Precision Machine Design

Topic 17

Flexures

Purpose:

From the flip-top on a shampoo bottle to the piezo-beams on a scanning tunneling microscope, flexural bearings are one of the most widely used types of bearings. However, they are one of the least well-understood bearings by most engineers. This lecture introduces the concept of flexural bearings and their characteristics.

Outline:

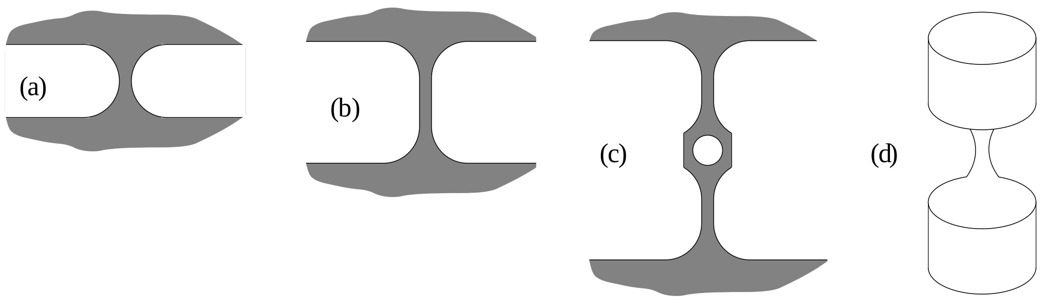
- **Introduction**
- **General characteristics**
- **Types of flexures**

"Genius can only breathe in an atmosphere of freedom"

John Stuart Mill

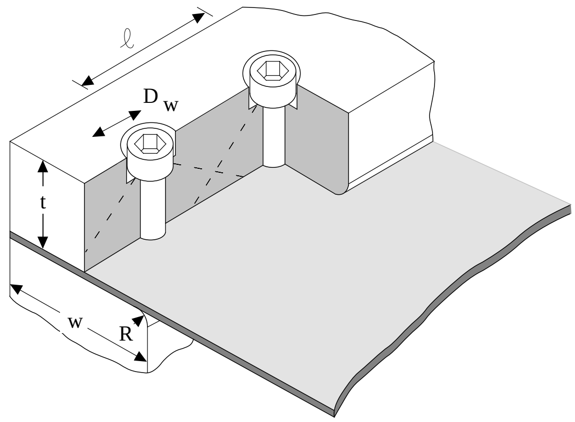
Introduction

- **Monolithic designs:**



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

- **Clamped designs:**



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

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.**

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.**

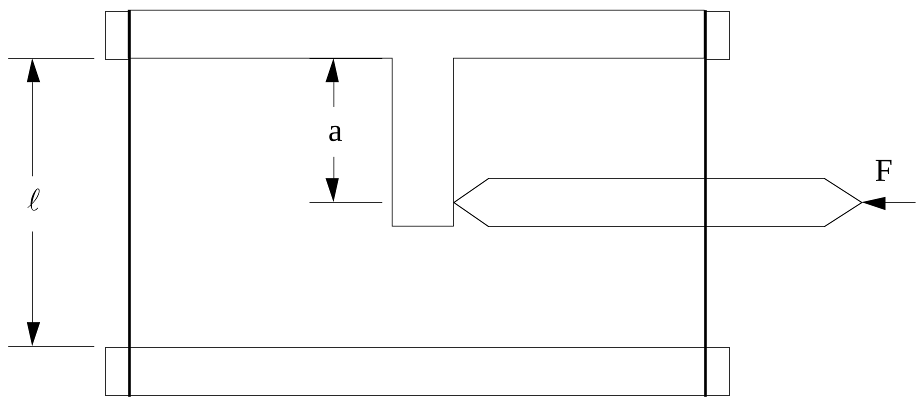
Damping capability

- **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.**
- **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)**

- **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:**



  - **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**

$$\theta_{pitch} = \left(\frac{6(\ell - 2a)\, t^2}{3b^2\ell - 2t^2\ell + 6at^2}\right)\left(\frac{x}{\ell}\right)$$

$$\delta_{vertical} \approx \frac{x^2}{2\ell}$$

  - **Note that there is no pitch error when a = ℓ/2**

- **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:**

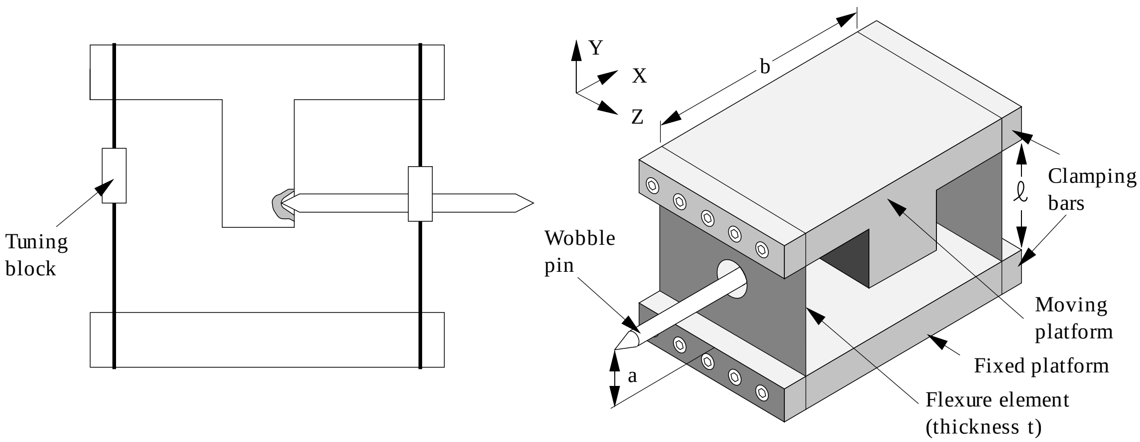
$$\theta_{spring} = \frac{\delta_{spring}\, x^2}{2\ell^2\, b}$$

$$\theta_{platform} = \frac{\delta_{platform}\, x}{\ell\, b}$$

- **Proven by Jones who gives typical tolerances on the spring and platform length to be 25 μm and 1-3 μm respectively.**

Types of flexures[1]

- **Four bar linkage flexure:**



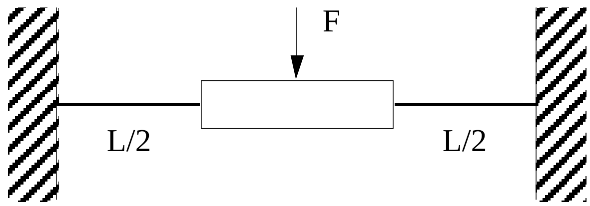
- **In the Y direction there is a small error motion δ_Y that is a function of the X motion δ_X and flexure length ℓ:**

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

- **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.**

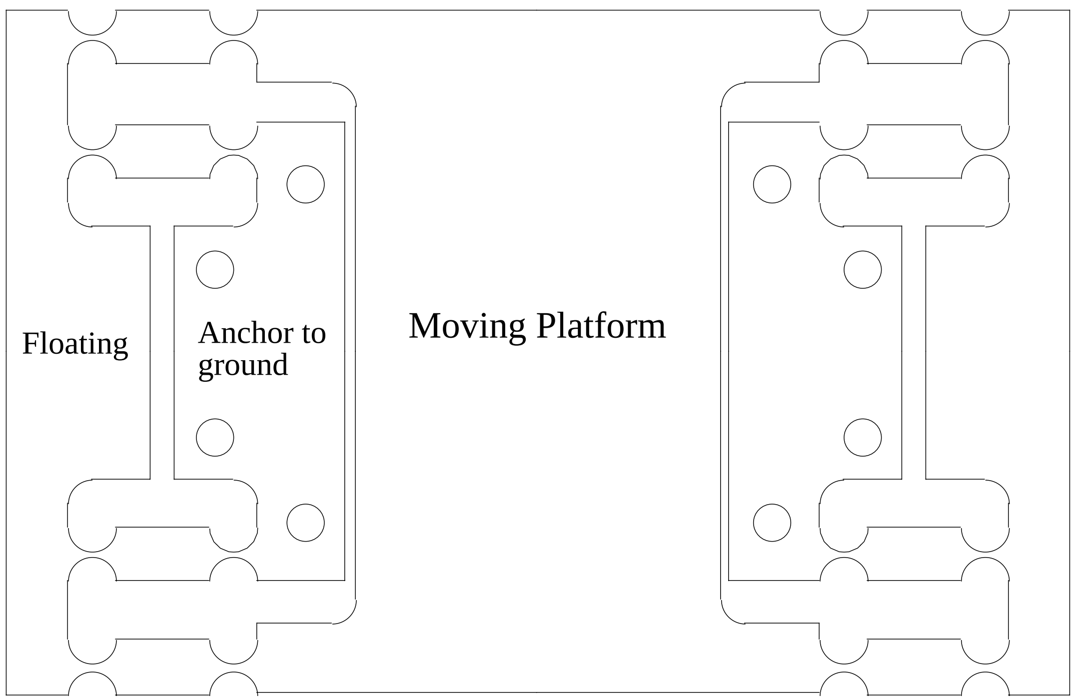
[1] Modular flexural bearing components can be purchased: Alson E. Hatheway Inc., Suite 400, 595 East Colorado Blvd., Pasadena, California 91101.

- **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:**



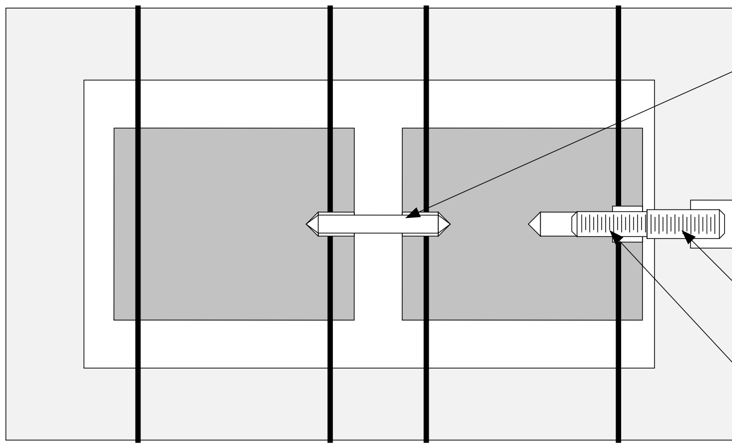
$$\delta = \frac{FL^3}{192EI}$$

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

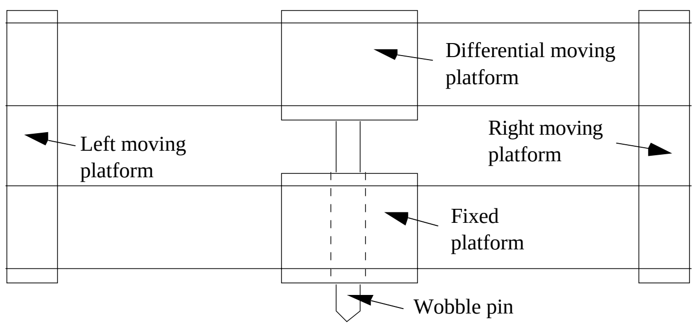


    - **The parasitic motions of one 4-bar cancel the parasitic motions of the second 4-bar.**
    - **Lateral and yaw stiffness will not be high, however, due to buckling effect.**
    - **Overcome by use of monolithic hourglass-type members.**

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



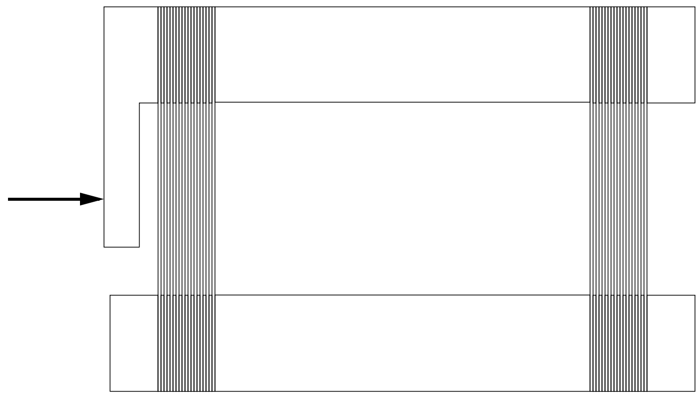
- **Alternate differential design:**



  - **Left and right platforms would be connected to a common rigid top-plate.**

- **When the flexure is built in to "walls", it needs extensional capability: (after F. Zhu at Delft):**

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



$$F_{\text{load capacity}} \approx Ntw$$

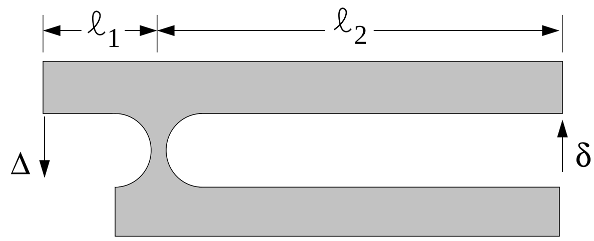
$$K_{\text{vertical}} = \frac{NtwE}{L}$$

$$K_{\text{axial multiblade}} \approx \frac{L^3}{ENt^3w}$$

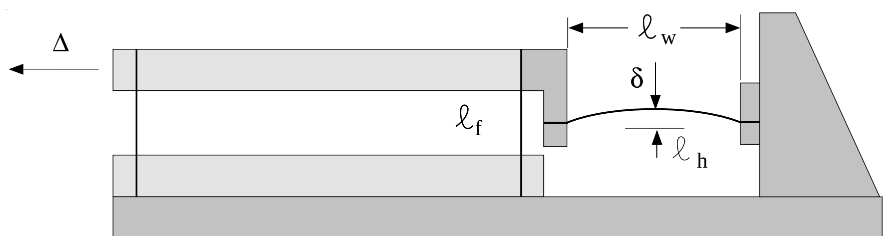
$$K_{\text{axial monolithic}} \approx \frac{L^3}{E(Nt)^3w}$$

- **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!**

- **Lever and fulcrum transmission:**



- **A bowed flexure used as a high reduction transmission:**



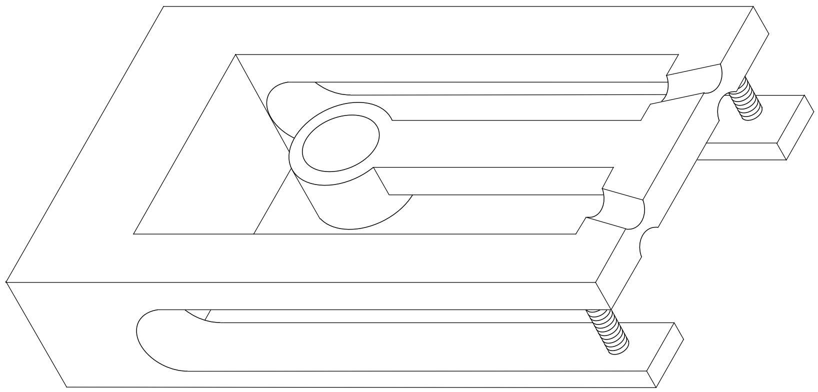
- **A downward motion δ causes a lateral motion Δ:**

$$\Delta \approx \frac{4\delta \ell_h}{\ell_w}$$

- **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.**

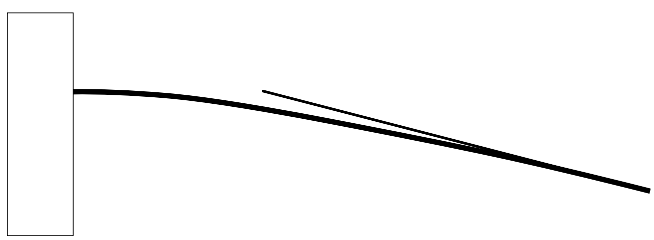
Flexures that provide angular motion

- **Device for adjusting pitch and yaw** (Courtesy of Polaroid Corp.)**:**



  - **Note the transmission effect, where the screws push up on the upper beam, using the lower beam as a base.**
  - **If the top beam were 1/2" thick, and the bottom beam were 1/8" thick, then the transmission ration would be $((1/2)/(1/8))^3 = 64$!**

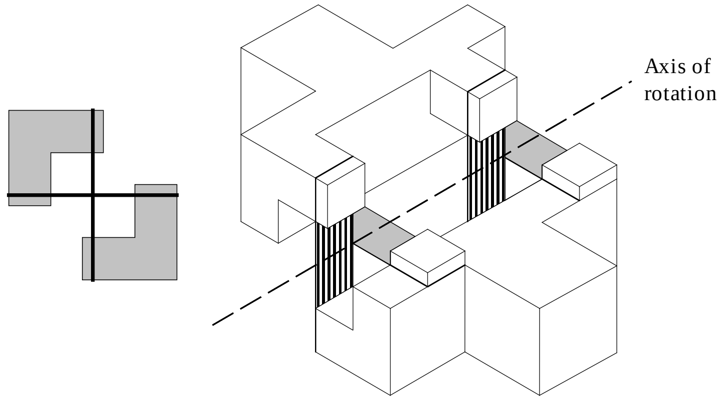
- **The slope at the end of the beam causes an Abbe error in the beam that holds the optic which cancels the beam deflection ($\delta=\alpha(2/3L)$):**



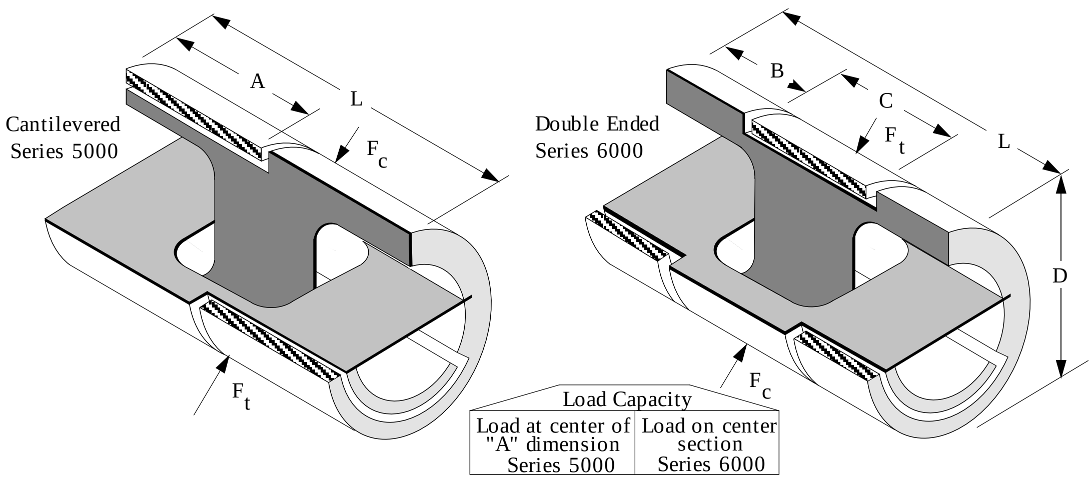
$$\delta = \frac{F L^3}{3EI}$$

$$\alpha = \frac{F L^2}{2EI}$$

- **Cross-strip flexure for angular motion:**



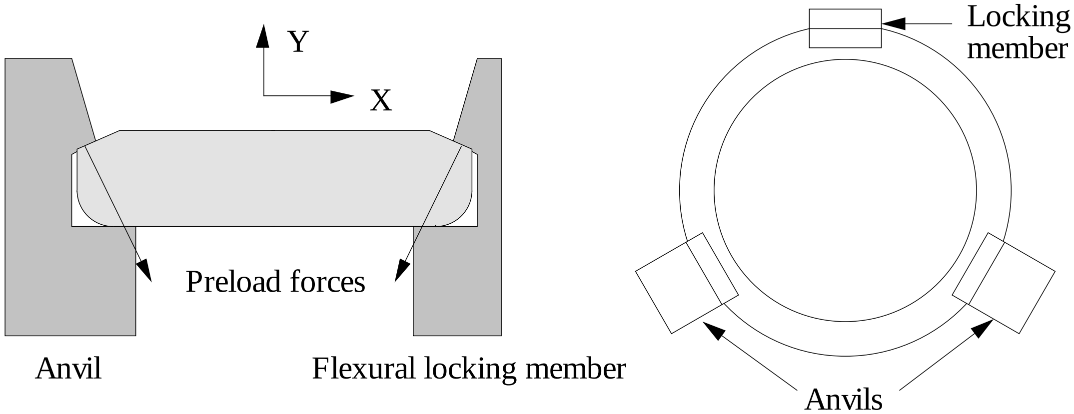
- **Lucas flexural pivots** (Courtesy of Lucas Aerospace Power Transmission Corporation.)**:**



  - **For limited motion applications use in place of rolling element bearings.**
  - **Flexural pivots are not subject to fretting problems.**

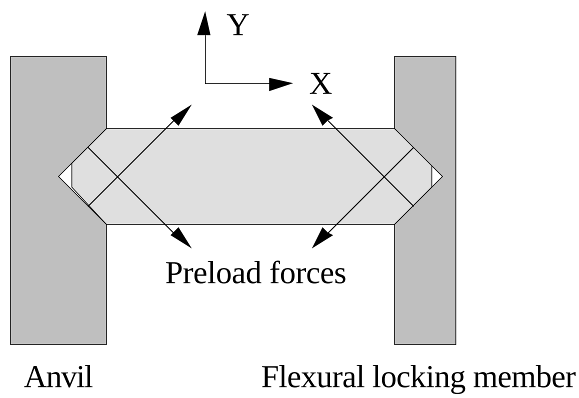
Flexures to guide and lock components into place

- **Flexures can be used as one-shot hinges to guide components into alignment and then lock them into place:**

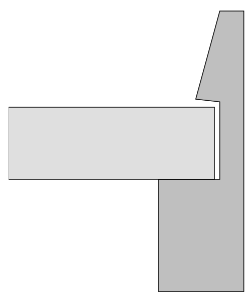


- **X direction stiffness of the clamping system is equal to:**
    - **The sum of the X direction stiffness of the anvil and locking member due to the preload effect.**
- **Small taper keeps component preloaded in both the X and Y directions.**
- **To minimize distortion caused by bending, line of force must pass through the support ledge.**
- **A lens could be kinematically held by two anvils and a single locking member.**
- **The geometry is tolerant of manufacturing errors.**

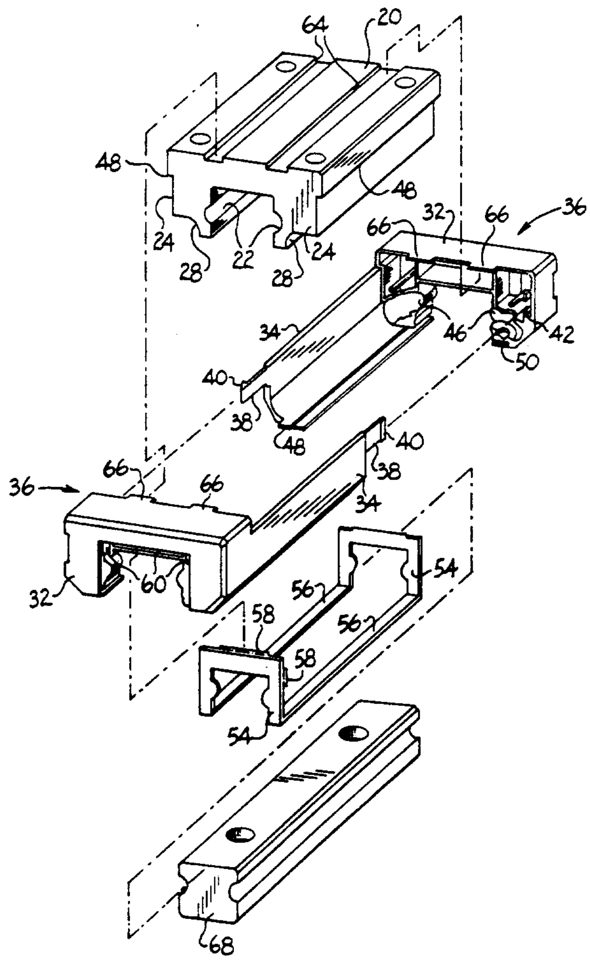
- **For precise X position location, utilize a grooved structure:**



- **Numerous permutations are possible.**
- **The moral of the story is don't do this:**



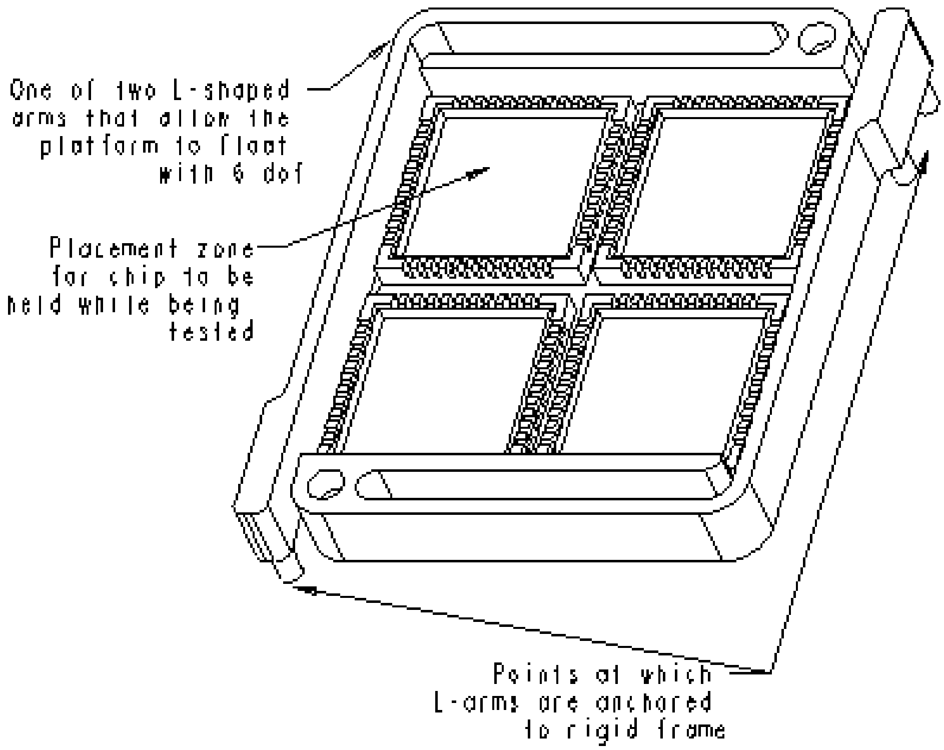
- **Flexures allow for snap assembly of components which make the design of systems more efficient:**



(From US Patent 5,102,235 by Peter Mugglestone of Thomson Industries Inc.)

- **End caps click together.**
- **Seal is a single molded piece.**
- **No screws required.**

- **Flexures for fixturing: Opposed L's support a platform so it can move in six degrees of freedom[2].**



- **This allows chips held in the platform to be operated on (tested in this case).**

[2] Patent Pending, Kinetrix, Inc. 33 Constituition Drive, Bedford, MH 03110-6000. Contact Dr. Alexander Slocum.