lubricated bearing, continuously supplied lubricant is fed by the rotating journal into a wedged-shaped region, lifting the rotating journal off the stationary bearing.

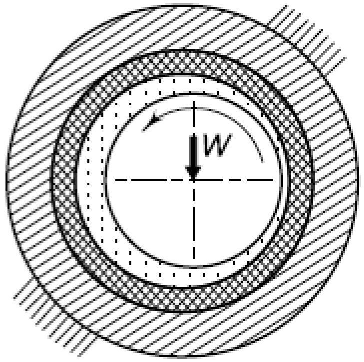
As the journal and bearing are completely separated, there is no metal-to-metal contact, resulting comparably low friction.

Hydrodynamically lubricated bearings are usually for high rotating speeds with impact and momentary overloads.

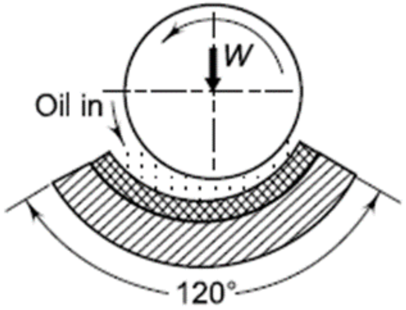
Hydrodynamic lubrication requires three things.

1. Relative motion of the surfaces to be separated.
2. “Wedging action,” as provided by the shaft eccentricity.
3. The presence of a suitable fluid.

Hydrodynamic lubrication



(a) Full bearing

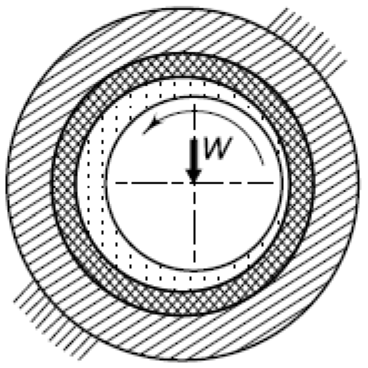


(b) Partial bearing

Hydrodynamic lubrication

Full journal bearing

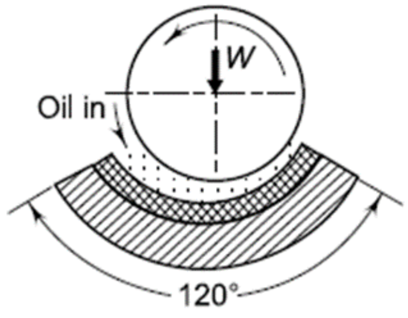
- the angle of contact of the bushing with the journal is 360°.
- can take loads in any radial direction.
- Most of the bearings used in industrial applications are full journal bearings.



(a) Full bearing

Partial bearings

- the angle of contact is always less than 180°. Most of them have 120° angle of contact.
- Can take loads in only one radial direction.
- Used in railroad-cars.



(b) Partial bearing

(i) Partial bearing is simple in construction.
(ii) It is easy to supply lubricating oil to the partial bearing.
(iii) The frictional loss and hence temperature rise is low in partial bearing.

Journal bearing

Clearance bearing

- radius of the journal is less than the radius of the bearing.
- there is a clearance space between the journal and the bearing
- most of the journal bearings are of this type.

Fitted bearing

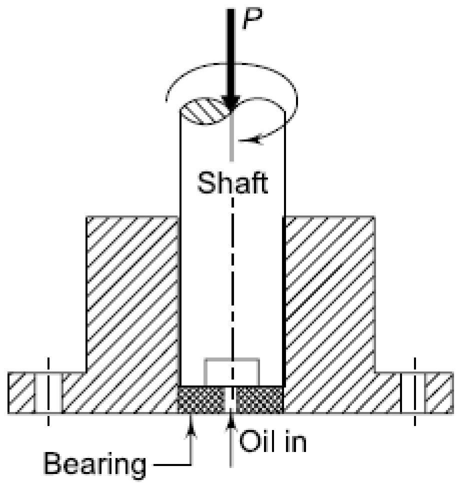
- radius of the journal and the bearing are equal.
- it is a partial bearing and the journal must run eccentric with respect to the bearing in order to provide space for lubricating oil.

Thrust Bearings

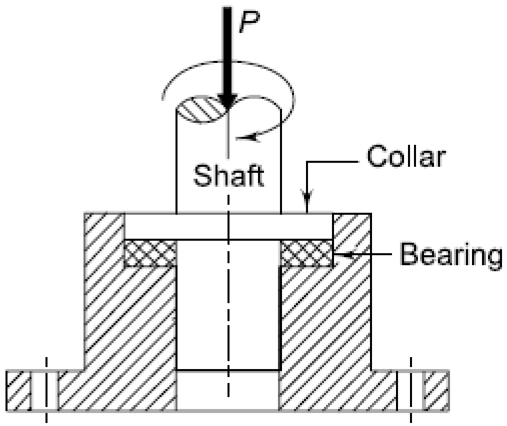
Thrust bearings are generally flat and carry axial loads parallel to the shaft axis.

The **footstep bearing** or simply ‘step’ bearing is a thrust bearing in which the end of the shaft is in contact with the bearing surface.

The **collar bearing** is a thrust bearing in which a collar integral with the shaft is in contact with the bearing surface. In this case, the shaft continues through the bearing. The shaft can be with single collar or can be with multiple collars.



(a) Footstep bearing



(b) Collar bearing

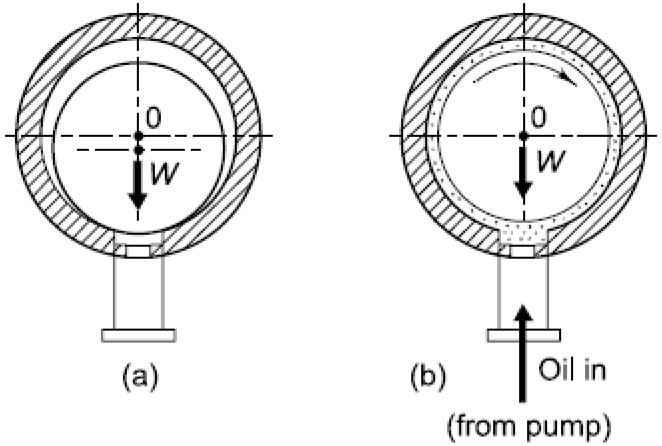
Hydrostatic lubrication

It is defined as a system of lubrication in which the load supporting fluid film, separating the two surfaces is created by an external source, like a pump, supplying sufficient fluid under pressure.

Since the lubricant is supplied under pressure, this type of bearing is called externally pressurised bearing.

Initially, the shaft rests on the bearing surface. As the pump starts, high pressure fluid is admitted in the clearance space, forcing the surfaces of the bearing and journal to separate out.

Hydrostatic bearings are used on vertical turbo generators, centrifuges and ball mills.



Hydrostatic Lubrication: (a) Journal at Rest (b) Journal at Full Speed

Hydrostatic bearings vs Hydrodynamic bearings

Compared with hydrostatic bearings, hydrodynamic bearings are simple in construction, easy to maintain and lower in initial as well as maintenance cost.

- One major disadvantage of hydrodynamic bearings is that a certain minimum speed is required to generate a full fluid film that completely separates the sliding surfaces.
- Below that speed, there is mixed or boundary lubrication, subjecting the bearing to excessive friction and wear at low speed, such as during starting and stopping of journal rotation.
- In particular, hydrodynamic bearings undergo severe wear during start-up, when they accelerate from zero speed, because static friction is higher than dynamic friction.

Hydrostatic bearings, although costly, offer the following advantages: (i) high load carrying capacity even at low speeds; (ii) no starting friction; (iii) no rubbing action at any operating speed or load. (iv) High stiffness to radial displacement making them suitable for precision machines.

Questions

How does the lubricating fluid does not spill out during operation in partial journal bearing? In partial bearing is there any possibility that shaft coming out of bearings? Force balance in partial bearing if the radial load application vary?

How to classify which kind of bearings should be used on different load?

Wedging action is not clear?

Would uniform pressure distribution in hydrostatic bearings as an advantage?

Do bushes act the same way as bearings?

Is the pressure developed at the contact is due to surface tension?

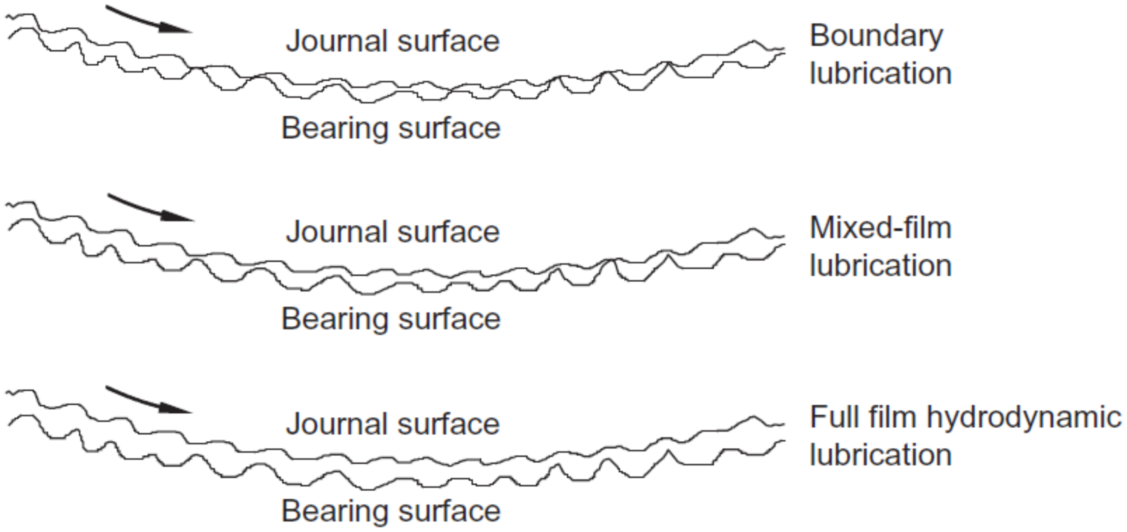
Are there chances to sliding and rolling to happen together?

How are we preventing the lubricant from escaping along the axial direction because of high pressure?

Thin film lubrication or boundary lubrication

Thin film lubrication, which is also called boundary lubrication, is defined as a condition of lubrication where the lubricant film is relatively thin and there is partial metal to metal contact.

Boundary-lubricated bearings are used successfully in light service, low speed or unimportant applications, such as electric fans, office machinery and home appliances.

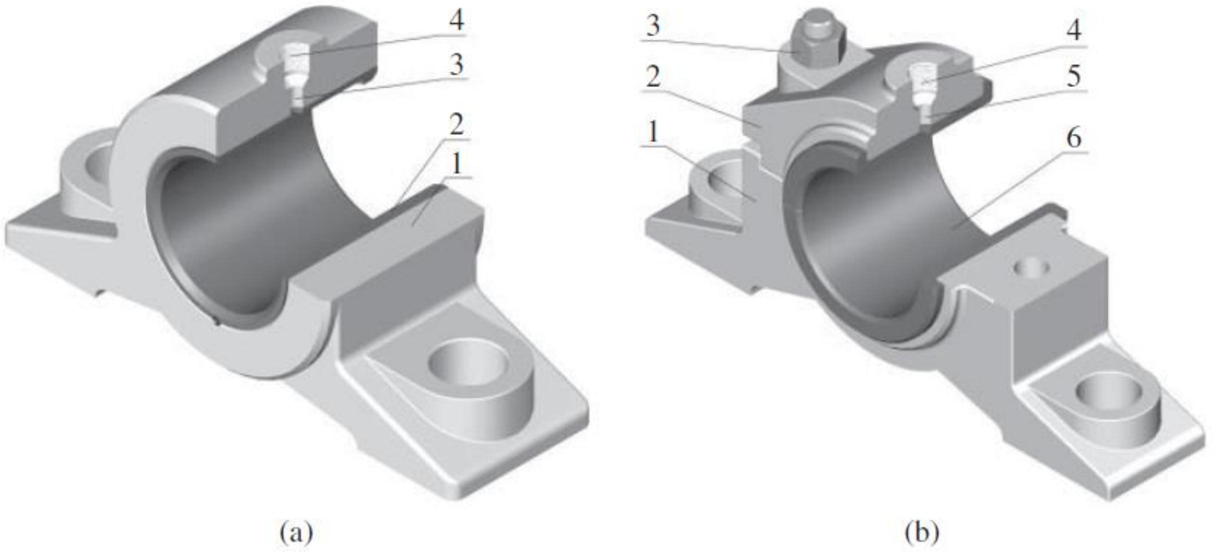


Sliding bearings – Solid and Split types

A sliding bearing normally consists of a housing, a liner or insert supporting shafts, and lubricating and protective devices.

Solid bearings have simple structure, high rigidity, and are easy to manufacture at low cost. However, they present difficulties for axial assembly of heavy or large diameter shafts.

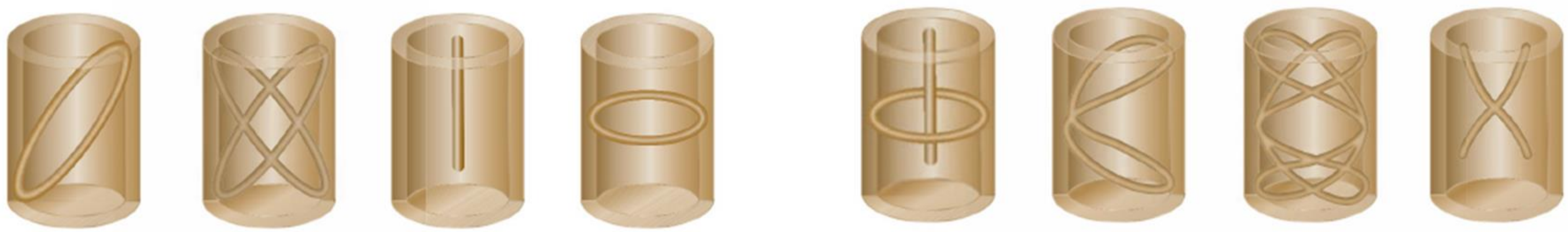
Split bearings, on the other hand, facilitate such assembly and allow adjustment of bearing clearance. They are especially suitable for supporting heavy elements like crankshafts.

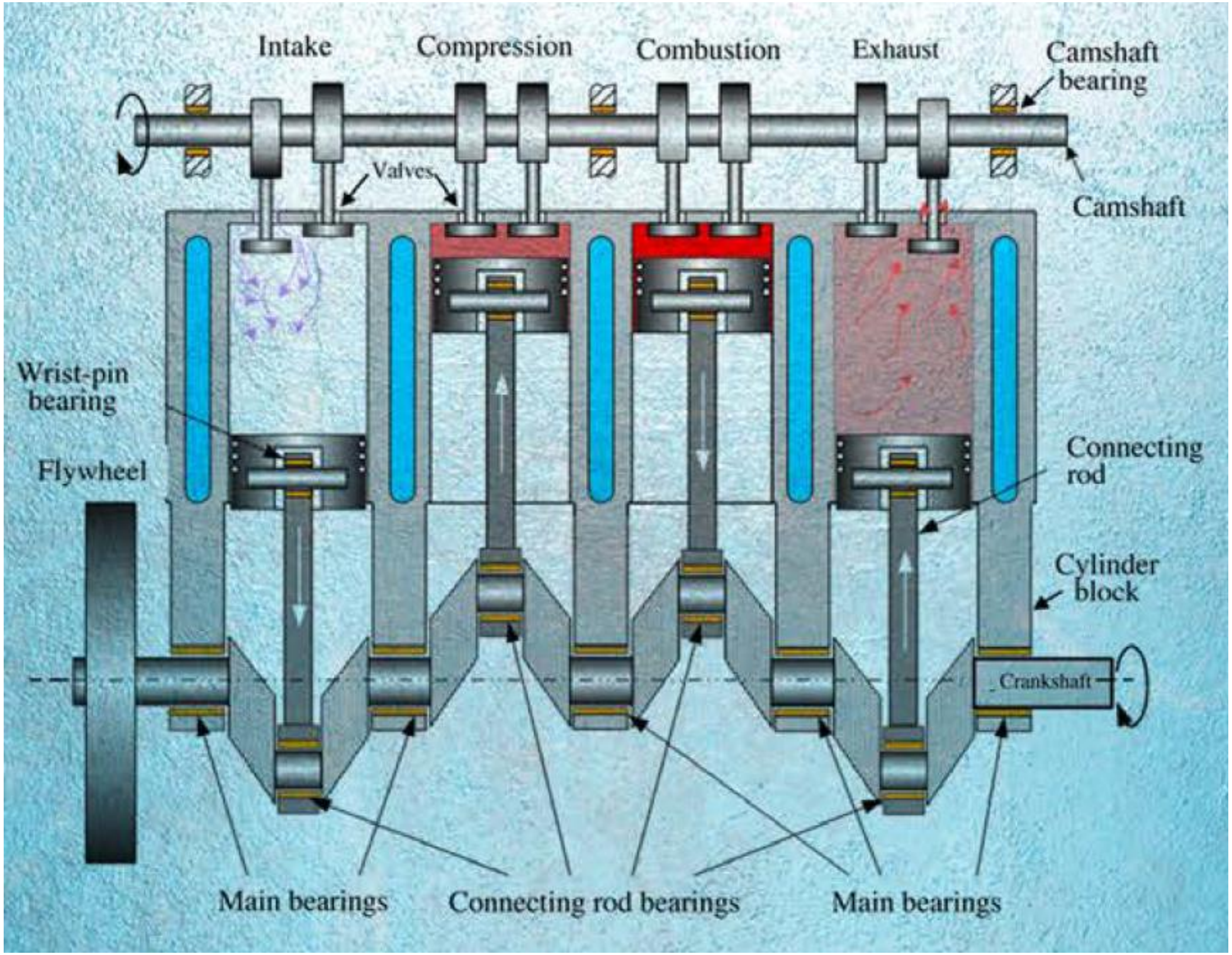


Structures of sliding bearings:
(a) 1 housing, 2 bushing, 3 oil hole and 4 screw;
(b) 1 housing, 2 housing cover, 3 stud, 4 screw, 5 oil hole and 6 liner or bushing.

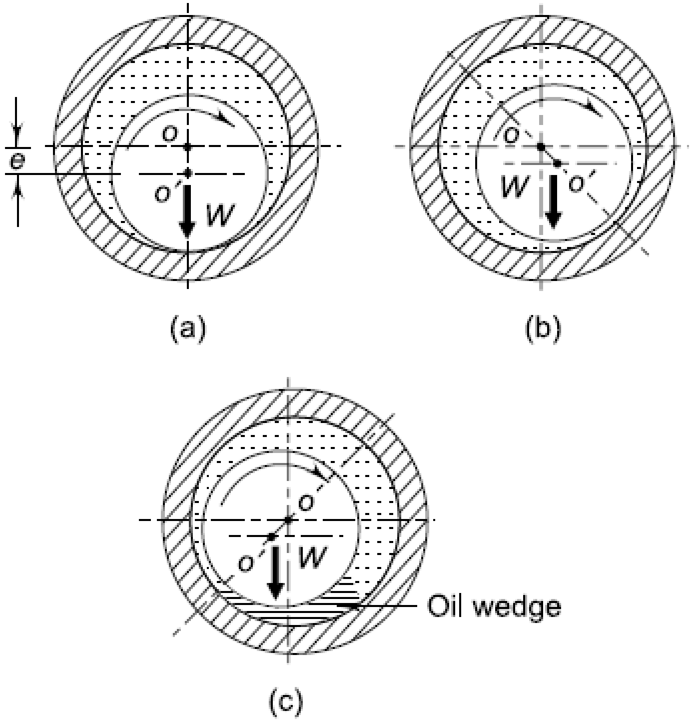
Sliding bearings

- Lubricant oil is usually delivered through the oil hole, and distributed over the width of bearing by grooves cut in the bushings. Oil holes normally locate at the centre of bushing in the low-pressure region .
- Grooves should not be cut in the load carrying region and should terminate before the end of bearing to avoid pressure drop and side leakage.




Intake
Compression
Combustion
Exhaust
Camshaft bearing
Valves
Camshaft
Wrist-pin bearing
Flywheel
Connecting rod
Cylinder block
Crankshaft
Main bearings
Connecting rod bearings
Main bearings

Hydrodynamic lubrication



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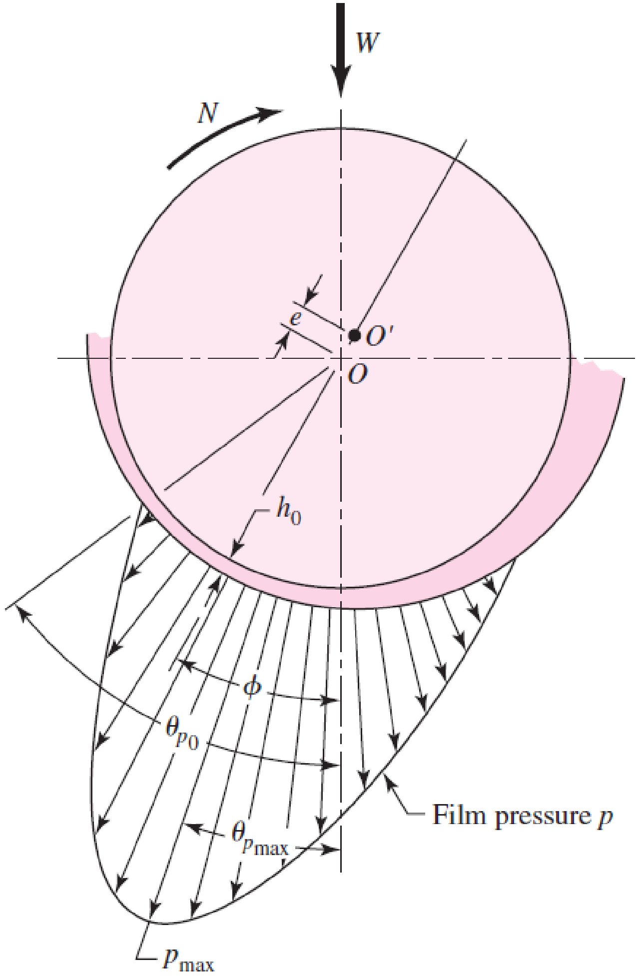
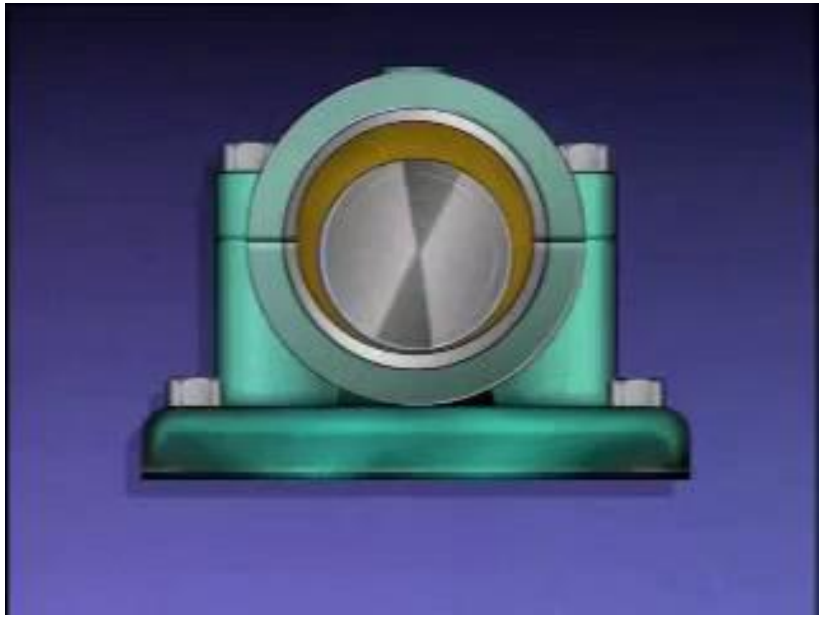
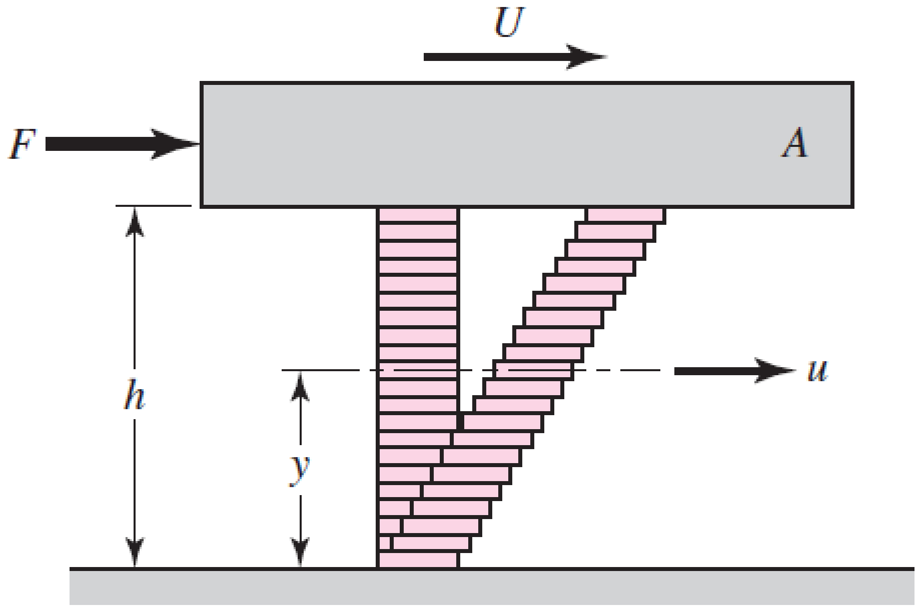




Viscosity

A fluid film of thickness h is sheared between two plates one stationary and other moving at a velocity U, assuming that there is no slip condition, means the fluid and the plate velocities are same.

Newton's viscous effect states that the shear stress in the fluid is proportional to the rate of change of velocity with respect to y.



$$\tau = Z\frac{du}{dy}$$

Z is absolute viscosity or dynamic viscosity in Ns/m^2 (Pa S)

The CGS unit is the poise (P, or $g \cdot cm^{-1} \cdot s^{-1}$ = 0.1 Pa·s), named after Jean Léonard Marie Poiseuille.
1 poise (P) = 100 centi poise (cP)

Viscosity

Kinematic viscosity (Z_k) is the ratio between the dynamic viscosity and the density of a fluid.

Kinematic viscosity has SI units of m^2/s.

The physical unit for kinematic viscosity is the stokes (St), named after George Stokes.

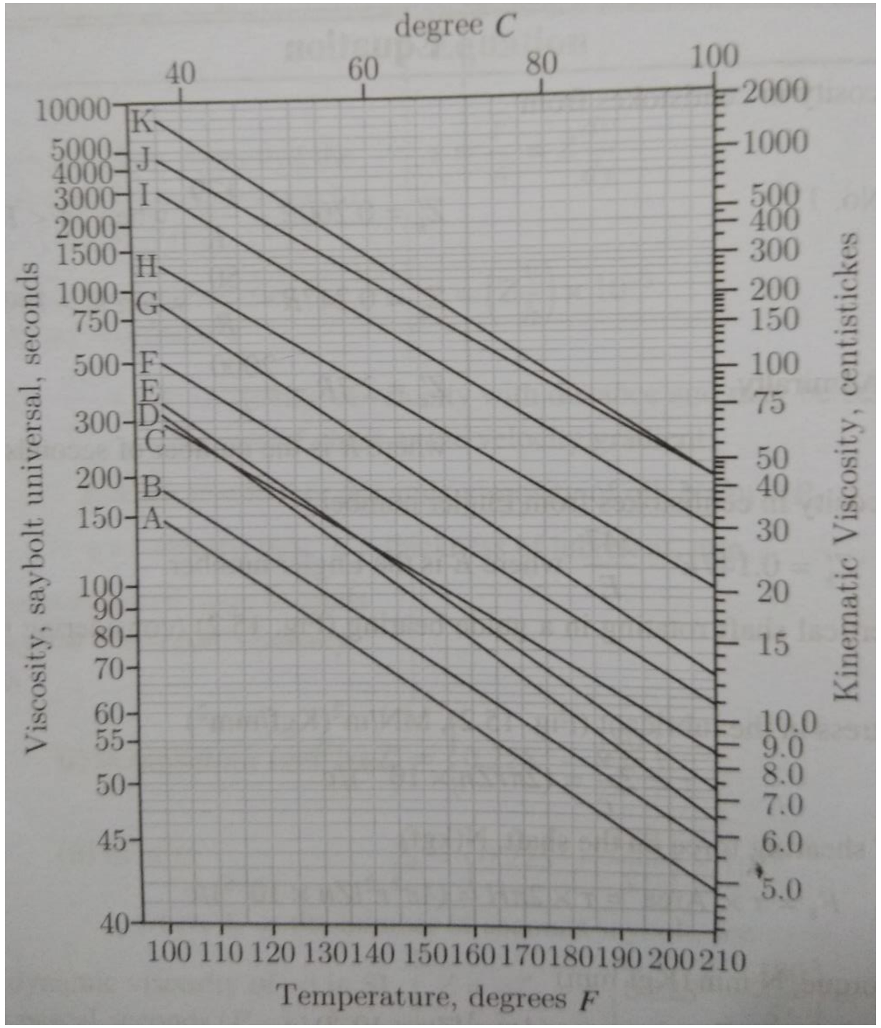
1 stokes (St)= 100 centistokes (cSt) = 1 cm^2/s = 0.0001 m^2/s.

Kinematic viscosity is measured by Saybolt Universal Viscometer in Saybolt Seconds (t)

Effect of temperature on viscosity

Table 15.1 *Specific Gravity of Oils at 15°C (Fig. 15.3)*

No.	Oil Characteristic	ρ_{15}
A	Turbine oil, ring-oiled bearing	0.8877
B	Turbine oil, ring-oiled bearing, SAE 10	0.8894
C	All-year automobile oil, SAE 20	0.9036
D	Ring-oiled bearing oil, high-speed machinery	0.9346
E	Automobile oil, SAE 20	0.9254
F	Automobile oil, SAE 30	0.9263
G	Automobile oil, SAE 40, medium-speed machinery	0.9275
H	Airplane oil 100, SAE 60	0.8927
I	Transmission oil, SAE 110, spur and bevel gears	0.9328
J	Gear oil, show-speed worm gears	0.9153
K	Transmission oil, SAE 160, slow-speed gears	0.9365

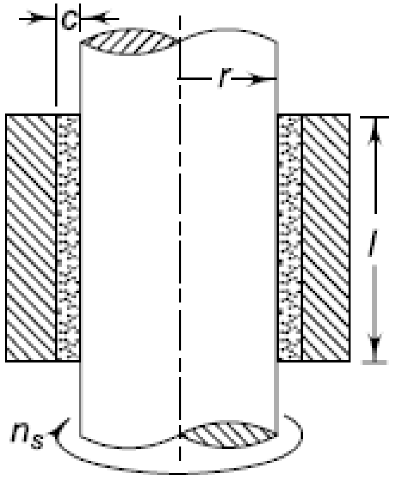


Design Data Handbook (4th edition)
K. Mahadevan and K. Mahaveera Reddy

The viscous resistance of lubricating oil is due to intermolecular forces. As the temperature increases, the oil expands and the molecules move further apart, decreasing the intermolecular force in consequence.

Petroff’s Equation

- The Petroff equation gives the coefficient of friction in journal bearings.
- It assumes that the shaft is concentric with the bearing and the bearing is subjected to light load. In practice, such conditions do not exist.
- However, Petroff’s equation is important because it defines the group of dimensionless parameters that govern the frictional properties of the bearing.



A vertical shaft rotating in the bearing is shown in the figure.

The following notations are used:

r = radius of the journal (mm)
l = length of the bearing (mm)
c = radial clearance (mm)
n_s = journal speed (rev/sec)

Petroff's Equation

The velocity at the surface of the journal is given by $U = (2\pi r)\, n_s$

According to Newton's law of viscosity,

$$P = \mu A\left(\frac{U}{h}\right)$$

Applying the above equation for viscous flow through the annular portion between the journal and the bearing in the circumferential direction,

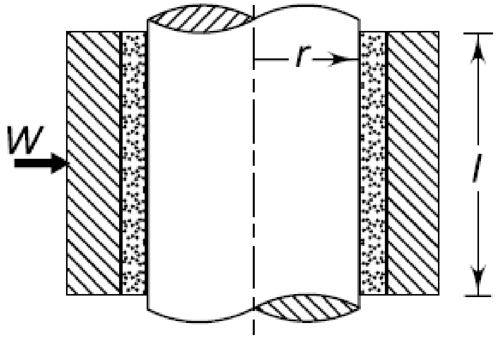
P = tangential frictional force
A = area of journal surface = $(2\pi r)l$
U = surface velocity = $(2\pi r)n_s$
h = distance between journal and bearing surfaces = c

$$P = \mu(2\pi rl)(2\pi rn_s)\left(\frac{1}{c}\right) = \frac{4\pi^2 r^2 l\mu n_s}{c}$$

The frictional torque is given by,

$$(M_t)_f = Pr = \frac{4\pi^2 r^3 l\mu n_s}{c}$$

Petroff's Equation



Let us consider a radial force (W), acting on the bearing as shown in figure. The unit bearing pressure (p) acting on the bearing is given by

$$p = \frac{W}{\text{projected area of bearing}} = \frac{W}{(2rl)}$$

$$W = 2\,prl$$

The frictional force will be $(f\,W)$ and frictional torque will be $(f\,Wr)$. Therefore,

$$(M_t)_f = f\,Wr = f(2prl)r = f(2pr^2l)$$

where f is the coefficient of friction.

$$\frac{4\pi^2 r^3 l \mu n_s}{c} = f(2\,pr^2\,l)$$

$$f = (2\pi^2)\left(\frac{r}{c}\right)\left(\frac{\mu n_s}{p}\right) \quad \text{(Petroff's equation)}$$

Petroff's equation indicates that there are **two important dimensionless parameters** that govern the coefficient of friction and other frictional properties like frictional torque, frictional power loss and temperature rise in the bearing.

$$f = (2\pi^2 \times 10^{-6})\left(\frac{Zn}{p}\right)\left(\frac{r}{c}\right)$$

Petroff's equation in databook

Questions

Why to equate frictional torque and torque from equation? Explain once more

In case of journal bearing, oil hoes are kept region of low pressure. What will do in case of operating shaft in both direction?

Questions

While calculating bearing pressure, entire system is closed and filled with lubricant.
Pressure should remain constant at all point they why we consider projection of journal as area instead of total surface area?

How can frictional torque and lubrication providing torque? Can you explain the Petroff's equation?

Can you share the ppt?

Questions

Do we have a method to evaluate the friction factor with changing clearance, which is the actual conditions?

Petroff's equation limitations

Why max pressure and min clearance points do not coincide in journal bearing?

Why is final expression in terms of p which actually defined in terms of W? Because of W is what we can measure directly. Why did we bring P into picture?

Mckee's Investigation – Stribeck curve

Stribeck curve is a plot showing the frictional characteristics of a liquid lubricant over conditions usually spanning the Boundary, Mixed and Hydrodynamic regimes.

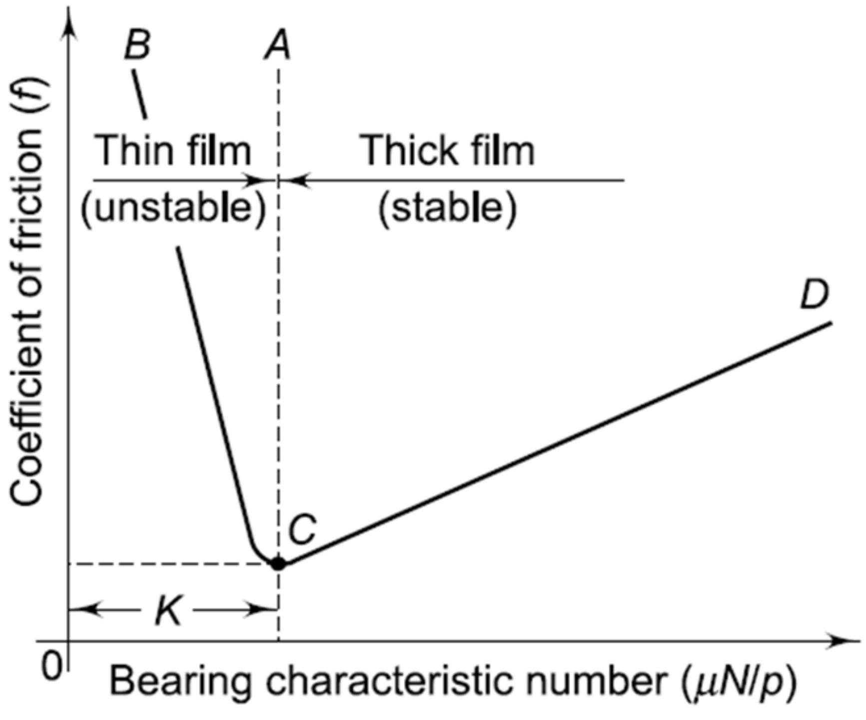
The transition from thin film lubrication to thick film hydrodynamic lubrication can be better visualized by means of a curve called μN/p curve. is an experimental curve developed by McKee brothers.

The value of the bearing characteristic number corresponding to the minimum coefficient of friction is called the **bearing modulus**. It is denoted by K in the figure.

Mckee's empirical relation **considering end leakage and angle of contact**

$$f = 541.33\, \beta \left(\frac{Zn}{p}\right)\left(\frac{r}{c}\right) \times 10^{-10} + \Delta f$$

β is circumferential length of bearing in degrees, p is in MPa

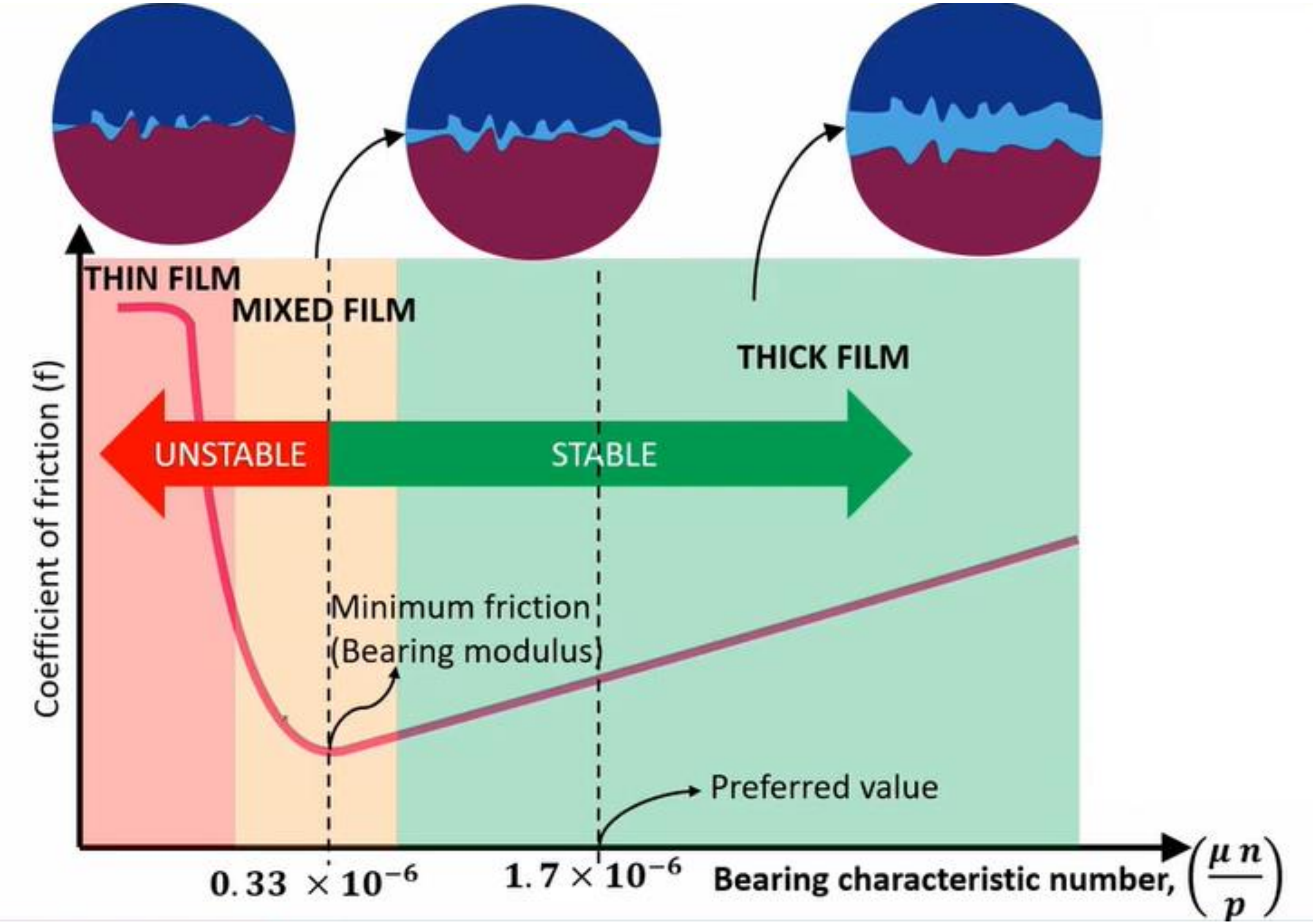


μN/p Curve

Stable Lubrication

- The bearing should not be operated near the critical value K. A slight drop in the speed (N) or a slight increase in the load (p) will reduce the value of μN/p resulting in boundary lubrication.
- In order to avoid seizure, the operating value of the bearing characteristic number (μN/p) should be at least 5 to 6 times the bearing modulus.
- If the bearing is subjected to fluctuating loads or impact conditions, the operating value of the bearing characteristic number should be at least 15 times the bearing modulus.

Stable Lubrication



Questions

How do we ensure heat dissipation in a bearing?

Can we use the same Petroff's equation in ball bearing?

Is it true that we do not have any control over the speed? As friction decreases resistive torque decreases, hence the speed can be increasing?

Can you explain the unstable region once more. Is the unstable region of the stribeck curve relevant. Is stribeck curve purely experimental?

Is 50 mm the diameter of journal on bearing?

Hydrodynamic Theory

The present mathematical theory of lubrication is based upon Reynolds' work following the experiment by Tower. The original differential equation, developed by Reynolds, was used by him to explain Tower's results.

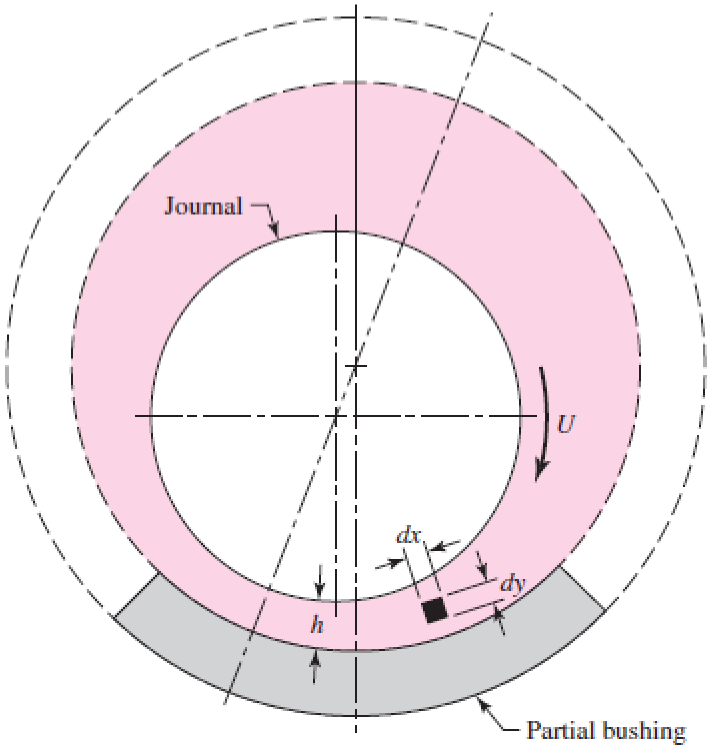
Reynolds pictured the lubricant as adhering to both surfaces and being pulled by the moving surface into a narrowing, wedge-shaped space so as to create a fluid or film pressure of sufficient intensity to support the bearing load.

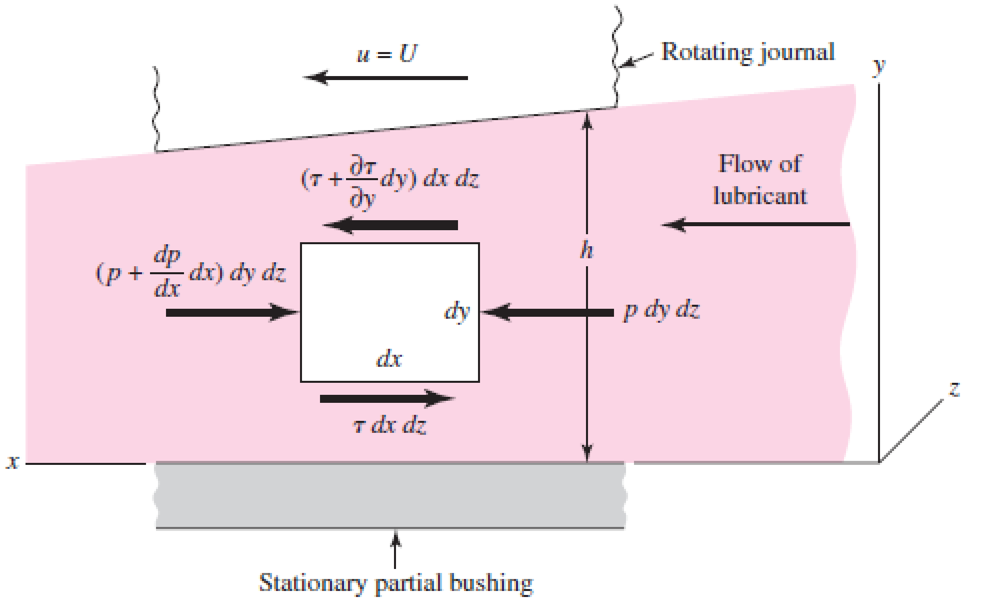
As the fluid films are so thin in comparison with bearing radius, curvature could be neglected and hence the curved partial bearing could be replaced with a flat bearing, called plane slider bearing.

Other assumptions made were:

The lubricant obeys Newton's viscous effect.
The forces due to the inertia of the lubricant are neglected.
The lubricant is assumed to be incompressible.
The viscosity is assumed to be constant throughout the film.
The pressure does not vary in the axial direction.

Hydrodynamic Theory



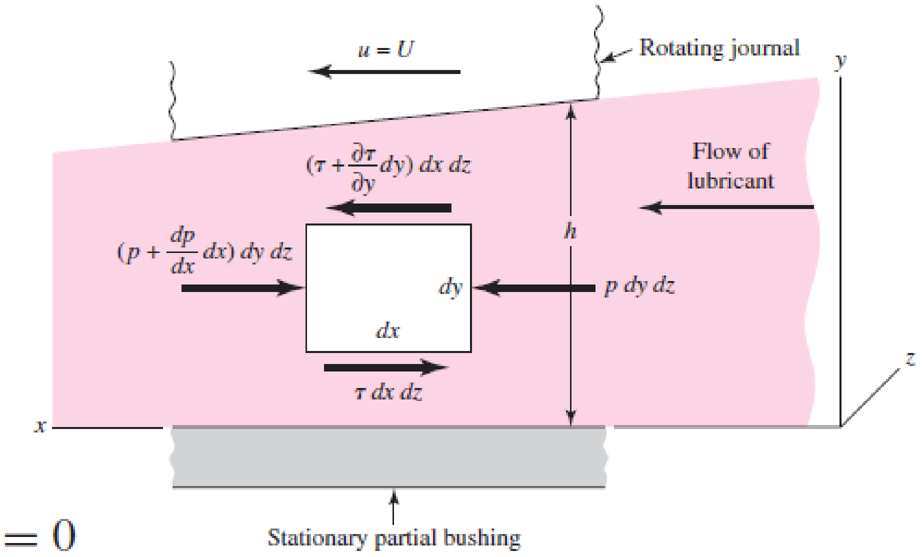


Additional assumptions

The bushing and journal extend infinitely in z direction and hence no lubricant flow in z direction.
The film pressure is constant in y direction. Thus the pressure depends only on the coordinate x.
The velocity of any particle of lubricant in the film depends only on the coordinates x and y.

Hydrodynamic Theory

Normal forces, due to the pressure, act upon the right and left sides of the element, and shear forces, due to the viscosity and to the velocity, act upon the top and bottom sides.



Summing the forces in the x direction gives

$$\sum F_x = p\,dy\,dz - \left(p + \frac{dp}{dx}dx\right) dy\,dz - \tau\,dx\,dz + \left(\tau + \frac{\partial \tau}{\partial y}dy\right) dx\,dz = 0$$

This reduces to $$\frac{dp}{dx} = \frac{\partial \tau}{\partial y}$$

we have $$\tau = \mu \frac{\partial u}{\partial y}$$

$$\frac{dp}{dx} = \mu \frac{\partial^2 u}{\partial y^2}$$

the partial derivative is used because the velocity u depends upon both x and y.

Hydrodynamic Theory

$$\frac{dp}{dx} = \mu \frac{\partial^2 u}{\partial y^2}$$

Holding x constant, we now integrate this expression twice with respect to y. This gives

$$\frac{\partial u}{\partial y} = \frac{1}{\mu} \frac{dp}{dx} y + C_1$$

$$u = \frac{1}{2\mu} \frac{dp}{dx} y^2 + C_1 y + C_2$$

Note that the act of holding x constant means that C_1 and C_2 can be functions of x. We now assume that there is no slip between the lubricant and the boundary surfaces. This gives two sets of boundary conditions for evaluating the constants C_1 and C_2:

$$\text{At} \quad y = 0, \; u = 0$$

$$\text{At} \quad y = h, \; u = U$$

Hydrodynamic Theory

Substituting these conditions and solving for the constants gives

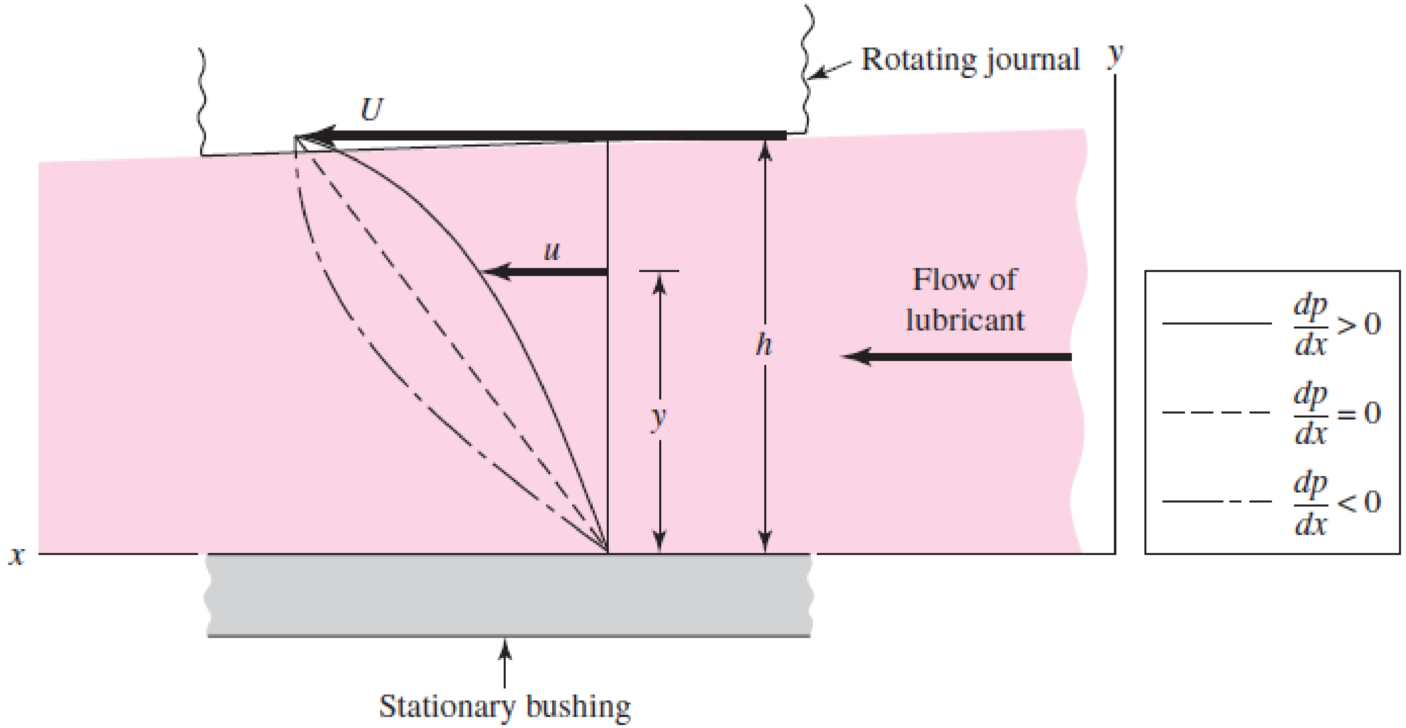
$$C_1 = \frac{U}{h} - \frac{h}{2\mu}\frac{dp}{dx} \qquad C_2 = 0$$

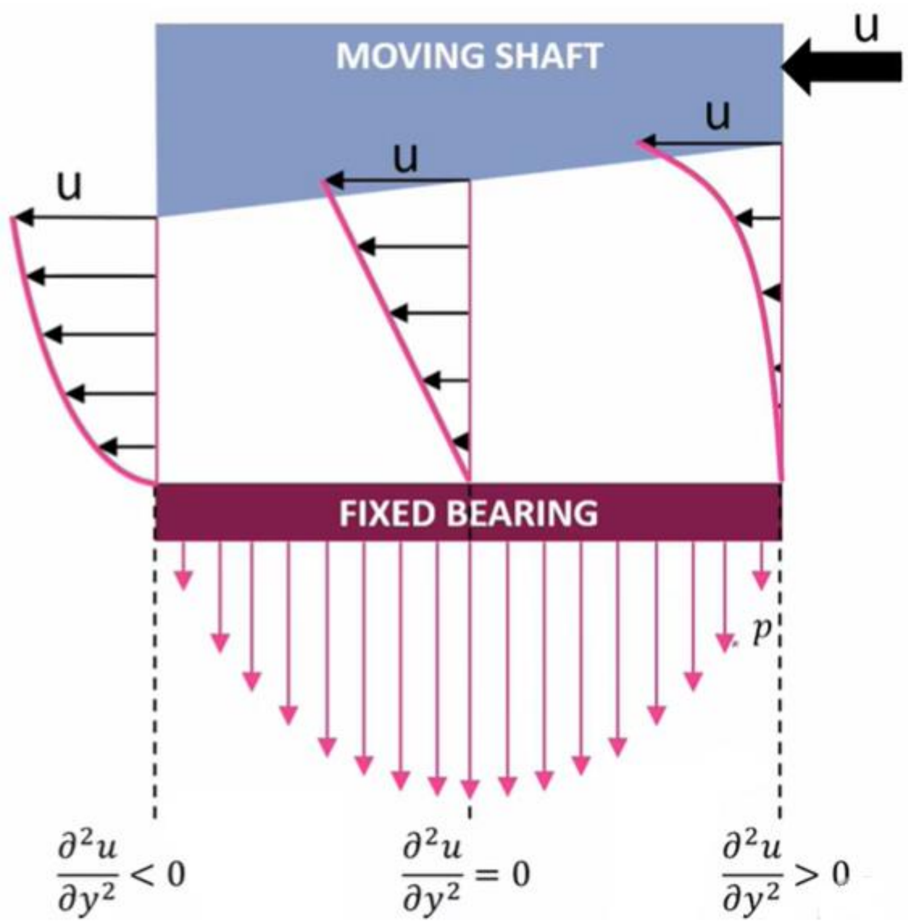
$$u = \frac{1}{2\mu}\frac{dp}{dx}(y^2 - hy) + \frac{U}{h}y$$

This equation gives the velocity distribution of the lubricant in the film as a function of the coordinate y and the pressure gradient dp/dx.

The equation shows that the velocity distribution across the film (from y = 0 to y = h) is obtained by superposing a parabolic distribution onto a linear distribution.

Hydrodynamic Theory





In general, the parabolic term may be additive or subtractive to the linear term, depending upon the sign of the pressure gradient. When the pressure is maximum, dp/dx = 0 and the velocity is having a linear relation

$$u = \frac{U}{h} y$$

Questions

What is the significance of max pressure point?

How does the pressure vary along x?

Hydrodynamic Theory

We next define Q as the volume of lubricant flowing in the x direction per unit time. By using a width of unity in the z direction, the volume may be obtained by the expression

$$Q = \int_0^h u\,dy$$

$$u = \frac{1}{2\mu}\frac{dp}{dx}(y^2 - hy) + \frac{U}{h}y$$

$$Q = \frac{Uh}{2} - \frac{h^3}{12\mu}\frac{dp}{dx}$$

The next step uses the assumption of an incompressible lubricant and states that the flow is the same for any cross section. Thus

$$\frac{dQ}{dx} = 0$$

Hydrodynamic Theory

$$\frac{dQ}{dx} = \frac{U}{2}\frac{dh}{dx} - \frac{d}{dx}\left(\frac{h^3}{12\mu}\frac{dp}{dx}\right) = 0$$

$$\boxed{\frac{d}{dx}\left(\frac{h^3}{\mu}\frac{dp}{dx}\right) = 6U\frac{dh}{dx}}$$

Classical Reynolds equation for one-dimensional flow (neglects side leakage, that is, flow in the z direction).

When side leakage is not neglected, the resulting equation is

$$\frac{\partial}{\partial x}\left(\frac{h^3}{\mu}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{h^3}{\mu}\frac{\partial p}{\partial z}\right) = 6U\frac{\partial h}{\partial x}$$

Hydrodynamic Theory

There is no general analytical solution to Reynolds equation.

Approximate solutions have been obtained by using electrical analogies, mathematical summations, relaxation methods, and numerical and graphical methods.

One of the important solutions is by Sommerfeld and may be expressed in the form

$$\frac{r}{c} f = \phi\left[\boxed{\left(\frac{r}{c}\right)^2 \frac{\mu N}{P}}\right]$$

Sommerfeld number

where ϕ indicates a functional relationship. Sommerfeld found the functions for half-bearings and full bearings by using the assumption of no side leakage.