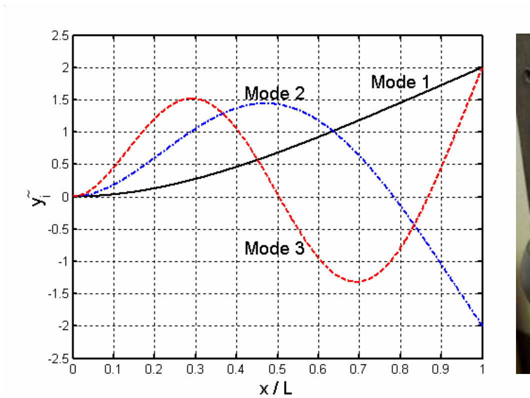
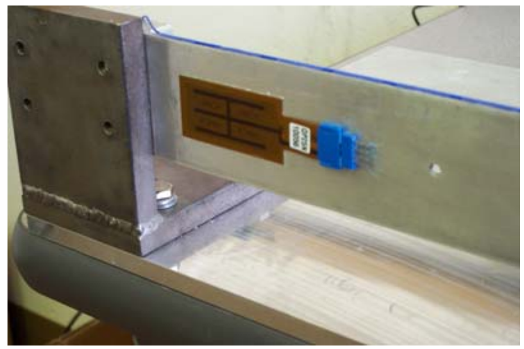
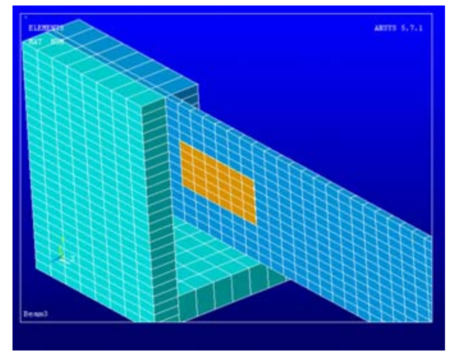
Passive Modal Damping With Piezoelectric Shunts







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Passive Modal Damping with Piezoelectric Shunts

Outline

- Project Background
- Theory
- Experimentation
- Results
- Lessons Learned

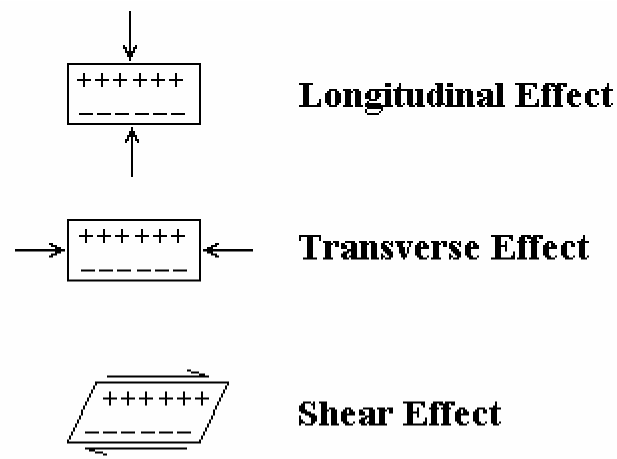
Active and Passive Damping

- Active damping refers to energy dissipation utilizing system feedback for control.

- Passive damping does not make use the system's response for control, but relies on energy dissipation on structural components, or add-on materials.

The Piezoelectric Effect

- Polarized molecules align themselves to an induced electric field.
- When the material is strained, an electric field is generated.
- Conversely, when an electric field is applied, the material strains.

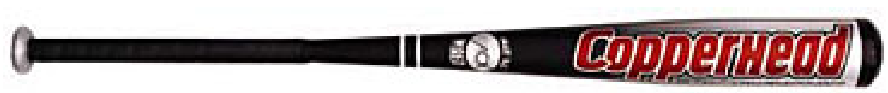


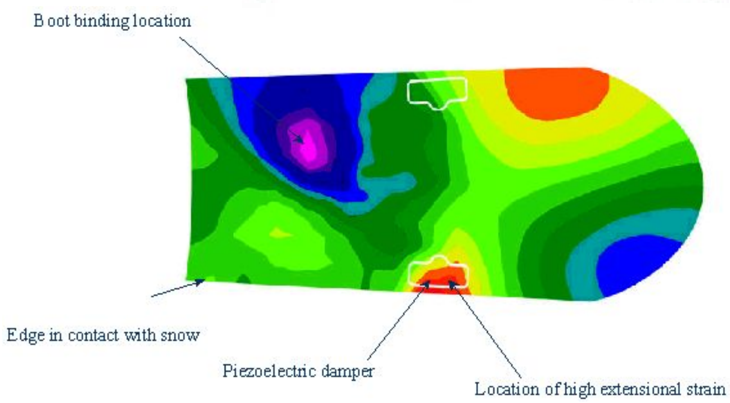
Applications of Piezoelectric Materials

Sensors
- Ultrasound
- Accelerometers
- Microphones

Actuators
- Speakers
- Inkjet printers

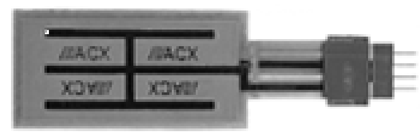
Structural Dampers
- Airplanes
- Snowboards / Skis
- Baseball Bats





Project Goal

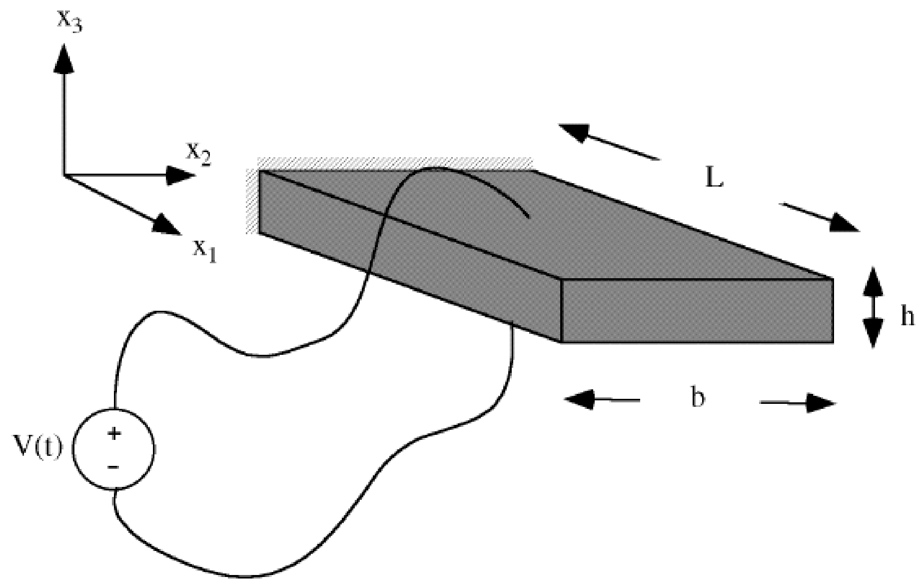
The goal of our project was to damp a single mode of vibration in an aluminum cantilever beam using shunted bimorph piezoelectric tiles (PZT).



Electro-Mechanical Coupling

Coupling coefficients, k_{ij}, describe energy transfer within a specific piezoelectric tile.

The transverse coupling coefficient, k_{31}, describes how efficient the conversion of mechanical energy to electrical energy is between the 1 and 3 axes.



Energy Dissipation

A PZT can act as a passive damper if the electrical energy it produces is dissipated through a resistor. Power dissipated through a resistor is given by:

$$P = i^2 R = \frac{V^2}{R}$$

Shunt Circuits

Shunt circuits provide the elements necessary to dissipate energy produced by the piezoelectric.

The circuits can be configured for specific applications:

1. Broad band shunting (resistor only)
2. Tuned shunting (resistor, capacitor, and inductor)
    - Requires a band-pass filter tuned to desired frequency

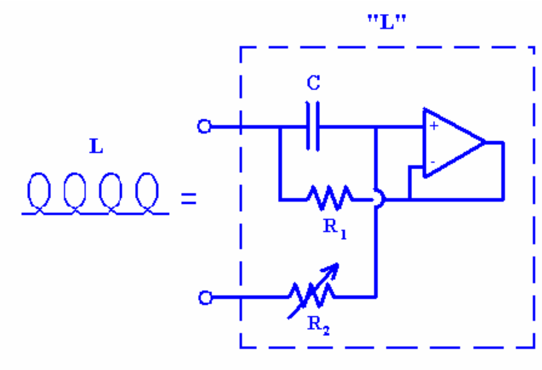
Synthetic Inductors

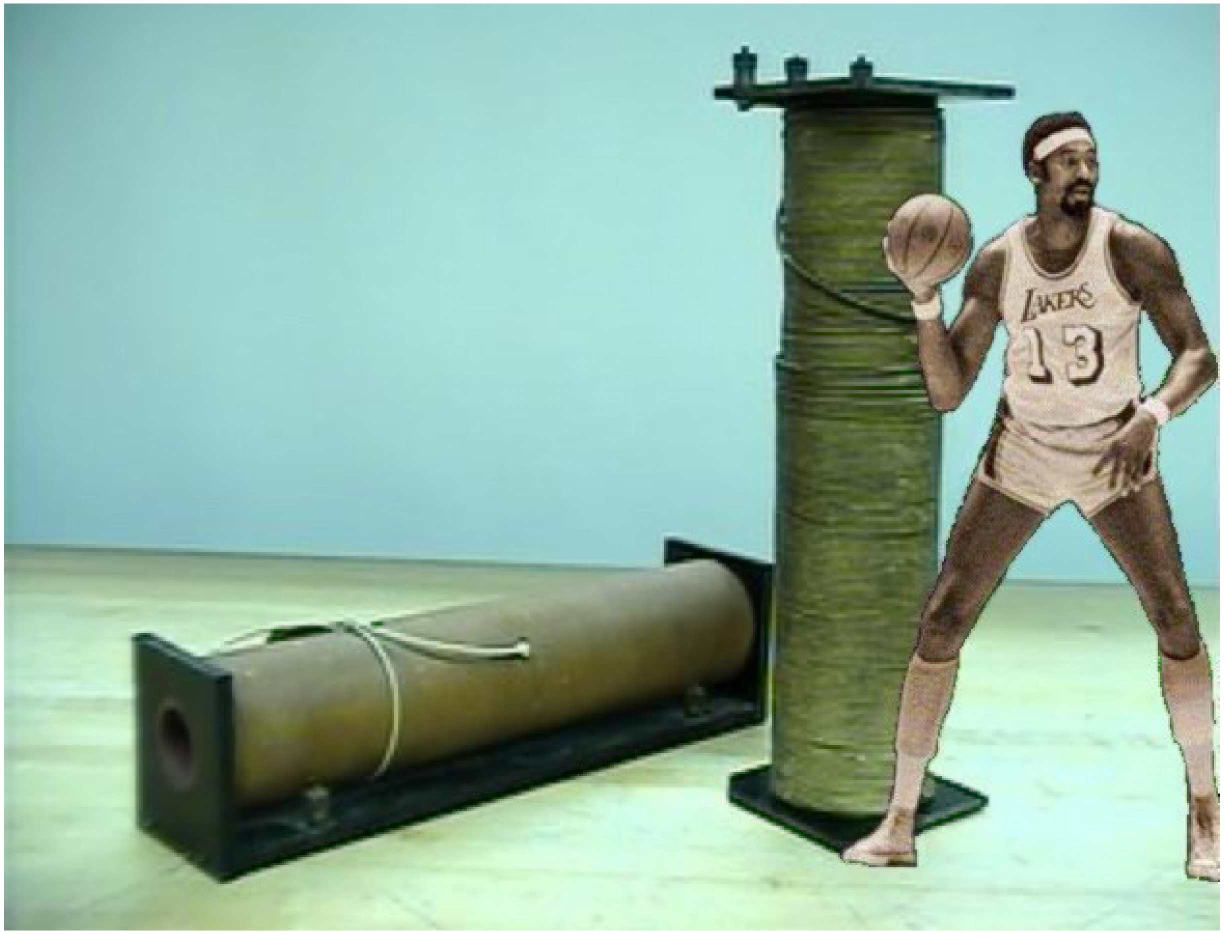
For shunting low modal frequencies, large inductance is required.

- Large inductors are impractical.

$$\omega_e = \frac{1}{\sqrt{LC}}$$

The alternative was to design a circuit with an operational amplifier (op-amp), a resistor, and a capacitor.

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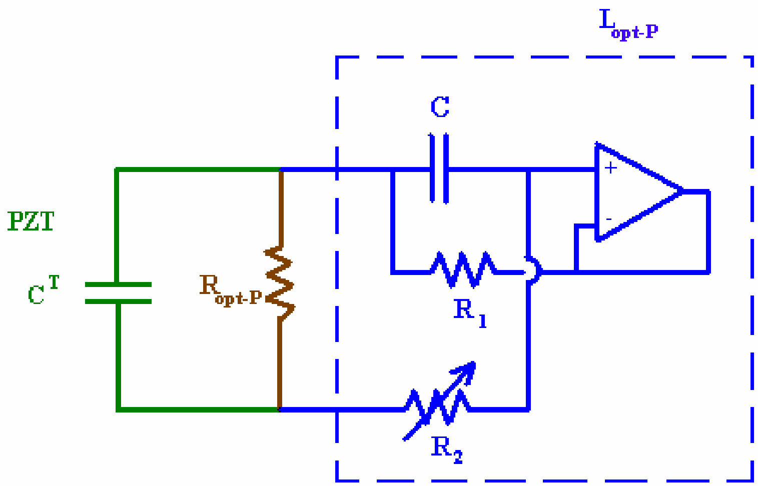
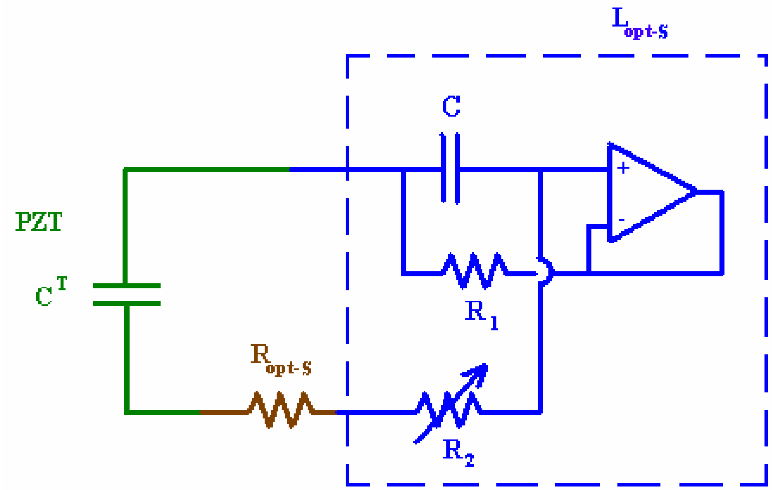
A Shunt Circuit Tuned for Single Mode Damping

Parallel RL Circuit



Series RL Circuit



Parallel Circuit Optimization*

1. Experimentally determine ω_o and ω_s

2. Generalized EM coupling coefficient:

$$K_{31} = \sqrt{\frac{\omega_o^2 - \omega_s^2}{\omega_s^2}}$$

3. Determine C^S:

$$C^S = (1 - k_{31}^2) C^T$$

4. Calculate the normalized tuning frequency:

$$\alpha = \sqrt{1 - \frac{K_{31}^2}{2}}$$

*Wu and Bicos, 1997.

Parallel Circuit Optimization*

With K_{31}, C^S, and α, the following are obtained:

$$L_{opt\text{-}P} = \frac{1}{C^S(\omega_s \alpha)^2} \qquad R_{opt\text{-}P} = \frac{1}{\sqrt{2}\omega_s C^S K_{31}}$$

*Wu and Bicos, 1997.

Series Circuit Optimization*

Given K_{31}, the optimum circuit damping is found by:

$$r_{opt} = \frac{\sqrt{2}K_{31}}{\left(1 + K_{31}^2\right)}$$

So the optimum resistance is:

$$R_{opt\text{-}S} = \frac{r_{opt}}{C^S \omega_o}$$

And the optimum inductance is:

$$L_{opt\text{-}S} = \frac{1}{C^S \omega_s^2}$$

*Hagood and von Flotow, 1990.

Cantilever Beam Analysis

Mode shapes for a cantilever beam are given by:

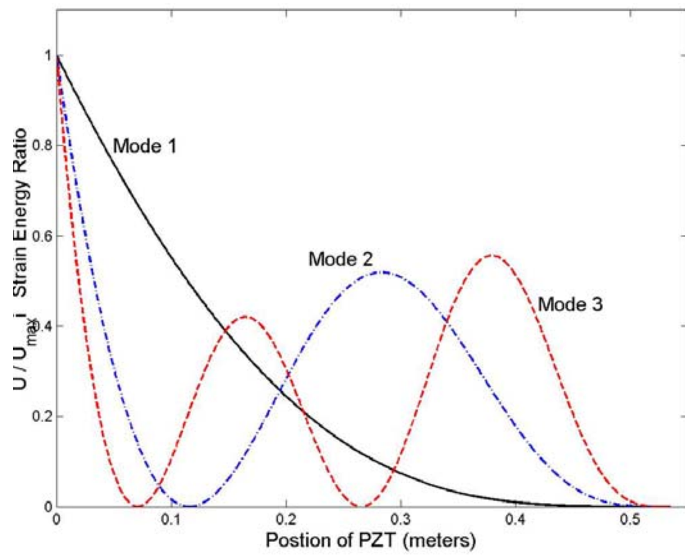
$$\tilde{y}_i = \cosh\frac{\lambda_i x}{l} - \cos\frac{\lambda_i x}{l} - \sigma_i\left(\sinh\frac{\lambda_i x}{l} - \sin\frac{\lambda_i x}{l}\right)$$

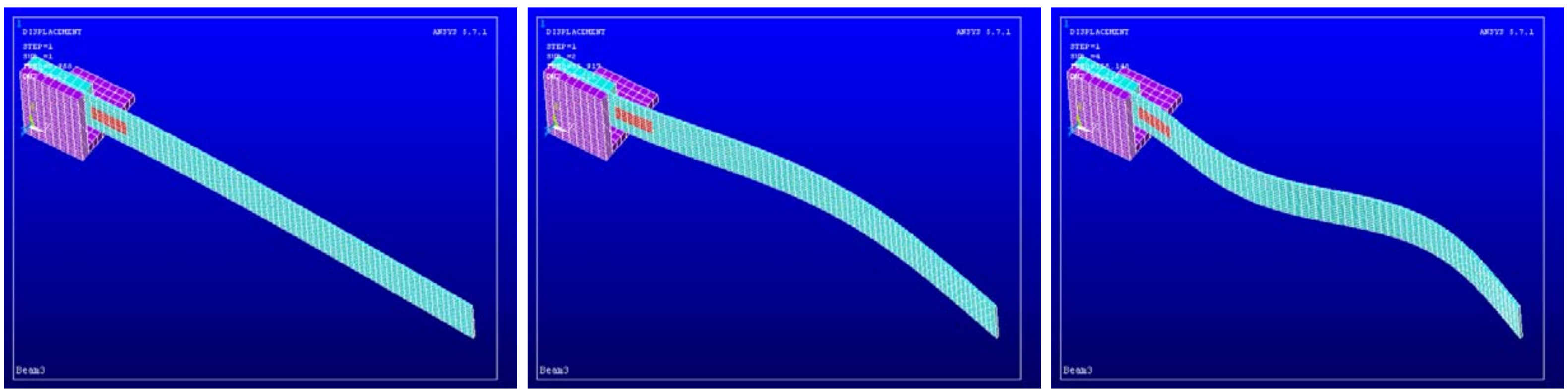
The natural frequency for each mode can be found with:

$$f_i = \frac{\lambda_i^2}{l^2}\sqrt{\frac{EI}{m}}$$

Cantilever Beam Analysis

Finite element analysis confirmed the analytical calculations for mode shapes and modal frequencies.

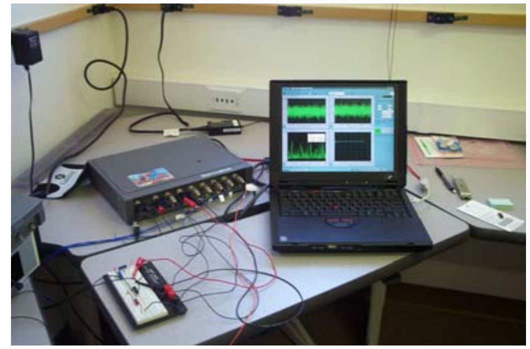


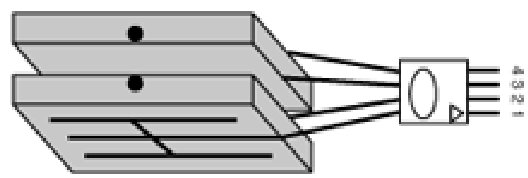


The Experiment

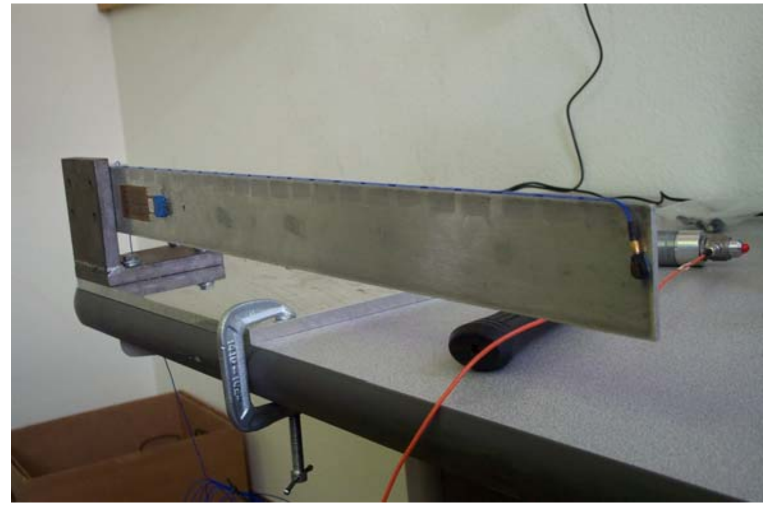
<u>Equipment</u>

- Dactron Spectrabook 24-bit data acquisition system
- RT Pro Software
- PCB ±10mV/g accelerometers
- ACX QP25N bimorph piezoelectric tiles





The Experiment

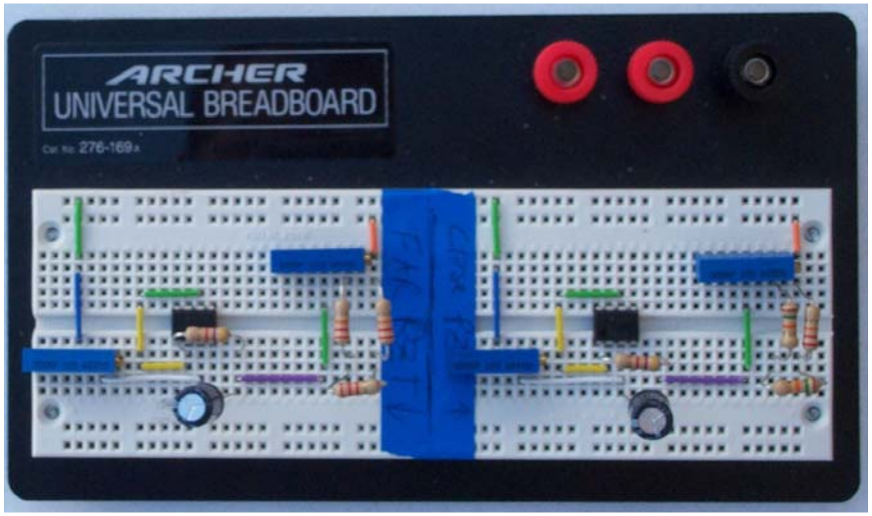


Experimental Model Setup

- Material: 6061-T6 Aluminum
- Dimensions (cm): 53.5 X 5.2 X 0.3
- Stainless steel bracket
- PZTs mounted 17mm from fixed end of beam
- Accelerometer placed on free end

The Circuit

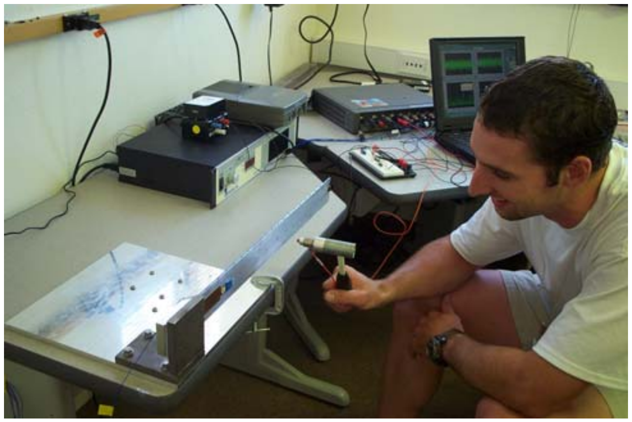
Two shunt circuits were designed, one circuit for each tile.

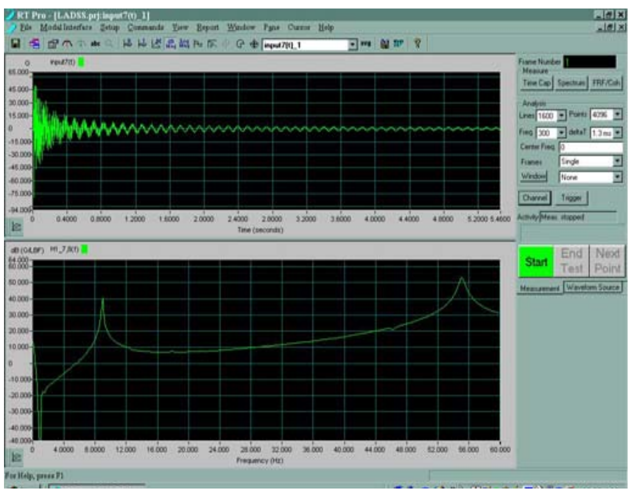


Resistors and synthetic inductors were wired in series.

Reason: Problems with damping efficiency in parallel circuit

Testing Procedure





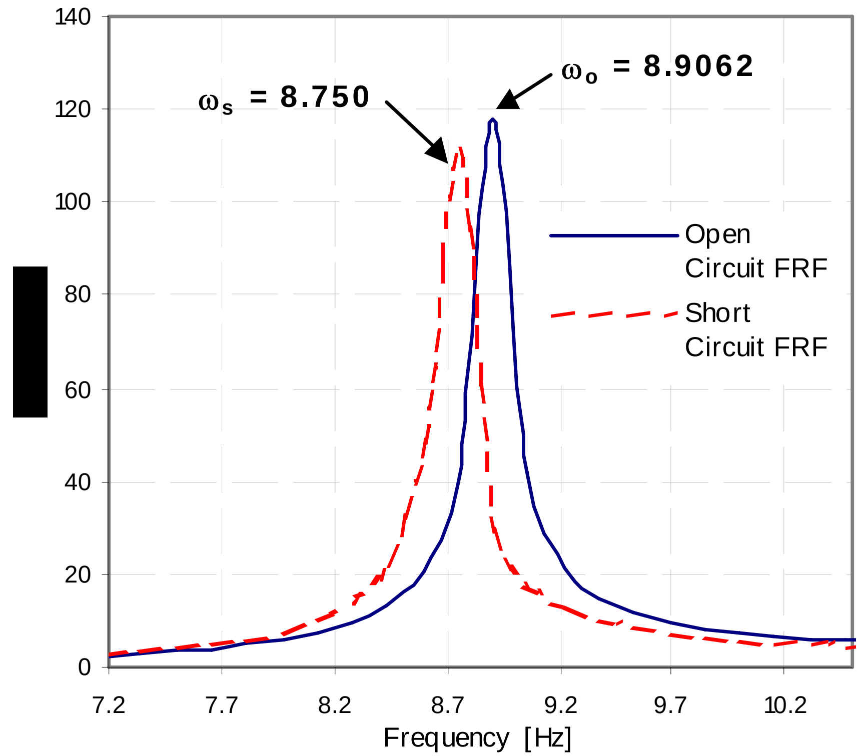
Impact tests with a modal hammer were used for finding ω_o and ω_s, which allowed the shunt circuit to be designed.

Both input and response data were taken with the piezoelectric tiles short-circuited, and connected to the shunt circuit.

Experimental Results

Modal Resonant Frequency

- The resonant frequency of the first mode shifted from 8.906 Hz to 8.750 Hz when short circuited.
- Shift caused by local stiffness at the fixed end of the beam



$$K_{31} = 0.186$$

Experimental Results

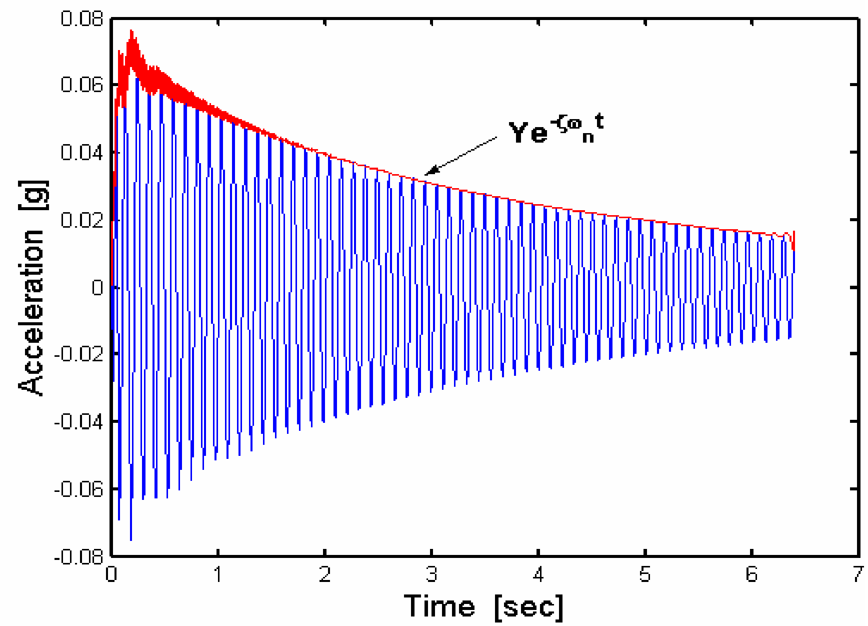
Short Circuit Damping

- Hilbert transform applied to acceleration time response
- Linear curve fit developed from natural log of envelope

$$m = \ln(Ye^{-\zeta\omega_n t}) = -\zeta\omega_n t$$

$$\zeta = -m/\omega_n$$

$$\zeta = 0.415\%$$

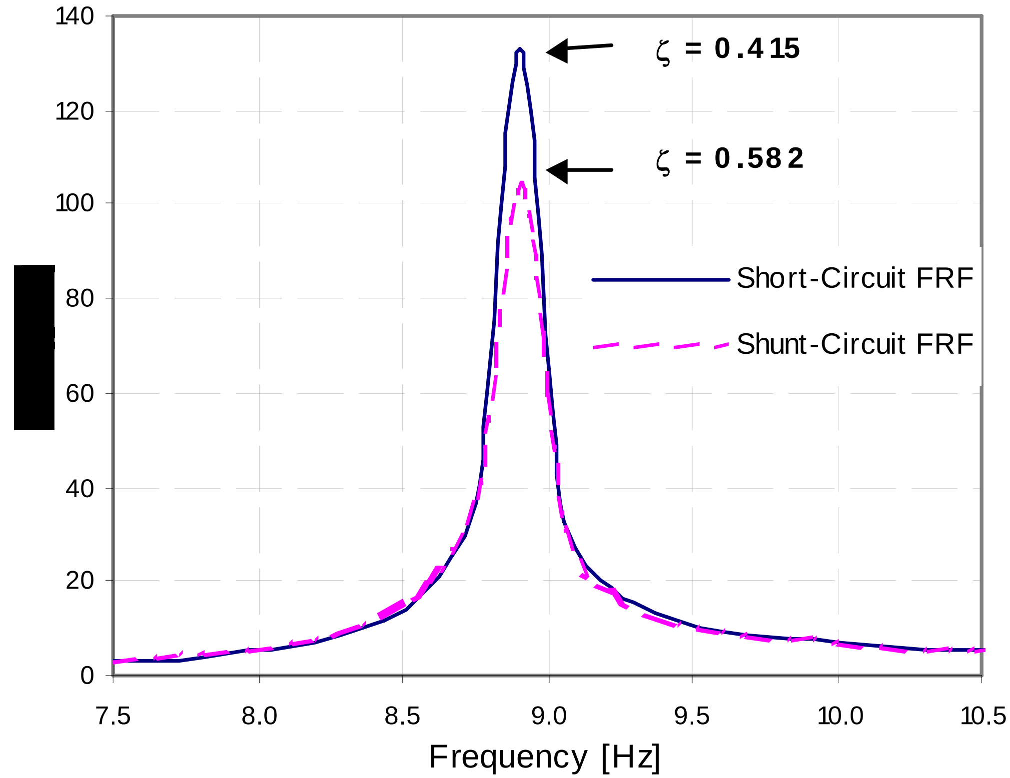


Experimental Results

Shunt Circuit Damping

- System damping increased by 40% (from inherent damping).
- Results are for mode 1

$$\zeta = 0.582\%$$



Lessons Learned

Problems encountered with the project

1. Damping increase with shunted piezoelectrics was much lower than expected.
2. Shift in resonant frequencies between open and short circuit configurations were questionably small.
3. Problems with the circuit
   - Inability to measure inductance
   - Inaccurate manufacturer specs were misleading
   - General lack of sufficient knowledge of circuit design with op-amps.

Lessons Learned

Possible Explanations for Problems

1. Weak PZTs
2. Bimorph tiles require special and irregular wiring
3. Aliasing concerns
   - Could not obtain the desired resolution

Lessons Learned

Looking Ahead

1. Try an experiment with single piezoelectric tiles
2. Extend the finite element model to determine strain energy
   - estimate damping increase quantitatively
3. Design an experiment using PZTs as active dampers

Thank you

Special Thanks to:

•Dactron, Inc. (data acquisition hardware)

•Vibrant Technologies (experimental modal analysis software)

•The Mathworks, Inc. (numerical analysis software)

•ANSYS, Inc. (finite element software)