Externally Pressurized Fluid Film Bearings

ME EN 7960 – Precision Machine Design

Topic 11

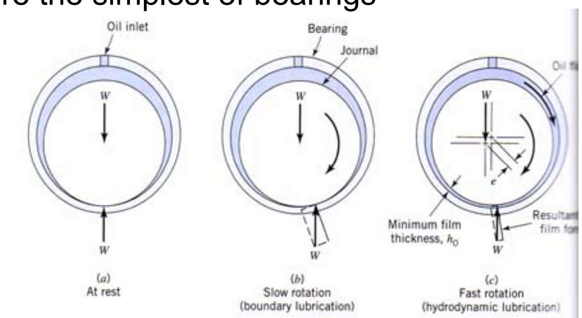
General Characteristics

- Bearings with an externally pressurized fluid film have no mechanical contact
  - Instead, bearing surfaces are separated by a thin fluid layer
- As a result, error motions are extremely small and the system is extremely well damped (harmonics die quickly)

Source: Alexander Slocum, *Precision Machine Design*

Hydrodynamic Bearings

- Viscous fluids are dragged between bodies as they move past each other, so the rotating shaft acts like a pump
- The pressure gradient is limited, and so is the load capacity and stiffness
- They are the simplest of bearings



Source: Juvinall RC, Marshek KM, *Fundamentals Of Machine Component Design*

Hydrodynamic Bearings

- Optimum speed is reached immediately after shaft has lifted off
  - Increasing speed further causes significant losses due to viscous friction
- Generally not useful for design that require a wide range of rotational speeds (e.g. spindles)
- Very useful for applications that require a single, constant speed (e.g. power generators)

Source: Juvinall RC, Marshek KM, *Fundamentals Of Machine Component Design*

Hydrostatic and Aerostatic Bearings

- Metered flow to each side of the bearing creates a pressure differential proportional to the displacement
- Load capacity and stiffness can be very high
- They require the expense of a clean pressure supply system

Overview

	Liquid (Oil, Water)	Gas (Air, Nitrogen)
Type	Capillary, orifice, slot or diaphragm restricted	Porous, orifice, or slot restricted
Typical applications	Large machining forces (Milling machines, etc.)	Moderate forces (Measuring equipment, grinding spindles, diamond turning)
Load capacity	Very high	Moderate
Stiffness	Very high	High
Damping	Very high	Moderate
Friction	Low at low speeds	Very low at all speeds

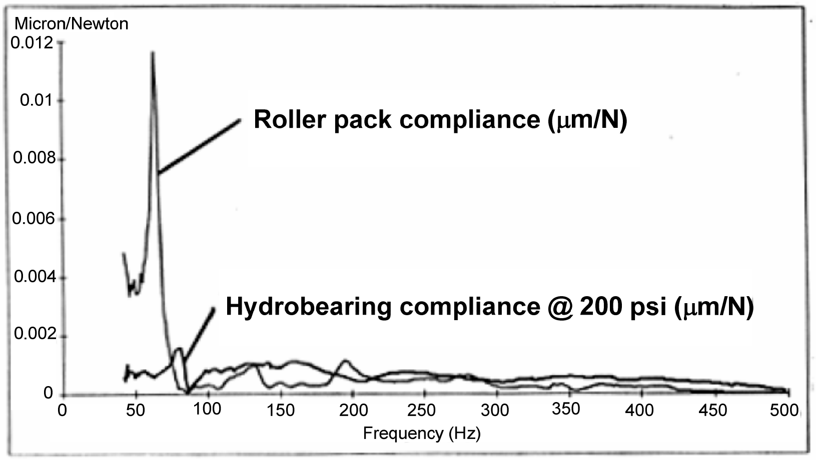
Performance

- Accuracy
  - Axial: Limited only by control system
  - Lateral: Limited by straightness of rails and isolation from pressure system
- Applied loads
  - Large surface area allows for high load capacity
  - Virtually insensitive to crashes
- Preload
  - Most designs are inherently preloaded
- Stiffness
  - Easily made many times greater than other components in the machine
  - Dynamic stiffness is very high due to squeeze film damping

Performance (contd.)

- Vibration and shock resistance
  - Excellent for liquid bearings
  - Modest-to-poor for gas bearings
- Damping capability
  - Excellent normal to direction of motion, due to squeeze film damping
  - Low along direction of motion
  - Bearing area, gap, and stiffness must be considered to maximize squeeze film damping
  - Squeeze film damping greatly affects the dynamic stiffness

Performance (contd.)



Source: Alexander Slocum, *Precision Machine Design*

Performance (contd.)

- Friction
  - Zero static friction
  - Dynamic friction depends on gap and fluid viscosity
- Thermal performance
  - Finite dynamic friction coefficient generates heat
  - Fluid flowing at pressure released to atmospheric pressure shears and generates heat equal to pump power
  - A cooler is often needed to control fluid temperature
  - Expanding gas creates cooling (Joule Thompson cooling)

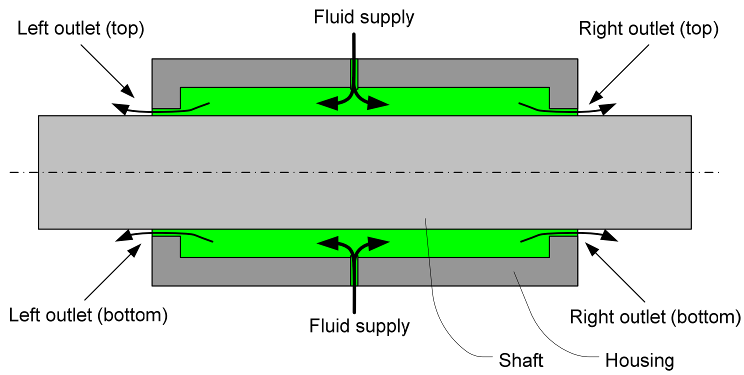
Performance (contd.)

- Environmental sensitivity
  - Very intolerant of dirt
  - Where the fluid has to flow past a tiny gap (a capillary or an orifice), it can clog
  - Gear pump flow-dividers and self-compensating bearings are "self cleaning“
  - A particle lodged in a small gap can score the bearing or the rail

Support Equipment

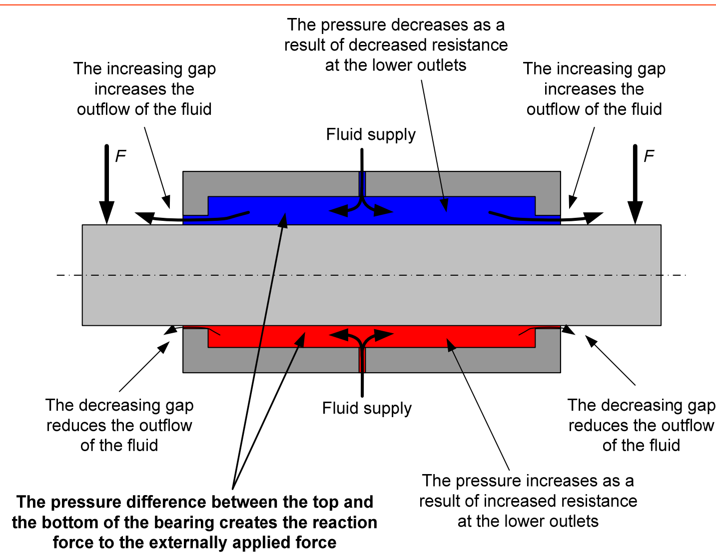
- Pumps
  - Screw-type pumps are most quiet
  - Piston pumps are noisiest
  - Accumulators and pressure relief valves are needed to keep pressure pulsations from increasing error motions
  - Pumps generate heat
  - If linear motors are used on the machine, they will require an order-of-magnitude more cooling than the hydrostatic bearings
- Filters
  - Air bearings ideally are fitted with desiccant dryers
  - Fluid bearings require filters
  - Water bearings require fluid chemistry control
  - Centrifugal filters work well, but are expensive
  - Cartridge filters must be changed

Theory of Fixed Compensation

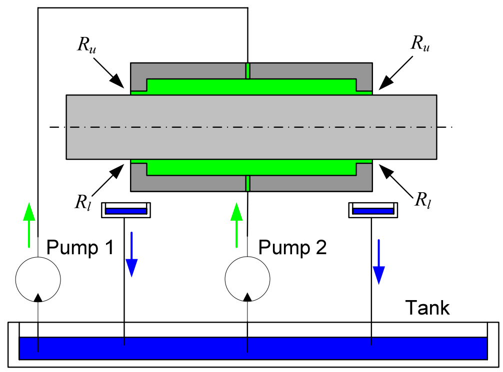


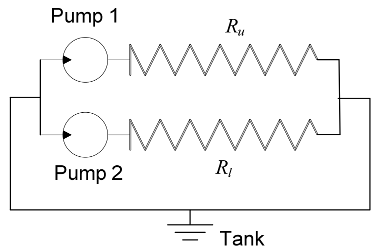
- Fluid flow into the bearing is regulated by a resistance that is created at the outlets of the bearing
  - outlets are formed by a small gap between the housing and the shaft

Theory of Fixed Compensation



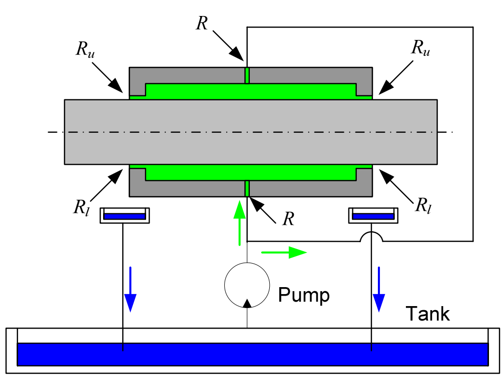
Theory of Fixed Compensation

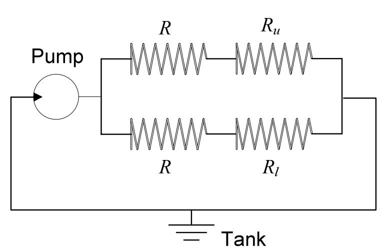




- If a bearing only regulates the outflow of the fluid, a separate pump for each side of the bearing is required to allow the pressure to be regulated independently

Theory of Fixed Compensation





- To eliminate the need for a separate pump for each bearing side, a resistance *R* at the inlets is added

Theory of Fixed Compensation (contd.)

- The difference in pressure between the upper and lower pads of the bearing is:

$$\Delta p = p_u - p_l = p_s\left(\frac{R_u}{R+R_u} - \frac{R_l}{R+R_l}\right)$$

- For a nominal gap *h* and small excursions δ of the structure:

$$R_u = \frac{\gamma}{(h-\delta)^3} \qquad R_l = \frac{\gamma}{(h+\delta)^3}$$

γ = constant of proportionality

- The difference in pressure across the bearing is:

$$\Delta p = p_s\gamma\left[\frac{1}{R(h-\delta)^3+\gamma} - \frac{1}{R(h+\delta)^3+\gamma}\right]$$

Theory of Fixed Compensation (contd.)

- If the inlet flow resistance *R* was zero, the bearing could support no load
- If the inlet flow resistance was infinite, the bearing could support no load
  - There must be some ideal inlet resistance (compensation) between these two extremes
- Taking the partial derivative of the pressure difference with respect to the inlet flow resistance;
  - Ignoring all terms with δ^2 and higher terms:

$$\frac{\partial \Delta p}{\partial R} = p_s\gamma h^2\left[\frac{-(h-3\delta)}{\left(Rh^2(h-3\delta)+\gamma\right)^2} - \frac{(h+3\delta)}{\left(Rh^2(h+3\delta)+\gamma\right)^2}\right]$$

Theory of Fixed Compensation (contd.)

- The "optimal" inlet flow resistance to maximize load capacity is:

$$R = \frac{\gamma}{h^3}$$

- A prime issue is the h^3 term
- The resistance of a capillary restrictor is proportional to $(D_{capillary}{}^4)^{-1}$
- There is the potential for a very high degree of sensitivity to manufacturing tolerances

Theory of Fixed Compensation (contd.)

- For an opposed pad bearing with supply pressure p_s and inlet restrictor resistance R, the total flow is

$$Q = \frac{p_s}{R}$$

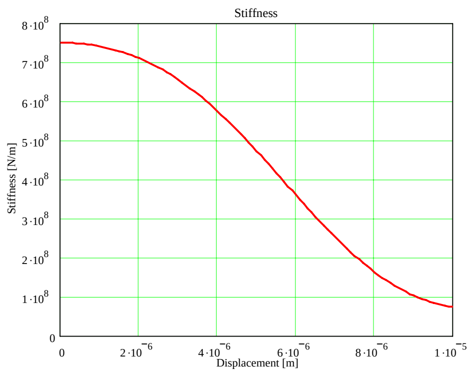
- Stiffness is the change in load for a given change in bearing gap ($A\partial(\Delta P)/\partial\delta$) where $A_{effective}$ is the effective bearing area

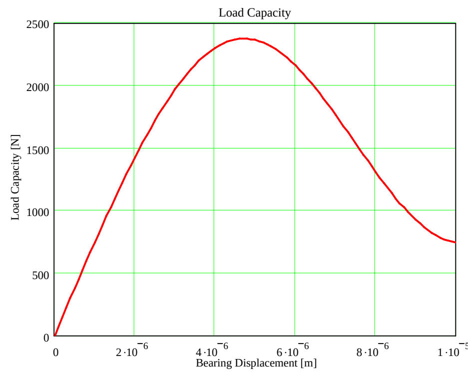
$$k = A_{effective}\frac{\partial \Delta p}{\partial \delta} = 3 p_s A_{effective} h^3 \left[\frac{(h-\delta)^2}{\left[(h-\delta)^3 + h^3\right]^2} + \frac{(h+\delta)^2}{\left[(h+\delta)^3 + h^3\right]^2} \right]$$

Example

- Supply pressure p = 2 MPa (= 20 bar)
- Bearing pad width a = 0.05 m
- Bearing pad length b = 0.05 m
- Bearing gap h = 10 μm

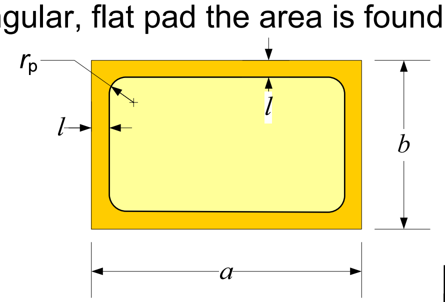
$$A_{effective} = ab = 0.00125m^2$$





Theory of Fixed Compensation (contd.)

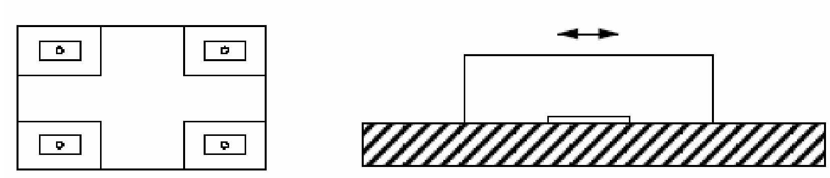
- Bearing effective area consists of the bearing pocket and portions of the land regions
- For a rectangular, flat pad the area is found as:



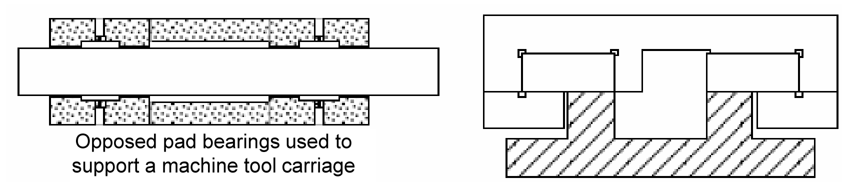
$$A_{effective} = (a-2l)(b-2l) + r_p^2(\pi - 4) + l\left[a + b - 4(l + r_p)\right] + \pi\left[\frac{l(2r_p + l)}{2\ln\left(\frac{r_p + l}{r_p}\right)} - r_p^2\right]$$

Some Examples

Single pad hydrostatic bearings to support a two degree of freedom plate:



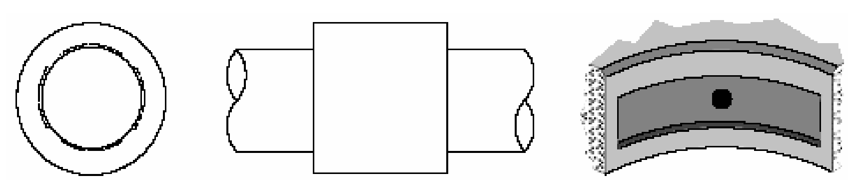
Opposed pad bearings used to support a machine toll carriage:



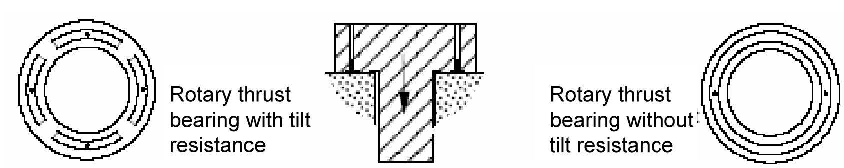
Source: Alexander Slocum, *Precision Machine Design*

Some Examples

Shaft supported by journal bearing:



Rotary thrust bearing:



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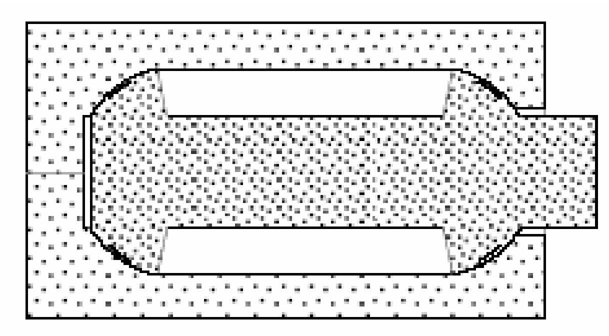
Some Examples

Spherical journal and thrust bearing:

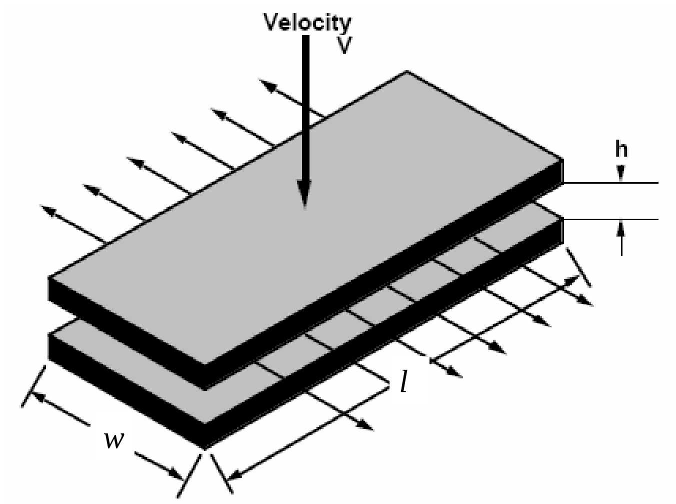


Source: Alexander Slocum, *Precision Machine Design*

Squeeze Film Damping

- The fluid between the lands and the bearing surface is essentially incompressible
- When high frequency (velocity) loads are applied, fluid particles must be squeezed out
- Viscous shear dominates fluid flow out of the land region
- Typical damping coefficients of systems with hydrostatic bearings are ζ = 0.1-1
- Geometric parameters involved in the calculation of the squeeze film damping constant:

Squeeze Film Damping



Source: Alexander Slocum, *Precision Machine Design*

Squeeze Film Damping

- Most of the damping area is rectangular
- The damping factor ξ is calculated as:

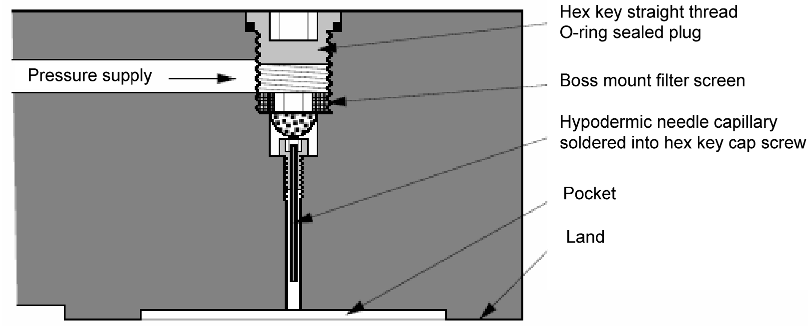
$$\xi = K_s \frac{\mu w^3 l}{h_0^3}$$

K_s is a geometric factor related to the bearing, μ is the viscosity

$$K_s = 0.7925 - \frac{1.1005}{e^{\frac{w}{l}}} + \frac{0.0216}{\frac{w}{l}} + 0.0153\frac{w}{l}$$

Capillary Compensation

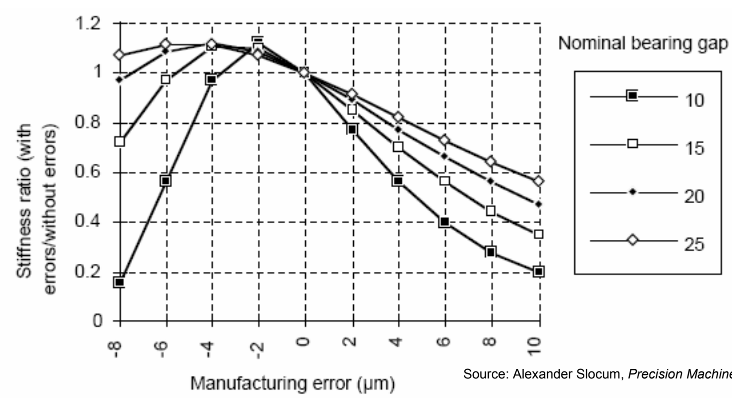
- Opposed pad, capillary restricted bearings are one of the most common hydrostatic bearing designs
- The flow resistance of a capillary is: $R = \dfrac{8l\mu}{\pi r_c^4}$
- Typical design:



Source: Alexander Slocum, *Precision Machine Design*

Capillary Compensation

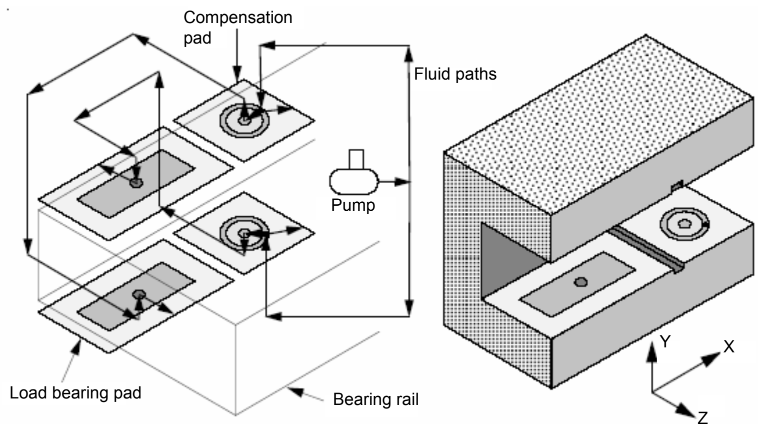
- If the gap should change significantly, however, stiffness can be rapidly lost
- Effect of mfg. errors on capillary compensated bearing:



Source: Alexander Slocum, *Precision Machine Design*

Self Compensation

- The bearing gap itself can be used as a means of regulating the flow of fluid to the opposed bearing



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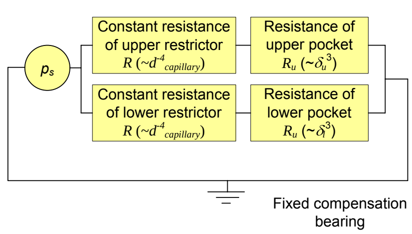
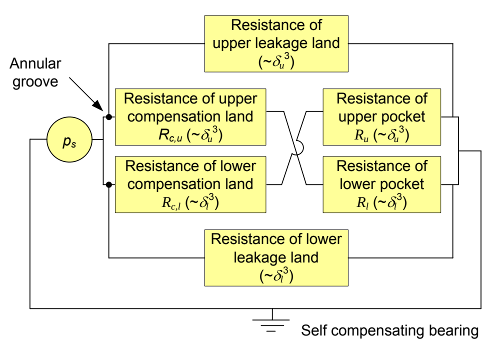
Self Compensation





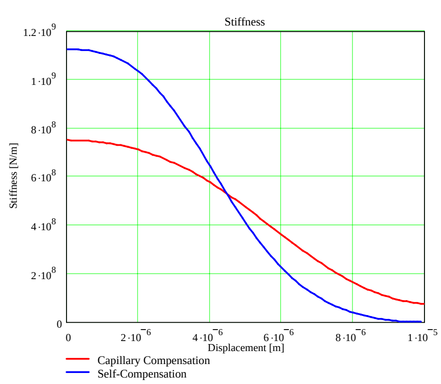
Adapted from: Alexander Slocum, *Precision Machine Design*

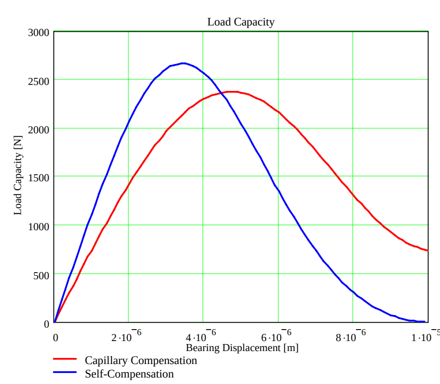
Self Compensation

$$k = 3A_{effective}\,p_s\left(\frac{\dfrac{\gamma}{(h-\delta)^4}-\dfrac{1}{(h+\delta)^4}}{(h+\delta)^3\left(\dfrac{\gamma}{(h-\delta)^3}+\dfrac{1}{(h+\delta)^3}\right)^2}+\frac{1}{(h+\delta)^4\left(\dfrac{\gamma}{(h-\delta)^3}+\dfrac{1}{(h+\delta)^3}\right)} - \frac{\dfrac{1}{(h-\delta)^4}-\dfrac{\gamma}{(h+\delta)^4}}{(h-\delta)^3\left(\dfrac{1}{(h-\delta)^3}+\dfrac{\gamma}{(h+\delta)^3}\right)^2}+\frac{1}{(h-\delta)^4\left(\dfrac{1}{(h-\delta)^3}+\dfrac{\gamma}{(h+\delta)^3}\right)}\right)$$

With γ = 3 for self-compensation

Capillary vs. Self-Compensation





p_s = 2E6 Pa a = 50mm
h = 10 μm b = 50 mm

Self Compensation vs. Capillary

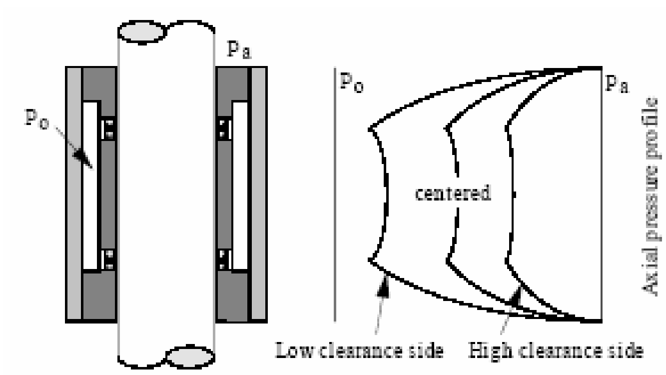
- It makes the system far less sensitive to contamination, especially if water is used
- It provides greater stiffness and load capacity
- It makes the system insensitive to manufacturing tolerances
- The bearings are self-tuning
  - The stiffness automatically optimizes itself for the bearing as soon as it is turned on
- No manual tuning of capillary or orifice size is required

Water vs. Oil

- In addition, it would be preferable to use water (or a water based coolant) instead of oil for the following reasons:
  - Environmentally friendlier
  - No fire hazard
  - Greater heat capacity, which minimizes temperature rise
  - Lower viscosity, which allows for higher speeds
  - Very tolerant of crosstalk between lubrication and coolant systems
- In order to use water, the gap must be small to keep flow rates reasonable
- Self compensated bearings are not significantly affected by large gap variations caused by manufacturing tolerances
  - Thus they are suitable for use with water as a bearing fluid

Aerostatic Bearings

- Aerostatic bearings utilize a thin film of high pressure air (typically 690 kPa) to support a load:



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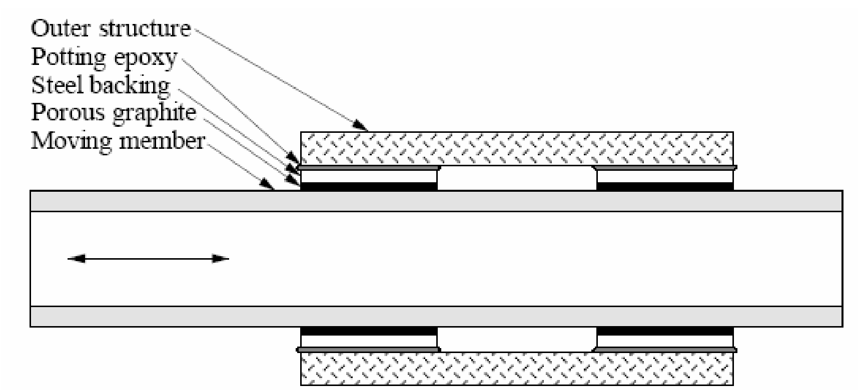
Aerostatic Bearings

- Since air has a very low viscosity, bearings gaps are small, on the order of 1-10 microns
- Aerostatic bearings can be configured in virtually all the ways hydrostatic bearings can
- Because air bearings have essentially zero friction and are very clean running:
  - They have extensive use in metrology equipment and in machines used in clean rooms

Making Aerostatic Bearings

- Modular fluidstatic bearing systems can be easily made from off-the-shelf components:
  - Porous graphite bearing pads (e.g., from Devitt Machinery in Aston PA)
  - Ceramic Hydroguide™ pads from Wilbanks International
  - Hollow alumina beams (e.g., from Wilbanks International in Hillsboro OR)
  - Hollow cast iron square tube (e.g., from Smith Tool Co. in Manasquan, NJ)
  - Epoxy potting compound (with metal fillers to increase modulus) (e.g., DWH epoxy from Devitt Machinery)

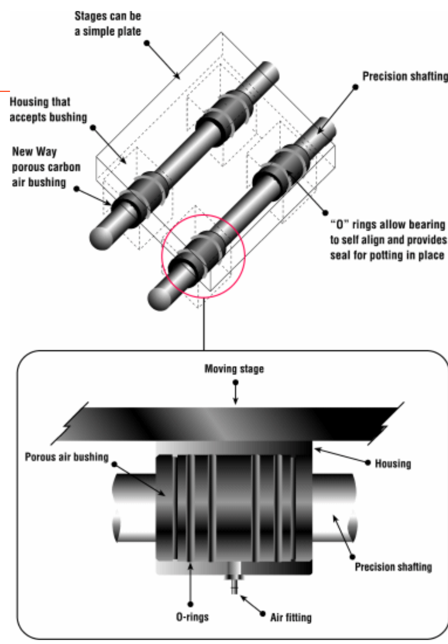
Making Aerostatic Bearings



Source: Alexander Slocum, *Precision Machine Design*

Assembly Procedure

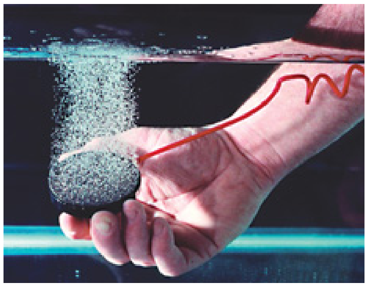
- The outside of the cast iron tube is finish ground
- The modular porous graphite air bearing pads are held to the precision alumina beam by a vacuum
- The beam is positioned with jigs with respect to the outside of the cast iron tube
- The potting epoxy is injected between the pads and the cast iron
- After curing, when the air is off, the alumina beam is locked in place (self-braking)
- When air is applied, the cast iron tube expands a few μm and the alumina beam floats



Source: New Way Airbearings

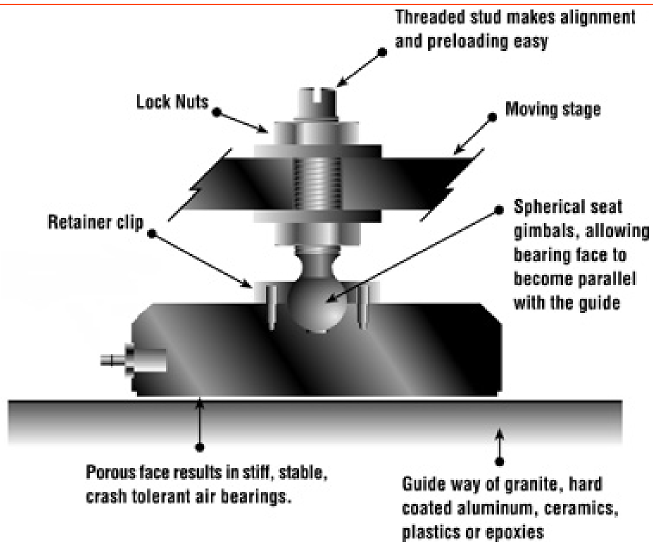
Porous Graphite Bearings

- The fluid film of the bearing is achieved by supplying a flow of air through the bearing itself to the bearing surface
- Unlike traditional 'orifice' air bearings, porous graphite bearings deliver the air through a porous medium to ensure uniform pressure across the entire bearing area
- The design of the air bearing is such that, although the air constantly dissipates from the bearing site, the continual flow of pressurized air through the bearing is sufficient to support the working loads



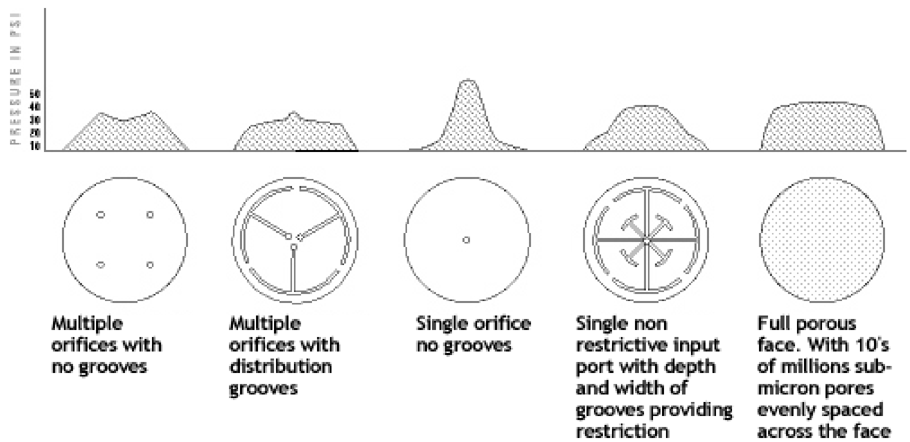
Source: New Way Airbearings

Schematic of a Flat Air Bearing



Source: New Way Airbearings

Pressure Distribution of Air Bearings



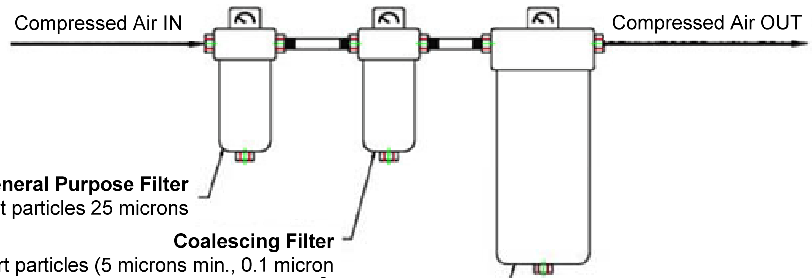
Source: New Way Airbearings

Supply Equipment

- Compressed air used to supply an air bearing must be properly cleaned and dried
- Air bearing performance and useful lifetime greatly depends on the quality of the compressed air
- An efficient system ensures minimum pressure loss, removal of contaminants such us water, oil, dirt, rust, and other foreign materials
- Particles will not affect the performance or life of porous air bearings, but oil and water will
- In order to ensure the specified performance and useful lifetime of the bearings, it is recommended that the following minimum criteria be met:

Source: New Way Airbearings

Supply Equipment



Adapted from New Way Airbearings