Lecture 1. Structural Design of Instruments

王代华，博士，教授，博士生导师

Dr. Dai-Hua, Wang, Professor

精密與智能實驗室
Precision and Intelligence Laboratory

http://www.pilab.coe.cqu.edu.cn/

Email: dhwang@cqu.edu.cn

Tel: 023-65112105(O), 65102511(Lab)

重庆大学，光电工程学院

Outline

- ❒ Concept: Structural configurations for machine tools and measuring machines
- ❒ Structural Design Requirements
- ❒ Structural Configurations
- ❒ Other Structural System Considerations
- ❒ Summary

Structural Configurations

- ❒ 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.
- ❒ 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.
- ❒ Next slide…

Structural Configurations

- ❒ Beware of the technology you are using, and is it time to move to a more advanced technology?!
- ❒ 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.

E-mail: dhwang@cqu.edu.cn
URL: http://www.pilab.coe.cqu.edu.cn/

Structural Design Requirements

- ❒ Accuracy
- ❒ Stiffness
  - Static stiffness
  - Dynamic stiffness
- ❒ Damping
- ❒ Thermal expansion

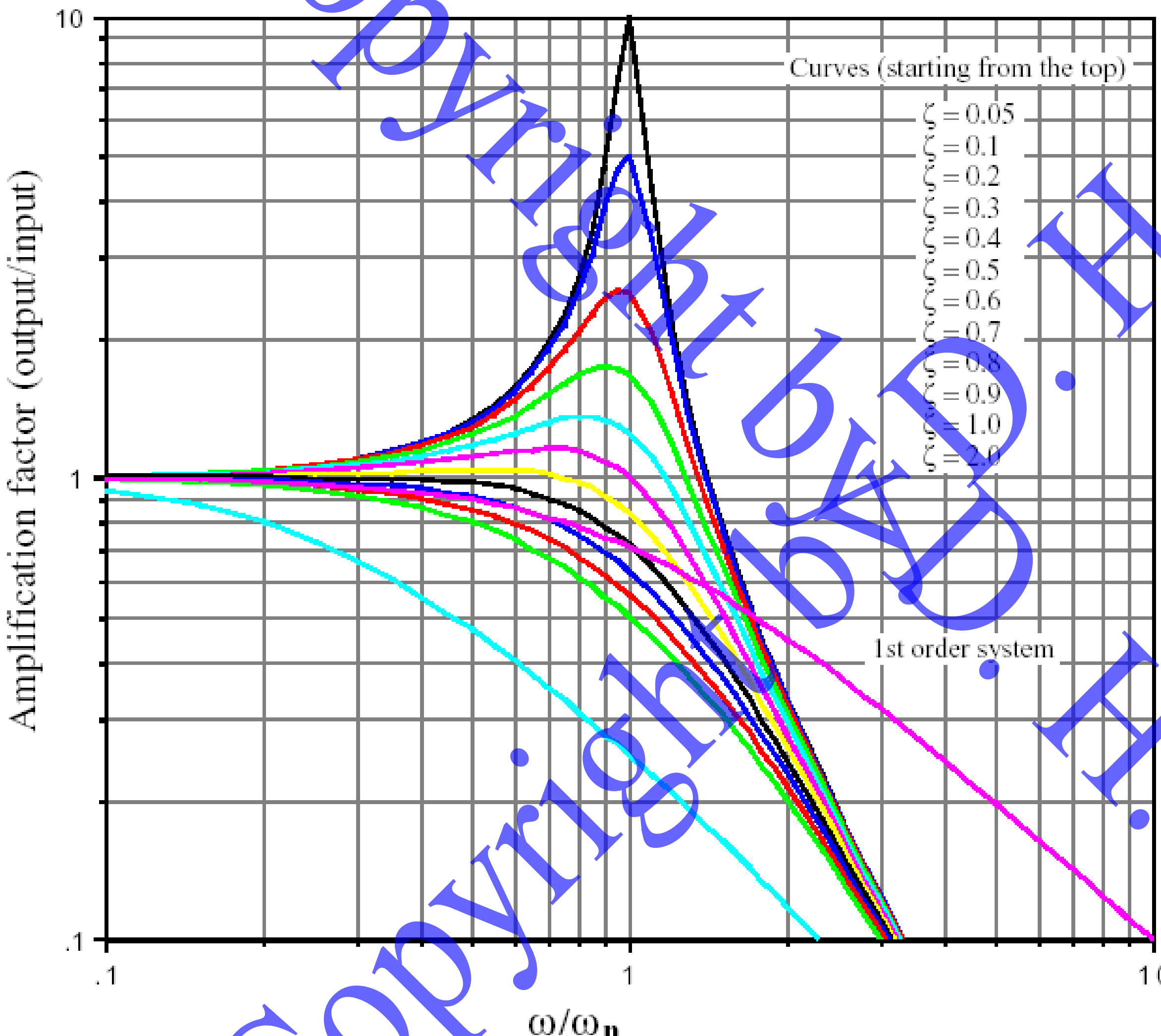
Stiffness Requirements: Static Stiffness

- ❒ 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.

Stiffness Requirements: 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.

Stiffness Requirements: Dynamic Stiffness



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

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

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

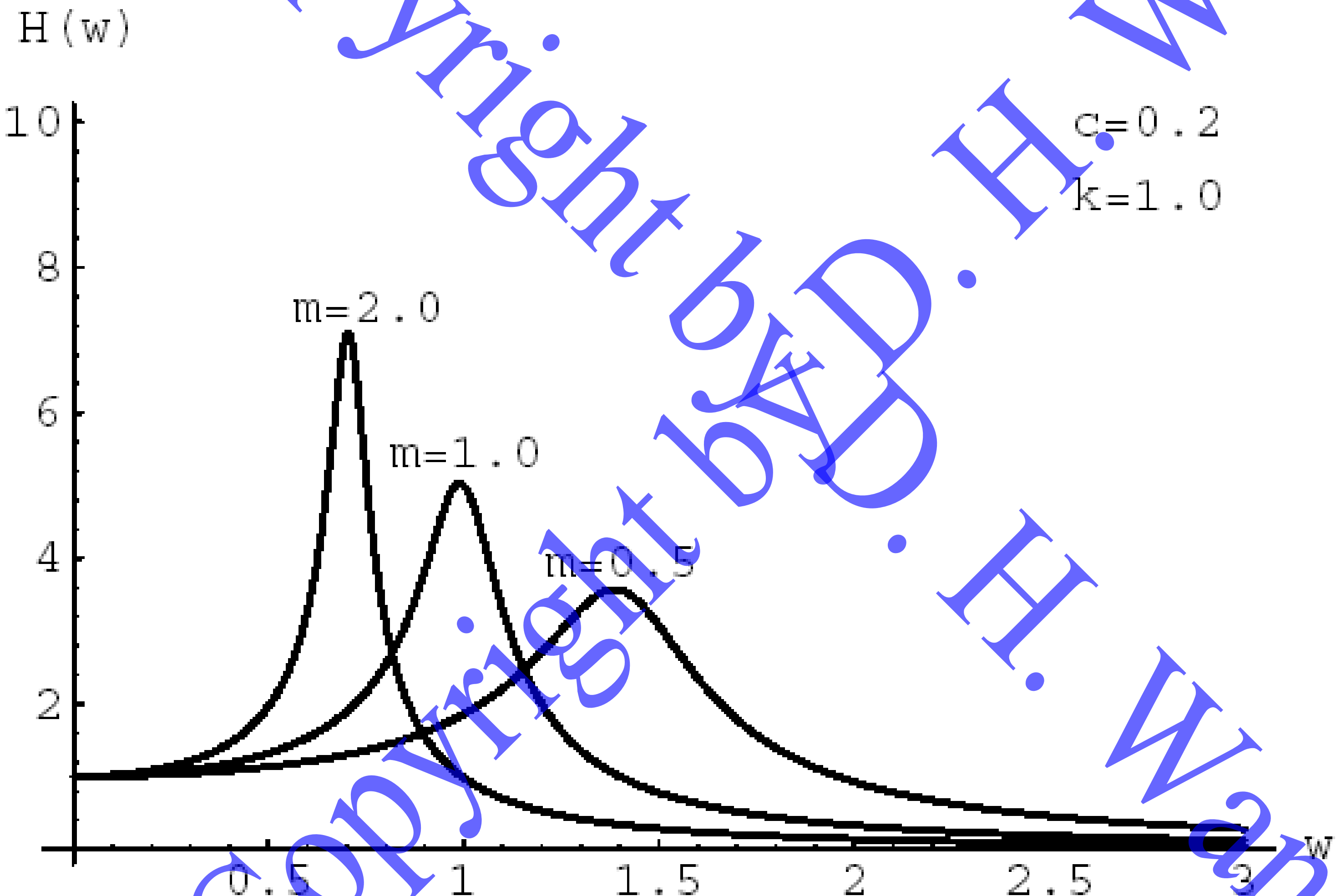
$$Q = \frac{\text{Output}_{peak}}{\text{Input}} = \frac{1}{2\zeta\sqrt{1-\zeta^2}} = \frac{K_{static}}{K_{dynamic}} \approx \frac{1}{2\zeta}$$

Damping Requirements

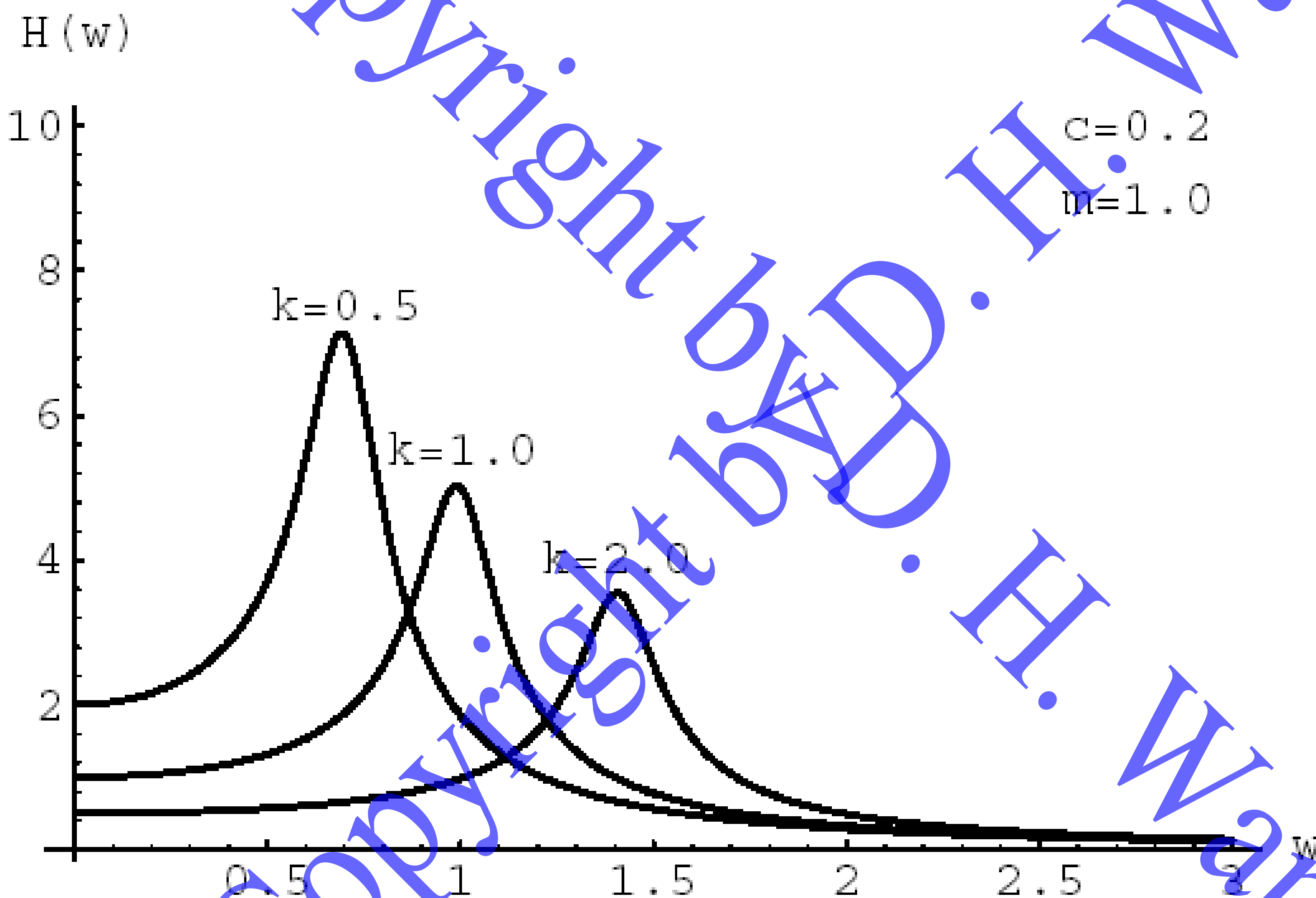
- For unity gain or less, ζ must be greater than 0.707.
- Cast iron can have a damping factor of 0.0015.
- Epoxy granite can have a damping factor of 0.01-0.05
- All the stuff bolted to the structure (e.g., slides on bearings) helps to damp the system. To achieve more damping, a tuned mass damper or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

Effects of Changing System Mass

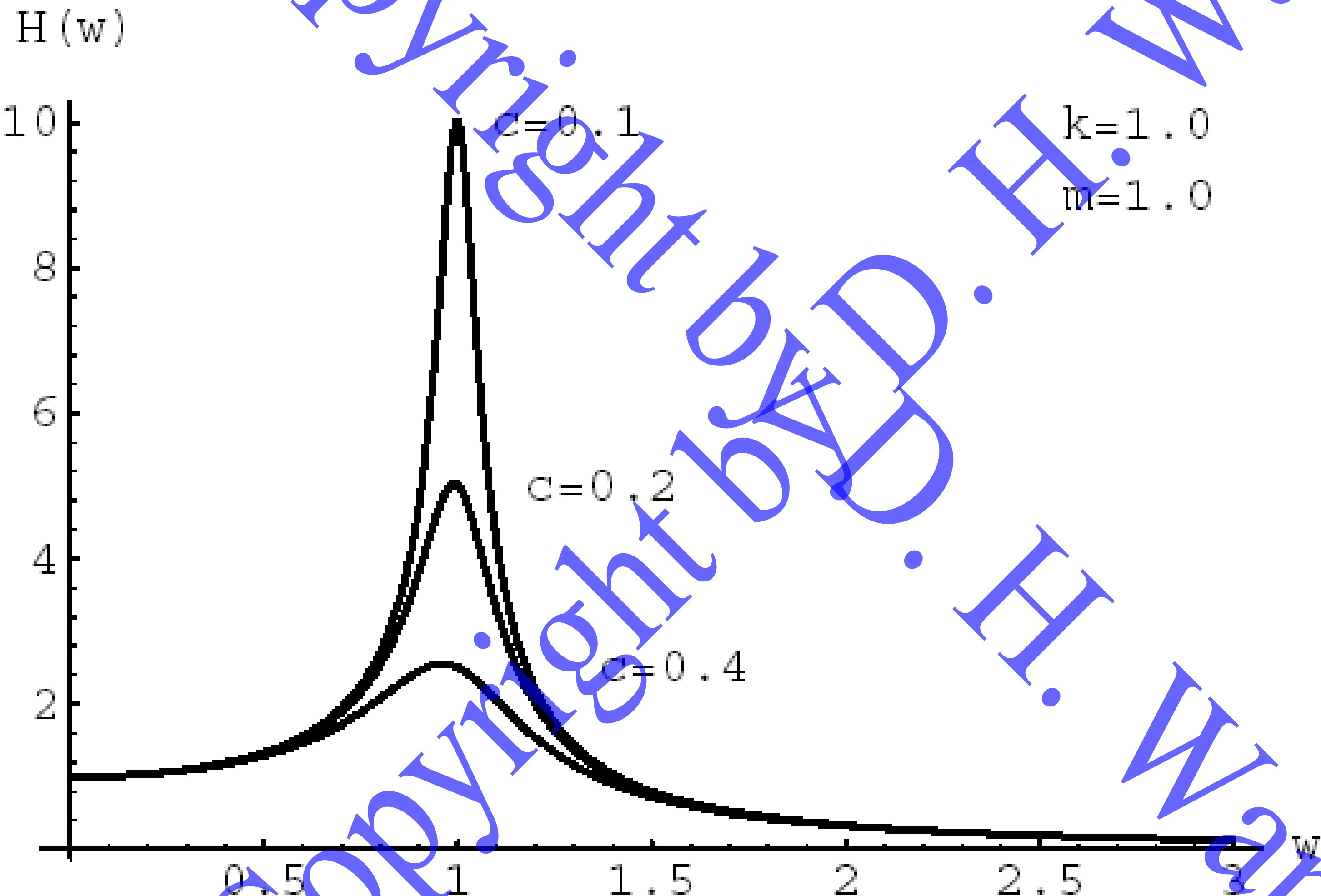
- Adding mass



Effects of Adding Stiffness



Effects of Adding Damping



Damping Requirements

- Passive
  - Material and joint-μslip damping.
  - Constrained layers, tuned mass dampers.
- Active
  - Servo-controlled dampers.
- Hybrid
- Semi-active
  - Semi-active controlled dampers

Thermal Expansion

❒ **Passive temperature control:**

- **Minimize and isolate heat sources.**
- **Minimize coefficient of thermal expansion.**
- **Maximize thermal diffusitivity.**
- **Insulate critical components.**
- **Use indirect lighting.**
- **Use PVC curtains to shield the machine from infrared sources.**

❒ **Active temperature control:**

- **…**

Thermal Expansion

- ❒ **Passive temperature control:**
- ❒ **Active temperature control:**
  - **Air showers.**
  - **Circulating temperature controlled fluid.**
  - **Thermoelectric coolers to cool hot spots.**
  - **Use proportional control.**

Structural Configurations

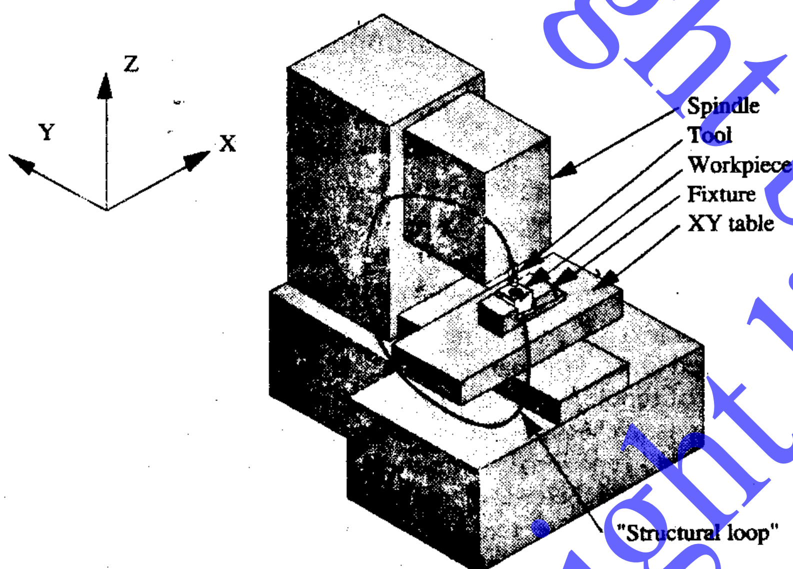
- ❒ Common configurations include:
  - Open frames (G type).
  - Closed frames (Portal type).
- ❒ New configurations include
  - Spherical (NIST's M3).
  - Tetrahedral (Lindsey's Tetraform).
  - Ingersoll Milling Machine's octahedral hexapod (Stewart platform).
  - Cube structures (Hexel Corporation's Hexapod)
- ❒ Other major structural components
- ❒ Connectivity between elements

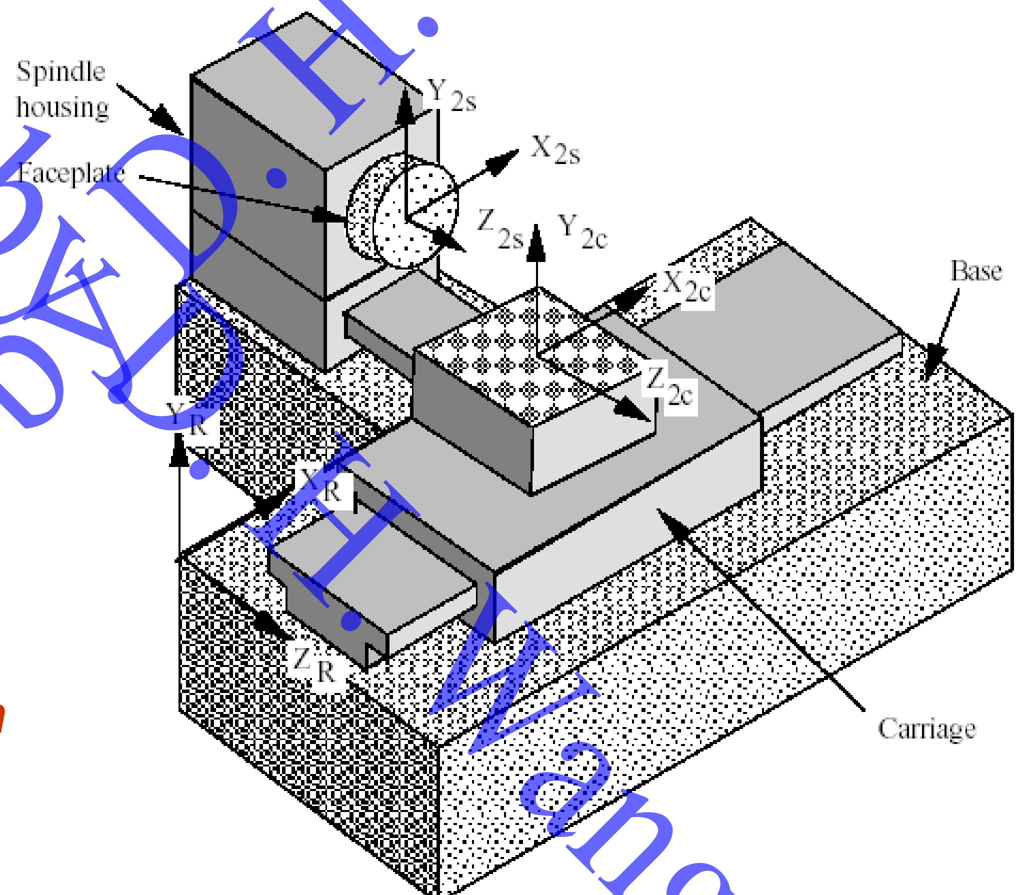
Structural Configurations

- Other major structural components include:
  - Compensating curvatures.
  - Counterweights.
- Connectivity between elements must also be considered:
  - Kinematic design.
  - Elastically averaged design.

Open Frame Structures

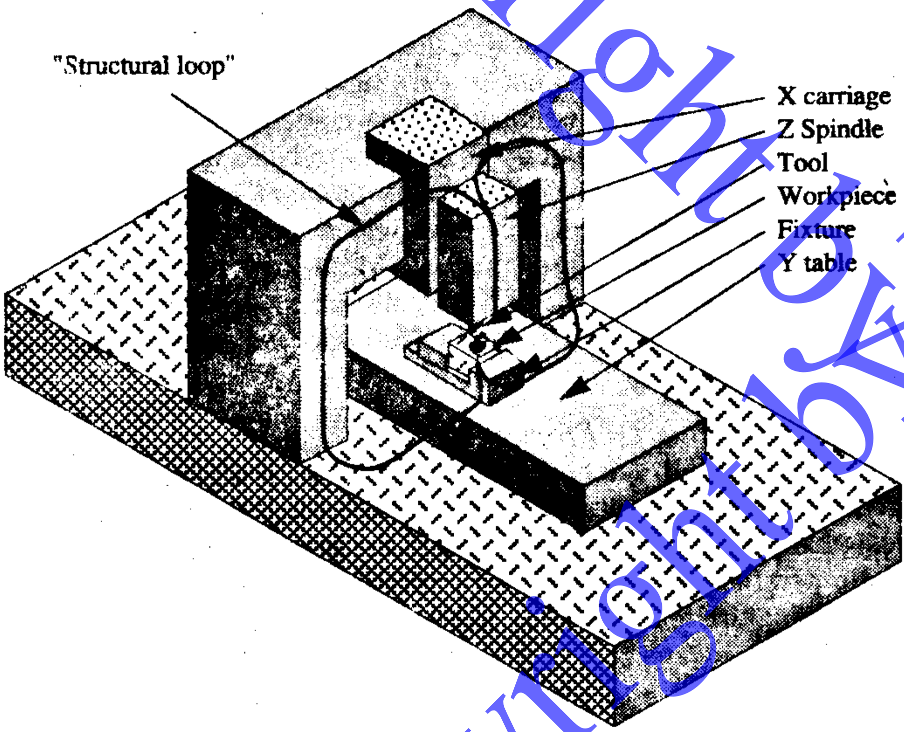
- ❒ Easy access to work zone.
- ❒ Structural loop prone to Abbe errors (like calipers!)





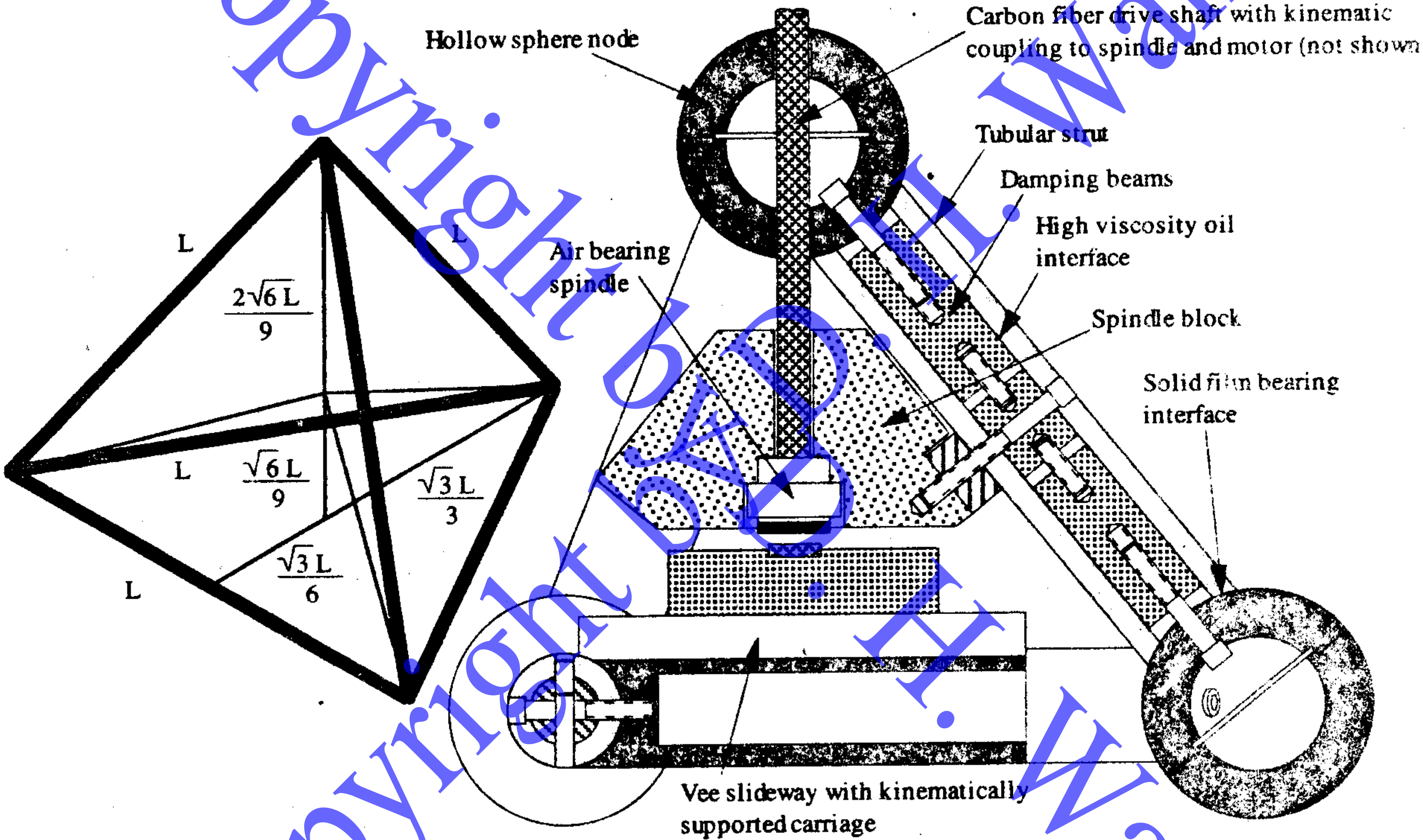
Alexander H. Slocum, *Precision Machine Design*, Prentice Hall, Inc., 1992

Closed Frame Structures



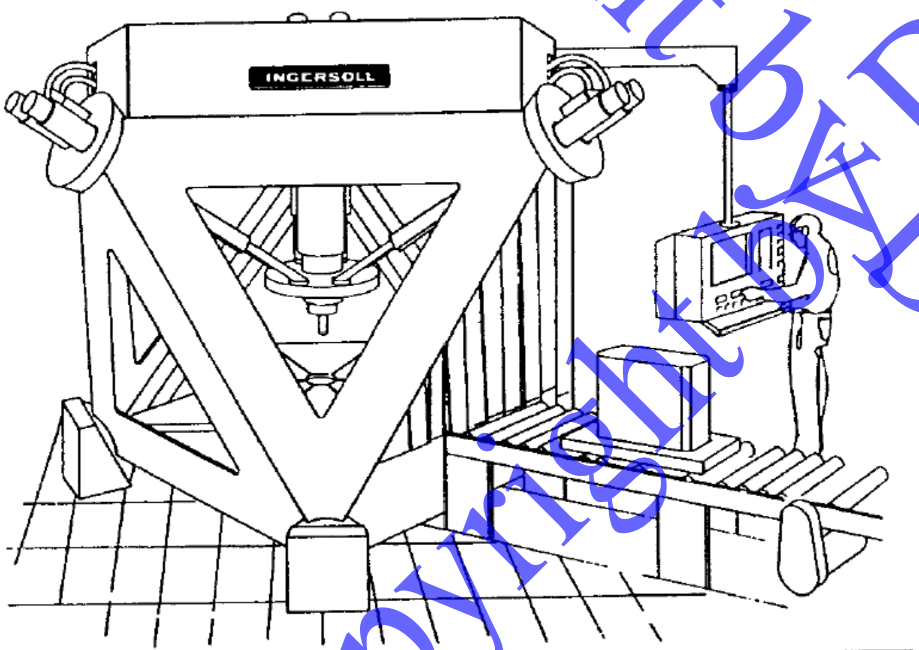
- Moderately easy access to work zone.
- Moderately strong structural loop (like a micrometer!).
- Primary/follower actuator often required for the bridge.
- Easier to obtain common centers of mass, stiffness, friction

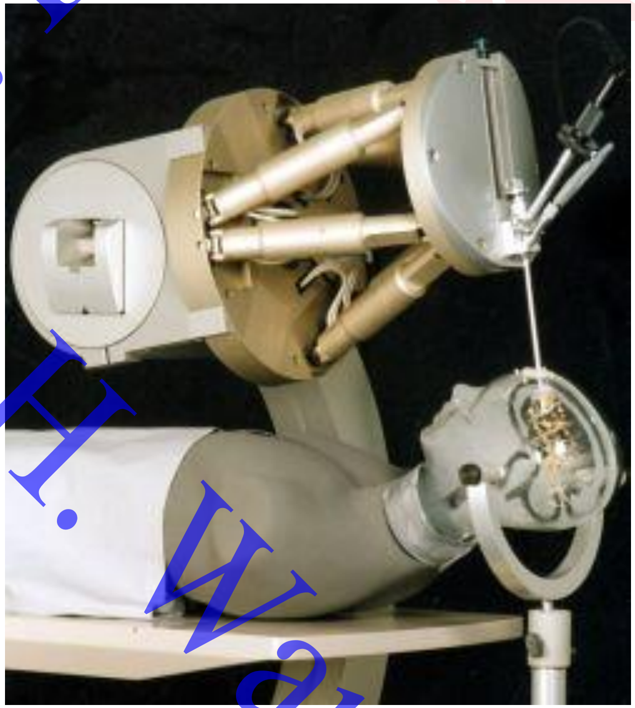
Tetrahedral Structures



Octahedral Hexapod Configuration

- Ingersoll Milling Machine's Octahedral Hexapod (enclosed Stewart platform):
- Hexapod Structures in Surgical Applications





Other Structural System Considerations

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

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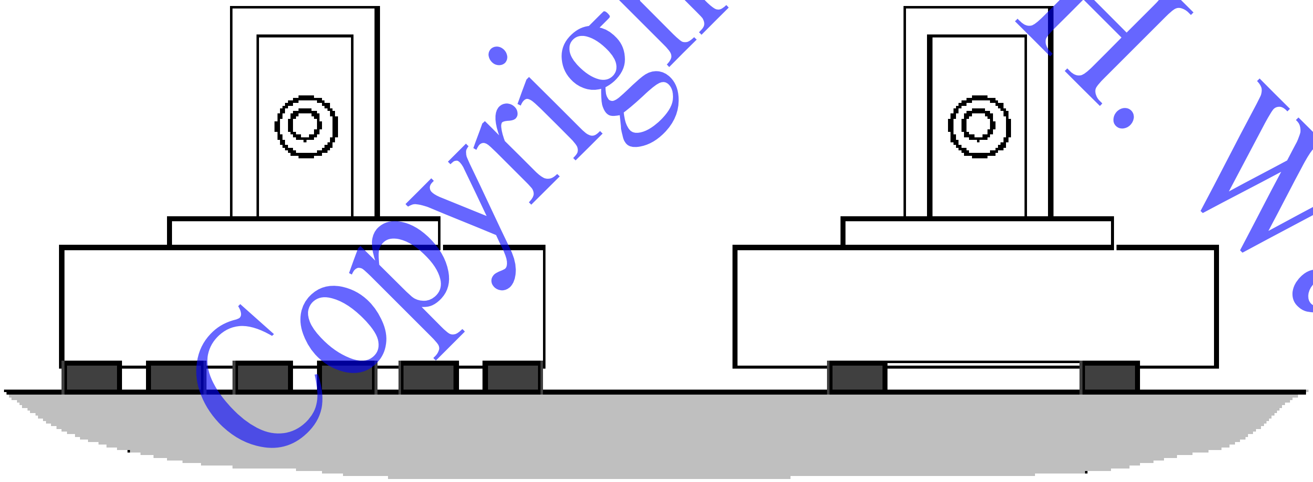
Foundation Support

- 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!



Foundation Support

- 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.

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:

Vibration Isolation

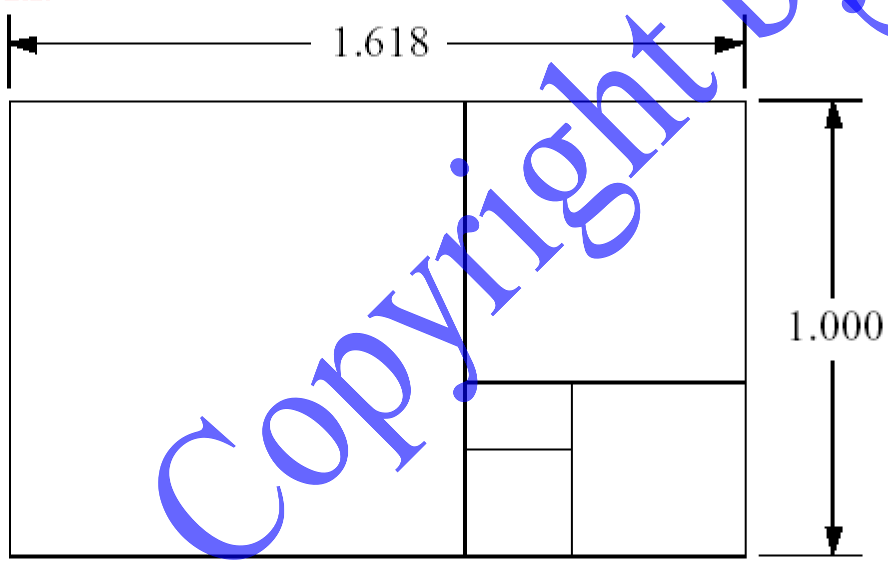
- Passive:
- Active: Servo-controlled dampers
- Semi-active: Semi-active controlled dampers

Research Grade Optical Tables:

The Vibration damper (Snubber) is an elastomer-based system that limits and damps the motion of a table supported by I-2000 vibration isolators.

http://www.newport.com/store/xq/ASP/lone.Vibration+Control/ltwo.Isolators/lthree.VS+Series%253Cbr%253EVibration+Damper/lfour./id.4385/lang.1/qx/product.htm

- After a configuration is chosen from all the conceptual designs, a few simple rules of thumb to follow include:
  - **Keep the proportions of the golden rectangle in mind.**
    - **This usually yields structurally stiff and aesthetically pleasing designs.**



Summary (2/4)

- After a configuration is chosen from all the conceptual designs, a few simple rules of thumb to follow include:
  - Keep the proportions of the golden rectangle in mind.
    - This usually yields structurally stiff and aesthetically pleasing designs.
  - Utilize symmetry whenever possible.
    - Asymmetric structures often have internal gradients which are an indicator of potential problems.

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URL: http://www.pilab.coe.cqu.edu.cn/

Summary (3/4)

- Minimize the structural loop and use closed sections whenever possible.
  - Remember the principle behind the strength and stiffness of an I-beam.
    - Also remember that shear strains are greatest near the neutral axis.
  - Large plate sections should be stiffened with ribs or other means to keep them from vibrating like drumheads.
    - When needed, use active damping systems.
  - Maximize the thermal diffusivity of the machine and minimize heat input.

Summary (4/4)

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

E-mail: dhwang@cqu.edu.cn
URL: http://www.pilab.coe.cqu.edu.cn/

Acknowledgement

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URL: http://www.pilab.coe.cqu.edu.cn/