

2.72

*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 de

Quiz Tuesday

- ❑ Bearings (conceptual)



www.renault4.co.uk/

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...

Step 2: Bearing type/layout

Step 3: System design & mfg issues

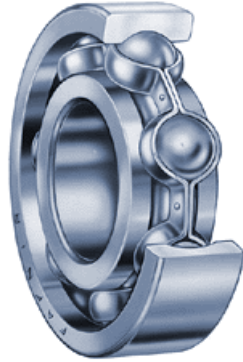
- | | |
|--------------------|----------------|
| ❑ Housing geometry | Shaft geometry |
| ❑ Shaft deflection | Preload |
| ❑ Thermal | Tolerances |

Step 4: Assembly specifications

Iteration

*Types of rolling contact
bearings*

Examples of rolling element bearings



static.howstuffworks.com



www.gm-exports.com/



www.machinedesign.com



www.bearingsworld.com

Elements: Rotary rolling contact bearing

Inner

- Ring

Race

Outer

- Ring

Race

Diameters

- Outer

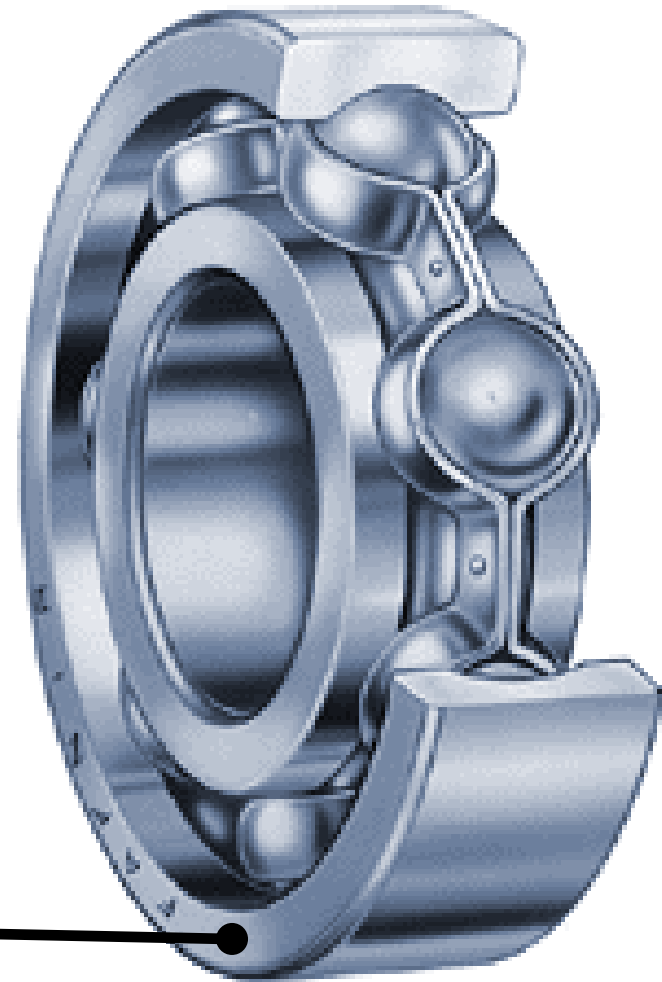
Bore

Ball/roller

Cage/separator

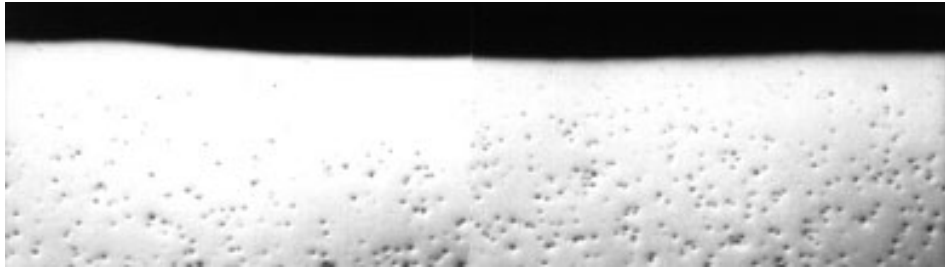
Face

Width

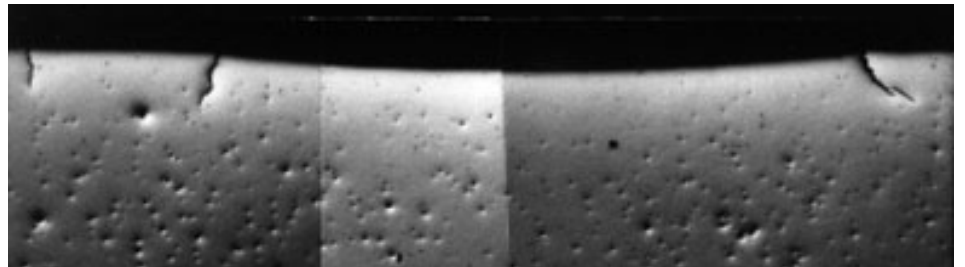


*Bearing failure:
Causes and
failure mode*

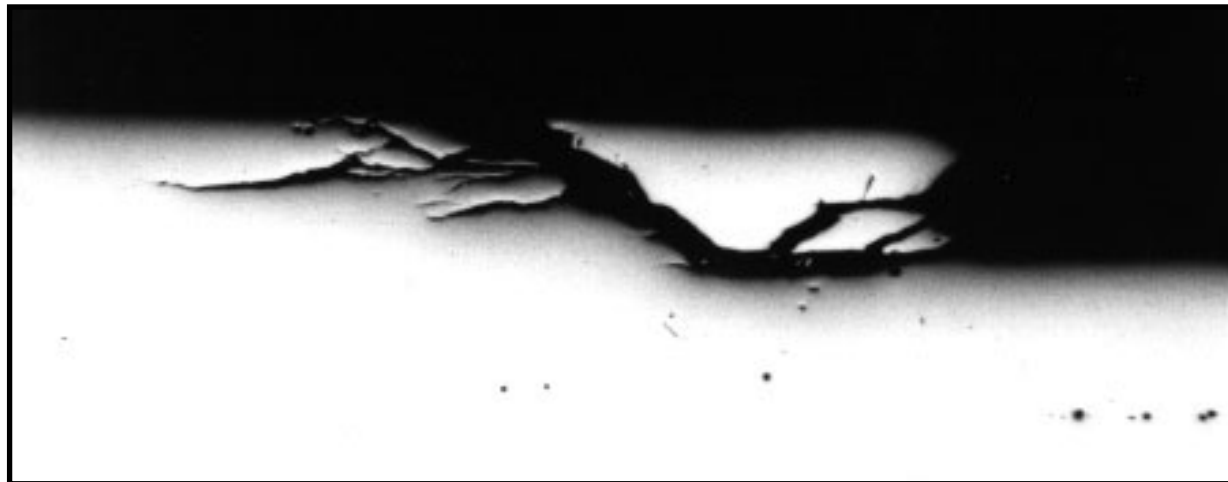
Cracks in bearings elements



Brinelling of surface



Brinelling plus cracks



Subsurface face fatigue crack that has progressed to surface. Magnification 100X

Failure mode: Spalling



<http://www.tsb.gc.ca>



<http://www.tsb.gc.ca>

Causes of spalling

Spalling

- ❑ Surface fatigue that occurs as a result of contact

Seeds of failure

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

Steel quality key to making long-lasting bearings



<http://www.tsb.gc.ca>

Once it starts, what happens?

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



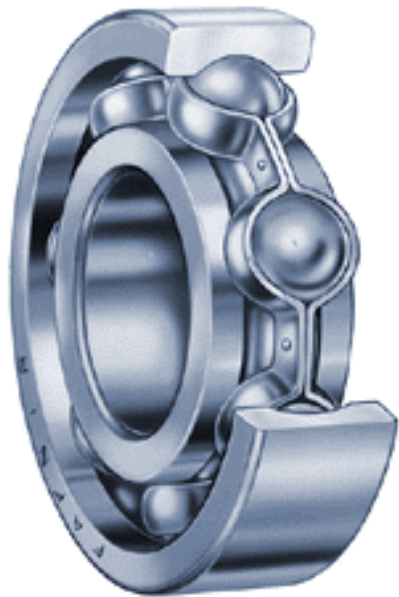
<http://www.tsb.gc.ca>

Preload

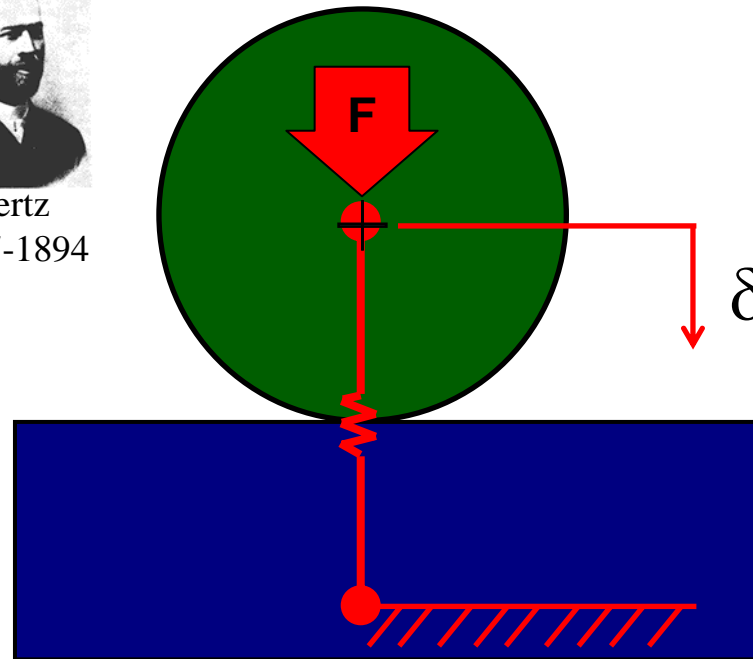
Ball-flat elastomechanics: Hertz contact

Model ball-groove contacts as six balls on flats

Hertzian contacts act as non-linear springs



Hertz
1857-1894



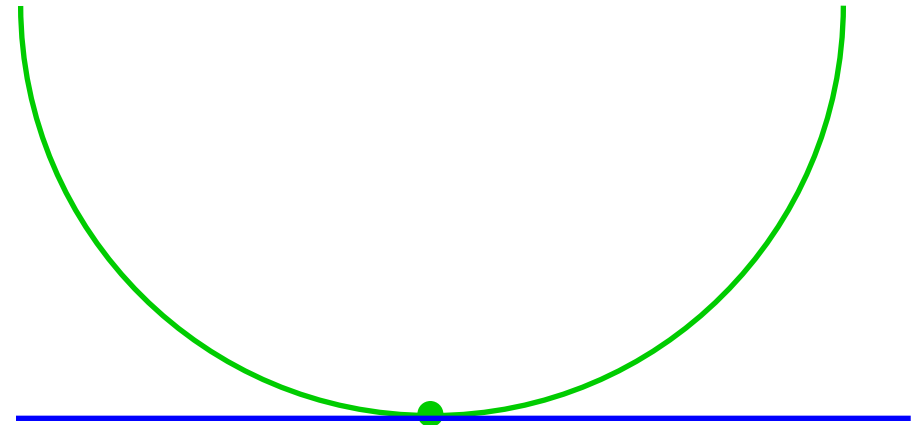
Important relationships for ball-flat contact

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

Location, magnitude of max shear stress

Equivalent radius

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



Max τ

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

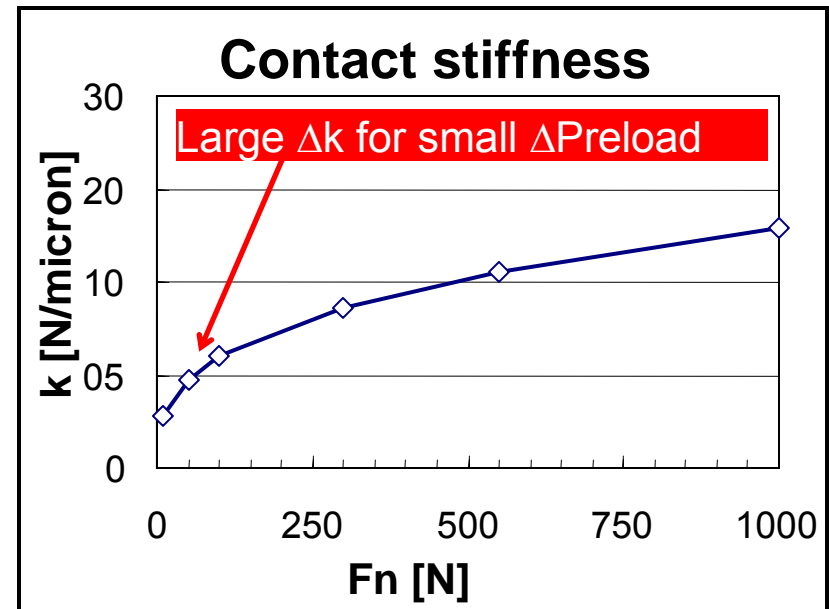
$$\tau_{\max} \left| \begin{array}{l} \text{center of contact} \\ \text{depth} = 0.48 \cdot \text{contact radius} \end{array} \right. = 0.31 \cdot \frac{1}{\pi} \cdot \left(\frac{6 \cdot F \cdot E_e^2}{R_e^2} \right)^{\frac{1}{3}}$$

Sensitivity of contact stiffness to ΔF

Preload increases stiffness

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

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

Internal

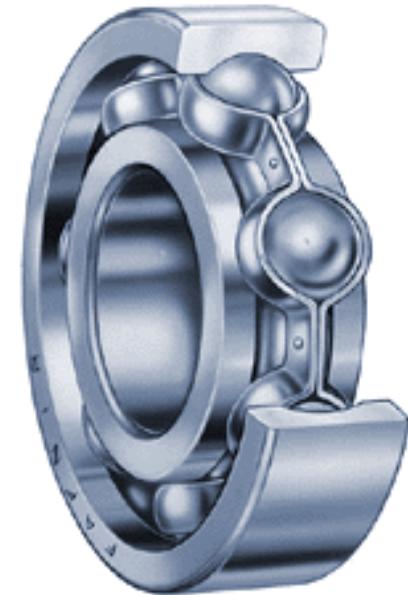
- ❑ Oversized balls
- ❑ Uses compliance of ball-race contacts

Nuts-springs

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

Many bearings come preloaded “out of the box”

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



Think in terms of relative stiffness because...

- ❑ Sensitivity of force to the displacement...

*Bearing life and
reliability*

Bearing life at rated reliability

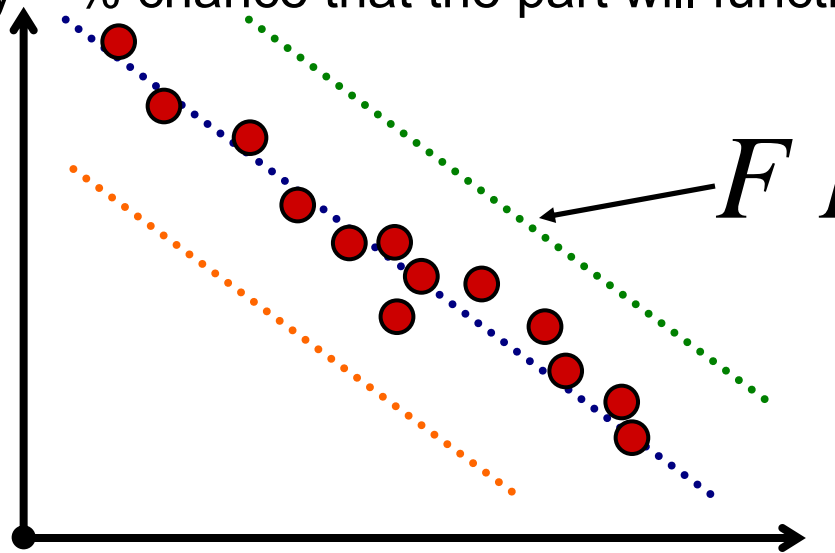
Bearing life depends on:

- Load and revolutions

From experimentation: For a given R, linear log behavior

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

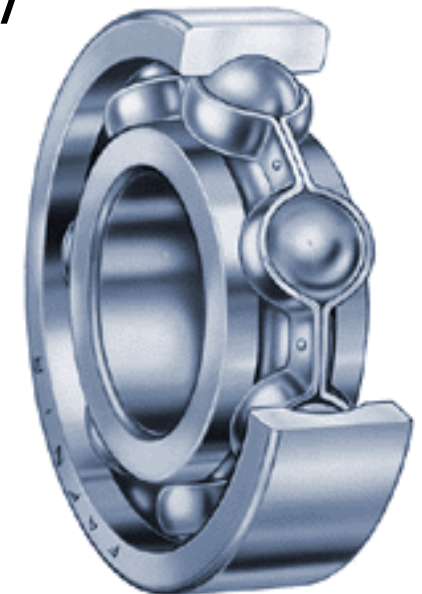
$\log(F)$



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

Where

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



Regression fit to experimental data

Manufacturers provide a match of:

- ❑ Cycle rating: Revolutions
- ❑ Load rating: Force

For example 10^6 or 90^6 revs
Anything...

that defines bearing failure for a given reliability

This is for common reliability

Given these two numbers, and:

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

Units of force → F Units of revolutions → $L^{\frac{1}{a}}$ Constant → ψ

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

$$C_i L_i^{\frac{1}{a}} = F_{design} L_{design}^{\frac{1}{a}}$$

Why C vs. F? → C_i

Design life in terms of hours or revolutions?

We can think in terms of life as time if:

$$\text{Dynamic load rating} \quad t [hr] \quad \omega \left[\frac{rev}{min} \right] \quad 60 \left[\frac{min}{hr} \right] = L$$

Revs at failure

Be careful with units

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

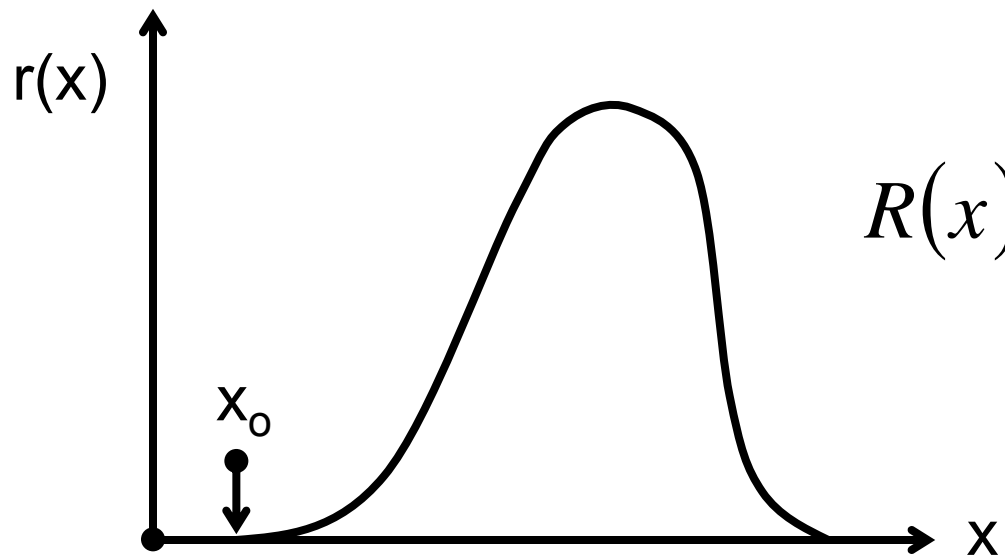
$$C_{10} (t_{rated} \omega_{rated} 60)^{\frac{1}{a}} = F_{design} (t_{design} \omega_{design} 60)^{\frac{1}{a}}$$

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

Reliability vs. life

Reliability often well-predicted via Weibull distribution

- x_0 = minimum guaranteed value of x
- θ = corresponds to 63.2 percentile of the variate (stochastic variable)
- b = a shape parameter (controls skew, large = right)



$$R(x) = \exp \left[- \left(\frac{x - x_0}{\theta - x_0} \right)^b \right]$$

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....

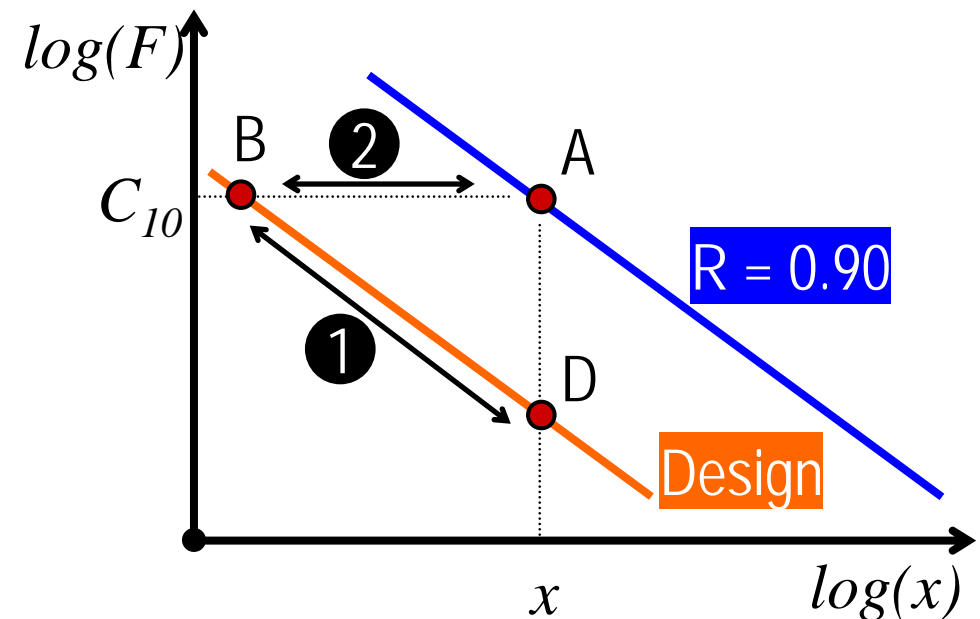
- ❑ My exact desired load
- ❑ My exact desired life
- ❑ Situations when I want a reliability that is different than $R = 0.90$

Constant reliability :

$$\textcircled{1} \quad F_B x_B^{\frac{1}{a}} = \psi = F_D x_D^{\frac{1}{a}}$$

Constant load

$$\textcircled{2} \quad R(x) = \exp \left[- \left(\frac{x_B - x_o}{\theta - x_o} \right)^b \right]$$

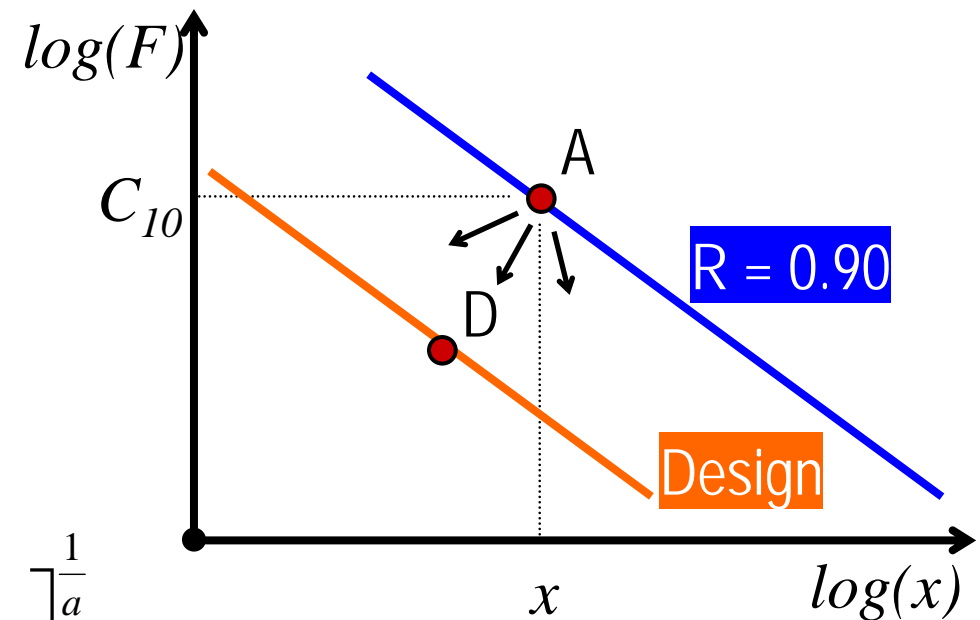


$$x = \frac{L}{L_{PF}}$$

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 $L = L_{10}$



$$C_{10} = F_D \left[\frac{x_D}{x_0 + (\theta - x_0) \left(\ln \left\langle \frac{1}{R_D} \right\rangle \right)^{\frac{1}{b}}} \right]^{\frac{1}{a}}$$

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

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, F_r , and axial loading, F_a ?

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

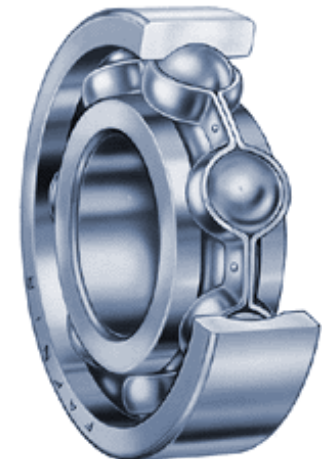
$$F_e = X_i V F_r + Y_i F_a$$

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, F_a
- Static load rating, C_o



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