ADAPTIVE STRUCTURES

Faculty Members

• George Lesieutre (AERSP)
• Mary Frecker (MNE)
• Reginald Hamilton (ESM)
• Zoubeida Ounaies (MNE)
• Chris Rahn (MNE)
• Kenji Uchino (EE)
• Gordon Warn (CEE)
ADAPTIVE STRUCTURES

• Zoubeida Ounaies
  – Active fiber composites for vibration control

• Chris Rahn
  – Piezo energy harvesters via MEMS compliant mechanisms
  – Fluidic flexible matrix composites for vibration attenuation

• Gordon Warn
  – Stability of elastomeric bearings under large lateral disps
  – Structural concepts and optimization for the seismic design

• George Lesieutre
  – Two-material topology optimization for structures under thermo-mechanical loads

• Reggie Hamilton
  – Shape Memory Alloys: material design

• Landen Bowen, PhD student (Mary Frecker)
  – Multi-field responsive origami structures
Active fiber composites for vibration control

Hassene Ben Atitallah and Zoubeida Ounaies, Penn State University
Anastasia Muliana, Texas A&M University

CAV presentation
Active fiber composites

- Flexible

- Piezoelectrics: both sensing and actuation

- Coupling coefficients of AFCs stand between piezopolymers and piezoceramics

- Potential applications: active vibration control of hoses, rotor blades and sporting goods
Objective and approach

- Better understand the behavior of AFC and the impact of its constituents on coupled response

- Conduct a parametric study of AFC design based on FE model

- Redesign an improved AFC device with optimized electro-mechanical coupling
Results: experimental

• Strong dependence of mechanical properties on temperature

• Non-linear piezoelectric behavior observed at small electric field (compared to coercive field)
Results: numerical

- AFC actuation capability increased by:
  - Higher matrix dielectric constant
  - Higher electrode gap
  - Electrode closer to the fiber

![Graph showing the relationship between electrode gap/fiber diameter and $d_{33}$ (10^{-12} m/V).]
Conclusions and ongoing work

- Higher glass transition temperature ($T_g$) epoxy will reduce temperature dependence and preserve actuation capability
- High dielectric nanoparticle in the epoxy will reduce dielectric mismatch and improve actuation

- Temperature and time characterization of constituent properties for use in the FE model
Efficient Piezoelectric Energy Harvesters Using MEMS Compliant Mechanisms

Xiaokun Ma, Graduate Student
Christopher D. Rahn, Professor
Department of Mechanical and Nuclear Engineering

Hong Goo Yeo, Graduate Student
Susan Trolier-McKinstry, Professor
Department of Material Science and Engineering

The Pennsylvania State University
Energy harvesting from human motion has unique challenges

- Weak base excitation
  - Low frequency (<10Hz)
  - Low amplitude (<1g)

- Shock rather than vibration inputs
  - Broad band (not tonal) frequency distribution
  - Potential for damage due to large shocks

- Small footprint – on the order of cm²

- Thin PZT films (low active material volume)

- Fragile thin films and structures
  - Shock inputs can damage structure
  - Self limiting design for robust performance (bump stops and/or bridges)

- ASSIST Goals
  - Small devices
  - Low frequency excitation
  - High power sensitivity $mW / g^2$
Piezoelectric Compliant Mechanism

Impedance Matching:

\[ R_{opt} = \frac{1}{C_p \omega} \Rightarrow P_{max} = \frac{(S_{max} F_p d_{31})^2 A h_p \omega}{2 e_{33} S} \]

Maximum harvested power is obtained when the entire volume of PZT is sinusoidally strained to its limit \( S_{max} \) at a given frequency \( \omega \).

Satisfies Quadratic Condition:

100% mode shape efficiency \( \Rightarrow \) uniform strain throughout the PZT \( \Rightarrow \) quadratic mode shape \( \Rightarrow \) zero shear force and nonzero moment at \( L \) \( \Rightarrow \) solve for \( K \) and \( M_{eq} = M \left( \frac{l_2}{l_1} + \frac{l_2}{l_1} \right)^2 + J \frac{1}{l_1^2} \)
Frequency Domain Performance

Higher Sensitivity, Larger Power and Higher Mode Shape Efficiency

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<tr>
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<th>Power Sensitivity (mW/g²)</th>
<th>Mode Shape Efficiency</th>
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<tbody>
<tr>
<td>Proof Mass Cantilever (PMC)</td>
<td>4.95</td>
<td>20.5%</td>
</tr>
<tr>
<td>Piezoelectric Compliant Mechanism (PCM)</td>
<td>5.08, 113.8, 86.03, 108.50</td>
<td>79.3%</td>
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</table>
Time Domain Performance

Wrist data from running:

PMC and PCM models

PMC

PCM

1.4944 μW

7.9935 μW
Piezoelectric compliant mechanisms outperform proof mass cantilevers

• Mechanism amplifies inertia
  – Smaller proof mass for same resonance frequency
  – Lighter design for low frequency performance
  – 5X more sensitive to base acceleration inputs

• Stiffness tuning enforces quadratic boundary condition
  – More efficient mode shape – closer to a parabola
  – 4X higher power generation at resonance
  – 5X higher power for realistic base excitation inputs
Motivation: Integrate fluidic flexible matrix composite (F²MC) tubes into structures to achieve tunable vibration damping, absorption, and isolation by utilizing strain induced fluid pumping.
Modal Testing Setup

- 3-layer: fiber reinforced polyurethane;
- 2 mm diameter, 0.2 mm thickness;
- Overall fiber volume fraction: $V_f = 7\%$;
Experimental Validation

- An experimental damping ratio of 5.3% was achieved at the first resonance;
- Bulk modulus of fluid is back calculated to be 25 MPa;
- A variety of damping treatment designs are available.
F$^2$MC Damping Treatment

- Bonding locations need to match with the maximal modal slope difference (shown as $\Delta$ in fig.) to maximize energy dissipation;
- Adding an F$^2$MC tube can introduce significant damping at bare beam resonances with optimal designs.
An attenuation of 35 dB was obtained experimentally at the first resonance.

- **Shear Force Transmitted**
  - Below “0” Notch

**Absorber Effect**

**Stiffness Increase**

- **Graphs**
  - $|H(j\omega)|$ (dB) vs. $\omega$ (Hz)
  - Experiment vs. Theory
A mechanistic model to simulate the stability of elastomeric bearings under large lateral displacements

Team:
Gordon P Warn, PI, Ass’t Professor
Xing Han, PhD Student, Penn State
Jared Weisman, MS, Modjeski and Masters

Sponsors:
CMMI-1031362, 9/1/2010 – 9/1/2014 (with 1 year extension)
NEES Shared-Use Partnering Policy in collaboration with UB-NEES
Basic research questions …

What is the mechanism controlling the observed behavior?

Can a practical, parsimonious model be developed to replicate this behavior?

![Graph showing shear force vs. lateral displacement](image)
The proposed model uses vertical springs and a bilinear, elastic, constitutive relationship.

**Vertical spring constitutive relationship:**

\[ \sigma \begin{cases} = \sigma_y & \text{for } \varepsilon \geq \varepsilon_y \\ = E_c \varepsilon & \text{for } \varepsilon < \varepsilon_y \end{cases} \]

**Vertical spring compatibility:**

\[ \frac{\varepsilon_{s1} l_s}{d_{s1} + x} = \frac{\varepsilon_{s2} l_s}{d_{s2} + x} = \ldots = \frac{\varepsilon_{s2} l_s}{d_{sn} + x} = \theta \]

Han and Warn 2014
The vertical spring model agrees sufficiently well with experimental observed behavior.

**Experimental**
Sanchez et al. 2013
$S=10.2$

**Vertical spring**
Han and Warn 2014
CAREER: A Performance-Based Multi-Objective Optimization Framework to Define Innovative Structural Concepts and Support the Seismic Design of Critical Buildings

Team:
Gordon P Warn, PI, Assistant Professor
PhD Student(s) to be named

Sponsors:
CMMI-1351591, 7/1/2014 – 6/30/2019
CAREER: A Performance-Based Multi-Objective Optimization Framework to Define Innovative Structural Concepts and Support the Seismic Design of Critical Buildings

Integrated Performance-based design, multi-objective optimization, framework

- Seismic Hazard
- Design variables and constraints
- Population initialization
- PBSD Seismic performance assessment
- Pareto optimal solution convergence

Multi-objective evolutionary algorithm

- Defined innovative structural concepts and tradeoffs

Illustration of innovative structural topologies and possible design tradeoffs

- Moment Resisting Frame (MRF)
- Base-isolated
  - MRF with Dampers
  - Base-isolated with VDF

Key terms:
- Direct Cost
- Probable Maximum Loss
- Pareto optimal solution

Equations:
- $\theta_1$
- $\theta_2$
- $\theta_n$
Two-Material Topology Optimization for Structures under Thermomechanical Loads

**Researchers:** Pierre Thurier, George Lesieutre, Mary Frecker, Jim Adair  
**Sponsor:** Air Force Office of Scientific Research (AFOSR)

**Motivation:** To passively control heat transfer from electronic components to a spacecraft thermal bus.
Differential thermal expansion can create conduction paths through internal contact.

What is the optimal 2-D topology?
Minimize “compliance” under combined thermal and mechanical loads

- Objective function: $c_0 = F_m^T u_m$

- Boundary conditions: Mechanical and Thermal

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\begin{align*}
&u_x = 0 \\
&u_y = 0
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\[
\begin{align*}
&u_x = 0 \\
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Material 1 is softer and more conductive than Material 2

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**Void**

**Optimum Design**
The input heat flux affects the topology and material placement:

- For $q = 0$, $c_0 = 14.39$
- For $q = 25$, $c_0 = 20.75$
- For $q = 100$, $c_0 = 56.26$

30% Mat’l 1
20% Mat’l 2
With relaxed constraint, the amount of high-CTE material increases with heat flux

q = 0, c_0 = 11.12

q = 25, c_0 = 19.13
7.6% Material 1
42.4% Material 2

q = 50, c_0 = 27.92
12.8% Material 1
37.2% Material 2
Continuing Research

• Modeling mechanical contact and thermal contact resistance
• Objective and optimization scheme for thermal conduction with and without contact

• Extend to dynamics (Tianliang Yu)
  • Design topology of sandwich panel core with integral vibration reduction / damping
  • Manufacture using 3-D printing
  • Demonstrate effectiveness
Shape Memory Alloys: Material Design

Reginald F. Hamilton, PhD
Assistant Professor of Engineering Science and Mechanics
Multi-field responsive origami structures – advancing the emerging frontier of active compliant mechanisms

Landen Bowen
PhD Student
Mechanical Engineering

April 30, 2014