Flexures

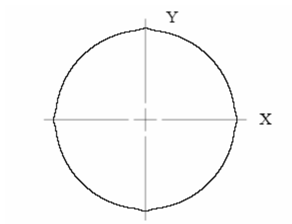
ME EN 7960 – Precision Machine Design
Topic 12

General

- Flexural Bearings are widely used in practice
- Application range from:
  - Flip-top on a shampoo bottle
  - Piezo-beams on a scanning tunneling microscope
- Because of the bending stresses created in the flexure, great care needs to be taken when designing these bearings
- Flexures, if designed properly, are very stiff & robust, light weight, maintenance free, and provide nanometer to sub-nanometer-level guiding precision (simple designs induce cosine runout errors)
- They are frictionless and do neither require lubricants nor air films

Friction in Conventional Linear Bearings

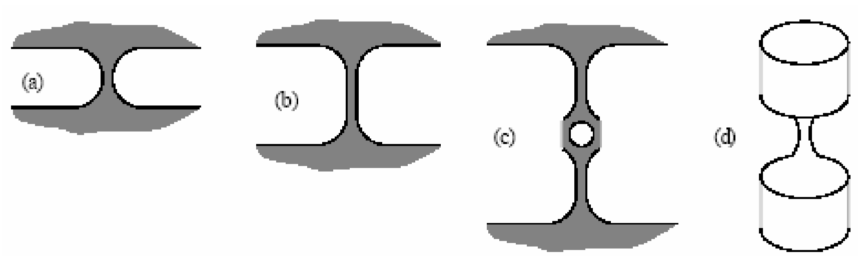
- Static friction approximately equals dynamic friction at low speeds, so stick slip is often minimized
- For heavily loaded tables, static friction is still significantly greater than dynamic friction
  - Errors will appear at velocity crossovers:



Source: Alexander Slocum, *Precision Machine Design*

Bearing	**"Dimple" size**
Sliding contact	10 – 20 μm
Recirculating rolling element	3 – 5 μm
Crossed rollers	1 – 2 μm
Hydrostatic or aerostatic	0 μm

Monolithic Design



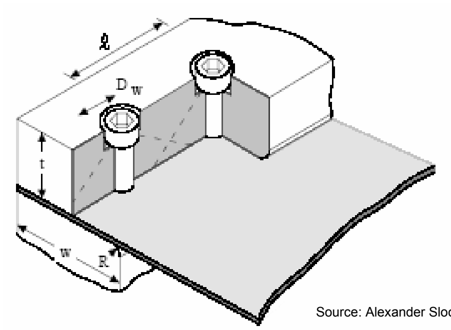
Source: Alexander Slocum, *Precision Machine Design*

- Most accurate
- Sometimes difficult to machine:
  - Abrasive water jet machining is an economical way to cut non-critical areas (links)
  - Wire EDM can be used for precision cuts in critical hinge areas

Monolithic Design

- May require localized heat treating of the material in the flexure
- Applications include flexural couplings, mirror mounts, STM's, and many others
- Size is about 20 times the range of motion

Clamp Design



Source: Alexander Slocum, *Precision Machine Design*

- Nanometer accuracy and better can be obtained if the bolted joint is properly designed
  - Rounded edges
  - Bolt cones-of-action overlap

Clamp Design

- Easy to assemble from annealed parts and hardened spring steel
  - Careful when tightening bolts, as the torque can twist the flexure
    - Lubricated thrust washers can help
- Care is required to make sure residual stresses don't create asymmetries that create parasitic error motions
  - Cut spring metal with EDM or WaterJet
  - Use dual lubricated washers under bolt heads and guides for clamp plates
- Applications include wafer steppers, mirror mounts, and many others
- Size is about 10 times the range of motion

Performance

Speed and acceleration limits

- Limited only by yield strength and design

Range of motion

- Typically used for motions less than a few millimeters
- Monolithic designs: flexure length/motion = 20 or more
- Clamped designs: flexure length/motion = 5-10

Applied loads

- Design goal is to obtain load capacity with minimum spring constant

Repeatability

- Axial: limited only by the drive system
- Lateral: less than nanometers for monolithic designs

Performance

Resolution

- Axial: limited only by the drive system

Preload

- Inherently preloaded

Stiffness

- The greater the motion and the lower the spring rate, the less the stiffness
- Theory of elasticity or finite element analysis yields very accurate predictions of performance
- Flexures often have low transverse stiffness, so they are more susceptible to parasitic forces

Vibration and shock resistance

- Very good

Performance

Damping capability

- Material damping only (2-5%)
- Damping mechanisms (constrained layer dampers) can be used to obtain high damping

Accuracy

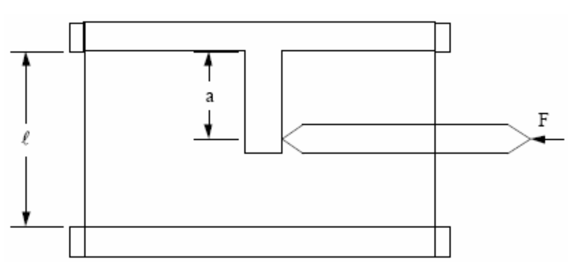
- Axial: limited only by the drive system
- Lateral: can be less than nanometers for monolithic designs
- Depends on how well the bearing was assembled or machined
- Even if there is a small off-axis error motion associated with the primary motion:
  - The error motion is usually very predictable and highly repeatable

Performance

- Flexural bearings cannot attain perfect motion because of:
  - Variation in spring strength
  - Elastic modulus varies with rolling direction in steels
  - Variation in spring geometry
  - Overall inaccuracies of manufacture
  - Bending of the bearing in an unintended manner
  - Bending of structure
  - External applied loads (e.g., gravity and the manner in which the actuation force is applied)

Performance

- The most common errors are the pitch angle and vertical motion
  - They accompany linear motion in a four bar linkage flexure
- For small displacements, the errors are a function of:



Source: Alexander Slocum, *Precision Machine Design*

Performance

- The distance moved x
- The length of the springs l
- The spring thickness t
- The platform length b
- The distance of force application *a* above the fixed end of the springs

$$\theta_{pitch} = \left(\frac{6(l - 2a)t^2}{3b^2 l - 2t^2 l + 6at^2} \right) \left(\frac{x}{l} \right) \qquad \delta_{vertical} \approx \frac{x^2}{2l}$$

- At $a = l/2$ there is no pitch error.

Performance

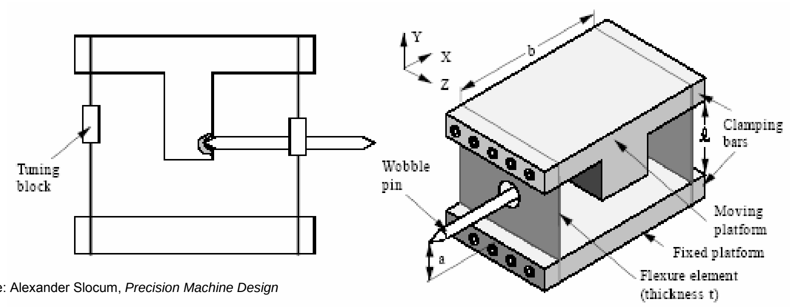
- If the force is applied at a point other than halfway between the platforms:
  - A bending moment is generated which causes a pitch error to occur
- The pitch errors caused by the difference in spring length and difference in platform length are respectively:

$$\theta_{spring} = \frac{\delta_{spring} x^2}{2l^2 b}$$

$$\theta_{platform} = \frac{\delta_{platform} x}{lb}$$

Types of Flexures

- 4 bar linkage



Source: Alexander Slocum, *Precision Machine Design*

- In the y direction there is a small error motion δ_y that is a function of the x motion δ_x and flexure length l:

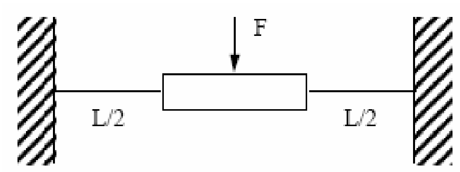
$$\delta_y \approx \frac{\delta_x^2}{2l}$$

Types of Flexures

- Consider other parasitic motions mentioned earlier
- x direction stiffness is equal to two fixed-fixed beams acting together in a side by side mode
- y direction stiffness is equal to that of two columns
- Buckling effect is negligible for small motions and should be prevented by the x direction servo

Minimize Errors

- To minimize parasitic motions:
  - Symmetrical dual four bar linkage eliminates δ_y error
  - Strains along flexure's length resisted by the frame
  - Stiffness is increased: range of motion is decreased



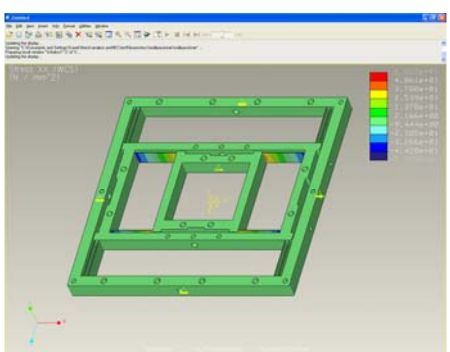
$$\delta = \frac{FL^3}{192EI}$$

Source: Alexander Slocum, *Precision Machine Design*

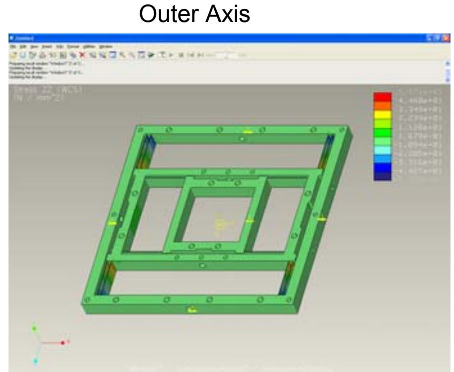
Minimize Errors

- Use a two stage (stacked) four bar linkage:

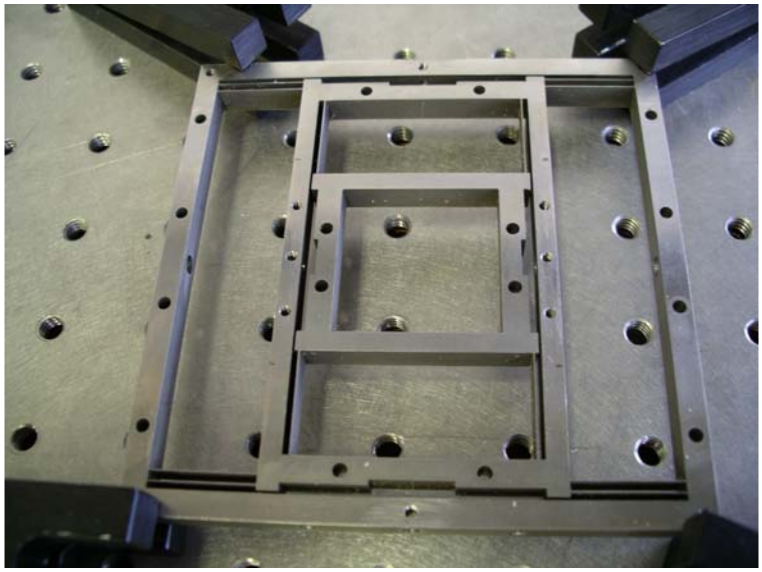
Inner Axis



Outer Axis

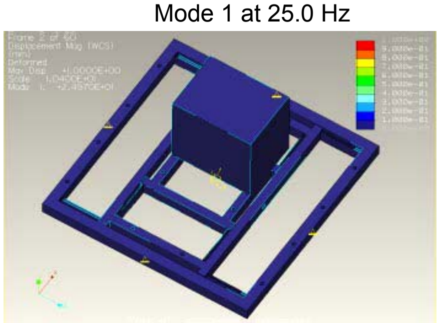


Stacked Axes

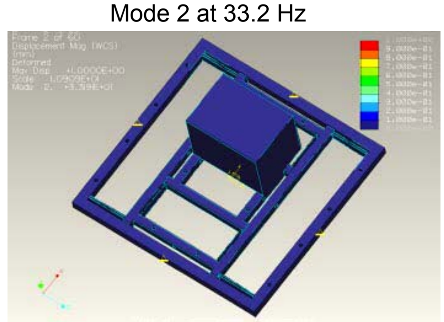


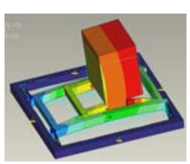
Modal Analysis

Mode 1 at 25.0 Hz

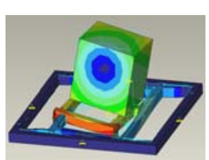


Mode 2 at 33.2 Hz

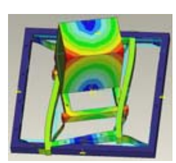




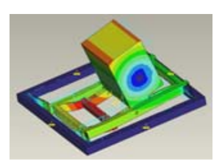
Mode 3: 319.7 Hz



Mode 4: 471.2 Hz

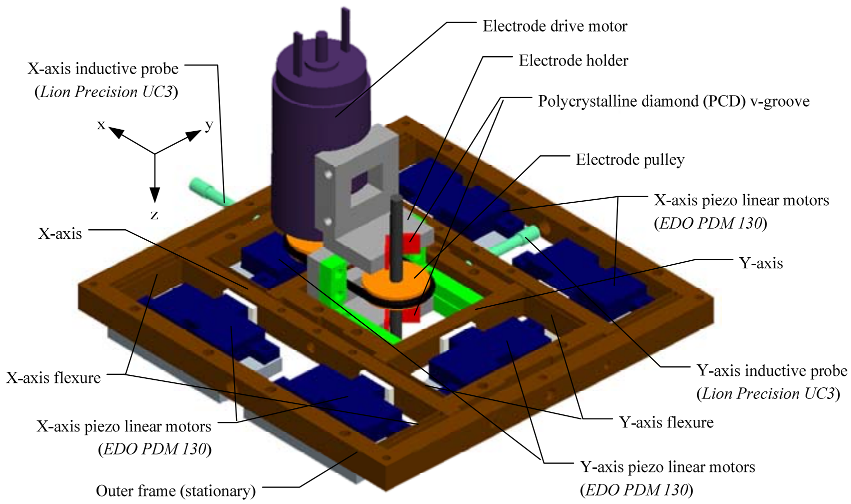


Mode 5: 516.5 Hz



Mode 6: 642.9 Hz

Design of Flexural X-Y Micro-EDM Head



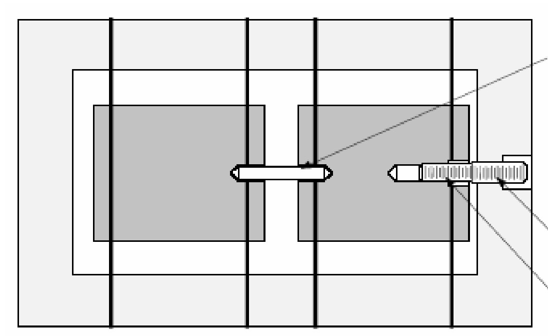
Flexural 2-axis EDM head with piezo linear motors and non-contact inductive probes

Minimize Errors

- The parasitic motion of one 4-bar cancels the parasitic motion of the second 4-bar
- Lateral and yaw stiffness will not be high, however, due to buckling effect
- Overcome by use of monolithic hourglass-type members

Minimize Errors

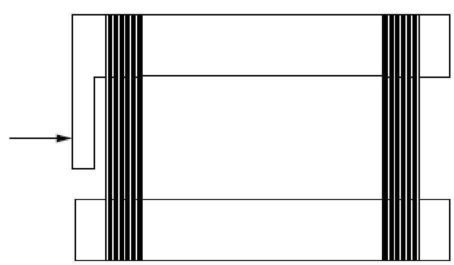
- A differential actuation system can be used to increase resolution
  - A wobble pin will minimize parasitic force actuation errors



Source: Alexander Slocum, *Precision Machine Design*

Minimize Errors

- Many thin blades can be used to increase lateral stiffness and load capacity while keeping axial stiffness and stress low



Source: Alexander Slocum, *Precision Machine Design*

$$F_{load\ capacity} \approx Ntw \qquad k_{axial\ multiblade} = \frac{L^3}{ENt^3 w}$$

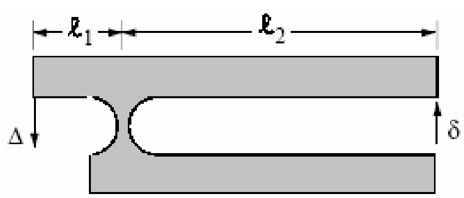
$$k_{vertical} = \frac{NtwE}{L} \qquad k_{axial\ monolithic} = \frac{L^3}{E(Nt)^3 w}$$

Minimize Errors

- Be careful of alignment and slip problems between the blades
- EDM process can be used to prevent these problems
- Rubber placed between the blades can increase damping
- Careful when tightening bolts, as the torque can twist the flexure

Flexural Transmission Systems

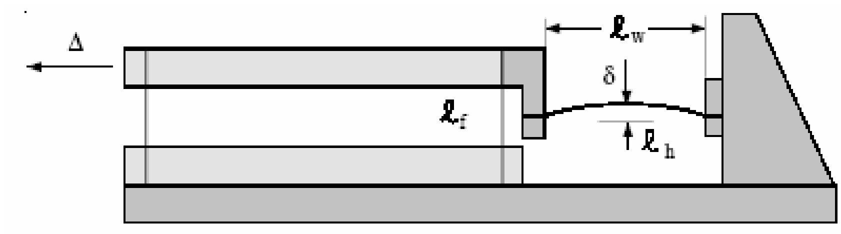
- Lever and fulcrum transmission:



Source: Alexander Slocum, *Precision Machine Design*

Flexural Transmission Systems

- A bowed flexure used as a high reduction transmission:



- A downward motion δ causes a lateral motion Δ:

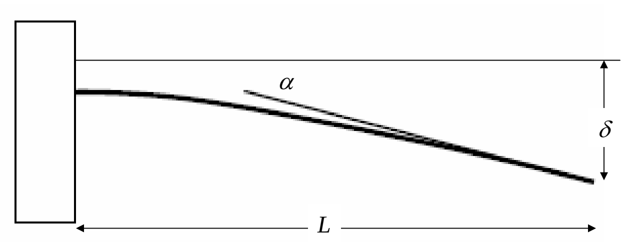
$$\Delta \approx \frac{4\delta l_h}{l_w}$$

Flexural Transmission Systems

- It is possible to chain together a series of these bowed flexures at right angles to each other
  - This can yield a very high transmission ratio
  - Assume that l_h = 2 mm and l_w = 20 mm, then the transmission ratio is 5
  - In series, the ratios become 25, 125, 625... for 2, 3, 4... units respectively
- A variation to this bowed beam approach is to use two beams laid on top of each other and tied together at one end
- When the beams bend there will be differential motion along the interface between them

Angular Flexures

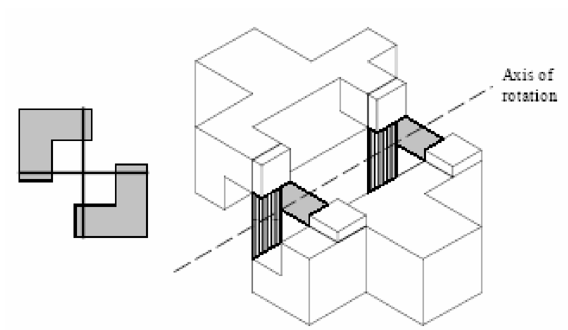
- The slope at the end of the beam causes an Abbe error in the beam that holds the optic which cancels the beam deflection $\delta = \alpha(2/3L)$:



$$\delta = \frac{FL^3}{3EI} \qquad \alpha = \frac{FL^2}{2EI}$$

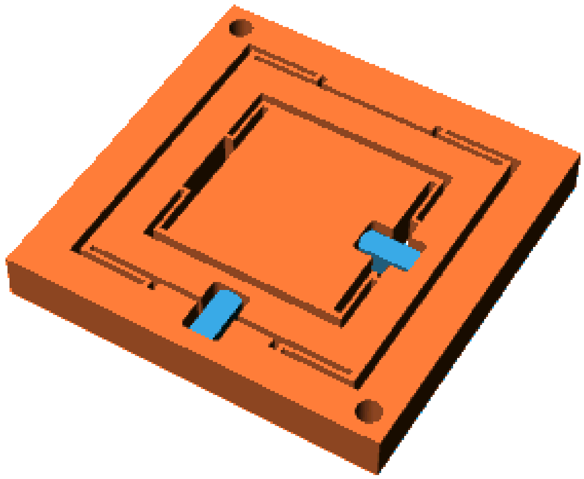
Angular Flexures

- Cross-strip flexure for angular motion:



Source: Alexander Slocum, *Precision Machine Design*

Application Examples



Source: Physikinstrumente at www.physikinstrumente.de

Piezo-Driven Linear Axis