Precision Machine Design

Topic 9

Design of the machine's structure

Purpose:

The structure is the skeleton of the machine. Without a good structure, the rest of the machine will be ineffective. This lecture describes some of the basic issues involved in the design of the machine structure.

Outline:

- **Overall design approach for the structure**
- **Stiffness requirements**
- **Damping requirements**
- **Structural configurations for machine tools**
- **Other structural system considerations**

"Total grandeur of a total edifice,
Chosen by an inquisitor of structures
For himself. He stops upon this threshold
As if the design of all his words takes form
And frame from thinking and is realized."

Wallace Stevens

Defining design strategies

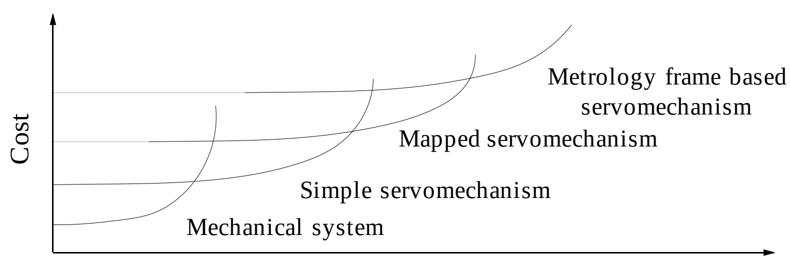
- **Strategy for attaining accuracy**
  - **Accuracy obtained from component accuracy:**
    - **Most machine tools are built this way.**
  - **Accuracy obtained by error mapping.**
    - **Most coordinate measuring machines are built this way.**
  - **Accuracy obtained from a metrology frame.**
    - **Special machines are built this way (usually one-of-a-kind cost-is-no-object machines).**
- **Kinematic design:**
  - **Deterministic.**
  - **Less reliance on manufacturing.**
  - **Stiffness and load limited, unless pot in epoxy.**
- **Elastically averaged design:**
  - **Non-deterministic.**
  - **More reliance on manufacturing.**
  - **Stiffness and load not limited.**

- **Passive temperature control:**
    - **Minimize and isolate heat sources.**
    - **Minimize coefficient of thermal expansion.**
    - **Maximize thermal diffusivity.**
    - **Insulate critical components.**
    - **Use indirect lighting.**
    - **Use PVC curtains to shield the machine from infrared sources.**
- **Active temperature control:**
    - **Air showers.**
    - **Circulating temperature controlled fluid.**
    - **Thermoelectric coolers to cool hot spots.**
    - **Use proportional control.**

- **Structural configurations:**
  - **Where are the center of mass, friction and stiffness located?**
  - **What does the structural loop look like?**
    - **Open frames (G type)**
    - **Closed frames (Portal type)**
    - **Spherical (NIST's M^3).**
    - **Tetrahedral (Lindsey's Tetraform).**
    - **Hexapods (Stewart platforms).**
    - **Compensating curvatures.**
    - **Counterweights.**
- **Damping:**
  - **Passive:**
    - **Material and joint-µslip damping.**
    - **Constrained layers, tuned mass dampers.**
  - **Active: Servo-controlled dampers.**

Overall design approach for the attainment of accuracy

- **Accuracy obtained from component accuracy:**
  - **Inexpensive once the process is perfected.**
  - **Accuracy is strongly coupled to thermal and mechanical loads on the machine.**
- **Accuracy obtained by error mapping:**
  - **Inexpensive once the process is perfected.**
  - **Accuracy is moderately coupled to thermal and mechanical loads on the machine.**
- **Accuracy obtained from a metrology frame:**
  - **Expensive, but sometimes the only choice.**
  - **Accuracy is uncoupled to thermal and mechanical loads on the machine.**



$$\text{Difficulty} = \frac{\text{Environment} \times \text{Load} \times \text{Range} \times \text{Speed}}{\text{Accuracy}}$$

Stiffness requirements

- **Engineers commonly ask "how stiff should it be?"**
- **A minimum specified static stiffness is a useful but not sufficient specification.**
- **Static stiffness and damping must be specified.**
- **Static stiffness requirements can be predicted.**
- **Damping can be specified and designed into a machine.**

Specifying the minimum required static stiffness for measuring machines and instruments

- **For high speed positioning, use the earlier servo-bandwidth determination.**
- **Heavily loaded machine tools, required stiffness may be a function of cutting force.**
- **For lightly loaded machines quasi-statically positioning, use the following:**
- **First make an estimate of the system's time constant:**

$$\tau_{mech} = 2\pi \sqrt{\frac{M}{K}}$$

- **The control system loop time τ_{loop} must be at least twice as fast to avoid aliasing.**
- **Faster servo times create an averaging effect by the factor $(\tau_{mechanical}/2\tau_{loop})^{1/2}$.**
- **For a controller with N bits of digital to analog resolution, the incremental force input is:**

$$\Delta F = \frac{F_{max}}{2^N \sqrt{\frac{\tau_{mech}}{2\tau_{servo}}}}$$

- **The minimum axial stiffness is thus:**

$$K \geq \left\{ \frac{F_{max}\, \tau_{servo}^{1/2}}{2^N\, \pi^{1/2}\, M^{1/4}\, \delta_K} \right\}$$

- **While the controller is calculating the next value to send to the DAC, the power signal equals the last value in the DAC.**
- **The motor is receiving an old signal and is therefore running open loop.**
- **Assume that there is no damping in the system.**
- **The error δ_M due to the mass being accelerated by the force resolution of the system for a time increment τ_{servo} is**

$$\delta_M = \frac{1}{2}\left(\frac{\Delta F}{M}\right)\tau_{servo}^2$$

- **The maximum allowable servo-loop time is thus**

$$\tau_{servo} = \sqrt{\frac{2\delta_M M}{\Delta F}}$$

- **The minimum axial stiffness is thus:**

$$K \geq \frac{F_{max}\,\delta_M^{1/4}}{2^{N-1/4}\,\pi^{1/2}\,\delta_K^{5/4}}$$

  - **It must be greater than the stiffness to resist cutting loads or static loads not compensated for by the servos:**

$$K \geq \frac{F_{max}}{\delta}$$

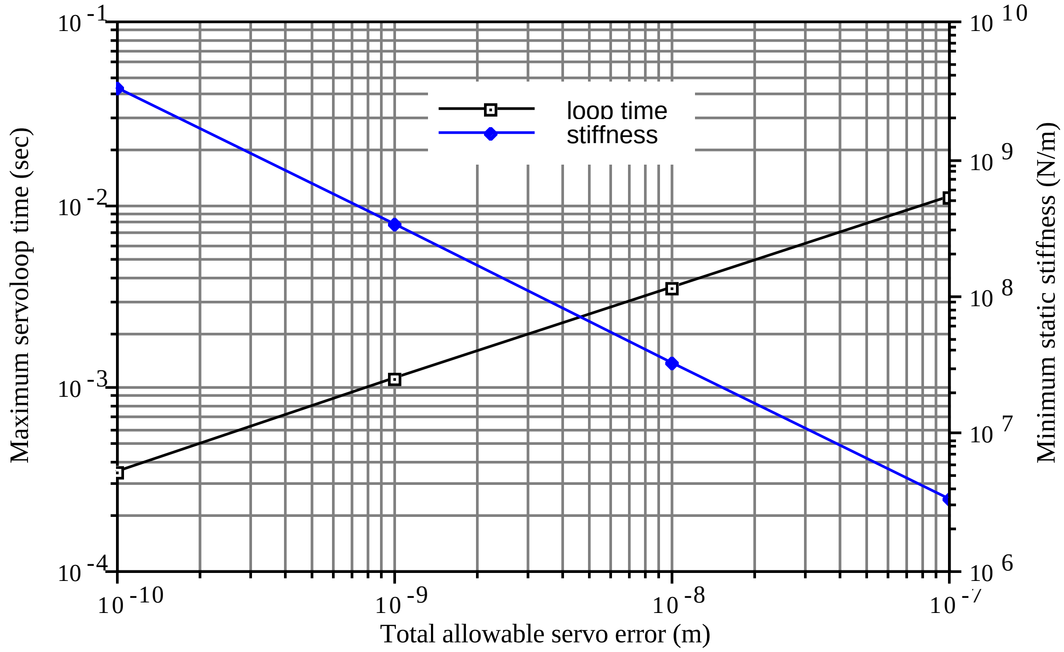
- **The maximum servo-loop time is thus:**

$$\tau_{servo} \leq \sqrt{\frac{\pi^{1/2}\,2^{(4N+3)/4}\,\delta_M^{3/4}\,M\,\delta_K^{1/4}}{F_{max}}}$$

- **Typically, one would set $\delta_K = \delta_M = 1/2\delta_{servo}$**

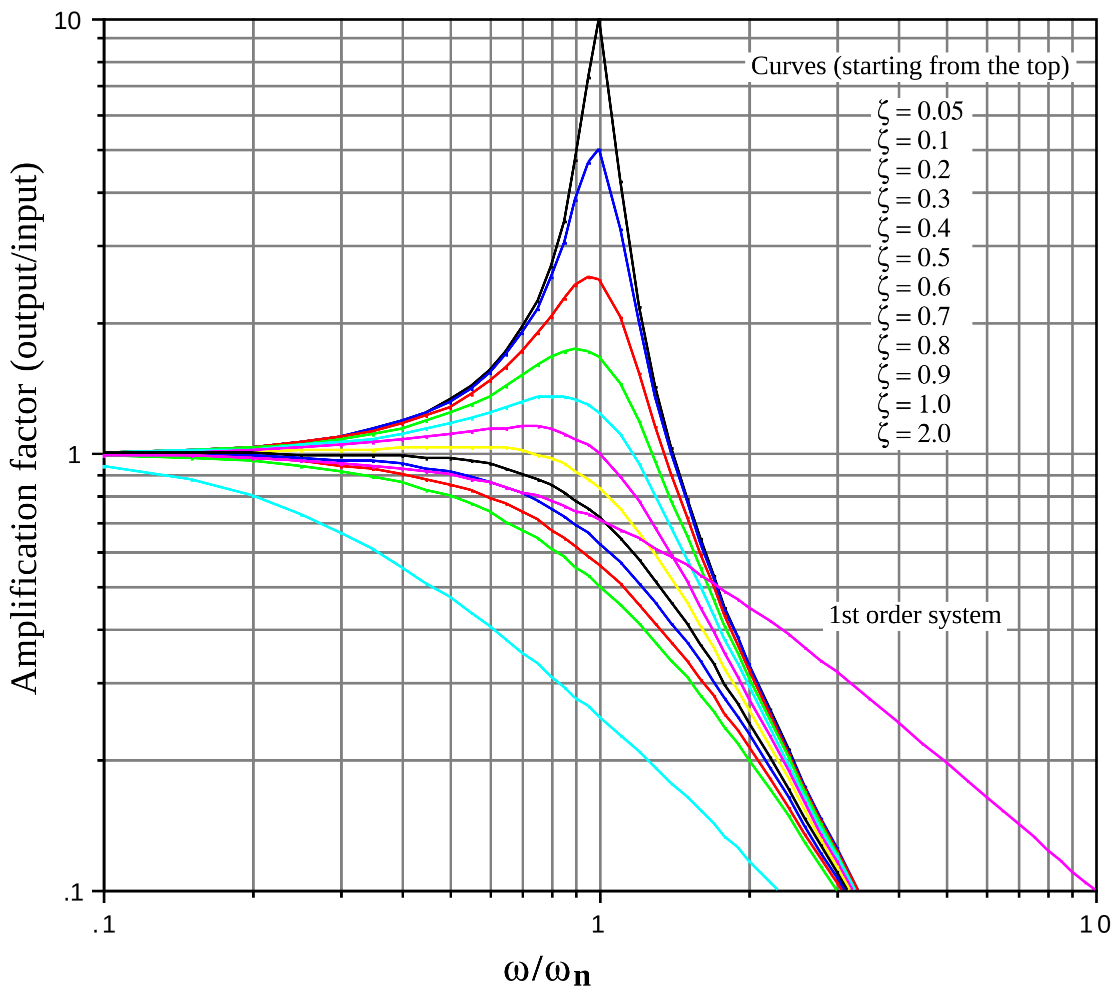
- **Usually, $\tau_{servo\ actual} = \tau_{servo}/L$, where L is the number of past values used in a recursive digital control algorithm.**

- **Example: Required static stiffness for a machine with 1000 N max. axial force, 200 kg system mass, and 12 bit DAC.**



Dynamic stiffness

- **Dynamic stiffness is a necessary and sufficient specification.**
- **Dynamic stiffness:**
  - **Stiffness of the system measured using an excitation force with a frequency equal to the damped natural frequency of the structure.**
- **Dynamic stiffness can also be said to be equal to the static stiffness divided by the amplification (Q) at resonance.**



- **It takes a lot of damping to reduce the amplification factor to a low level.**

Damping requirements

- **Material and joint damping factors are difficult to predict and are too low anyway.**
- **For high speed or high accuracy machines:**
  - **Damping mechanisms must be designed into the structure in order to meet realistic damping levels.**
- **The damped natural frequency and the frequency at which maximum amplification occurs are**

$$\omega_d = \omega\sqrt{1 - \zeta^2}$$

$$\omega_{dpeak} = \omega\sqrt{1 - 2\zeta^2}$$

- **The amplification at the damped natural frequency and the peak frequency can thus be shown to be**

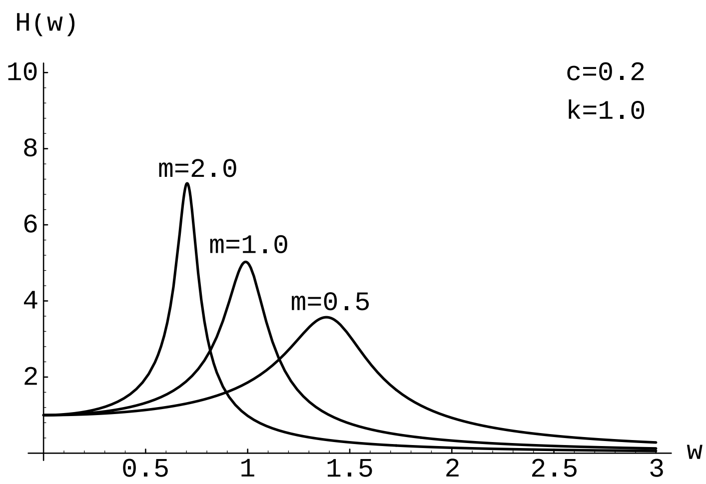
$$Q = \frac{\text{Output}}{\text{Input}} = \frac{1}{\sqrt{4\zeta^2 - 3\zeta^4}}$$

$$Q = \frac{\text{Output}_{peak}}{\text{Input}} = \frac{1}{2\zeta\sqrt{1 - \zeta^2}} = \frac{K_{static}}{K_{dynamic}} \approx \frac{1}{2\zeta}$$

- **For unity gain or less, ζ must be greater than 0.707.**
- **Cast iron can have a damping factor of 0.0015.**
- **Epoxy granite can have a damping factor of 0.01-0.05**
- **All the stuff bolted to the structure (e.g., slides on bearings) helps to damp the system.**
- **To achieve more damping, a tuned mass damper or a shear damper should be used.**

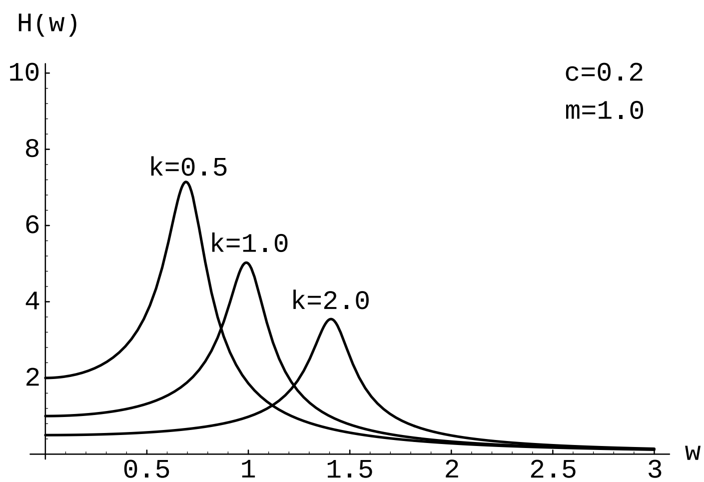
Effects of Changing System Mass

- **Adding mass:**
  - **Mass can only be purely added by adding a fluid.**
  - **Adding sand or lead shot increases mass and damping via the particles rubbing on each other.**
  - **Higher mass slows the servo response, but helps attenuates high frequency noise.**
- **Decreasing mass**
  - **It can enhance the ability of the machine to respond to command signals with alacrity.**
  - **The system with decreased mass offers a higher natural frequency.**
    - **Higher speed controller signals can be used without compromising the accuracy of the system.**
  - **Low mass systems also shows improved damping, a result of the increased loss factor (the loss factor $\zeta = c/(2m)$).**
  - **However, low mass systems shows less noise rejection at higher frequencies.**
    - **This suggests that the machine will be less able to attenuate noise and vibration.**



Effects of Adding Stiffness to the Machine System

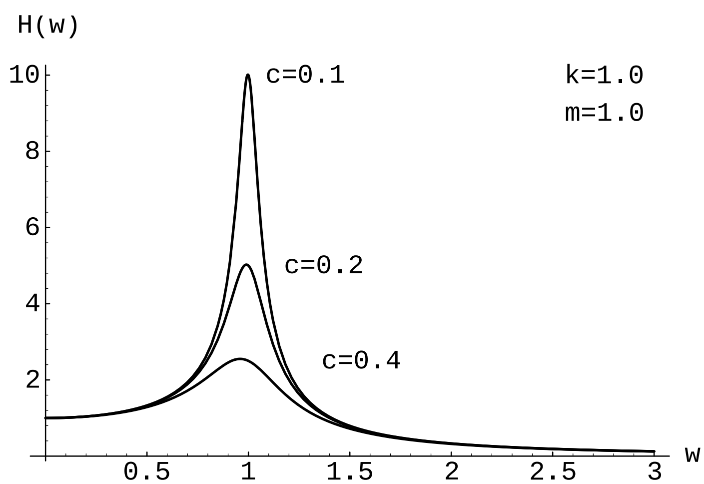
- **Higher stiffness gives a flatter response at low frequencies and give smaller displacements for a given force input.**
- **The compromise of decreased noise attenuation is not as dramatic as is the case with lowering the system mass.**
- **This is shown by the similar shapes in the three response curves at high frequencies:**



- **This suggests that raising the stiffness of a system is always a desirable course of action.**
- **However, acoustical noise may be worsened by adding stiffness.**

Effects of Adding Damping to the Machine System

- **Increasing the system damping can make a dramatic improvement in the system response.**
- **The trend is for decreasing amplification of the output at resonance with increasing damping.**
- **Although a damping coefficient of 0.4 may be difficult to obtain in practice.**
- **The plot shows the dramatic improvement available by doubling the system damping:**

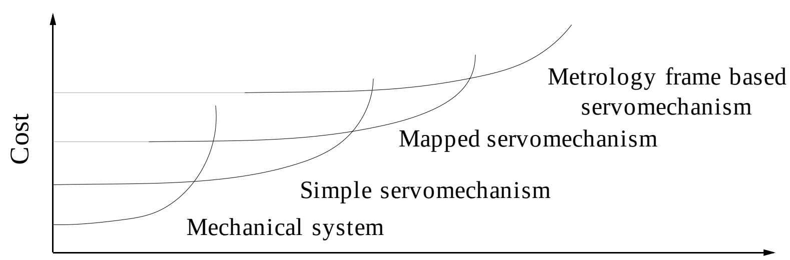


Summary

- **For a servo controlled machine:**
  - **The stiffness of the machine structure should be maximized to improve positioning accuracy.**
  - **The mass should be minimized to reduce controller effort and improve the frequency response and loss factor (ζ).**
  - **Damping, however, must be present to attenuate vibration in the machine system.**

Structural configurations for machine tools

- **The structure provides the means by which all components are brought together.**
- **It is important to minimize thermal and elastic structural loops.**
- **Extreme care must be paid to dynamic performance (see the next lecture on modal analysis.**
- **Metrology frames and mapping techniques can be used to compensate for some structural deformation errors.**
- **It pays to make the design as good as possible before advanced techniques are applied.**
- **Beware of the technology you are using, and is it time to move to a more advanced technology?!**



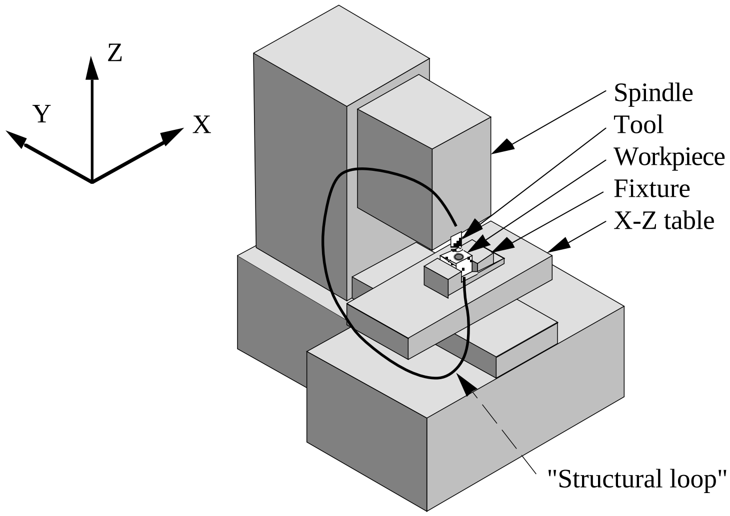
$$\text{Difficulty} = \frac{\text{Environment} \times \text{Load} \times \text{Range} \times \text{Speed}}{\text{Accuracy}}$$

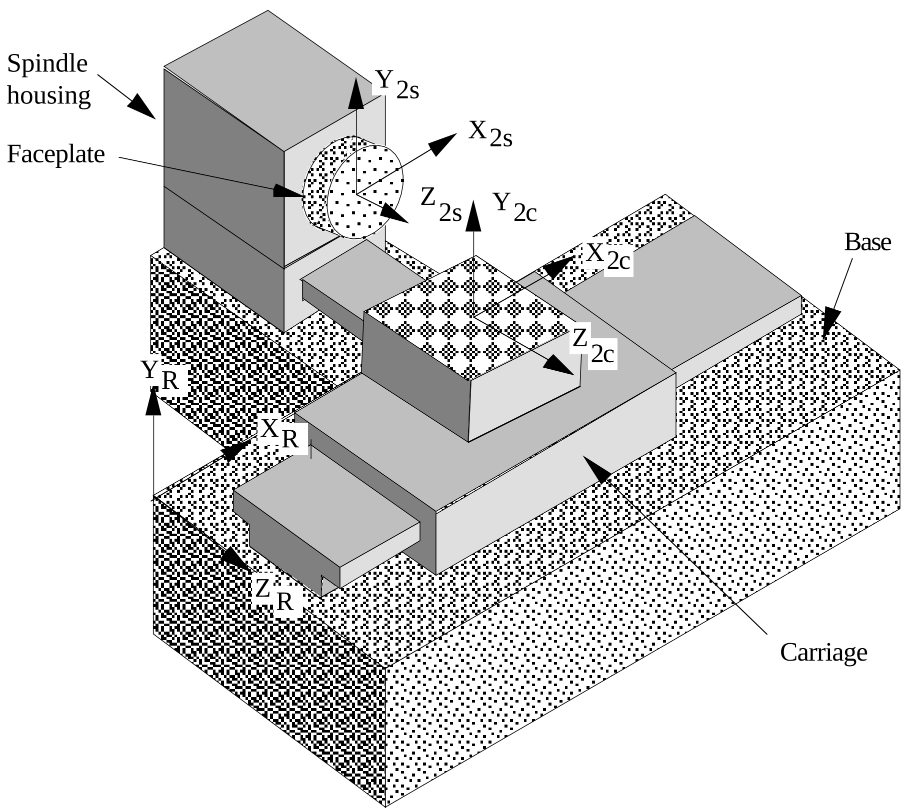
- **Since the structure is defined at the earliest stage (the stick figure concept), its selection is critical.**
- **Once the design detailing starts, its hard to change the shape of the machine.**

- **Common configurations include:**
  - **Open frames (G type).**
  - **Closed frames (Portal type).**
- **New configurations include:**
  - **Spherical (NIST's M^3).**
  - **Tetrahedral (Lindsey's Tetraform).**
  - **Ingersoll Milling Machine's octahedral hexapod (Stewart platform).**
  - **Cube structures (Hexel Corporation's Hexapod)**
- **Other major structural components include:**
  - **Compensating curvatures.**
  - **Counterweights.**
- **Connectivity between elements must also be considered:**
  - **Kinematic design.**
  - **Elastically averaged design.**

Open frame structures

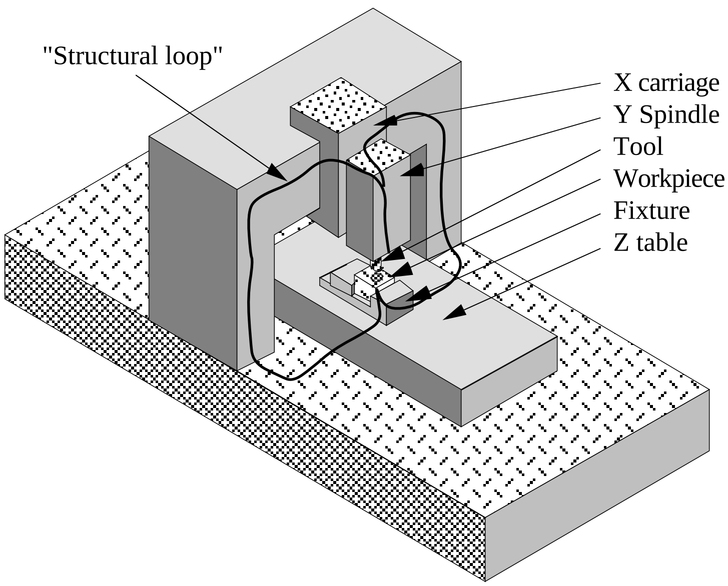
- **Easy access to work zone.**
- **Structural loop prone to Abbe errors (like calipers!)**





Closed frame structures

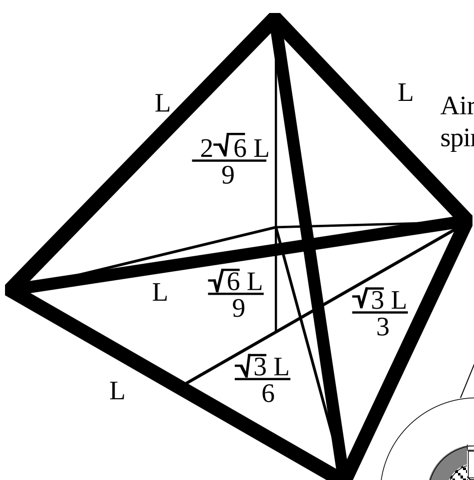
- **Moderately easy access to work zone.**
- **Moderately strong structural loop (like a micrometer!).**
- **Primary/follower actuator often required for the bridge.**
- **Easier to obtain common centers of mass, stiffness, friction.**

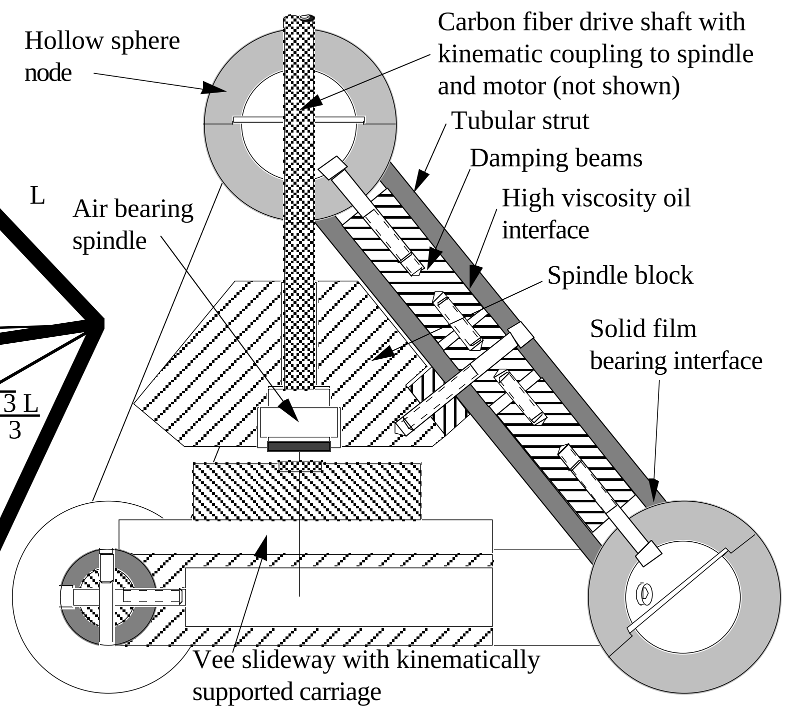


Lidköping Machine Tool’s Double Disk Grinder:

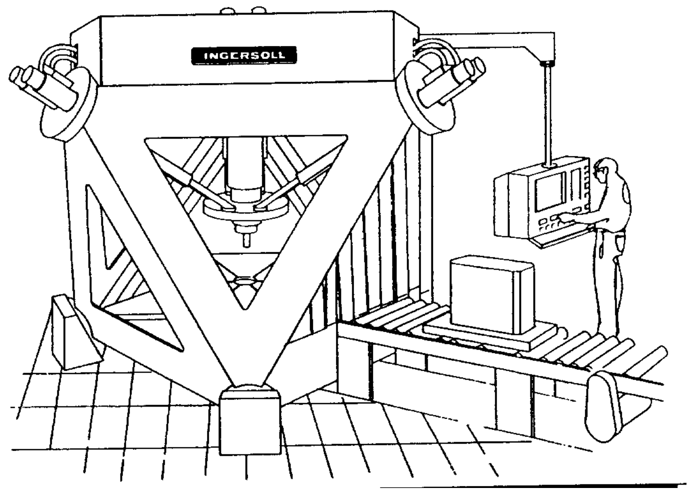
Tetrahedral structures

- **Composed of six legs joined at spherical nodes.**
- **Work zone in center of tetrahedron.**
- **Bearing ways bolted to legs.**
- **High thermal stability.**
- **High stiffness.**
- **Viscous shear damping mechanisms built into the legs.**
- **Damping obtained at the leg joints by means of sliding bearing material applied to the self centering spherical joint.**
- **Inherently stable shape.**
- **Concept developed by the late Dr. Kevin Lindsey at NPL (patented).**





Ingersoll Milling Machine's Octahedral Hexapod (enclosed Stewart platform):



- **Like the tetrahedron, the octahedron is a stable truss-type geometry (comprised of triangles).**
    - **As the work volume increases, the structure grows less fast than a tetrahedron.**
- **The hexapod (*Stewart* platform concept originally developed for flight simulators[1]) gives six limited degrees of freedom.**
    - **The tool angle is limited to about 20 degrees from the vertical.**
- **Advanced controller architecture and algorithms make programming possible.**

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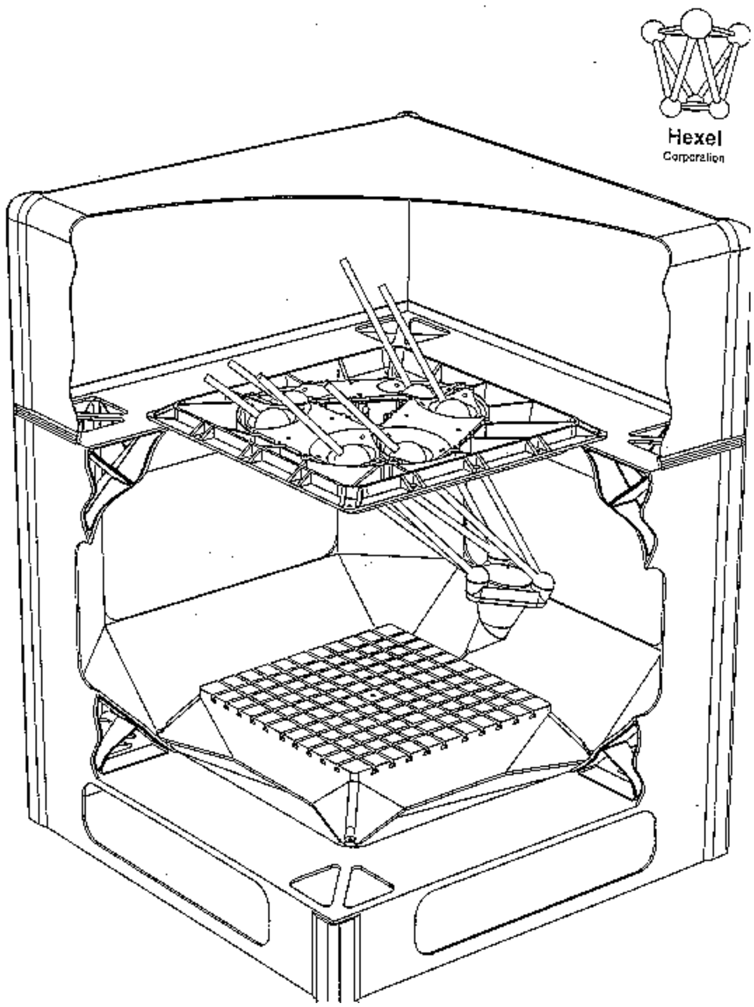
1 Stewart, "A Platform with Six Degrees of Freedom", The Inst. of Mech. Eng., Vol. 180, Part 1, No. 15, pp. 371-386, Proceeding 1965-1966.

Hexel Corporation's Cubic Hexapod (enclosed Stewart platform):



- **Fabricated steel is about $1/lb (less than hamburger), and factory space is $200/ft^2.**
    - **As the work volume increases, the structure grows less fast than a tetrahedron or octahedron.**
    - **The structure is damped with internal ShearDampers™[2] to minimize vibration in the supporting frame.**
- **This hexapod has an additional two axes on the platform supported by the six struts.**

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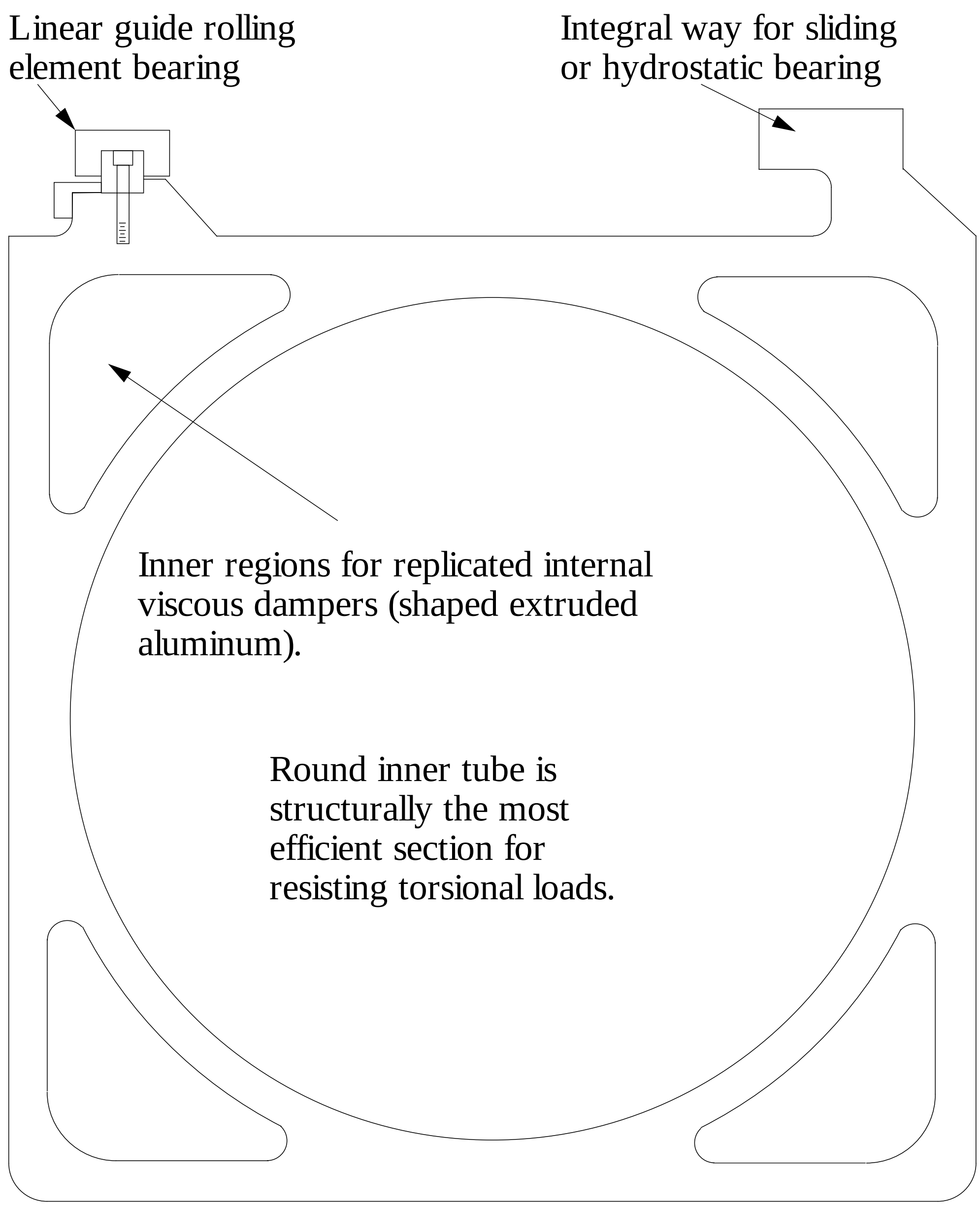
2 Damping is discussed in Topic 11.

Cast iron structures

- **Widely used.**
- **Stable with thermal anneal, aging, or vibration stress relieve.**
- **Good damping and heat transfer.**
- **Modest cost for modest sizes.**
- **Integral ways can be cast in place.**
- **Design rules are well established (see text).**

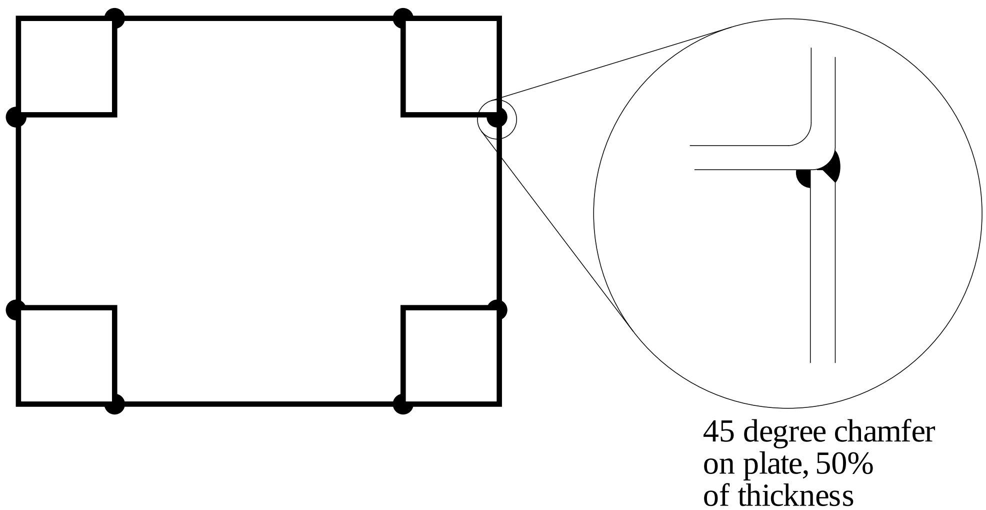
- **Structure that can use replicated-in-place internal viscous dampers:**



Round inner section leaves open a big region for coolant and/or hydraulic tank and pump to be located on the inside (if vibration and thermal issues are addressed).

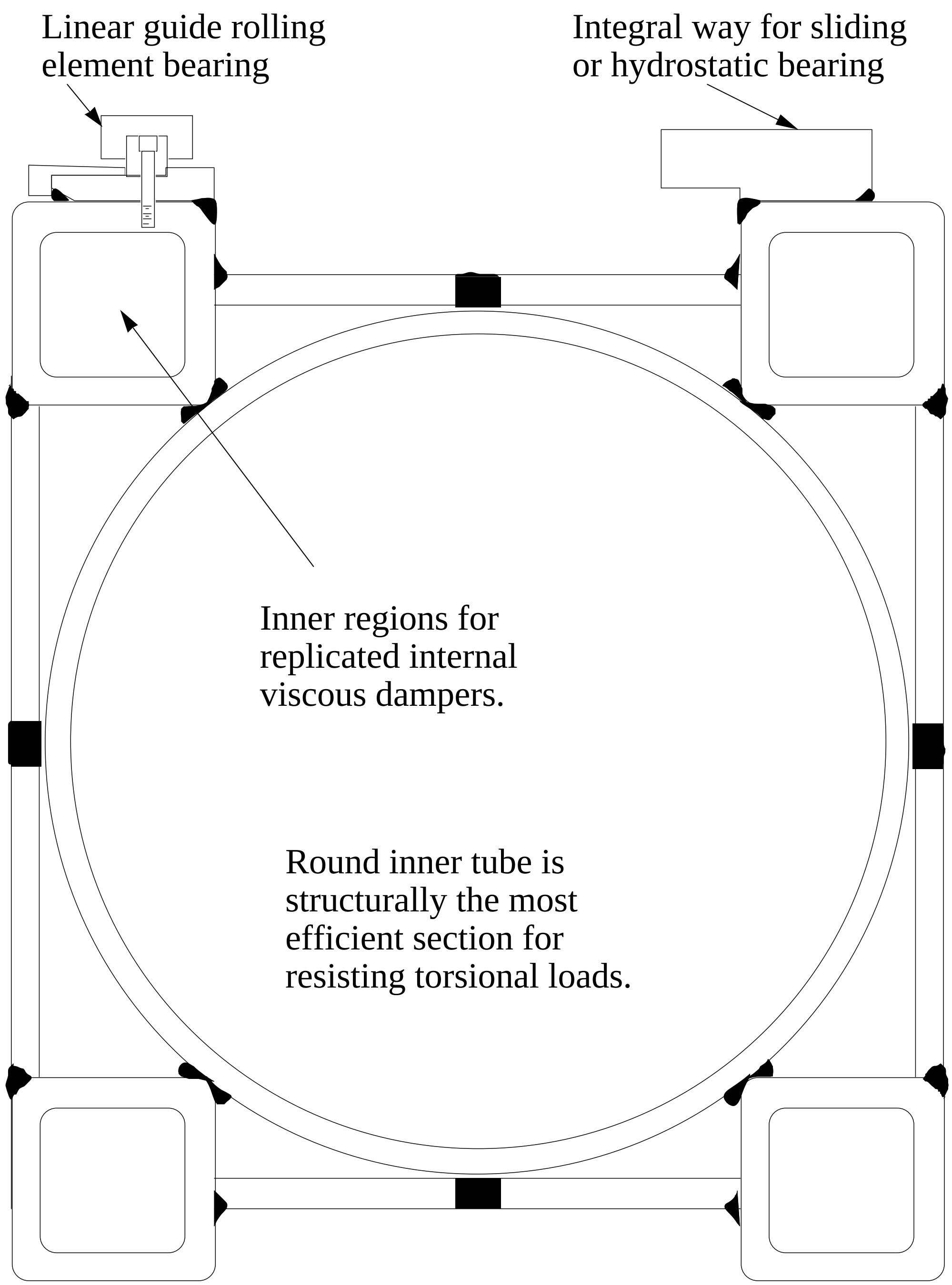
Welded steel structures

- **Often used for larger structures or small-lot sizes.**
- **Stable with thermal anneal.**
- **Low damping, improved with shear dampers.**
- **Modest cost.**
- **Integral ways can be welded in place.**
- **Structures can be made from tubes and plates:**



- **Replicated in place viscous shear dampers can be placed in the tubes.**

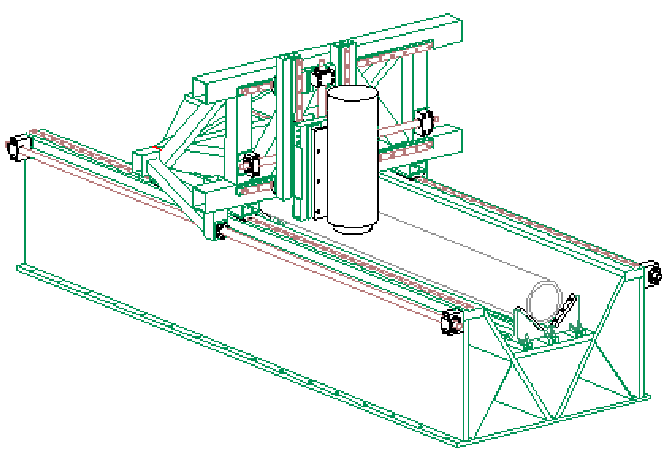
- **Welded structure that can use replicated-in-place internal viscous dampers:**



Plates welded to inner tube through 50 mm x 10 mm access ports located every 200 mm along the length of the column.

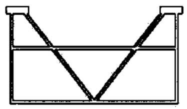
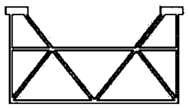
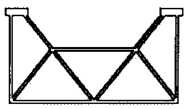
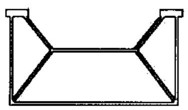
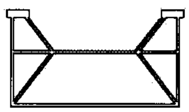
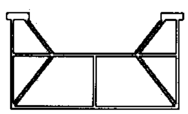
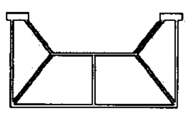
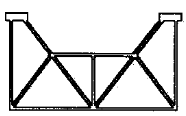
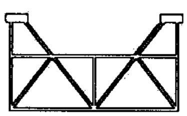
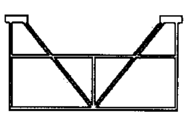
The "Tubemill"

- **Designed for precision milling of grooves for linear guides in long tubes that serve as precision machine structural components[3].**
- **Welded steel structure.**
- **ShearDamped™ as needed.**
- **3-point support to floor.**
- **During the concept phase, every reasonable plate configuration was considered, and FEA was used to study stiffness and natural frequency.**
- **Manufacturing was consulted (what can they make).**
- **Marketing was consulted (how accurate must it be, and how heavy a cut does the customer really want to make).**



[3] This is part of Eberhard Bamberg's Ph.D. thesis in modular precision machine tools, being conducted in Prof. Slocum's lab at MIT.

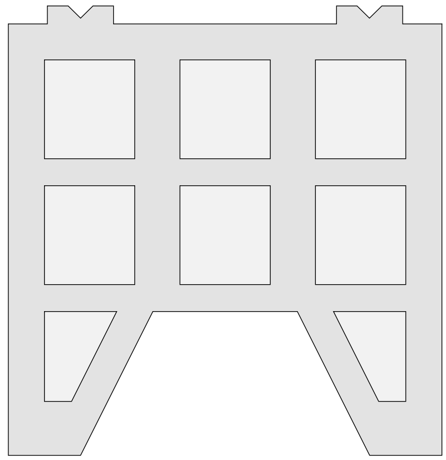
At the start of the detailed design phase, many different detailed structural configurations should be systematically analyzed:

Base Design	Disp [inch] 1000 lbf cutting force	Stiffness [N/micron] cutting f.	Disp [inch] 3000 lb carriage weight	Stiffness [N/micron] load	1. Mode [Hz]	2. Mode [Hz]	3. Mode [Hz]	4. Mode [Hz]
1 	0.001894	92.4	0.001428	368.0	33.5	37.4	71.7	90.5
2 	0.000491	356.9	0.000513	1023.4	39.9	66.7	135.6	139.6
3 	0.000626	279.7	0.000572	919.0	39.9	67.9	103.5	103.9
4 	0.001407	124.5	0.023576	22.3	12.2	22.0	43.8	56.9
5 	0.001192	147.0	0.022586	23.3	11.9	22.1	43.0	58.1
6 	0.000835	209.8	0.001186	442.9	27.6	50.0	51.6	68.8
7 	0.000994	176.1	0.001489	352.8	27.9	49.1	52.6	70.0
8 	0.000617	283.8	0.000572	917.7	39.7	66.4	103.9	104.9
9 	0.000489	358.4	0.000520	1011.2	40.1	66.1	135.2	155.8
10 	0.001595	109.8	0.001177	446.2	33.4	40.1	71.9	90.3

Epoxy granite structures

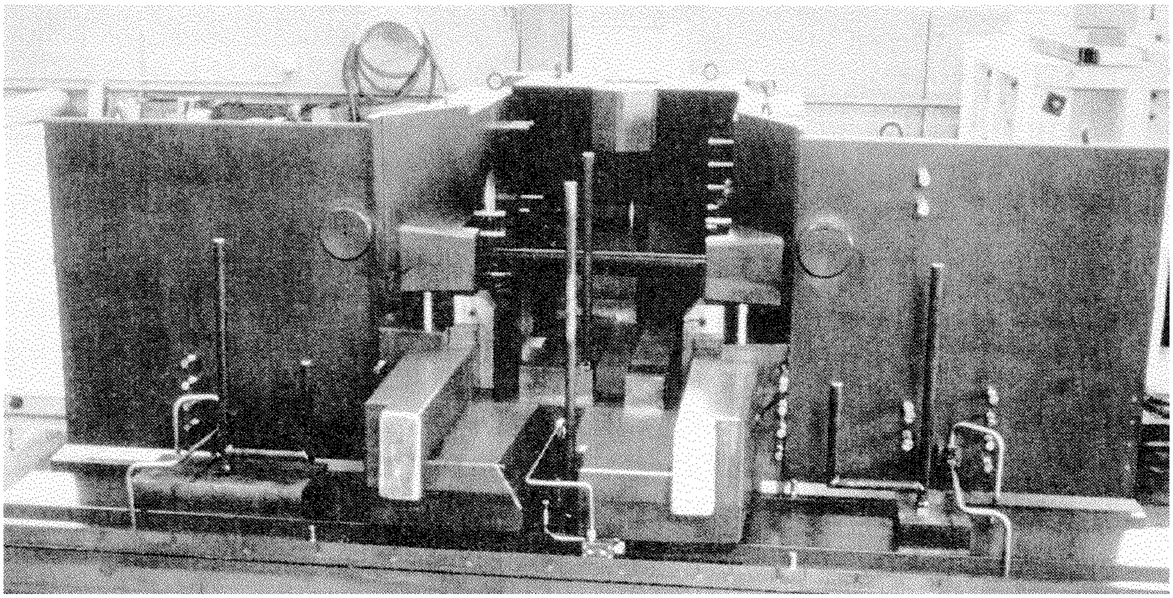
- **Can be cast with intricate passages and inserts.**
- **$E_{epoxyg\ ranite}/E_{cast\ iron} = 5/20$**
- **Exterior surface can be smooth and is ready to paint.**
- **Cast iron or steel weldments can be cast in place, but beware of differential thermal expansion effects.**
- **Epoxy granite's lower modulus, and use of foam cores means that local plate modes require special care when designing inserts to which other structures are bolted!**
- **Sliding contact bearing surfaces can be replicated onto the epoxy granite.**

- **Foam cores reduce weight:**



- **For some large one-of-a-kind machines:**
  - **A mold is made from thin welded steel plate that remains an integral part of the machine after the material is cast.**
  - **Remember to use symmetry to avoid thermal warping.**
- **Consider the effects of differential thermal expansion when designing the steel shell.**
  - **The steel shell should be fully annealed after it is welded together.**

- **Instead of ribs, polymer concrete structures usually use internal foam cores to maximize the stiffness to weight ratio.**
- **Polymer concrete castings can accommodate cast in place components** (Courtesy of Fritz Studer AG.)**:**



- **With appropriate section design:**
  - **Polymer concrete structures can have the stiffness of cast iron structures.**
  - **They can have much greater damping.**
- **Highly loaded machine substructures (e.g. carriages) are still best made from cast iron.**
- **Polymer concrete does not diffuse heat as well as cast iron.**
  - **Attention must be paid to the isolation of heat sources to prevent the formation of hot spots.**
- **When bolting or grouting non-epoxy granite components to an epoxy granite bed, consider the bimaterial effect.**