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Mechanical Design 2

Class Section 01

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Problem 1

A full journal bearing has a shaft journal diameter of 25 mm with a unilateral tolerance of -0.01 mm. The bushing bore has a diameter of 25.04 mm with a unilateral tolerance of 0.03 mm. The l⁄d ratio is unity. The bushing load is 1.25 kN, and the journal rotates at 1200 rev/min. Analyze the minimum clearance assembly if the average viscosity is 50 mPa-s to find the minimum oil film thickness, the power loss, and the percentage of side flow.

Solution:

Known:

$$d_{max} = 25 \text{ mm} = 0.025 \text{ m}$$

$$d_{min} = 24.99 \text{ mm}$$

$$D_{min} = 25.04 \text{ mm} = 0.02504 \text{ m}$$

$$D_{max} = 25.07 \text{ mm}$$

$$W = 1.25 \text{ kN} = 1250 \text{ N}$$

$$N = 1200 \text{ rev/min} = 20 \text{ rev/s}$$

$$\mu = 50 \text{ mPa} \cdot \text{s} = 0.05 \text{ Pa} \cdot \text{s}$$

$$\frac{l}{d} = 1$$

Therefore,

$$2c_{min} = D_{min} - d_{max} = 0.04 \text{ mm}$$

$$c_{min} = 0.02 \text{ mm} = 2 \times 10^{-5} \text{ m}$$

$$l = d = 25 \text{ mm} = 0.025 \text{ m}$$

$$r = \frac{d}{2} = \frac{25\ \text{mm}}{2} = 0.0125\ \text{m}$$

Shaft average pressure:

$$P = \frac{W}{2rl} = 2.0000 \times 10^6\ \text{Pa}$$

Sommerfeld Number:

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 0.1953$$

Figure 12-16: minimum film thickness variable

$$\frac{h_0}{c} = 0.525$$

Therefore, minimum film thickness:

$$h_0 = 0.525c = 0.525 \times 0.02\ \text{mm} = 0.0105\ \text{mm}$$

Figure 12-18: coefficient of friction variable

$$\frac{r}{c}f = 4.5$$

Therefore, coefficient of friction:

$$f = 4.5\frac{c}{r} = 4.5 \times \frac{2 \times 10^{-5}\ \text{m}}{0.0125\ \text{m}} = 0.0072$$

Journal friction torque:

$$T = fWr = 0.0072 \times 1250\ \text{N} \times 0.0125\ \text{m} = 0.1125\ \text{N} \cdot \text{m}$$

Power loss:

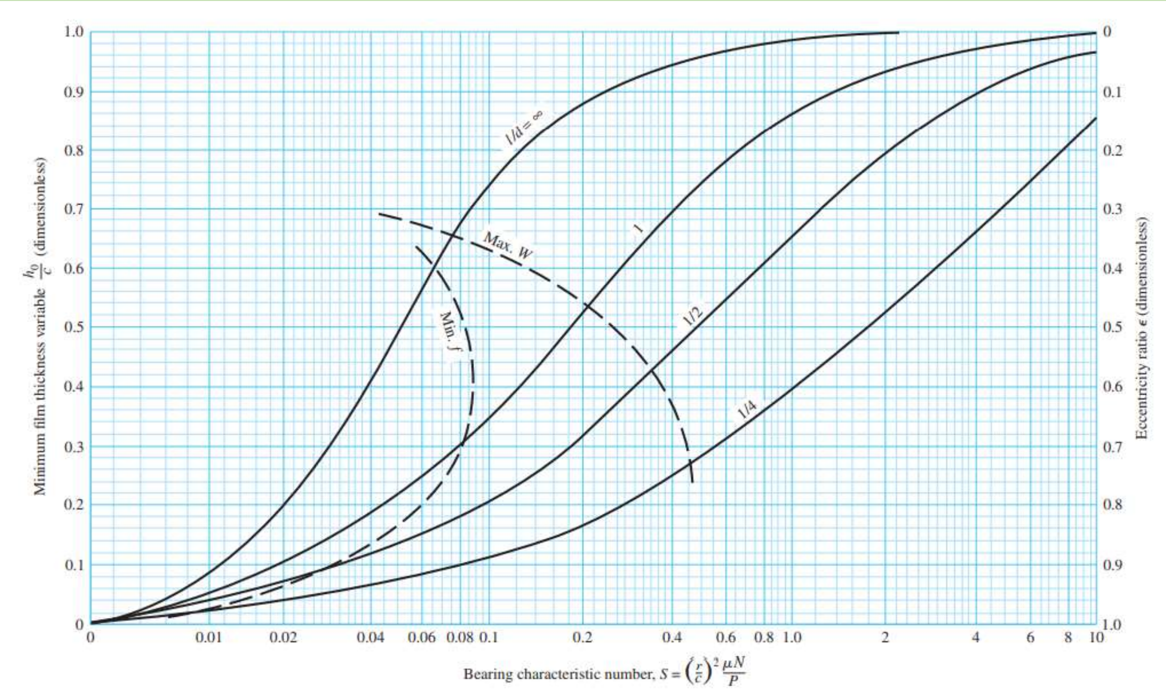
$$p_{loss} = 2\pi NT = 2\pi \times 20\ \text{rev/s} \times 0.1125\ \text{N} \cdot \text{m} = 14.1372\ \text{W}$$

Figure 12-20: flow ratio (the percentage of side flow)

$$\frac{Q_s}{Q} = 0.58 = 58\%$$

Problem 2

A sleeve bearing supports a load of 700 lbf and has a journal speed of 3600 rev/ min. Bearing length is 1.25-in and diameter is 1.25-in as well. An SAE 10 oil is used having an average temperature of 160°F. Using Raimondi–Boyd charts (Fig. 12-16 as shown below), estimate the radial clearance for minimum coefficient of friction f and for maximum load-carrying capacity W. The difference between these two clearances is called the clearance range. Define the range per your clearance.



Solution:

Prof. Sui told us we don't need to do this question.

Problem 3

A full journal bearing has a shaft diameter of 3.000 in with a unilateral tolerance of -0.0004 in. The bushing has a bore diameter of 3.003 in with a unilateral tolerance of 0.0012 in.

Lubricant used in bearing is the SAE 40 oil, which is supplied to the bearings at pump pressure of 60 psig.

The l/d ratio of the full bearing is unity. However, the bearing has a central axial-groove and its width is 20 percent of the full bearing width.

The radial bearing load is 1200 lbf while the shaft is rotating at 1800 rpm.

a. What is the full range of the diametric clearance? (10 points)

b. Calculate (1) the average film temperature, (2) the peak film pressure, (3) the minimum film thickness, (4) the heat loss rate, and (5) the lubricant side-flow rate under the following clearance conditions:

   - minimum clearance, and
   - maximum clearance.

   Iterate till temperature between two iterations are within 5 degF. Tabulate the calculated parameters versus corresponding clearance. Compare characteristics of your data to the trends in Figure 12-25 and outline your observations. (20 points)

c. What is the required capacity of the oil pump to prevent the bearing from starvation within the designed bearing clearance range? (10 points)

d. It is intended to maintain the sump temperature at 150degF during operation and an oil cooler is used to remove the heat from returning oil. Specify the required capacity of the oil cooler within the designed bearing clearance range. (10 points)

e. Use Trumpler's design criteria to evaluate the minimum film thickness and oil temperature rise of the designed journal bearing. Judge whether the bearing will survive the operation or not. (10 points)

Solution:

Known:

$$d_{max} = 3.000 \text{ in}$$

$$d_{min} = 2.9996 \text{ in}$$

$$D_{min} = 3.003 \text{ in}$$

$$D_{max} = 3.0042 \text{ in}$$

$$\text{Lubricant: SAE 40 oil.}$$

$$p_s = 60 \text{ psig}$$

$$\frac{l}{d} = 1$$

However, the bearing has a central axial-groove and its width is 20 percent of the full bearing width.

$$W = 1200 \text{ lbf}$$

$$N = 1800 \text{ rpm} = 30 \text{ rev/s}$$

a. Therefore,

$$2c_{min} = D_{min} - d_{max} = 0.003 \text{ in}$$
$$2c_{max} = D_{max} - d_{min} = 0.0046 \text{ in}$$

The full range of the diametric clearance:

$$2c \in [0.003 \text{ in}, 0.0046 \text{ in}]$$

b.

$$\frac{l'}{d} = \frac{1 - 20\%}{2} = 0.4$$
$$l' = 0.4d = 0.4 \times 3.000 \text{ in} = 1.200 \text{ in}$$

$$r = \frac{d}{2} = \frac{3.000 \text{ in}}{2} = 1.500 \text{ in}$$

Shaft average pressure:

$$P = \frac{W/2}{2rl'} = \frac{W}{4rl'} = 166.6667 \text{ psi}$$

[minimum clearance]

Initial guess: average film temperature $T_F = 170°\text{F}$.

SAE 40 oil viscosity:

$$\mu = \mu_0 \exp\left(\frac{b}{T_F + 95}\right) = 0.0121 \times 10^{-6} \text{ reyn} \times \exp\left(\frac{1474.4}{170 + 95}\right)$$
$$= 3.1557 \times 10^{-6} \text{ reyn}$$

Sommerfeld Number:

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 0.5680$$

Figure 12-16: eccentricity ratio

$$\epsilon = 0.54$$

Figure 12-18: coefficient of friction variable

$$\frac{r}{c} f = 13$$

$$\Delta T_F = 0.0123\left(\frac{fr}{c}\right)\frac{SW^2}{(1+1.5\epsilon^2)p_s r^4} = 299.5650°\text{F}$$

Estimated side flow oil temperature:

$$T_{av} = T_s + \frac{\Delta T_F}{2} = 150°\text{F} + \frac{299.5650°\text{F}}{2} = 299.7825°\text{F}$$

2nd Iteration: revised film temperature $T_F = 300°\text{F}$.

SAE 40 oil viscosity:

$$\mu = \mu_0 \exp\left(\frac{b}{T_F + 95}\right) = 0.0121 \times 10^{-6}\text{ reyn} \times \exp\left(\frac{1474.4}{299.7825 + 95}\right)$$
$$= 0.5057 \times 10^{-6}\text{ reyn}$$

Sommerfeld Number:

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 0.0910$$

Figure 12-16: eccentricity ratio

$$\epsilon = 0.84$$

Figure 12-18: coefficient of friction variable

$$\frac{r}{c}f = 3.6$$

$$\Delta T_F = 0.0123\left(\frac{fr}{c}\right)\frac{SW^2}{(1+1.5\epsilon^2)p_s r^4} = 9.2823°\text{F}$$

Estimated side flow oil temperature:

$$T_{av} = T_s + \frac{\Delta T_F}{2} = 150°\text{F} + \frac{9.2823°\text{F}}{2} = 154.6411°\text{F}$$

3rd Iteration: revised film temperature $T_F = 155°\text{F}$.

SAE 40 oil viscosity:

$$\mu = \mu_0 \exp\left(\frac{b}{T_F + 95}\right) = 4.4064 \times 10^{-6}\text{ reyn}$$

Sommerfeld Number:

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 0.7931$$

It is divergent. Hence, initial guess: average film temperature $T_F = 250°\text{F}$.

SAE 40 oil viscosity:

$$\mu = \mu_0 \exp\left(\frac{b}{T_F + 95}\right) = 0.0121 \times 10^{-6}\text{ reyn} \times \exp\left(\frac{1474.4}{250 + 95}\right)$$
$$= 0.86855 \times 10^{-6}\text{ reyn}$$

Sommerfeld Number:

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 0.1563$$

Figure 12-16: eccentricity ratio

$$\epsilon = 0.76$$

Figure 12-18: coefficient of friction variable

$$\frac{r}{c}f = 3.3$$

$$\Delta T_F = 0.0123\left(\frac{fr}{c}\right)\frac{SW^2}{(1+1.5\epsilon^2)p_s r^4} = 16.1187°\text{F}$$

Estimated side flow oil temperature:

$$T_{av} = T_s + \frac{\Delta T_F}{2} = 150°\text{F} + \frac{16.1187°\text{F}}{2} = 158.0593°\text{F}$$

Initial guess: average film temperature $T_F = 200°\text{F}$.

SAE 40 oil viscosity:

$$\mu = \mu_0 \exp\left(\frac{b}{T_F + 95}\right) = 0.0121 \times 10^{-6}\ \text{reyn} \times \exp\left(\frac{1474.4}{200+95}\right)$$
$$= 1.7922 \times 10^{-6}\ \text{reyn}$$

Sommerfeld Number:

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 0.3226$$

Figure 12-16: eccentricity ratio

$$\epsilon = 0.66$$

Figure 12-18: coefficient of friction variable

$$\frac{r}{c}f = 8$$

$$\Delta T_F = 0.0123\left(\frac{fr}{c}\right)\frac{SW^2}{(1+1.5\epsilon^2)p_s r^4} = 91.0144°\text{F}$$

Estimated side flow oil temperature:

$$T_{av} = T_s + \frac{\Delta T_F}{2} = 150°\text{F} + \frac{91.0144°\text{F}}{2} = 195.5072°\text{F}$$

2nd Iteration: revised film temperature $T_F = 197°\text{F}$.

SAE 40 oil viscosity:

$$\mu = \mu_0 \exp\left(\frac{b}{T_F + 95}\right) = 0.0121 \times 10^{-6}\ \text{reyn} \times \exp\left(\frac{1474.4}{197+95}\right)$$
$$= 1.8866 \times 10^{-6}\ \text{reyn}$$

Sommerfeld Number:

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 0.3396$$

Figure 12-16: eccentricity ratio

$$\epsilon = 0.64$$

Figure 12-18: coefficient of friction variable

$$\frac{r}{c}f = 8$$

$$\Delta T_F = 0.0123\left(\frac{fr}{c}\right)\frac{SW^2}{(1+1.5\epsilon^2)p_s r^4} = 98.1246°\text{F}$$

Estimated side flow oil temperature:

$$T_{av} = T_s + \frac{\Delta T_F}{2} = 150\text{°F} + \frac{98.1246\text{°F}}{2} = 199.0623\text{°F}$$

3rd Iteration: revised film temperature $T_F = 198\text{°F}$.

SAE 40 oil viscosity:

$$\mu = \mu_0 \exp\left(\frac{b}{T_F + 95}\right) = 0.0121 \times 10^{-6}\ \text{reyn} \times \exp\left(\frac{1474.4}{198 + 95}\right)$$
$$= 1.8543 \times 10^{-6}\ \text{reyn}$$

Sommerfeld Number:

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 0.3338$$

Figure 12-16: eccentricity ratio

$$\epsilon = 0.64$$

Figure 12-18: coefficient of friction variable

$$\frac{r}{c} f = 8$$

$$\Delta T_F = 0.0123 \left(\frac{fr}{c}\right) \frac{SW^2}{(1 + 1.5\epsilon^2) p_s r^4} = 96.4480\text{°F}$$

Estimated side flow oil temperature:

$$T_{av} = T_s + \frac{\Delta T_F}{2} = 150\text{°F} + \frac{96.4480\text{°F}}{2} = 198.2240\text{°F}$$

Therefore, the average film temperature is equal to $T_F = 198\text{°F}$.

Iteration Table:

Trial T_f	**$\mu\ (10^{-6})$**	**S**	**$\frac{fr}{c}$**	**ϵ**	**ΔT_f**	**T_{av}**
200	1.7922	0.3226	8	0.66	91.0144	195.5072
197	1.6222	0.3396	8	0.64	98.1246	199.0623
198	1.5961	0.3338	8	0.64	96.4480	198.2240

Figure 12-21: maximum-film-pressure ratio

$$\frac{p}{p_{max}} = 0.32$$

$$p_{max} = 520.8333\ \text{psi}$$

The peak film pressure:

$$p_{total} = p_{max} + p_s = 520.8333\ \text{psi} + 60\ \text{psi} = 580.8333\ \text{psi}$$

The minimum film thickness:

$$h_0 = (1 - \epsilon)c = 5.4 \times 10^{-4}\ \text{in}$$

The lubricant side-flow rate:

$$Q_s = \frac{\pi p_s r c^3}{3\mu l'} (1 + 1.5\epsilon^2) = 0.2308\ \text{in}^3/\text{s}$$

The heat loss rate:

$$H_{loss} = \rho C_p Q_s \Delta T$$

$$= (0.0311\ \mathrm{lbm/in^3}) \times \big(0.42\ \mathrm{Btu/(lbm \cdot °F)}\big) \times (0.2308\ \mathrm{in^3/s})$$

$$\times (96.4480\mathrm{°F}) = 0.2907\ \mathrm{Btu/s} = 1046.6\ \mathrm{Btu/h}$$

[maximum clearance]

Initial guess: average film temperature $T_F = 200\mathrm{°F}$.

SAE 40 oil viscosity:

$$\mu = \mu_0 \exp\left(\frac{b}{T_F + 95}\right) = 0.0121 \times 10^{-6}\ \mathrm{reyn} \times \exp\left(\frac{1474.4}{200 + 95}\right)$$

$$= 1.7922 \times 10^{-6}\ \mathrm{reyn}$$

Sommerfeld Number:

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 0.1372$$

Figure 12-16: eccentricity ratio

$$\epsilon = 0.80$$

Figure 12-18: coefficient of friction variable

$$\frac{r}{c} f = 4.5$$

$$\Delta T_F = 0.0123 \left(\frac{fr}{c}\right) \frac{SW^2}{(1 + 1.5\epsilon^2) p_s r^4} = 18.3688\mathrm{°F}$$

Estimated side flow oil temperature:

$$T_{av} = T_s + \frac{\Delta T_F}{2} = 150\mathrm{°F} + \frac{18.3688\mathrm{°F}}{2} = 159.1844\mathrm{°F}$$

2nd Iteration: revised film temperature $T_F = 180\mathrm{°F}$.

SAE 40 oil viscosity:

$$\mu = \mu_0 \exp\left(\frac{b}{T_F + 95}\right) = 0.0121 \times 10^{-6}\ \mathrm{reyn} \times \exp\left(\frac{1474.4}{180 + 95}\right)$$

$$= 2.5777 \times 10^{-6}\ \mathrm{reyn}$$

Sommerfeld Number:

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 0.1973$$

Figure 12-16: eccentricity ratio

$$\epsilon = 0.77$$

Figure 12-18: coefficient of friction variable

$$\frac{r}{c} f = 6$$

$$\Delta T_F = 0.0123 \left(\frac{fr}{c}\right) \frac{SW^2}{(1 + 1.5\epsilon^2) p_s r^4} = 36.5447\mathrm{°F}$$

Estimated side flow oil temperature:

$$T_{av} = T_s + \frac{\Delta T_F}{2} = 150\mathrm{°F} + \frac{36.5447\mathrm{°F}}{2} = 168.2724\mathrm{°F}$$

3rd Iteration: revised film temperature $T_F = 173\mathrm{°F}$.

SAE 40 oil viscosity:

$$\mu = \mu_0 \exp\left(\frac{b}{T_F + 95}\right) = 0.0121 \times 10^{-6} \text{ reyn} \times \exp\left(\frac{1474.4}{173 + 95}\right)$$
$$= 2.9652 \times 10^{-6} \text{ reyn}$$

Sommerfeld Number:

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 0.2270$$

Figure 12-16: eccentricity ratio

$$\epsilon = 0.74$$

Figure 12-18: coefficient of friction variable

$$\frac{r}{c} f = 6.5$$

$$\Delta T_F = 0.0123 \left(\frac{fr}{c}\right) \frac{SW^2}{(1 + 1.5\epsilon^2) p_s r^4} = 47.2402 \text{°F}$$

Estimated side flow oil temperature:

$$T_{av} = T_s + \frac{\Delta T_F}{2} = 150\text{°F} + \frac{47.2402\text{°F}}{2} = 173.6201\text{°F}$$

Therefore, the average film temperature is equal to $T_F = 173\text{°F}$.

Iteration Table:

Trial T_f	$\mu\ (10^{-6})$	S	$\frac{fr}{c}$	ϵ	ΔT_f	T_{av}
200	1.7922	0.1372	4.5	0.80	18.3688	159.1844
180	2.5777	0.1973	6	0.77	36.5447	168.2724
173	2.9652	0.2270	6.5	0.74	47.2402	173.6201

Figure 12-21: maximum-film-pressure ratio

$$\frac{p}{p_{max}} = 0.3$$

$$p_{max} = 555.5556 \text{ psi}$$

The peak film pressure:

$$p_{total} = p_{max} + p_s = 555.5556 \text{ psi} + 60 \text{ psi} = 615.5556 \text{ psi}$$

The minimum film thickness:

$$h_0 = (1 - \epsilon)c = 5.98 \times 10^{-4} \text{ in}$$

The lubricant side-flow rate:

$$Q_s = \frac{\pi p_s r c^3}{3\mu l'}(1 + 1.5\epsilon^2) = 0.5870 \text{ in}^3/\text{s}$$

The heat loss rate:

$$H_{loss} = \rho C_p Q_s \Delta T = 0.3622 \text{ Btu/s} = 1303.9 \text{ Btu/h}$$

c (in)	T_{av} (°F)	p_{total} (psi)	$h_0(10^{-4})$ (in)	H_{loss} (Btu/h)	Q_s (in^3/s)
0.0015	198	580.8333	5.40	1046.6	0.2308
0.0023	173	615.5556	5.98	1303.9	0.5870

Comparison: The greater the clearance, the smaller the film temperature, the greater the peak film pressure, the greater the minimum film thickness, the greater the lubricant side-flow rate, and the greater the heat loss rate.

c. [minimum clearance]

Trial T_f	$\mu\,(10^{-6})$	S	$\frac{fr}{c}$	ϵ	ΔT_f	T_{av}
198	1.5961	0.3338	8	0.64	96.4480	198.2240

$$Q_s = 0.2308\ \text{in}^3/\text{s}$$

Figure 12-21: flow ratio

$$\frac{Q_s}{Q} = 0.80$$

The required capacity of the oil pump:

$$Q = 0.2885\ \text{in}^3/\text{s}$$

[maximum clearance]

Trial T_f	$\mu\,(10^{-6})$	S	$\frac{fr}{c}$	ϵ	ΔT_f	T_{av}
173	2.9652	0.2270	6.5	0.74	47.2402	173.6201

$$Q_s = 0.5870\ \text{in}^3/\text{s}$$

Figure 12-21: flow ratio

$$\frac{Q_s}{Q} = 0.84$$

The required capacity of the oil pump:

$$Q = 0.6988\ \text{in}^3/\text{s}$$

d. [minimum clearance]

$$H_{loss} = 1046.6\ \text{Btu/h}$$

[maximum clearance]

$$H_{loss} = 1303.9\ \text{Btu/h}$$

e. [minimum clearance]

$$h_0 = 5.40 \times 10^{-4}\ \text{in} > 0.002 + 0.00004 \cdot d = 3.200 \times 10^{-4}\ \text{in}$$

$$T_{max} = T_s + \Delta T = 150°\text{F} + 96.4480°\text{F} = 246.4480°\text{F} < 250°\text{F}$$

[maximum clearance]

$$h_0 = 5.98 \times 10^{-4}\ \text{in} > 0.002 + 0.00004 \cdot d = 3.200 \times 10^{-4}\ \text{in}$$

$$T_{max} = T_s + \Delta T = 150°\text{F} + 47.2402°\text{F} = 97.2402°\text{F} < 250°\text{F}$$

Therefore, the bearing will survive the operation.