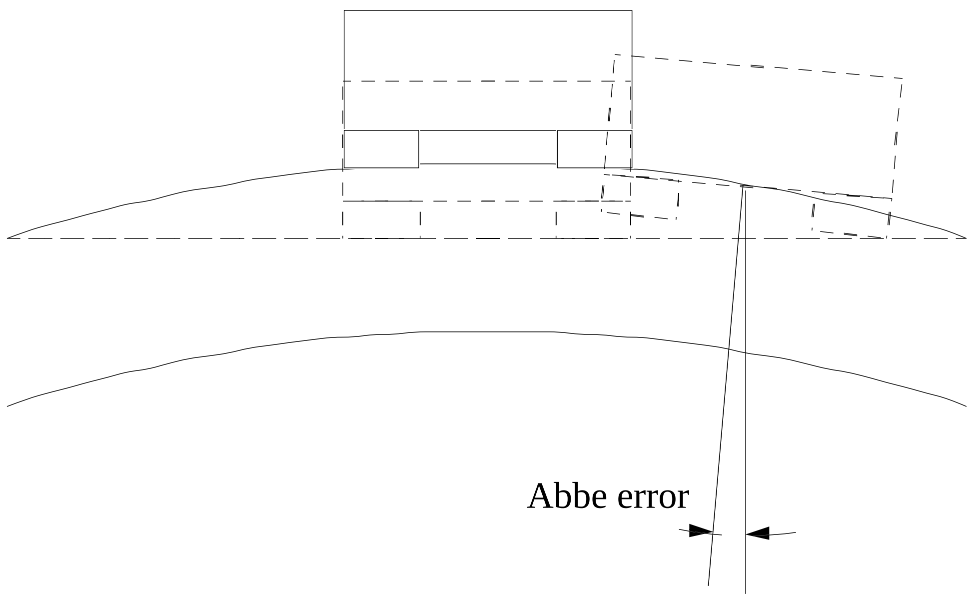
Other structural system considerations

- **Compensating curvatures**
- **Counterweights**
- **Foundation support**
- **Vibration isolation**
- **Structural connectivity**
- **Precision finishing operations**

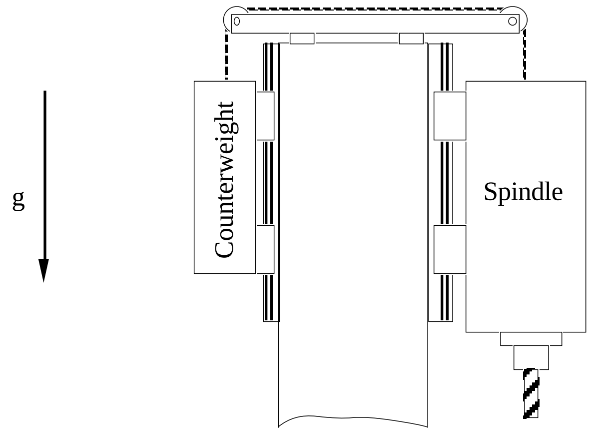
Compensating curvatures

- **The bearing rails are finished so they deform to the desired shape when the machine axes move.**
- **The manufacturing process is expensive, but it saves structural costs.**
- **When the primary weight is that of the machine axis, this method can be very effective.**
    - **Machines with a large bridge and a moving axis on the bridge often used a compensated curvature bridge.**



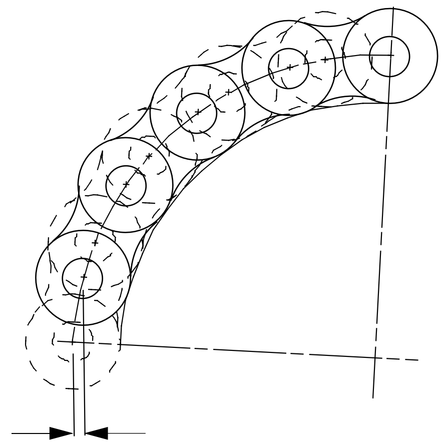
- **Typically, the bridge structure is fixed on its ends on a large grinder.**
    - **The carriage mass is placed in the center of the bridge, and the bridge rails are ground.**
    - **Ideally, the carriage mass needs to move along the bridge with the grinding head, or later there can be an Abbe error.**
- **When the primary weight is that of the part:**
    - **Due to a typical wide variation in part weight, this method will not be effective.**

Counterweights & Counterbalances



- **Why make a servo work to support deadweight?**
  - **For dynamic motions, ballscrew inertia can dominate, so counterweight not needed.**
  - **Linear motor driven machines need to a means to support static loads.**

- **Chains are commonly used to support counterweights:**
  - **A sprocket's pitch diameter varies slightly as it rotates producing a small cogging effect:**[1]



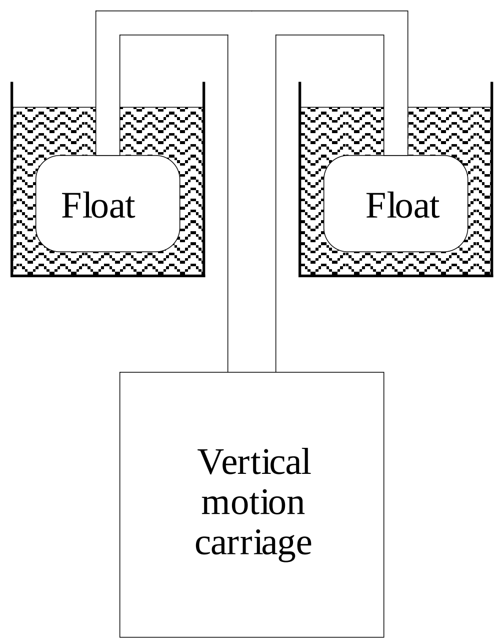
Pitch diameter variation

  - **For most machines, on the 10 micron level, this is not a problem.**

- **A cable and a smooth running pulley will give the least variation in force.**
  - **Cables are elastic compared to chains and hence they should only be used for quasistaticaly moving elements.**
  - **Pulley friction and friction in the counterweight's bearings should be scrutinized for precision machines.**

[1] This drawing illustrating the cogging effect was done by Ilya Shapiro of CNC Systems, Rochester, NY.

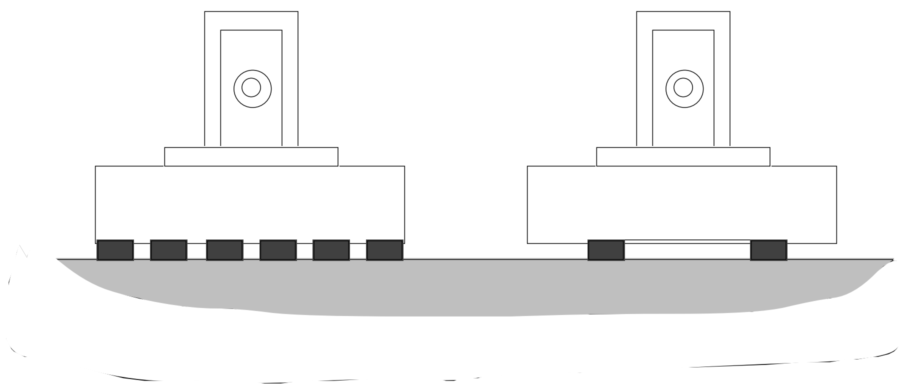
- **A float in oil can often be used to support the weight of an axis:**



- **This provides counterweight action without any friction.**
- **It also provides viscous damping.**
- **A similar effect can also be obtained from an air-bearing piston with servo-controlled cylinder pressure.**
- **Pneumatic and hydraulic cylinders also work well, but beware of seal friction.**

Foundation support

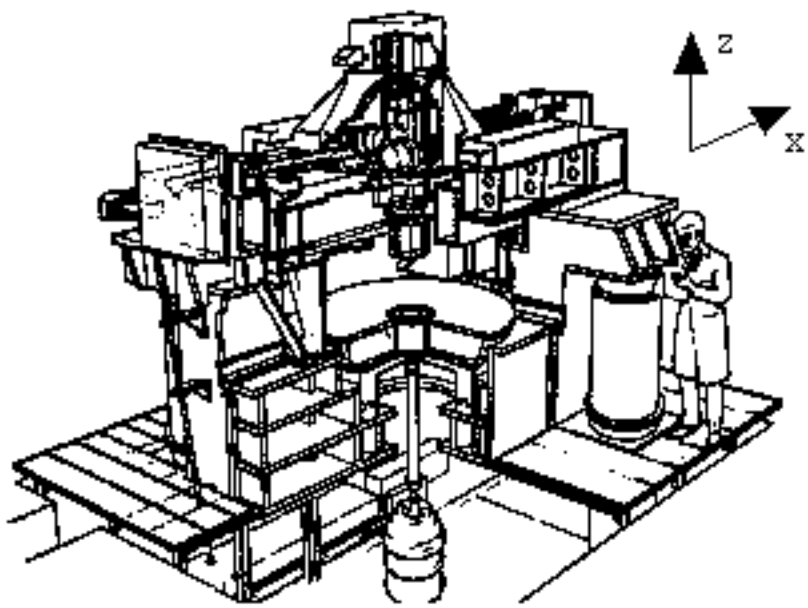
- **If the foundation under the machine is not on an isolated slab:**
  - **Neighboring machines can cause vibration in your machine.**
- **If the machine sits on a three-point mount, then the stability of the floor is not an issue.**
  - **BUT many contacts with the floor increase damping!**



- **If the machine rests on more than three points, then movement of the floor can deform the machine:**
  - **The use of many "soft" mounts can reduce these effects.**
  - **Concrete is hydrophilic and changes shape as it absorbs water, so it must be sealed.**
  - **A deep foundation's bottom will be relatively isothermal, while the top in air can change temperature.**
  - **Even a thick slab will warp when exposed to a gradient.**
    - **The long time constant is difference in room temperature in the summer and winter months.**
    - **Implant thermocouples into the concrete for diagnostic purposes, to later justify cost of keeping plant at uniform temperature.**

Vibration isolation

- **A precision machine must often be mounted on vibration isolators to minimize vertical and horizontal vibration transmission from the floor.**
- **The isolators should be placed in the plane of the work to minimize roll-acceleration effects.**
  - **This often requires construction of a steel cradle.**
  - **A good example is the LODTM at LLNL:**

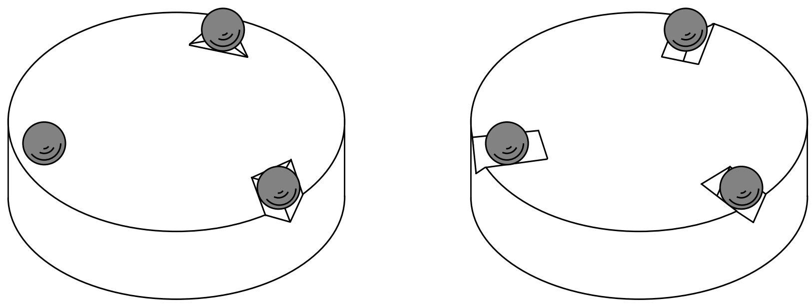


Structural connectivity:

Kinematic vs. Elastic Averaging

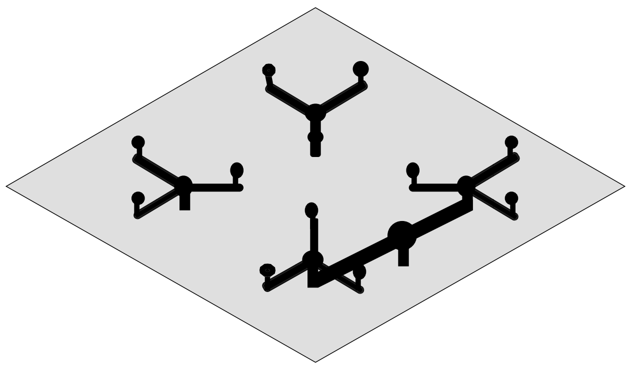
- *The principle of Kinematic Design*, contends that:
  - Point contact should be established at the minimum number of points required to constrain a body in the desired position and orientation.
  - Contact at six points minus the number of desired degrees of freedom).
- This prevents over constraint and thus an "exact" mathematically continuous model of the system can be made.
- Kinematic designs, however, are subject to high contact stresses.
  - After kinematic mounting, epoxy can be injected between the large surfaces.

- **Example: Flat-groove-tetrahedron (Kelvin clamp) and three vee groove kinematic couplings.**
  - **In both cases, the balls should be mounted in tetrahedrons formed in an upper plate.**

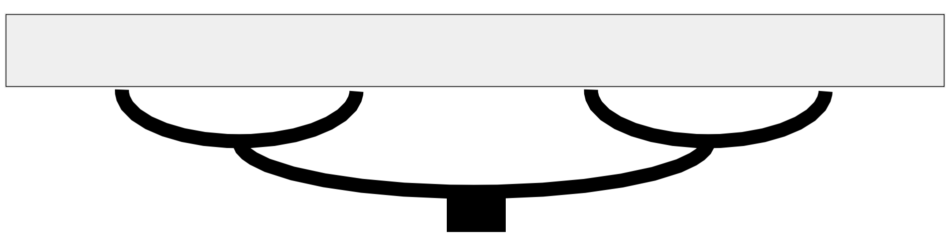


- **If stress and corrosion fatigue are controlled:**
  - **Repeatability can be on the order of the surface finish if the loads are repeatable or the preload high enough**
- **Finite contact areas do exist, and they effectively elastically average out the local errors due to surface roughness.**
- **Friction and micro indentation will limit the accuracy of the kinematic model.**

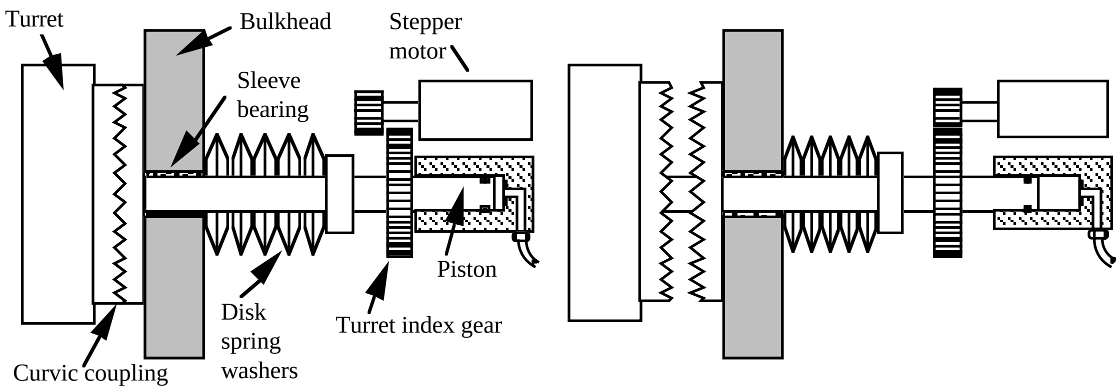
- **In order to minimize deformations, more than three points may be required to support the structure.**
  - **Note that one may not be able to afford to take the chance that the support itself may be uneven.**
- **A stacked arrangement of two or three point supports on balance beams (wiffle trees):**
  - **Allows for multiple support points on the structure while requiring only a three point mount on the floor:**



- **Don't ever support a critical component that is loaded only by its own weight (e.g. a mirror) with more than 3 points.**
  - **Unless a wiffle tree or compliant mount (e.g. seat the mirror on an elastic adhesive) is used.**
- **Most common wiffle tree: A car's windshield wiper:**



- ***The principal of Elastic Averaging* contends that:**
  - **There should be a very large number of contact points spread out over a broad region.**
- **Examples include Curvic or Hirth couplings which use meshed gear teeth to form a coupling:**



- **This type of mechanism causes the system to be over-constrained.**
- **Ideally:**
  - **The average contact stress will be low.**
  - **High points will wear themselves in with use.**
  - **Errors will be averaged out by elastic deformation.**
- **For a worn-in system, the repeatability is on the order of:**
  - **The accuracy of the manufacturing process used to make the parts divided by the square root of the number of contact points.**
- **Because of the large number of contact points, the chance of dirt contaminating the interface increases.**

- **In comparison:**
  - **Kinematic design:**
    - **Deterministic.**
    - **Less reliance on manufacturing.**
    - **Stiffness and load capacity limited.**
  - **Elastically averaged design:**
    - **Non-deterministic.**
    - **More reliance on manufacturing.**
    - **Stiffness and load capacity not limited.**
- **As discussed by Evans[2] in his assessment of the history of precision engineering:**

  "Contrast, for example, Pollard, in the introduction to his monograph on instrument design, bewailing non-kinematic design practices he attributes to machine tool design practice being brought to instrument design, and Rosenhain who bewails the flimsy designs of instrument makers and calls for an approach more akin to machine tool design".

2 C. Evans, Precision Engineering: An Evolutionary View Cranfield Press, Cranfield, Bedford MK43 0AL, England.

Manufacturing issues

- **The philosophy of Precision Machine Design can be applied to manufacturing (and visa versa).**
- **There are a number of techniques that can be used to prepare surfaces that are to be joined:**
    - **Grinding**
    - **Stoning**
    - **Replicating & potting**
    - **Scraping**
    - **Lapping**

Grinding

- **Most commonly used process to prepare two precision surfaces that are to be bolted together.**
- **One must be careful of fixturing errors (bolting a warped piece to a grinder bed results in a warped part.**
  - **If a part is not properly fixtured, it will be warped and will un-warp after removal.**
    - **The inverse warp will then be imparted to the surface,**
  - **Stoning can be used to make a part lie flat on a grinding table (that has been stoned).**
    - **Purposely lightly ding the surface to be placed on the grinding table.**
    - **Use a large granite surface plate to stone the dinged surface.**
    - **The dings will all be stoned to the same height, and the plate will rest flat on the grinder table.**
      - **This creates in effect an elastically averaged surface.**
  - **Re-mounting a part to be ground, then measured or used, and then returned for regrinding:**
    - **Put a three ball mount on the machine.**
    - **Put a three groove pattern on the back of the part.**
    - **Use this kinematic coupling to repeatably fixture the part on the machine.**

Stoning

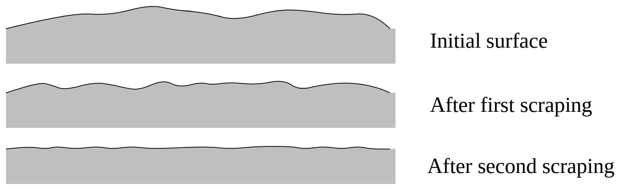
- **Precision assemblies cannot be made unless the surface of each part is carefully cleaned and de-burred.**
- **The slightest impact with another object can make an invisible (μms) crater on a surface.**
- **Cleaning and deburring are accomplished best by lightly stoning a surface with a precision diamond ground stone.**
- **Precision stones are available from Professional Instruments Corp. in Minneapolis MN which are ground flat to 0.1 μm.**

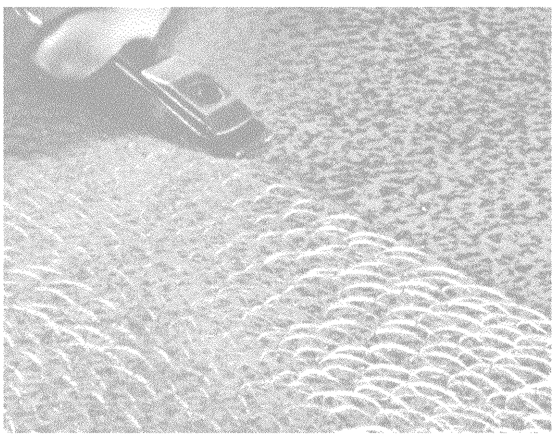
Replicating & Potting

- **Three point mount and adjust two parts with respect to each other**
- **Inject epoxy between them to make the surfaces match and obtain a full contact stiffness joint.**

Scraping

- **Removing layers of metal, typically 0.1-1 micron thick, with a sharp hand held tool:**





- **The master is coated with blue or rouge (coloring) and rubbed on the surface to be scraped.**
    - **Colored regions on the surface to be scraped indicate the high regions that are to be scraped.**
    - **Leads to a controlled surface finish while attaining straightness.**

- **Scraping removes high spots from joint surfaces and helps to increase joint stiffness.**
- **Scraping also imparts a finish to sliding bearing surfaces which help them to retain lubrication.**
- **Scraping requires a great deal of skill in order to achieve good results:**
  - **A straightforward process to learn, but it is a tedious job.**
  - **Really good scrapers, who scrape to the sub-micron level, are highly skilled artists of their trade.**
  - **Highly skilled scrapers are a asymptotically vanishing breed (there will always be a few around).**

Lapping

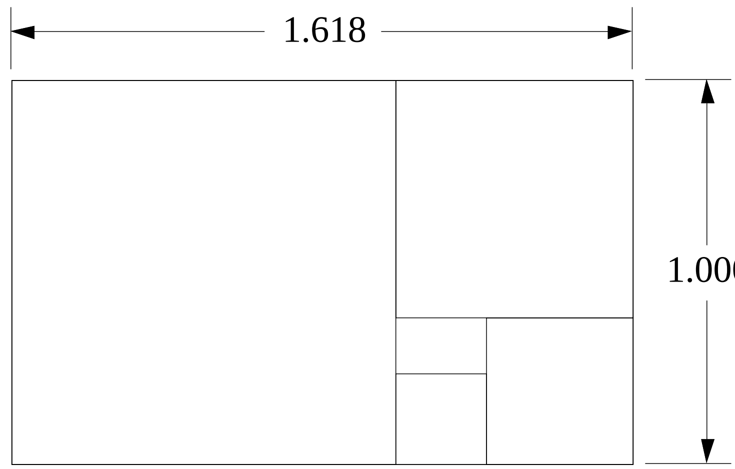
- **A free-abrasive finishing process can yield an accuracy based on the amount of time and care spent.**
- **Lapping can be done dry or wet and utilizes fine abrasive particles to make one surface take the form of another.**
- **Ball bearings are a commonly lapped component.**
- **Leadscrews can be lapped to fit a nut so backlash and accuracy are on the submicron level.**
- **Bearing ways can be lapped by hand to remove straightness errors.**
- **Hand lapping is a skilled artform that should be avoided if possible.**
- **Non-contact bearings and mapping or metrology frames can be used to attain accuracy without resorting to lapping.**

Structural Design Summary

- **After a configuration is chosen from all the conceptual designs, a few simple rules of thumb to follow include:**

  1. Keep the proportions of the golden rectangle in mind.

  - **This usually yields structurally stiff and aesthetically pleasing designs.**



- **You must watch the movie (available on video) Donald Duck in Mathemajicland!**

  2. Utilize symmetry whenever possible.

  - **Asymmetric structures often have internal gradients which are an indicator of potential problems.**

  3. Remember the principle behind the strength and stiffness of an I-beam.

  - **Also remember that shear strains are greatest near the neutral axis.**

  4. Minimize the structural loop and use closed sections whenever possible.

5. Large plate sections should be stiffened with ribs or other means to keep them from vibrating like drumheads.

- **When needed, use active damping systems.**

6. Maximize the thermal diffusivity of the machine and minimize heat input.

7. Start at the tool tip or workplace with estimates of cutting forces and acceleration requirements.

- **Work backward through the structural system and determine forces and moments on members.**

- **Use guesstimates for sensor, bearing, and actuator limitations to help size structural components.**

8. Locate the work volume at the center of mass and in the plane of support.