2.72 Elements of Mechanical Design
Spring 2009

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Elements of Mechanical Design

Lecture 07: Rolling contact bearings

Schedule and reading assignment

Quiz

- Constraints

Topics

- Bearing types & failure modes
- Experimental results to modeling
- Bearing load-life-reliability
- Start spindle exercise

Reading assignment

- None, work on getting bearings d

Quiz Tuesday

- Bearings (conceptual)

www.renault4.co.uk/

Courtesy of Clementine's Renault 4 Garage. Used with permission.

Besides the children's toy (sorry bout that), what do you notice about the bearing that should be of import?

Loose ends

Thermal stability

- Function of separation distance and contact geometry - cancellation
- Will you always have bearing death if it is not thermally stable?

$$\dot{q} = \frac{\Delta T}{R_T}$$

$$R_{T-Conv} = \frac{1}{h\,A_{surface}}$$

$$R_{T-Cond} = \frac{t}{k\,A_{cross}}$$

Mounting of races: Inside rotating vs. outside rotating

- Friction torques
- Look at the tapered roller example from lab

Rough design steps – Inherently iterative

Step 1: Functional requirements

- DOF
- Stiffness
- Lifetime/reliability
- Etc…

Iteration

Step 2: Bearing type/layout

Step 3: System design & mfg issues

- Housing geometry
- Shaft deflection
- Thermal

Shaft geometry

Preload

Tolerances

Step 4: Assembly specifications

Types of rolling contact bearings

Examples of rolling element bearings

Images removed due to copyright restrictions. Please see:

http://www.timken.com/en-us/products/bearings/productlist/ball/PublishingImages/radialball_150.jpg

http://images.machinedesign.com/images/archive/news1300jpg_00000036367.jpg

http://www.bearingsworld.com/image/pic-cp02.jpg

http://www.rlmcor.com/image-product/23134mbw33.jpg

Elements: Rotary rolling contact bearing

Inner

- Ring Race

Outer

- Ring Race

Diameters

- Outer Bore

Ball/roller

Cage/separator

Face

Width

Figure by MIT OpenCourseWare.

Bearing failure: Causes and failure mode

Cracks in bearings elements

Images removed due to copyright restrictions. Please see

http://www.amstedrail.com/techinfo/media/94_1f5b.jpg

http://www.amstedrail.com/techinfo/media/94_1f2d.jpg

Failure mode: Spalling

http://www.tsb.gc.ca

Courtesy the Transportation Safety Board of Canada.

Image removed due to copyright restrictions. Please see

http://www.theautoist.com/Bearing5.JPG

Causes of spalling

Spalling

- Surface fatigue that occurs as a result of contact

http://www.tsb.gc.ca

Courtesy the Transportation Safety Board of Canada.

Seeds of failure

- Crack growth
- Inclusions
- Impact
- Cyclic high stress
- Degradation of the lubricant

Steel quality key to making long-lasting bearings

Once it starts, what happens?

- Minor spalling + correct problem may slow/stop
- Typically increases in size with continued service

Image removed due to copyright restrictions.
Please see:
http://www.theautoist.com/Bearing5.JPG

Preload

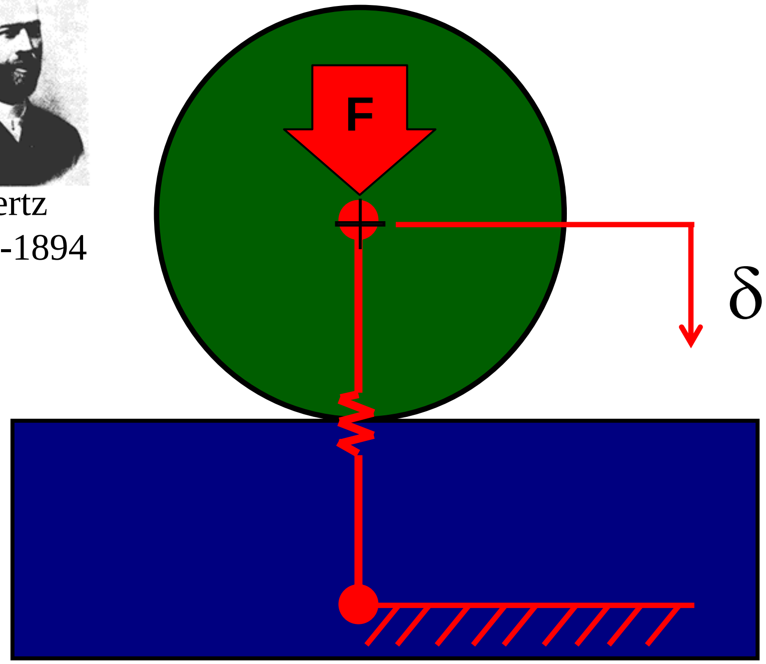
Ball-flat elastomechanics: Hertz contact

Model ball-groove contacts as six balls on flats

Hertzian contacts act as non-linear springs

Figure by MIT OpenCourseWare.

Hertz
1857-1894



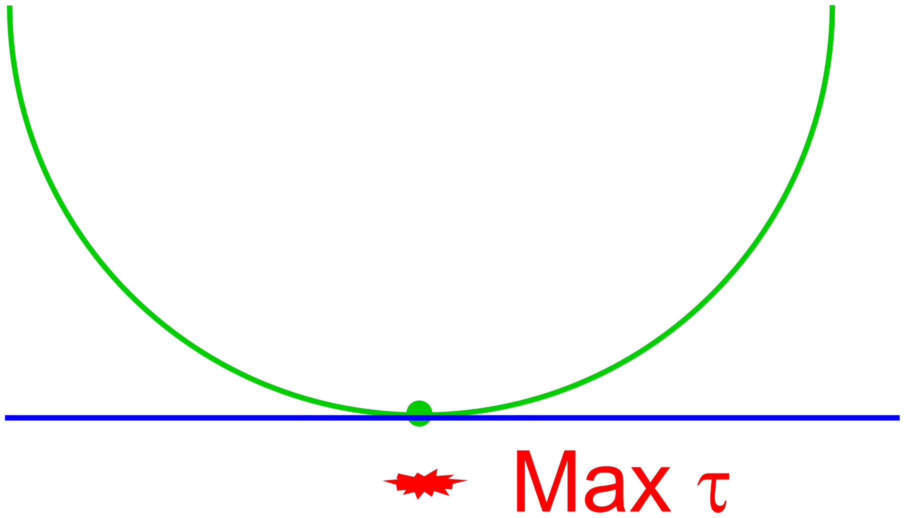
Important relationships for ball-flat contact

$$k_n = 2 \cdot \delta^{1/2} \cdot R^{1/2} \cdot E_e$$

Location, magnitude of max shear stress

Equivalent radius

$$R_e = \frac{1}{\frac{1}{R_{1major}} + \frac{1}{R_{1\min or}} + \frac{1}{R_{2major}} + \frac{1}{R_{2\min or}}}$$



Equivalent modulus

$$E_e = \frac{1}{\frac{1-\eta_1^{\ 2}}{E_1} + \frac{1-\eta_2^{\ 2}}{E_2}}$$

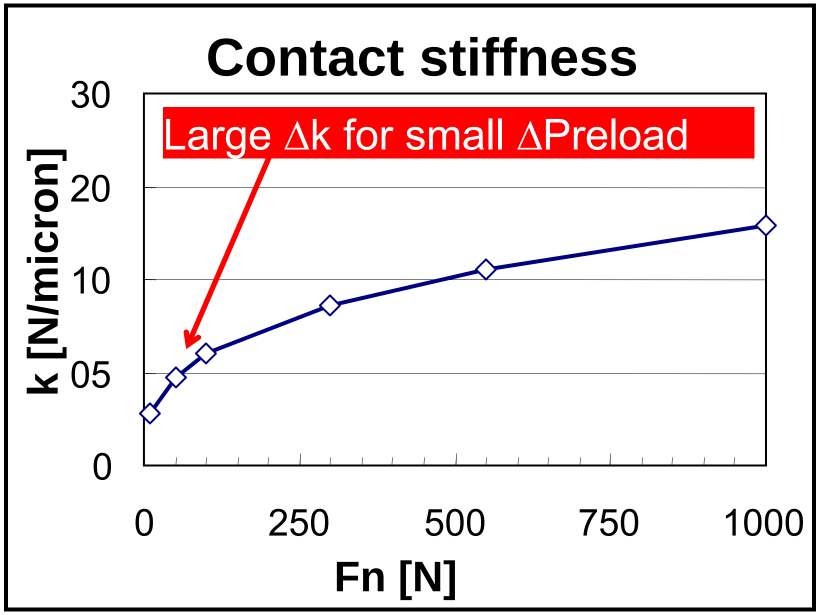
Max shear stress occurs below surface, in the member with largest R if ball and flat of same material

$$\tau_{\max}\Big|_{depth=0.48\cdot contact\ radius}^{center\ of\ contact} = 0.31 \cdot \frac{1}{\pi} \cdot \left(\frac{6 \cdot F \cdot E_e^{\ 2}}{R_e^{\ 2}} \right)^{\frac{1}{3}}$$

Sensitivity of contact stiffness to ΔF

Preload increases stiffness

$$k_n = \mathrm{K_o} \cdot \left(R_e^{1/3} \cdot E_e^{2/3} \right) \cdot F_n^{1/3}$$



A little preload goes a long way

Classes of preload, as % of static load capacity

- Heavy 5%
- Medium 3%
- Light 2%

How do you preload a bearing?

Direct

- Nuts pressing directly on races
- Uses compliance of contacts

Many bearings come preloaded "out of the box"

Check to make sure so that you do not add preload that will act to overload

Internal

- Oversized balls
- Uses compliance of ball-race contacts

Figure by MIT OpenCourseWare.

Nuts-springs

- Spring in series with bearing
- Primarily uses compliance of spring

Think in terms of relative stiffness because…

- Sensitivity of force to the displacement…

Bearing life and reliability

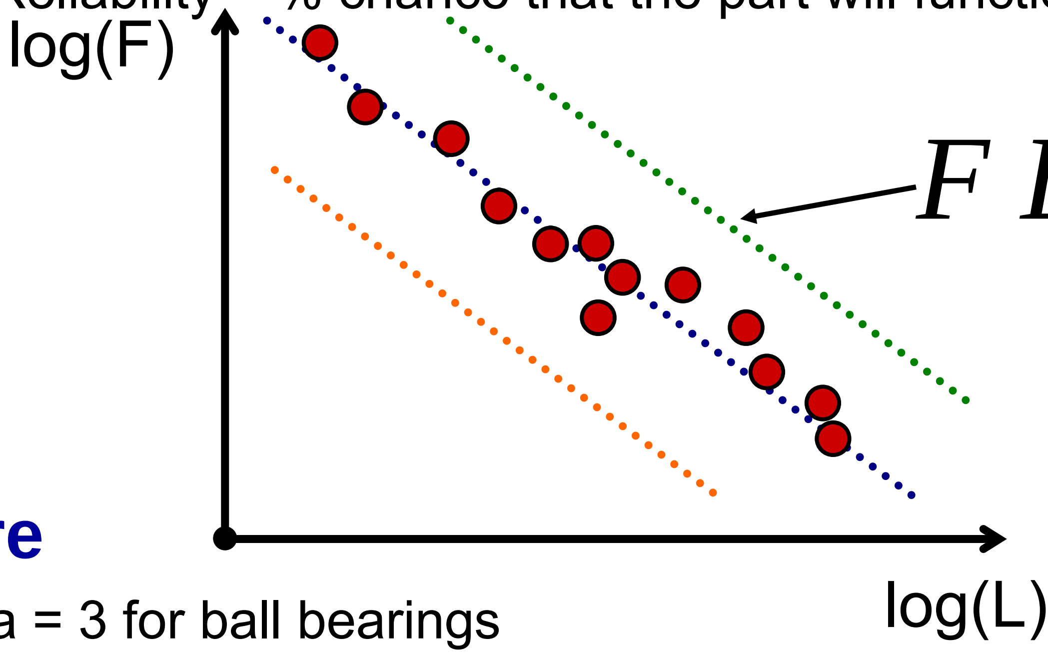
Bearing life at rated reliability

Bearing life depends on:

- Load and revolutions

From experimentation: For a given R, linear log behavior

- Reliability = % chance that the part will function as expected



$$F L^{\frac{1}{a}} = \psi$$

Where

- a = 3 for ball bearings
- a = 3.333 for roller bearings

Figure by MIT OpenCourseWare.

Regression fit to experimental data

Manufacturers provide a match of:

- Cycle rating: Revolutions — For example 10^6 or 90^6 revs
- Load rating: Force — Anything…

that defines bearing failure for a given reliability

This is for common reliability

Given these two numbers, and:

Units of force

Units of revolutions

$$F \, L^{\frac{1}{a}} = \psi$$

Constant

This may be used to extrapolate behavior at different loads and revs

Why C vs. F?

$$C_i \, L^{\frac{1}{a}}{}_i = F_{design} \, L^{\frac{1}{a}}{}_{design}$$

Design life in terms of hours or revolutions?

We can think in terms of life as time if:

$$t[hr] \; \omega\left[\frac{rev}{\min}\right] \; 60\left[\frac{\min}{hr}\right] = L$$

Dynamic load rating

Revs at failure

Be careful with units

$$C_{10} L_{10}^{\frac{1}{a}} = F_{design} L^{\frac{1}{a}}_{design} = F_{design} (t \; \omega \; 60)^{\frac{1}{a}}$$

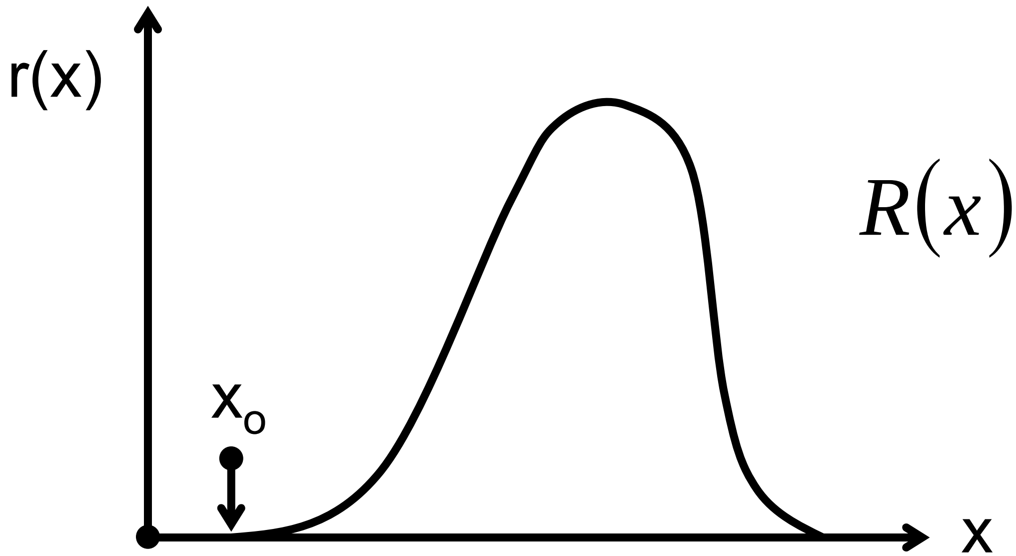
$$C_{10} (t_{rated} \; \omega_{rated} \; 60)^{\frac{1}{a}} = F_{design} (t_{design} \; \omega_{design} \; 60)^{\frac{1}{a}}$$

$$C_{10} = F_{design} \frac{(t_{design} \; \omega_{design} \; 60)^{\frac{1}{a}}}{(t_{rated} \; \omega_{rated} \; 60)^{\frac{1}{a}}}$$

Reliability vs. life

Reliability often well-predicted via Weibull distribution

- x_o = minimum guaranteed value of x
- θ = corresponds to 63.2 percentile of the variate (stochastic variable)
- b = a shape parameter (controls skew, large = right)



$$R(x) = \exp\left[-\left(\frac{x - x_o}{\theta - x_o}\right)^b\right]$$

This is for common load on bearings

- For bearings, we use this as:

$$x = \frac{L}{L_{10}}$$

Commonly used to fit experimental data; b & θ come from fit

Relationship between load, life and reliability

BUT the catalogue never tells me what happens for….

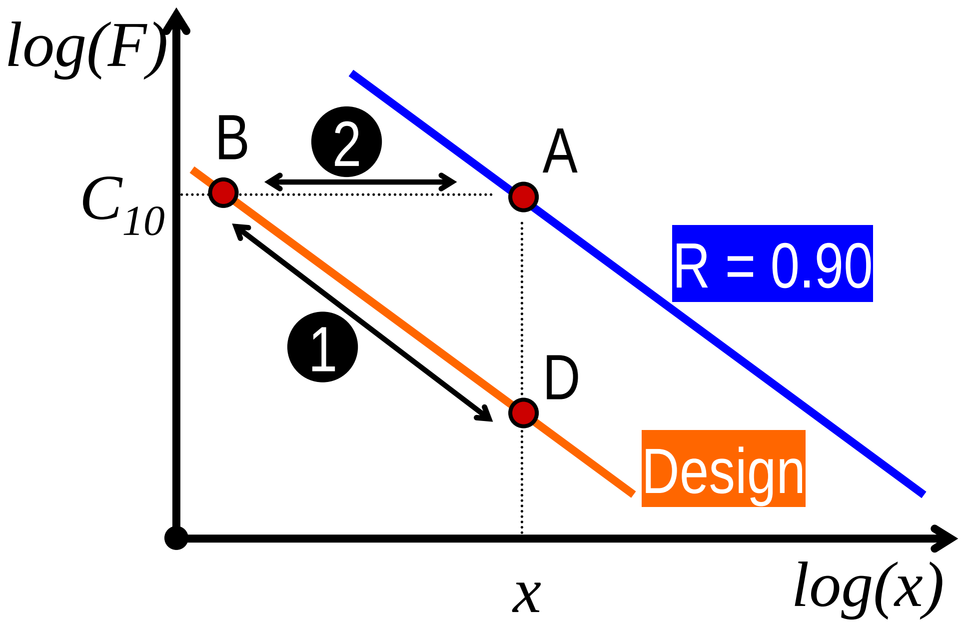
- My exact desired load
- My exact desired life
- Situations when I want a reliability that is different than R = 0.90

$$\text{Constant reliability:}$$

❶ $$F_B \, x_B^{\frac{1}{a}} = \psi = F_D \, x_D^{\frac{1}{a}}$$

$$\text{Constant load}$$

❷ $$R(x) = \exp\left[-\left(\frac{x_B - x_o}{\theta - x_o}\right)^b\right]$$

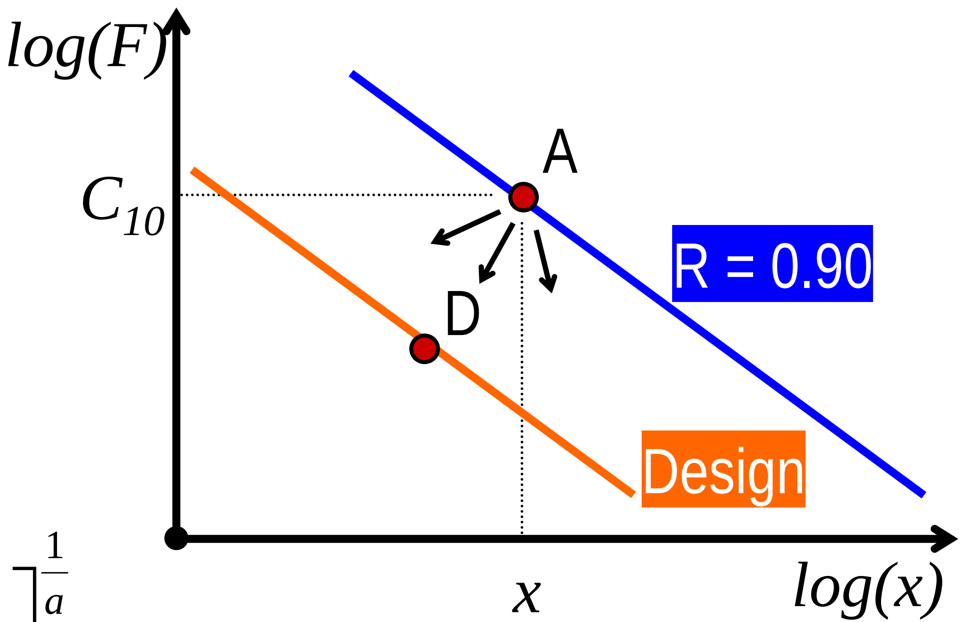


$$x = \frac{L}{L_{PF}}$$

Relationship between load, life and reliability

Load as a function of reliability & vice versa for given:

- C_{10}
- L_{10}
- R = 0.90; x = 1 when L = L_{10}



$$x = \frac{L}{L_{PF}}$$

$$C_{10} = F_D \left[\frac{x_D}{x_O + (\theta - x_O)\left(\ln\left\langle \frac{1}{R_D} \right\rangle \right)^{\frac{1}{b}}} \right]^{\frac{1}{a}}$$

Reliability of multi-bearing sets

What is the reliability of:

- One bearing?
- A spindle with two bearings?
- With N bearings?

For first order design, how should individual bearing reliability scale as a function of N?

How to handle combined loading

So far we have only considered radial loading…

What about combined radial, Fr, and axial loading , Fa?

- Use an equivalent load, Fe, that does the same amount of damage.

$$F_e = X_i \; V \; F_r + Y_i \; F_a$$

Where V = 1.2 for outer ring rotation and 1 for inner ring

- This has to do with the fact that outer ring fails more often

X_i and Y_i are a function of the

- Axial load, Fa
- Static load rating, Co

Figure by MIT OpenCourseWare.

Other issues, Shigley/Mischke covers well

Life recommendations (hrs)

❑ Aircraft engines	0 500	–	2 000
❑ 24-hour critical service	100 000	–	200 000

Application factors

❑ General commercial	1.1 – 1.3
❑ Moderate impact	1.5 – 3.0

Group exercise

Work on your spindle housing-shaft-bearing design

- Constraint layout
- Loads
- Preload
- Thermal stability
- Cost