MIT
Space
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OPTICAL INTERFEROMETER TESTBED

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OPTICAL INTERFEROMETER TESTBED: OUTLINE

1. Motivation for a laboratory testbed of a space based interferometer
2. Description of testbed in context of Controlled Structures Technology
    - performance metric
    - control hardware
3. Overview of testbed research in context of Controlled Structures Technology
    - structural design
    - disturbances and performance
    - sensor/actuator design
    - local/low authority control
    - global/high authority control

OPTICAL INTERFEROMETER TESTBED PROGRAM

Objective: to provide a versatile environment for well controlled experiments on complete controlled structure systems

Testbed is designed to capture the essential configuration, physics, and performance metric of actual spacecraft

Testbed was designed and constructed by students, staff, and faculty as a facility class experiment

Students will conduct their thesis experiment on the testbed by changing out structural components, control hardware and software

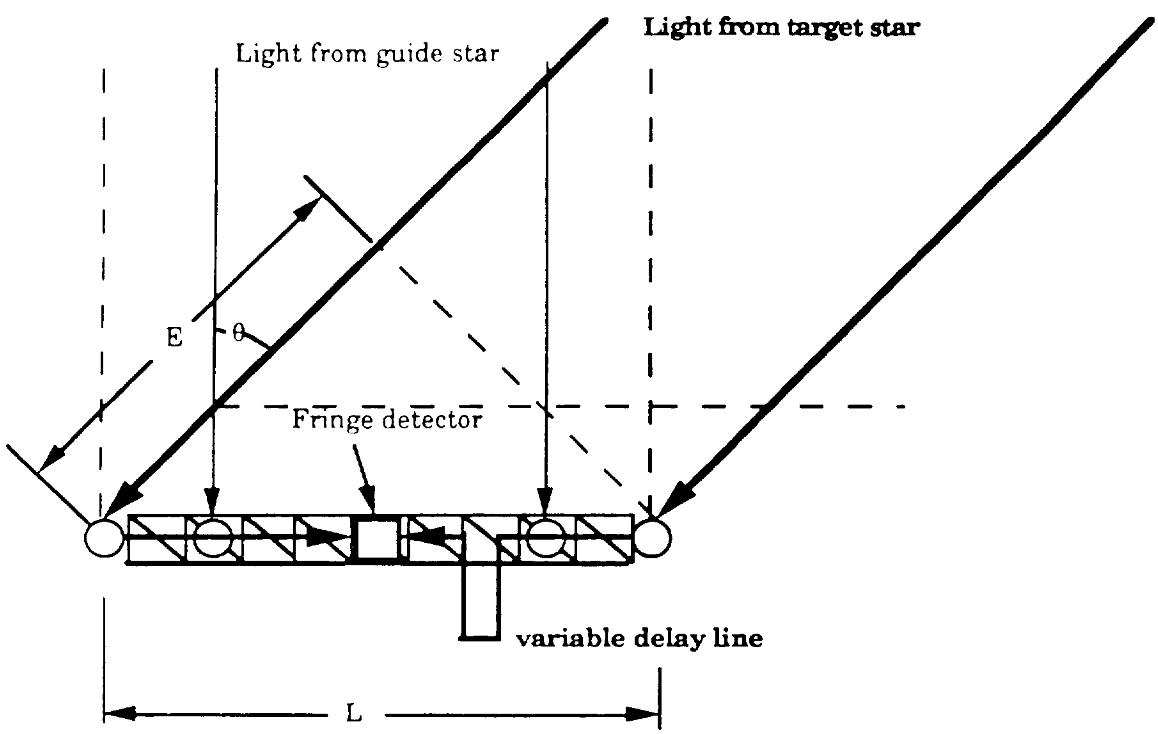
Process provides a realistic evaluation/demonstration of new approaches in *controlled structure design*

A Testbed Based on a Space-Based Optical Interferometer

- CST
  - SERC Scientific Mission Orientation
    - Candidate Missions
      - robotics
      - reflectors
      - masking
      - platforms
      - materials proc.
      - Optical Interferometry
        - Optical Interferometer Testbed Design Project

A Space-Based Interferometer

- used for astrometry:
  - measure baseline and delay lines using metrology system
- used for imaging
  - measure intensity (mag) and phase (via delay line distance) of central fringe of interference pattern
  - vary baseline and rotate siderostats about LOS to target star by rigid body motion
  - reconstruct image from 2-D spatial IFT of the measured intensity



OPTICAL METROLOGY

Unique feature of testbed is multi-axis laser metrology

At 3 mock siderostat locations are precision 3 axis active mirror mounts holding common endpoint retroreflectors (cat's eyes)

Fourth vertex holds laser and other optics

Use commercially available 670 μWatt laser from Hewlett-Packard

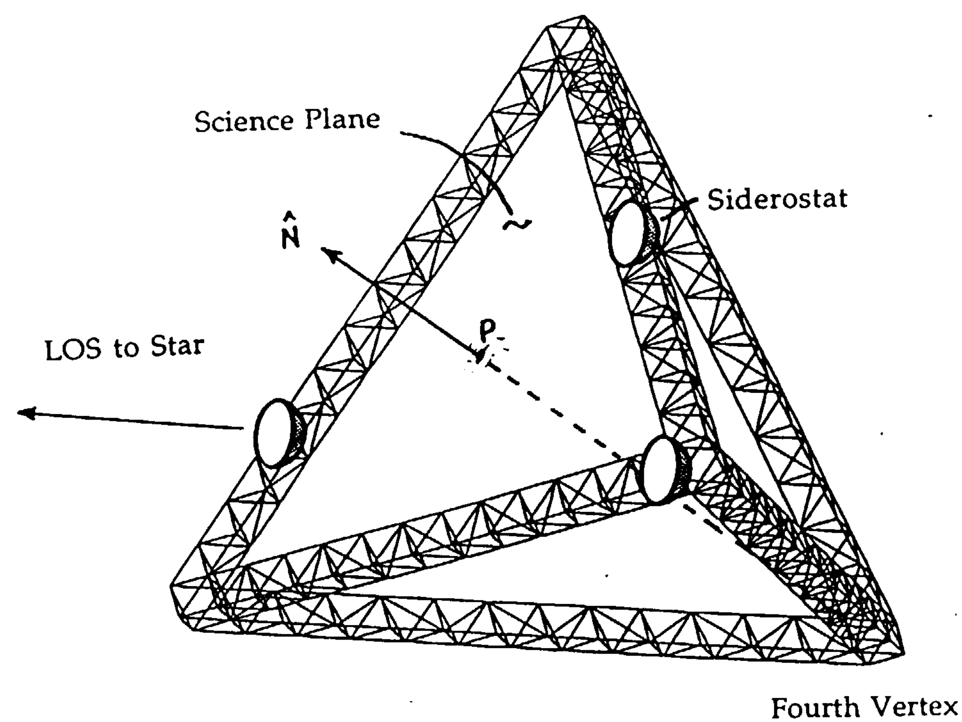
VME based fringe counting provides seamless link to real time controller

Optical components provide 5 laser pathlength measurements:

- defines baseline for metrology
- define "total starlight differential pathlength error" metric, simulating both internal and external error sources
- a subset of these measurements are available for feedback

OPTICAL INTERFEROMETER TESTBED (OVERVIEW)

- Testbed based on scientific mission for focus of graduate student theses.
- Testbed modelled on a 35 meter baseline earth-orbiting optical interferometer.
- Precision alignment requirement between three onboard optical elements is 50 nanometers RMS above 1/10th of a hertz.



SENSORS AND ACTUATORS

Sensors for Identification and Control

- 32 Kistler accelerometers for modal identifications testing
- 9 Sunstrand micro-g accelerometers mounted at performance-critical locations
- 5 channels of laser measurement
- strain gages and load cells collocated with active struts

Actuators for Identification and Control

- 3 active struts capable of 60 microns of stroke and 250 Newtons of force at high bandwidth (Physik Intrumente)
- 3 three-axis precision mirror actuators (custom) at each mock siderostat location
- Passively shunted piezoelectric struts

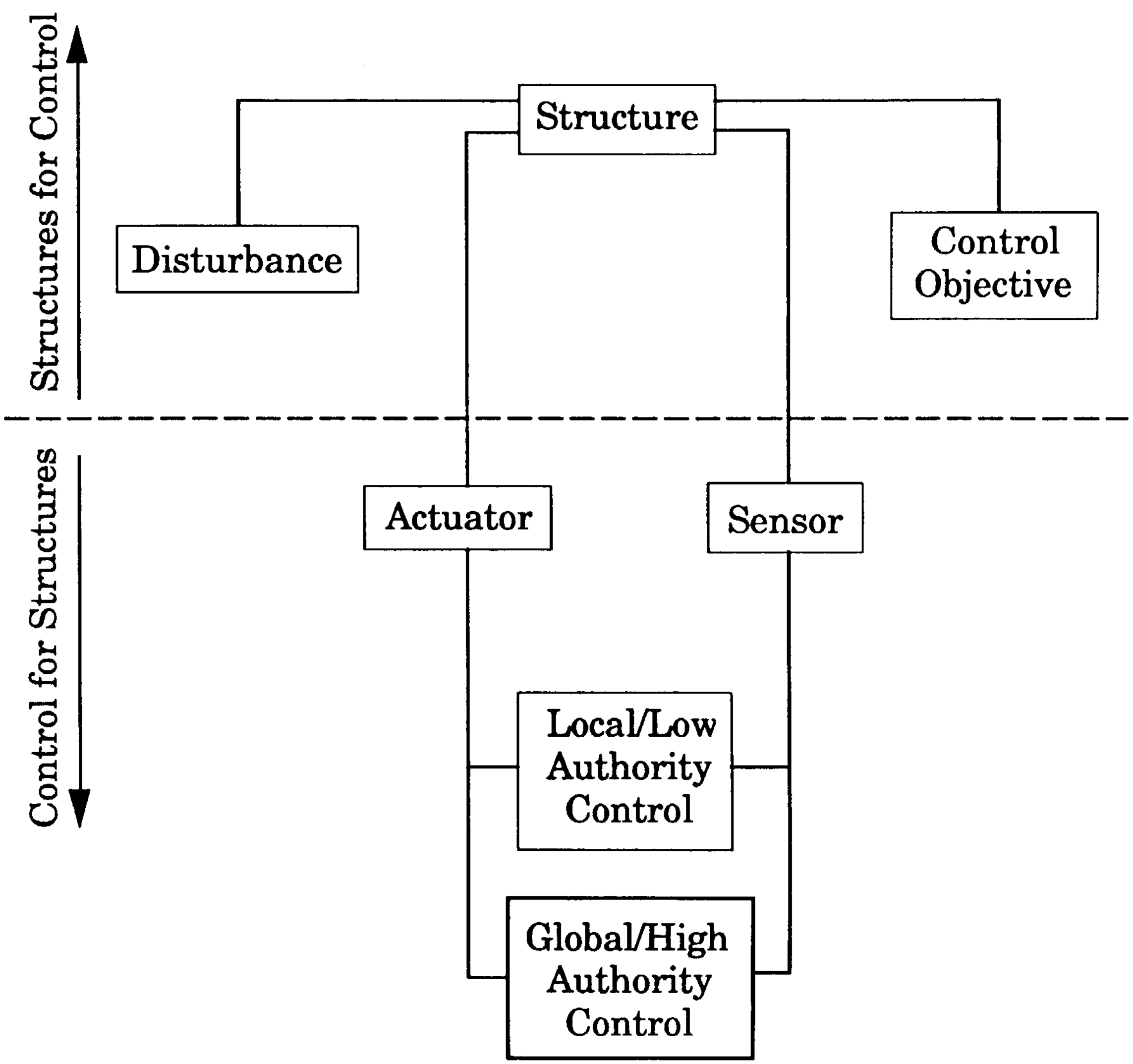
Real Time Control Hardware

- VME based digital control hardware
  - 68030 processor
  - CSPI vector processor
- Capability:
  - 16 inputs
  - 10 outputs
  - 32 states at 1000 Hz; scales by (ns + ni) * (ns + no)
- Direct link to six HP laser measurement boards
- Control design in MATLAB on Sun SparcStation

- <u>Analog:</u> circuits for displacement and velocity feedback to active struts

A CST DESIGN METHODOLOGY

1. Design structure.
2. Design disturbances and control objective.
3. Design actuator and sensor.
4. Design local/low authority control.
5. Design high authority control.



INTERFEROMETER: EXAMPLE OF CST DESIGN

The interferometer will be used not only as a testbed for the elements of Controlled Structures Technology but also for the evloution of the design process.

Step 0 - Mission Requirement Specification

Disturbance selected from spacecraft experience.

Performance metric established which captures challenge of real spacecraft mission.

Step 1 - Design Structure

Structure chosen for “rigid” alignment of primary performance measures - optical elements of the inteferometer

Structure serves as “host” to robust control

Passive damping augmentation for performance and robustness

Step 2 - Design disturbances and control objective

Mount onboard disturbances at locations of lower disturbability

Passive and active isolation at source and output

INTERFEROMETER: EXAMPLE OF CST DESIGN

Step 3 - Design Actuator and Sensor

pole-zero analysis
actuator and sensor combinations for active isolation
induced strain actuators
actuator and sensor placement for global control
quasi-static shape control

Step 4 - Local/Low Authority Control

impedance matching
wave control
active isolation at disturbance input and at quiet payloads

Step 5 - Global/High Authority Control

modelling and MIMO identification for control
global control using distributed active struts
heirarchic control formulation to simultaneously optimize local and global controllers

IDENTIFICATION FOR MIMO CONTROL

SISO Block 1

- Experimental measurement
- LLS Estimation
- NLLS Estimation
- Partial Fraction Expansion

⋮

SISO Block n

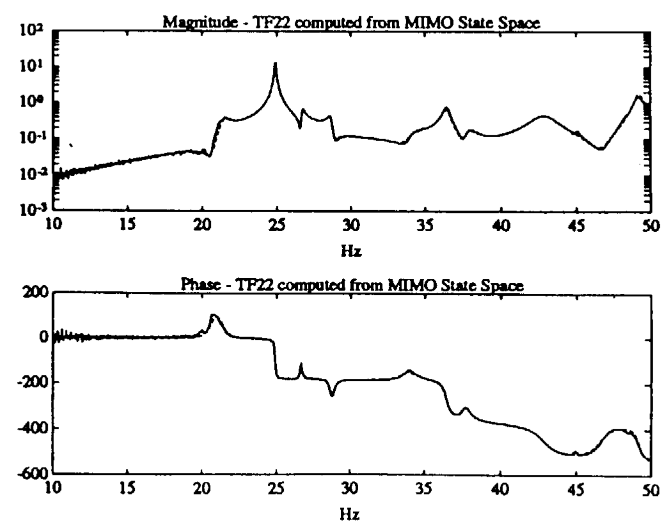
⇒

MIMO Synthesis

- Matrix Partial Fraction Expansion
- Dyadic Decomposition
- MIMO State Space

⇓

Strut 3 to Accel. 8



Model Validation

___ experiment
------ model

FEM/ID CORRELATION FOR THE NAKED TRUSS

Frequencies

Measured	FEM 1	FEM 2
31.35 Hz	suspension	
31.75 Hz	suspension	
(35.1) Hz	3.5 %	0.4 %
35.1 Hz	3.5 %	0.4 %
38.9 Hz	4.7 %	1.8 %
(38.9) Hz	4.7 %	1.8 %
39.4 Hz	3.5 %	0.6 %
43.3 Hz	4.0 %	0.9 %
43.7 Hz	0.2 %	0.1 %
(43.7) Hz	3.2 %	0.1 %
52.1 Hz	3.3 %	0.2 %
54.7 Hz	3.3 %	0.6 %
55.2 Hz	2.4 %	-0.3 %
55.6 Hz	2.4 %	-0.4 %
62.7 Hz	suspension	
63.4 Hz	suspension	
94.1 Hz	suspension	
94.8 Hz	suspension	
95.0 Hz	suspension	
100.8 Hz	3.9 %	2.6 %
101.7 Hz	2.9 %	1.8 %
102.0 Hz	2.6 %	1.6 %

Modeshapes

Overall agreement with FEM modeshapes

Current Issues

Assessment of accuracy of measured residues for structure with high modal density

Correlation for incomplete ID and degenerated modes

Correction , based on ID results, of global parameters, to match the frequencies

Correction, based on ID results, of local parameters, to match the modeshapes

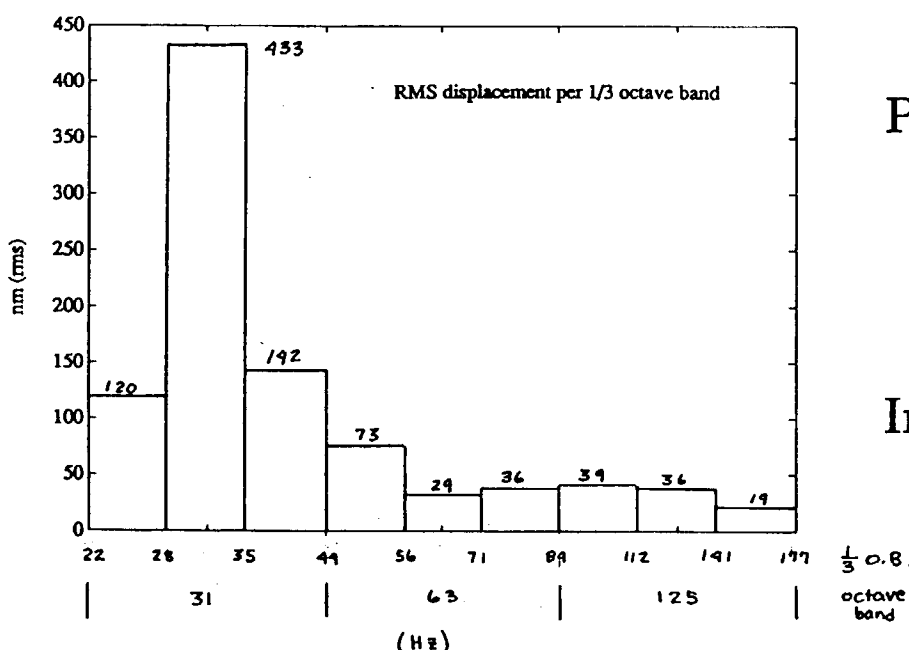
DISTURBANCE MODELLING

Performance degradation due primarily to disturbances from reaction wheels and other on-board machinary. Disturbance level at output expected to be 500 nm (rms) on full scale

Performance metric is not a function of baseline. Scale lab disturbance to same level of 500 nm (rms)

Disturbance source is piezo actuator mounted to vertex; two disturbances modelled are:

- broadband disturbance
- slowly time varying narrowband disturbance



Pathlength error due to broadband disturbance modeled using Statistical Energy Analysis, assuming a typical disturbance input location.

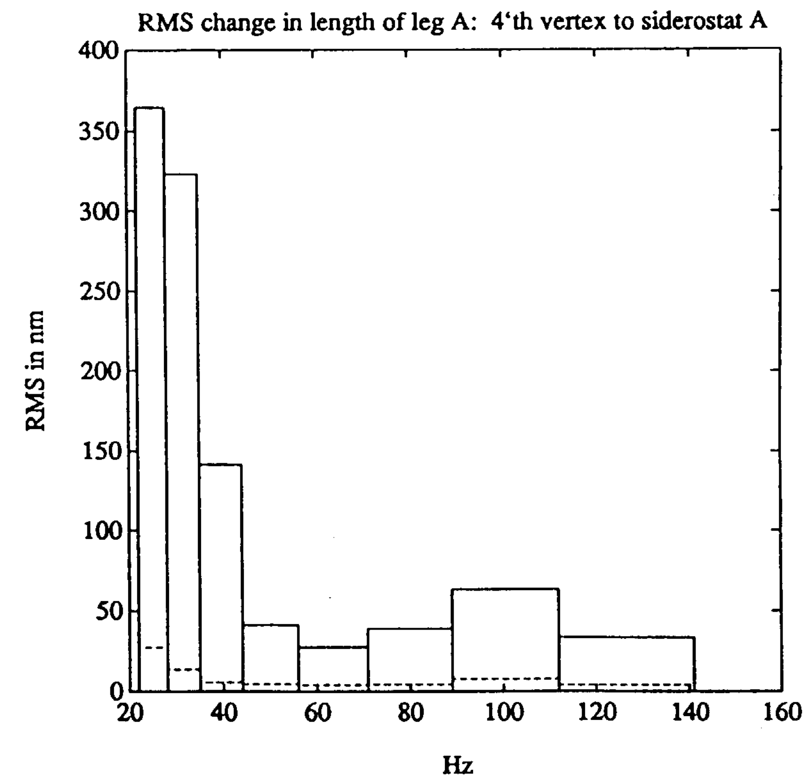
Indicates that 99% of the performance degradation occurs between 20 and 60 Hz.

DISTURBANCE SOURCE IMPLEMENTATION

<u>Goal</u>: Use 3-axis piezoelectric disturbance source to implement the broadband disturbance spectrum resulting in 500 nm (rms) pathlength error

<u>Test</u>: Measured optical pathlength from the fourth vertex to siderostat A with the disturbance source on and off. Computed the RMS change in length over 1/3 Octave bands.

<u>Results:</u> Disturbance source does degrade the pathlength as expected while concentrating energy in vicinity of first few structural modes.

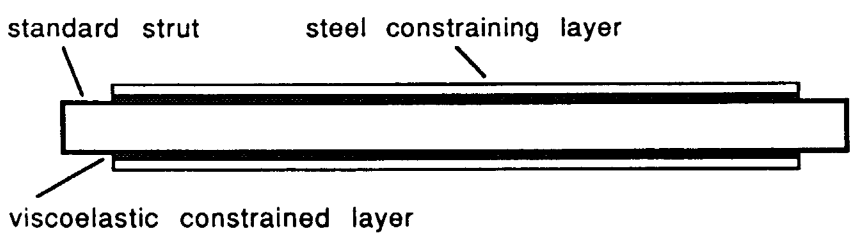


STRUCTURE DESIGN: PASSIVE DAMPING

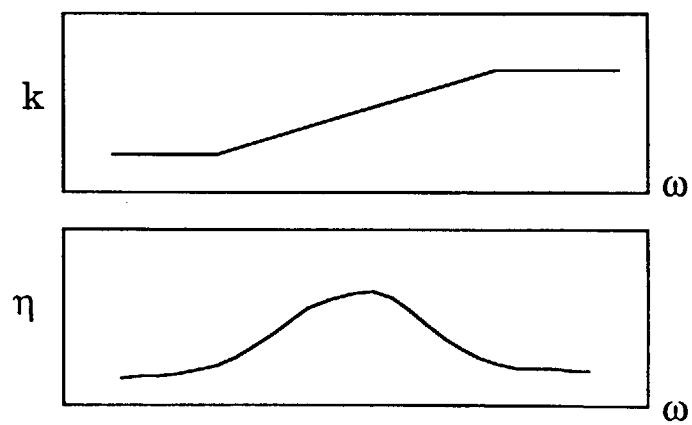
- damping provides some performance within bandwidth
- adds robustness to plant in rolloff region
- improves performance of high authority controllers within bandwidth, which are sensitive to frequency modelling errors

<u>Option: Constrained Layer Viscoelastic struts</u>

- advantages: inexpensive, easy to make
- disadvantages: temperature sensitive, loss factor not high (.05) many struts are required



Typical damped strut frequency response



STRUCTURE DESIGN: PASSIVE DAMPING

Option: Honeywell D-Strut Passive Damper

- can be tailored for specific structural impedances
- struts have high loss factor (1.5); fewer struts will be necessary
- analytical study: D-Struts placed in locations of highest weighted strain energy; spectrum of disturbance at pathlength output is improved.

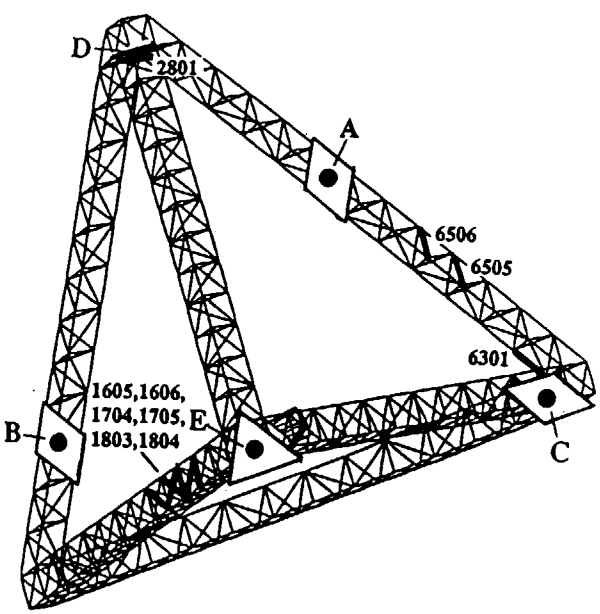
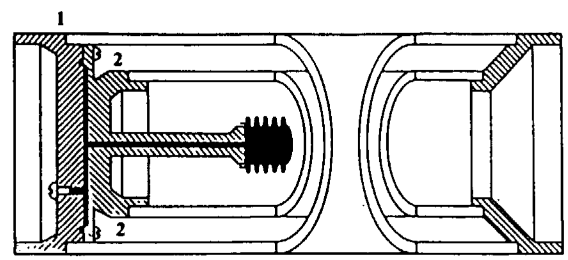
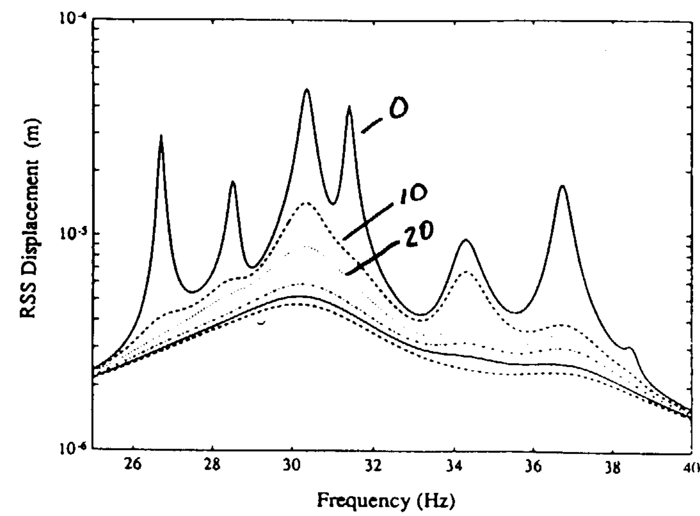


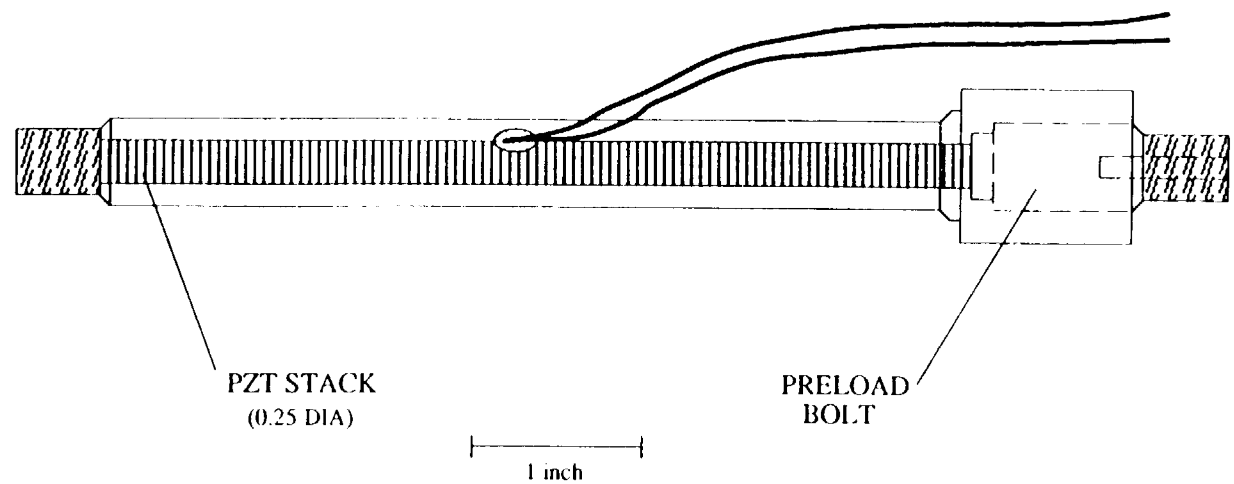
Figure 14: Locations of Struts with Highest Weighted Strain Energies

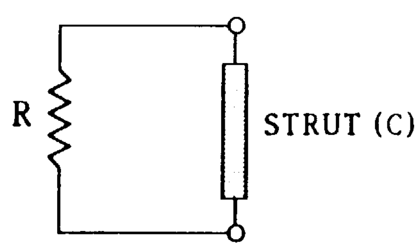


a) Inner-Outer Tube Strut

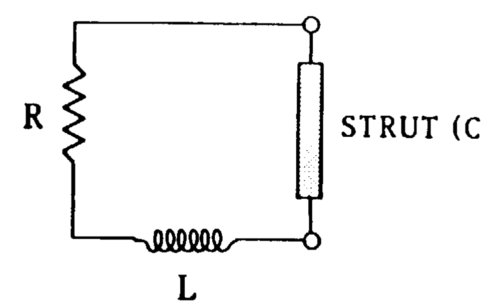


Shunted Piezoelectric Damping





Resistive Shunting



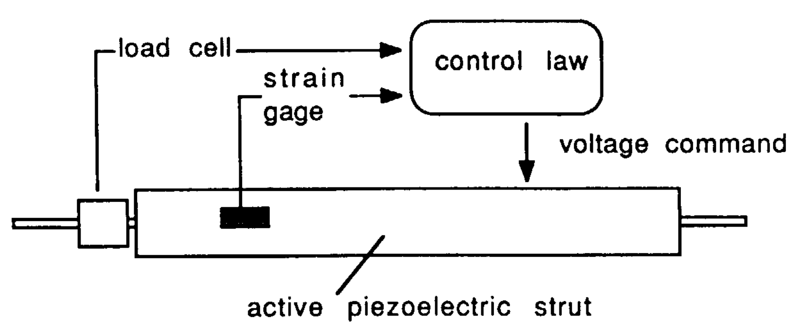
Resonant Shunting

LOW AUTHORITY CONTROL

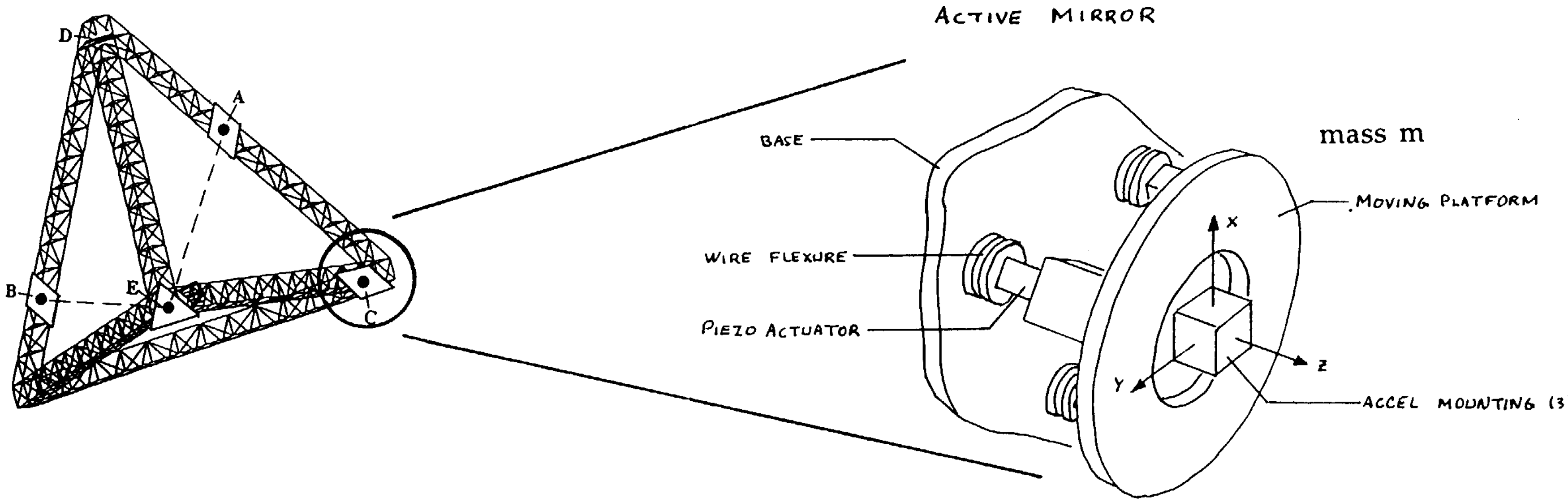
- adds some performance in control bandwidth
- adds robustness in rolloff region of high authority control
- similar benefits to passive damping

<u>Options:</u>

- velocity feedback using active struts
- impedance matching/power flow approaches using external power source
- same formulation, but using passive elements only (shunted piezoelectrics)



Active Isolation of Lightweight Mirrors on Flexible Structures

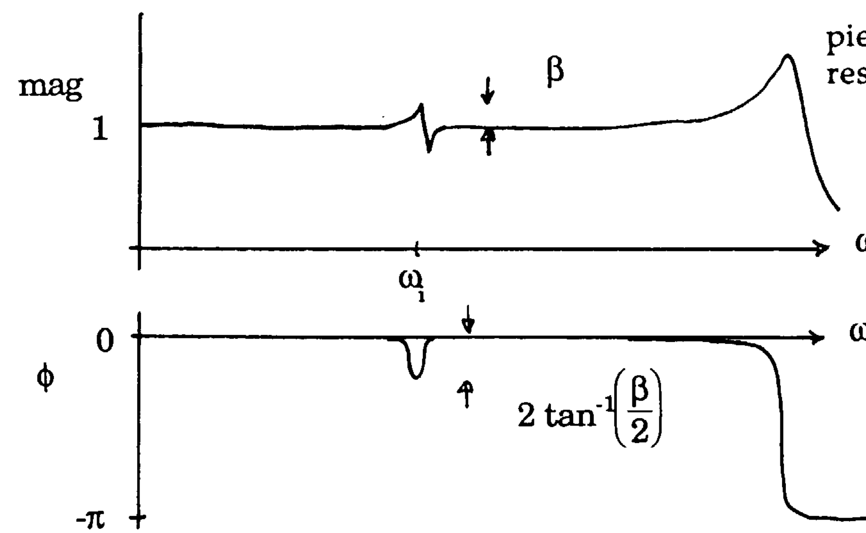


- Plant transfer function is

$$\frac{\text{mirror displacement}}{\text{piezo voltage}}$$

- Active mirrors located at locations A, B, C
- Non-dimensional parameter for flex coupling of the ith mode:

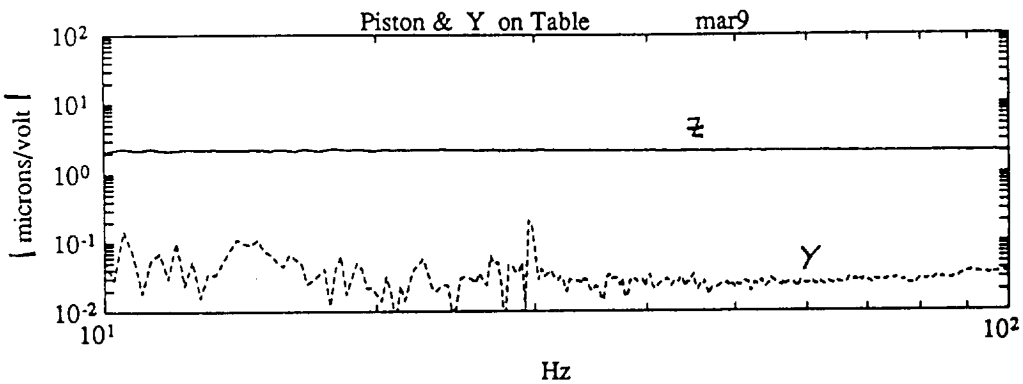
$$\beta = \left(\frac{1}{\zeta_i}\right)\left(\frac{m\phi_i^2}{2}\right)$$



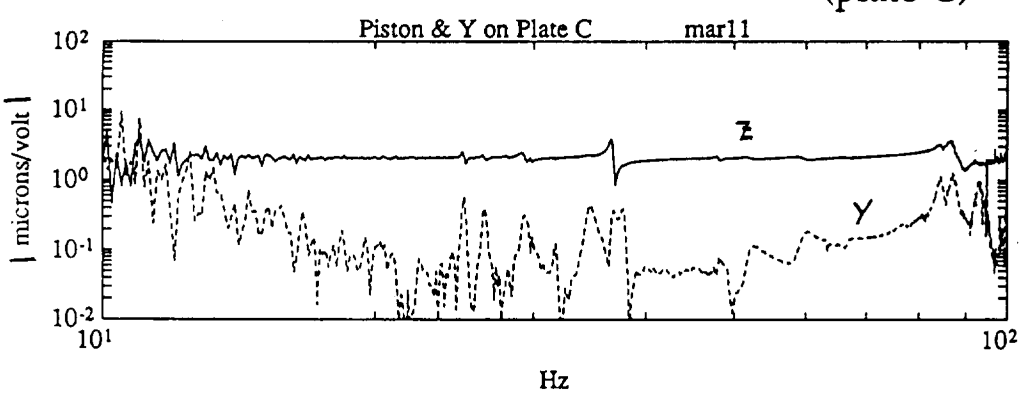
Open Loop Transfer Function of Mirror

- mirror actuated in piston (z) direction only

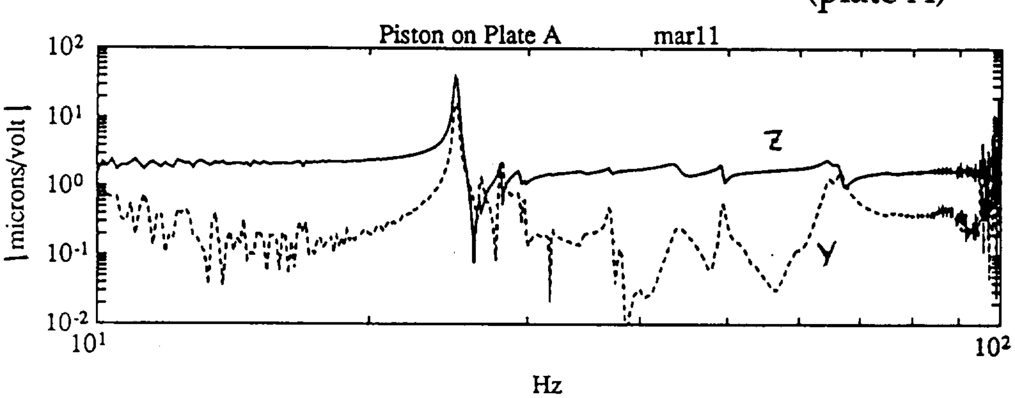
mirror mounted on rigid base



mirror mounted at truss vertex (plate C)



mirror mounted on truss beam (plate A)



GLOBAL/HIGH AUTHORITY CONTROL

Current areas of research:

- Active strut placement
- Sensor placement for control
- Static shape control problem
- Heirarchic control architectures that combine two or more levels of control design
- Probabilistic formulation of control design

SUMMARY

Optical Interferometer testbed captures essential configuration, physics, and performance metric of a class of spacecraft

Student theses directed at different aspects of controlled structures design

Near-term plans are demonstration of local and global control approaches on testbed and evaluation with full optical performance metric