Design of Machines and Mechanical Systems (PC-BTM711)

Session 13

Module 3: Hydrodynamic Bearing Design

Session Outcomes

- Describe terminology of sliding contact bearings
- Explain principles of working of hydrodynamic bearings
- Discuss Friction co-efficient – Petroff Equation
- Derive Reynold equation
- Discuss Raimondi and Boyd Solution to Reynold Equation
- Design hydrodynamic bearing after selecting key parameters

Principle of Hydrodynamic Bearing Operation

https://www.youtube.com/watch?v=7OY170iaGSA

QUIZ

Advantages of Hydrodynamic Bearings

The advantage/s of hydrodynamic bearing is/are

1. Minimal wear and tear
2. High load carrying capacity at low/medium speeds
3. Both of the above

QUIZ

Fundamental Principles of Hydrodynamic Bearing Operation

The fundamental principle/s governing the operation of hydrodynamic bearing is/are ___________

1. Formation of viscous oil wedge between shaft and sleeve
2. Externally supplied pressure to the oil
3. Both of the above

SELF-STUDY

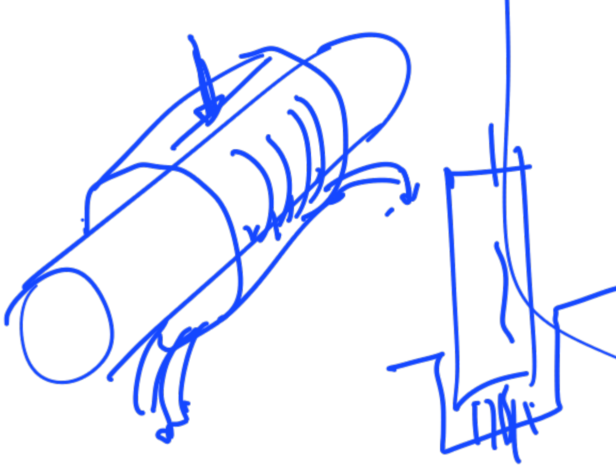
Sliding Contact Bearings

- Types of lubricants
- Objectives of lubricants
- Modes of Lubrication
  - Thick film
    - Hydrodynamic
    - Hydrostatic
  - Thin film
  - Zero film

- Types of lubricants → liquid (oil, grease); semi solid; solid → Graphite, MoS_2
- Objectives of lubricants → reduce friction; dissipation of heat; additives → corrosion; reduce wear
- Thick film → no metal to metal contact
- Thin film → M to M occasionally → m/c tools sliding operation
- Zero film → metal to metal contact

Types of Hydrodynamic Bearings

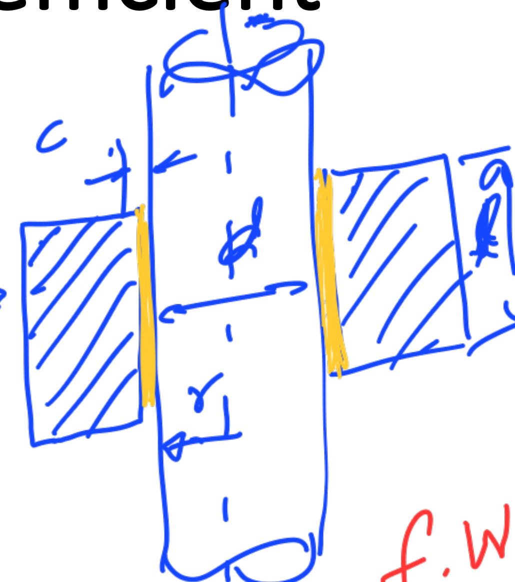
- Full bearing
- Partial bearing
- Thrust bearing



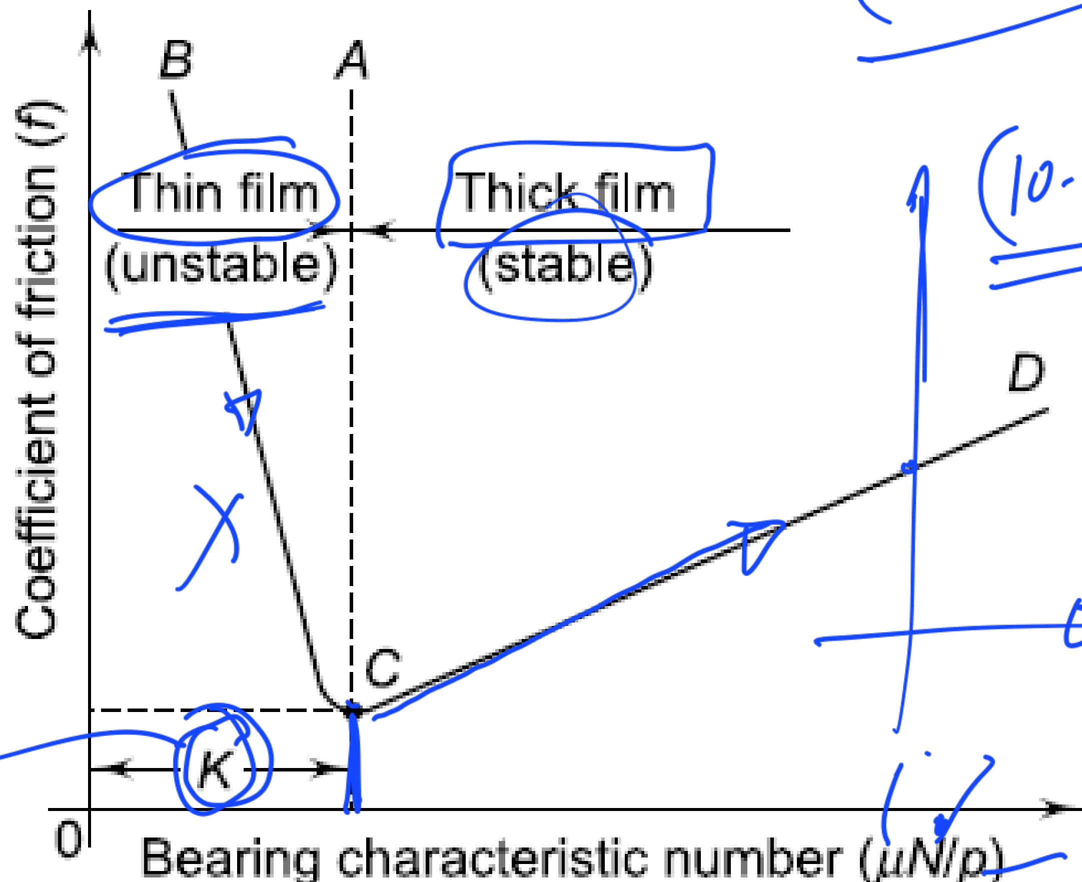
Determination of Friction Coefficient

- Petroff's Equation (1883)

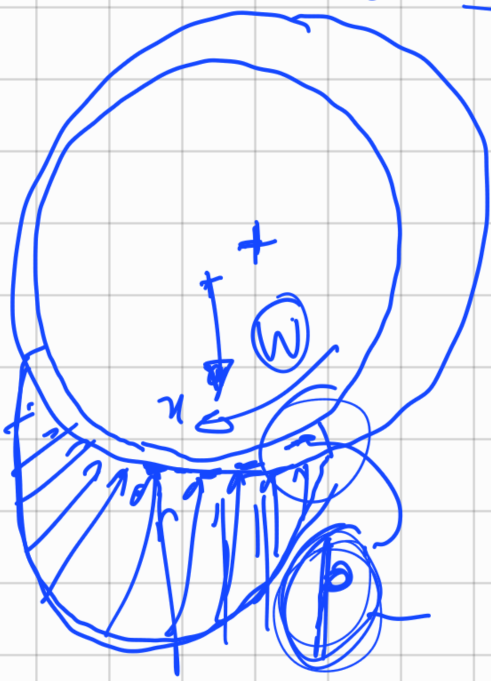
$$f = (2\pi^2)\left(\frac{r}{c}\right)\left(\frac{\mu n_s}{p}\right)$$



Stable Lubrication (McKee's Investigation, 1932)



Ref: Bhandari V.B., Design of Machine Elements (2017)

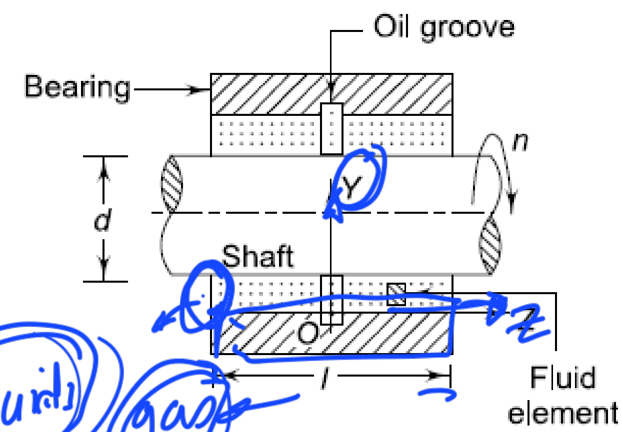


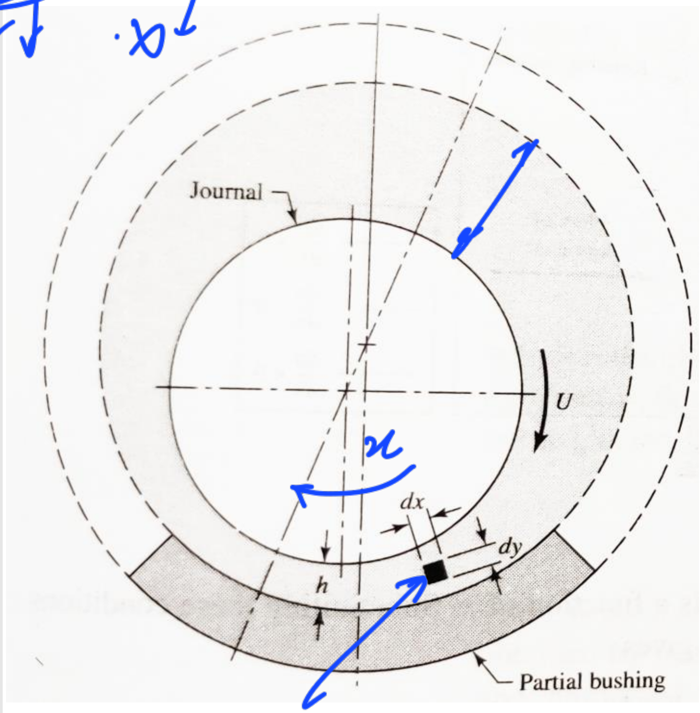
$\rightarrow (p, v)$

$p(x), \theta, x$

Reynold's Equation (1D)

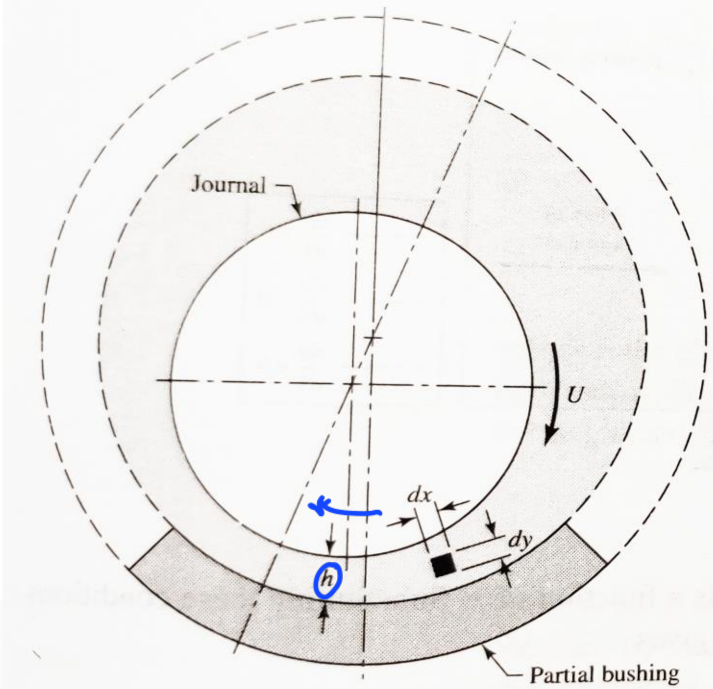
- Assumptions
  - Lubricant obeys __________ law of _____
  - Lubricant is ____________________
  - ______ forces in thin film are negligible
  - ___________ of lubricant is constant.
  - Pressure is constant across _______________
  - Shaft and bearings are ______________
  - There is continuous supply of _____________
  - No flow in ______ direction for 1D formulation

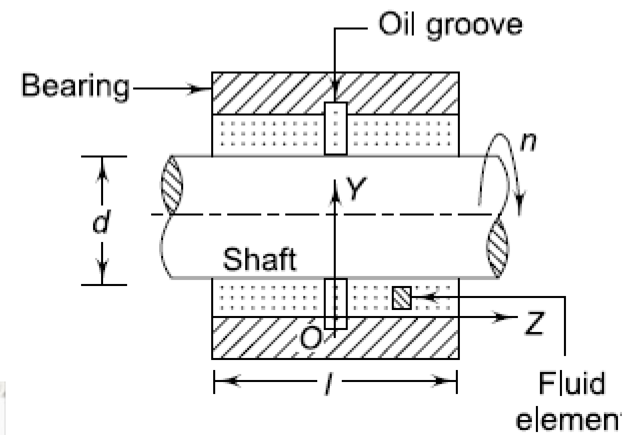


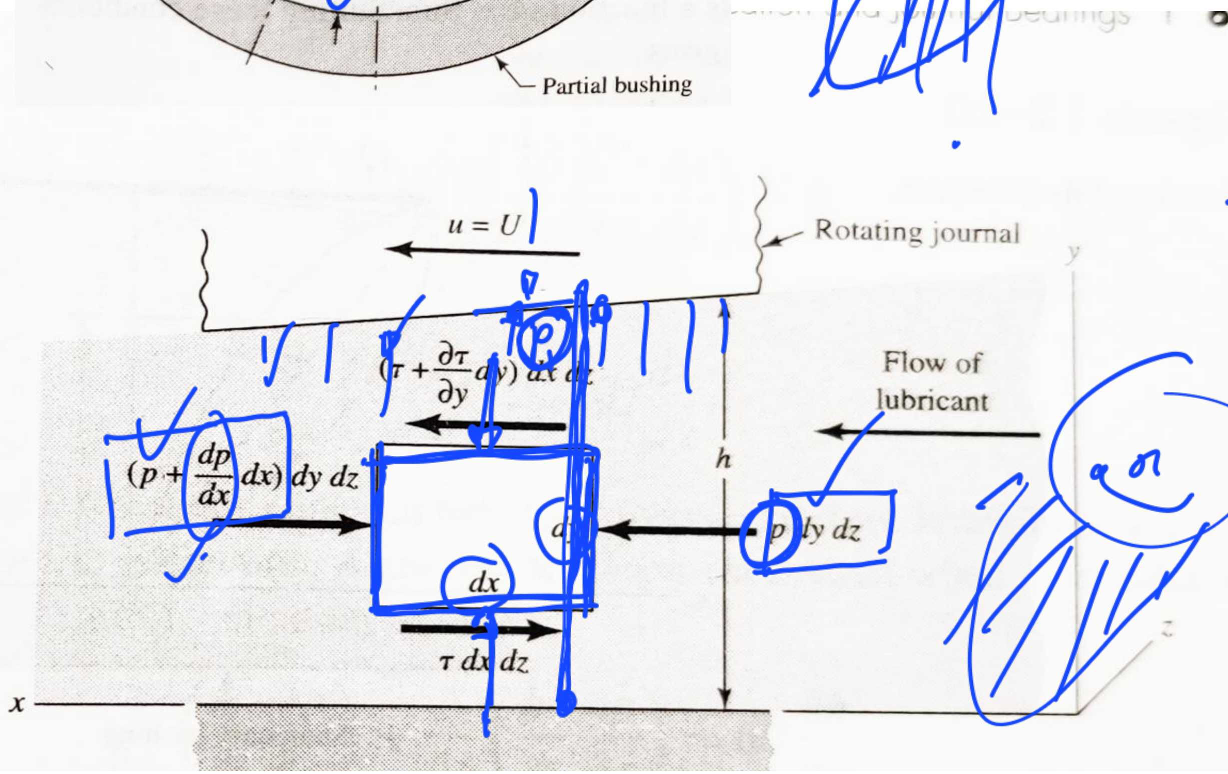


Ref: Shigley's Mechanical Engineering Design, 9 edn.)

Reynold's Equation (1D), (1886)







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

Ref: Shigley's Mechanical Engineering Design, 9 edn.)

Reynold's Equation in 2D

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

Sommerfield $\Rightarrow$ $l = \infty$

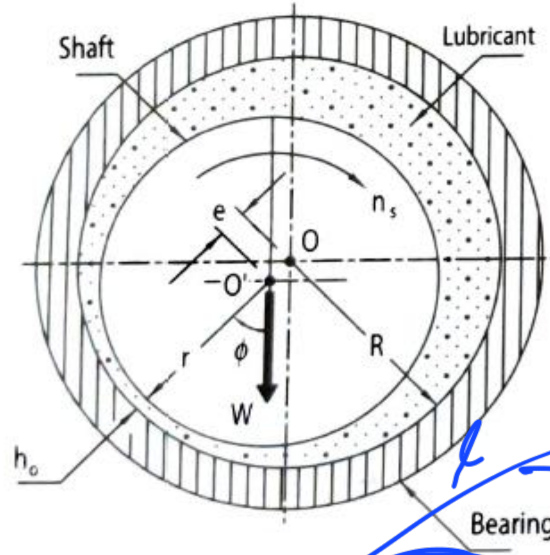
$l << \text{small}$

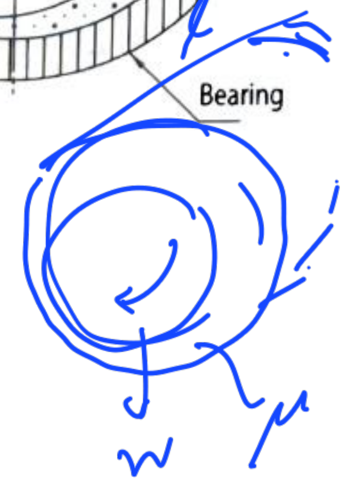
$p(x) =$

Raimondi & Boyd Solution to Reynold Equation (1958)

→ Table / Chart

$p(x, z)$





16.5 RAIMONDI AND BOYD TABLES

Table 16.6 *Performance characteristics for full journal bearings*

$\left(\frac{l}{d}\right)$	ε	$\left(\frac{h_o}{c}\right)$	θ_A	S	ϕ	$\left(\frac{r}{c}\right)f$	$\left(\frac{Q}{rcn_s l}\right)$	$\left(\frac{Q}{Q_s}\right)$	$\left(\frac{\rho C_p \Delta t}{p}\right)$	$\left(\frac{p}{p_{max}}\right)$	$\theta_{p_{max}}$	θ_{p_o}
∞	0	1.0	0	∞	(70.92)	∞	π	0	∞	—	0	(148.38)
	0.1	0.9	0	0.240	69.10	4.80	3.03	0	19.9	0.826	0.0	137
	0.2	0.8	0	0.123	67.26	2.57	2.83	0	11.4	0.814	5.6	128
	0.4	0.6	0	0.0626	61.94	1.52	2.26	0	8.47	0.764	14.4	107
	0.6	0.4	0	0.0389	54.31	1.20	1.56	0	9.73	0.667	20.8	86
	0.8	0.2	0	0.0210	42.22	0.961	0.760	0	15.9	0.495	21.5	58.8
	0.9	0.1	0	0.0115	31.62	0.756	0.411	0	23.1	0.358	19	44
	0.97	0.03	0	—	—	—	—	0	—	—	—	—
	1.00	0	0	0	0	0	0	0	∞	0	0	0
1	0	1.0	0	∞	(85)	∞	π	0	∞	—	0	(119)

QUIZ

Solution to Reynold's Equation

The analytical solution to Reynold's equation for hydrodynamic bearings is not yet determined.

1. True
2. False

Dimensionless Performance Parameters DDB T16.5

(Contd.)

Eccentricity		
e = distance OO' = eccentricity (mm)		O = axis of bearing O' = axis of journal
Radial clearance		
$c = R - r$	(16.9)	c = radial clearance (mm) R = radius of bearing (mm) r = radius of journal (mm)
Eccentricity ratio		
$\varepsilon = \frac{e}{c}$	(16.10)	ε = eccentricity ratio (dimensionless)
Minimum film thickness		
$R = e + r + h_o$	(16.11)	h_o = minimum film thickness (mm)
Minimum film thickness variable		
$\varepsilon = 1 - \left(\frac{h_o}{c}\right)$	(16.12)	$\left(\frac{h_o}{c}\right)$ = minimum film thickness variable (dimensionless)
Sommerfeld number		
$S = \left(\frac{r}{c}\right)^2 \frac{\mu n_s}{p}$	(16.13)	S = Sommerfeld number (dimensionless) μ = viscosity of the lubricant (MPa-s) or (N-s/mm^2) n_s = journal speed (rev/s) p = unit bearing pressure i.e., load per unit of the projected area (MPa) or (N/mm^2)
Unit bearing pressure		
$p = \frac{W}{ld}$	(16.14)	W = radial load acting on bearing (N) l = axial length of bearing (mm) d = journal diameter (mm)
Attitude angle		
ϕ = attitude angle = angle of eccentricity (deg). **Note** (ϕ) = locates the position of minimum film thickness with respect to the direction of load.		
Coefficient of Friction Variable (CFV)		
$(\text{CFV}) = \left(\frac{r}{c}\right) f$	(16.15)	(CFV) = coefficient of friction variable (dimensionless) f = coefficient of friction
Flow Variable (FV)		
$(\text{FV}) = \frac{Q}{r c n_s l}$	(16.16)	(FV) = flow variable (dimensionless) Q = flow of the lubricant drawn into clearance space by journal (mm^3/s)

Dimensionless Performance Parameters DDB T16.5

(Contd.)

Flow Ratio Variable (FRV)		
$(FRV) = (Q/Q_s)$	(16.17)	(FRV) = flow ratio variable (dimensionless) Q_s = out-flow of lubricant from both sides of bearing or side leakage (mm^3/s)

Temperature Rise Variable (TRV)		
$(TRV) = \frac{\rho C_p \Delta t}{p}$	(16.18)	(TRV) = temperature rise variable (dimensionless) ρ = density of lubricating oil (gm/cm^3) ($\rho \approx 0.86$ to 0.88 gm/cm^3) C_p = specific heat of lubricating oil (kJ/kg °C) ($C_p \approx 1.68$ to 1.76 kJ/kg °C) Δt = temperature rise (°C) t_2 = outlet temperature of lubricant (°C) t_1 = inlet temperature of lubricant (°C)
$\Delta t = (t_2 - t_1)$	(16.19)	

Pressure Ratio (PR)		
$(PR) = \left(\frac{p}{p_{max}}\right)$	(16.20)	(PR) = pressure ratio (dimensionless) p_{max} = maximum pressure developed in lubricant film (MPa) or (N/mm^2)

Position of Maximum film pressure ($\theta_{p_{max}}$)
$\theta_{p_{max}}$ = Position of maximum film pressure with respect to the direction of load (deg)

Position at which the lubricant film begins (θ_A)
θ_A = Angle from line of centres to start of lubricant film, measured in the direction of rotation (deg)

Position at which the lubricant film ends (θ_{p_o})
θ_{p_o} = Position at which lubricant film terminates with respect to the direction of load (deg)