Smart Vehicle Concepts Center (SVC) Projects

National Science Foundation (NSF)
Industry/University Collaborative Research Center (I/UCRC) in Smart Vehicle Concepts (SVC)

Center Director: Raj Singh <singh.3@osu.edu> (614) 292-9044
Department of Mechanical and Aerospace Engineering
The Ohio State University

www.SmartVehicleCenter.org
www.mecheng.osu.edu/svc/

2016-2017 Membership

<table>
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<tr>
<th>Battelle Memorial Institute</th>
<th>Bridgestone Americas Tire Operations</th>
<th>F.tech R&amp;D†</th>
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<tr>
<td>Ford</td>
<td>Honda R&amp;D†</td>
<td>Siemens LMS Software*</td>
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<td>Moog</td>
<td>MSC Software*</td>
<td>NASA Glenn</td>
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<td>Owens Corning</td>
<td>REL, Inc.</td>
<td>Romax*</td>
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<tr>
<td>Tenneco</td>
<td>Toyota Technical Center</td>
<td>Transportation Research Center†</td>
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Key: † Multiple Memberships
* Invited Observers

April 2017 Edition
Smart Vehicle Concepts Center
National Science Foundation Industry/University Cooperative Research Center (I/UCRC)

Cooperative Center Concept - I/UCRC
• Encourages collaborative research
• Focuses on pre-competitive research
• Projects driven and mentored by Industry
• Evaluator appointed by NSF to ensure quality control

SVC Mission
• Conduct basic and applied research, with application to ground and aerospace vehicle components and systems
• Build an unmatched base of research, engineering education, and technology transfer
• Develop well-trained engineers and researchers (at the undergraduate, MS, and PhD levels)

Industrial Advisory Board
• IAB consists of one representative from each member company.
• The board is responsible for evaluating current research thrusts, suggesting new opportunities, evaluating center operations, and matching center capabilities with unfilled research needs.
• IAB holds two meetings each year during the SVC review meetings.

Membership Fee Structure
The Ohio State University
• $40K/year - Full Membership (One vote per full membership; access to all Center projects)
• $10K/year - Affiliates (Access to one ongoing project only; no voting or intellectual property rights)

Leveraging: Membership fee, when combined with cost-sharing and NSF money, gives members access to over $750K per year of research

Additional Project Fee Schedule to Ensure a Guaranteed (Solo) Project

<table>
<thead>
<tr>
<th>Center Year</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
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<tr>
<td>Additional Fee</td>
<td>$6K</td>
<td>$8K</td>
<td>$10K</td>
<td>$12K</td>
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<td>Membership Fee + Project Fee</td>
<td>$46K</td>
<td>$48K</td>
<td>$50K</td>
<td>$52K</td>
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Key Researchers

PROF. MARCELO DAPINO
Expertise: Smart materials, nonlinear coupled systems, design, control

PROF. RAJENDRA SINGH
Expertise: Noise & vibration control, geared systems, nonlinear dynamics, DSP

PROF. VISHNU SUNDARESAN
Expertise: Piezoelectric materials, active polymers, bio-derived materials

PROF. SOHEIL SOGHRATI
Expertise: Advanced FEM; modeling multiscale response of advanced/bio-materials and structures

PROF. RYAN HARNE
Expertise: Vibration/noise damping, energy harvesting/transfer, sensing methodologies

PROF. JASON DREYER
Expertise: Experimental methods, vehicle dynamics, noise & vibration control

DR. LEON HEADINGS
Expertise: Energy systems, mechatronic systems, intelligent control

DR. SCOTT NOLL
Expertise: Structural dynamics, jointed assemblies, design, inverse methods
## Project Groups, Strategic Thrusts and Typical Sponsors

<table>
<thead>
<tr>
<th>Project Groups (PG)</th>
<th>Typical SVC Project #</th>
<th>Strategic Thrusts</th>
<th>Typical Sponsors</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG-1 Interfacial Forces and Stiffness</td>
<td>20C, 40C, 40E, 41</td>
<td>Interfacial Mechanisms, Safety</td>
<td>Eaton, Honda R&amp;D, TRC, Moog, F.tech, Tenneco</td>
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<tr>
<td>PG-2 Vibration, Noise, and Motion Control</td>
<td>31A, 31B, 40D, 42A, 42B, 45, 47</td>
<td>Adaptive NVH</td>
<td>Honda R&amp;D, Hyundai-Kia, TRC, F.tech, Toyota, NASA Glenn, Tenneco</td>
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<tr>
<td>PG-4 Manufacturing and System Integration</td>
<td>1, 31C, 43, 40B, 46</td>
<td>Interfacial Mechanisms, Adaptive NVH, Safety</td>
<td>Moog, MIT Lincoln Lab, Honda R&amp;D, TRC, F.tech, Tenneco</td>
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### Technology Summary

- Smart materials produce high force, high frequency, low displacement motion
- Hydraulic fluid is used to rectify motion to create large displacement and high force
- Frequency response of existing mechanical one-way fluid valves is a limiting factor

### Applications/Benefits

Advantages over traditional linear actuators:
- No need for separate pump/fluid lines
- Few moving parts
- Fast response
- High power-to-weight ratio

### Plan

- Investigate valve designs to improve high frequency operation:
  - Reed-type mechanical valves
  - Micro-machined valve array
  - Active valve concepts
- Design, model, and test progressively miniaturized actuator designs to reduce system compliance and inertance

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**Project leader:** Marcelo Dapino (dapino.1@osu.edu)

**Project Initiated by Moog Inc.**
Project # 20: Development of an Interfacial Force Sensing System
(Sub-Project # 20C: Characterization of Pump Bearing Surfaces)

Motivation

- Pump hydrostatic and boundary lubricated surfaces are poorly understood
- Knowledge of multidimensional force transmissibility through a pump’s bearings interface is vital for dynamic modeling and vibration reduction

Goals and Expected Benefits

- Static and dynamic measurements will improve system level modeling
- Understanding the lubrication regimes will be helpful in developing better math models
- Estimation of interfacial forces will lead to better efficiency and durability and reduced NVH concerns
- Characterization of the lubrication regimes will be helpful in developing math models

Problem Formulation

- Determine the nature of the lubrication regimes
- Conduct dynamic characterization experiments
- Model bearing interfaces using first principles
- Develop an improved bearing model in multi-body dynamic software
- Compare prediction with measurements

Analytical and Experimental Methods

- Determine lubrication regime on bearing surfaces via pressure and acceleration measurements conditions
- Analytical models will be used to understand the physics and identify the system
- Use commercial multi-body dynamics software to model the bearing system and tune its parameters

Project Leaders: Raj Singh (singh.3@osu.edu) and Jason Dreyer (dreyer.24@osu.edu)
Project Initiated by Eaton Corporation
Project # 31A: Ultrasonic Friction Control

Technology Summary

- **Ultrasonic lubrication**: the coefficient of dynamic friction between two surfaces decreases when ultrasonic vibrations are superimposed to the sliding velocity.
- This form of friction reduction is “solid state” and requires no greases or oils.
- **Piezoelectric actuators** can be used to create ultrasonic vibrations.
- The objective is to modulate the friction coefficient between “high friction” (off state) and “low friction” (on state) by driving the actuator at different voltages.

Application/Benefits

- Adaptive seat belt system capable of providing superior safety and comfort, reduced mass, simpler operation and more flexible design.
- Using smart materials to continuously measure and control the loading force can help design active systems with feedback control.
- The friction control concept is applicable to a wide range of traditional problems where lubricants are not feasible and future applications with active friction control as an enabling technology.

Plan

- Create a **proof-of-concept experiment** to fundamentally analyze and demonstrate ultrasonic lubrication at high speeds and high normal forces.
- Demonstrate the principle of active friction control on a **tabletop seat belt system**.
- Analyze and understand the dependence of friction on system parameters.
- **Analytical modeling** of friction behavior in the presence of ultrasonic vibrations.

Project leader: Marcelo Dapino (dapino.1@osu.edu)
Project Initiated by Honda R&D Americas and NASA Glenn
**Laser Vibrometer**

- **Non-contact out-of-plane velocity measurement**
- Scans to measure vibration of entire structure
- "Small" and "large" structures (mm² to m² scale)
- Measurements on complex shapes, ultrasonic devices, red-hot components
- **Geometry scan unit** to acquire 3D geometry and output to CAD software
- 4 analog inputs
- **Bandwidth:** up to 1 MHz
- **Velocity:** 1 cm/s to 20 m/s

**Measurement System**

- **Test Specimen**
- **Close-up Module**
- **Geometry Scanning Module**
- **Scanning Head**
- **Instrumentation Cabinet**

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**Dynamic Testing of UAM Al-Galfenol Composites**

**Experimental setup**

- UAM composite of Al containing Galfenol (a magnetostrictive material)
- Composite cantilevered within a magnetic circuit
- **Modal analysis** conducted on active cantilever beam under multiple bias magnetic fields

**Challenges**

- Composite response expected to be nonlinear; **complex models** required to extract full beam response from single point measurement
- Ability of fixture to produce cantilever condition unknown
- Many single point measurements required

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**Typical Data**

- **Composite mode identification**
- In-depth data processing

- **Change in modal frequencies due to applied magnetic field (constant current to coils)**

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**Project Leader:** Marcelo Dapino (dapino.1@osu.edu)

**Project Initiated by Honda R&D**
Background and Objective

Objective: Develop 3D model for ultrasonic lubrication under speed and stress conditions found in metal forming processes

- Ultrasonic lubrication: coefficient of dynamic friction between two surfaces decreases when ultrasonic vibrations are superimposed to the macroscopic sliding velocity
- This form of friction reduction is "solid state" and requires no greases or oils
- We use a piezoelectric actuator to create ultrasonic vibrations.
- Modulate the friction coefficient between "high friction" (off state) and "low friction" (on state) by driving the actuator at different voltages

Examples of Ultrasonic Metal Forming

- Sheet rolling: Severdenko et al. (1974)
- Wire drawing: Murakawa et al. (2001)
- Compressing: Siddiq and Ghassemieh (2008)

Literature Review

Experiments

Ultrasonic lubrication was tested between stainless steel pin and stainless steel disc under stress (31-35 MPa) and speed (266 mm/s) conditions found in metal forming

<table>
<thead>
<tr>
<th>Friction without US</th>
<th>22.88 - 27.52 N</th>
</tr>
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<tbody>
<tr>
<td>Friction with US</td>
<td>9.93 - 10.71 N</td>
</tr>
<tr>
<td>Friction reduction</td>
<td>56.8 - 61.1%</td>
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</table>
**Project # 40:**
**Modeling & Characterization of Passive & Adaptive Bushings & Mounts**
*(Sub-Project # 40A: Rubber Bushings)*

**Motivation**
- Complexity in Modeling Bushing Properties
  - Geometry
  - Static and Dynamic Loadings
  - Multi-axis coupling
  - Transient / Steady State
  - Static Pre-loading
  - Material / Manufacturing
  - Assembly issues
- Hysteresis
- Strain-rate Dependence
- Dynamic Amplitude / Frequency Dependence

**Experimental Component Study**
- Both frequency and time domain characterization of bushings, including amplitude-sensitive and frequency-dependent properties
  - Static load-deflection
  - Harmonic input (1 – 50 Hz)
  - Step-up and step-down inputs
  - Different controlled mean and dynamic displacements (strains)
  - 3 Different size specimens
  - 9 Material compositions
  - 3 Loading directions

**Objectives**
- Develop improved multi-dimensional linear and nonlinear dynamic models for elastomeric bushings (in both frequency and time domains)
- Develop and conduct systematic experimental characterization procedures to extract bushing parameters and validate dynamic models
- Examine the preloads effects and coupling between axial, radial and torsional stiffness elements
- Use models to examine geometric scaling and material considerations in bushing design
- Understand and quantify testing error
- Investigate feature / shape effects within components

**Alternate Component-Level Models**
- Multiple linear and nonlinear models have been developed and evaluated
- Multiple dimensional properties and coupling effects have been investigated analytically, computational, and experimentally

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**Project Leaders:** Raj Singh (singh.3@osu.edu), Jason Dreyer (dreyer.24@osu.edu); and Scott Noll (noll.34@osu.edu)

**Project Initiated by:** Honda R&D, TRC, F.tech R&D, Tenneco, & Ford
**Motivation:**
- Passive or adaptive hydro bushing can satisfy both motion control and vibration isolation requirements
- Many features of hydro bushings are described in patents but no analytical justifications are provided
- Very few scholarly articles on this topic are available
- Most hydro bushing designs are based on linear system principles, though their dynamic properties are highly frequency dependent and amplitude sensitive
- Apply expertise gained from recent SVC research on hydraulic mounts (SVC #3 and #20A)

**Project Goals:**
- Develop new models of hydro bushings
- Propose improved characterization methods
- Develop new adaptive concepts

**Research Plans:**
- Develop linear models of hydro bushings with two flow passages
- Investigate static and dynamic properties of production bushings
- Conduct experimental studies on a new prototype and validate linear models in frequency domain
- Conduct time domain experiments and analysis
  - Develop quasi-linear (spectrally-variant properties) and nonlinear models (stopper and flow passage nonlinearities)
  - Explore adaptive bushing design concepts

**Recent Results:**
- Significant frequency and amplitude dependence are observed from measured dynamic stiffness and examined by analytical models
- Narrow/broad band tuning can be achieved by adjusting the combinations of flow passages

**Fluid Model of a Bushing with Long and Short Passages**

**New prototype device**

**Dynamic Stiffness Measurements of the prototype**
Motivation:

Automotive elastomeric joints are used extensively to accommodate relative movement between metal parts and absorb shocks. Subframes are formed in complicated shapes that must be lightweight, high strength and compact. Subsystem designs must balance the competing needs for:

- Noise, Vibration, and Harshness
- Ride and Handling
- Durability

Benchmark Stiffness Coupling Experiments:

Direct Joint Measurements

Joint Identification Using Inverse Method

Joint II

Joint I

Recent Results: Elastic Beam with Viscoelastic Supports

Experimental data compared with theoretical predictions, showing good agreement for both acceleration and phase responses.
Motivation:

- Seeking to understand the sensitivity between rear subframe (including its modifications and end supports) and the sound pressure from within the vehicle compartment.
- Potential Benefits:
  - Improve target setting for NVH.
  - Improve subframe design and performance.
  - Minimize prototype iterations.
  - Improve modeling capability.

Problem Formulation:

- Particular components may be too difficult to model analytically with the required precision.

Recent Results:

- Discrepancy suspected due to lack of rotational constraint in connection model.

FRF Based Substructuring:

- Uncoupled System
- Coupled System

Flexible Connection Matrix (Bushing or Mount)

\[
\begin{bmatrix}
H_{c_A} & H_{c_B} & H_C \\
H_{c_B} & H_{c_A} & H_C \\
H_{c_A} & H_{c_B} & H_C \\
\end{bmatrix}
= \begin{bmatrix}
H_A & H_{d_c} & 0 \\
H_{d_c} & H_A & 0 \\
0 & 0 & H_B \\
\end{bmatrix}
- \begin{bmatrix}
H_{d_c} \\
H_{d_c} \\
H_B \\
\end{bmatrix}
= \begin{bmatrix}
H_A + H_{d_c} + [K] \\
H_{d_c} - H_B \\
\end{bmatrix}
\begin{bmatrix}
H_A \\
H_{d_c} \\
H_B \\
\end{bmatrix}^T
\]
Motivation:

- Exhaust hangers are widely used to isolate exhaust structure and powertrain vibration
- Many features of exhaust hanger and isolation systems are described in 5500+ patents but no analytical or scientific justifications are provided
- Very few scholarly articles on this topic are available

Project Goals:

- Improve modeling tools (including feature-based models)
- Refine dynamic characterization procedures
- Gain insight into contributions of various components to system performance
- Understand component and system design targets
- Resolve associated scholarly issues

Elements of Dynamic Performance:

- Dynamic behavior of elastomeric or plastic materials
  - Environment (temperature, humidity, chemical, age)
  - Loading conditions (mean load, dynamic amplitude, frequency)
- Nonlinear features within component
  - Shape effects of isolators and brackets (geometric nonlinearities)
  - Stoppers; friction and clearances within joints
- Modeling issues
  - Different models for time and frequency domains
  - Only linear models are used in spite of many nonlinearities
- Representation of connection dynamics in models
  - Multi-dimensional coupling; multiple structural paths
  - Local stiffness vs. global stiffness

Technical Issues:

- Environment (temperature, humidity, chemical, age)
- Loading conditions (mean load, dynamic amplitude, frequency)
- Shape effects of isolators and brackets (geometric nonlinearities)
- Stoppers; friction and clearances within joints
- Different models for time and frequency domains
- Only linear models are used in spite of many nonlinearities
- Multi-dimensional coupling; multiple structural paths
- Local stiffness vs. global stiffness

Project Leaders: Raj Singh (singh.3@osu.edu), Jason Dreyer (dreyer.24@osu.edu); and Scott Noll (noll.34@osu.edu)

Project Initiated by Honda R&D, TRC, F.tech R&D, Tenneco, & Ford
**Motivation**

- The move towards lighter weight vehicle components (say in the transmission) creates significant high frequency structure-borne noise and vibration.

- Design likely fixed: Source(s) (Powertrain, Transmission)
- Flexibility in design: Path(s) (Mounts)
- Design likely fixed: Receiver(s) (Sub-frame, chassis)

**Remark**

1. The path(s) may interact with the source(s), receiver(s), and each other. Care must be taken to sort out and properly account for these possible interactions.

**Methods**

- **STEP #1:** Apply a shaker force (400 Hz cosine wave) and measure the amplitude
- **STEP #2:** Calculate needed control effort(s) to counteract the disturbance
- **STEP #3:** Apply the calculated control effort(s) using the piezo stack(s)
- **STEP #4:** Adjust the phase(s) and magnitude(s) for best results

**Experimental Results**

- **Shaker turned on:** Source mass vibration is reduced by 8 dB.
- **Left stack turned on:** Further reduction of 8 dB observed.
- **Right stack turned on:** Additional 8 dB reduction achieved.

**Experimental results are similar to simulated results.**

**Remarks**

- **Feasibility for motion control of source mass using piezo stacks is demonstrated.**

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**Project Leaders:** Raj Singh (singh.3@osu.edu) and Jason Dreyer (dreyer.24@osu.edu)

**Project initiated by Hyundai Motor Company (R&D Division)**
**Project # 42B: Enhanced Methods for Reducing Powertrain Surface Radiated Noise**

**Motivation**
- New noise sources seen in hybrid and electric vehicles
- Characteristics of motor noise
  - Modulated sounds (with multiple sidebands)
  - Strong directivity
- May excite structural resonances at high frequencies
- Psycho-acoustic perception issues

**Objectives**
- Reduce surface radiated noise from surfaces through passive, active, or hybrid patches
  - Maximize the reductions in radiated noise using minimal patch material
- Use passive patches to determine optimal patch locations and capabilities of patch placement
- Develop control algorithm for use with active patches

**Passive Patch Investigations**
- Passive damping patches placed on structural anti-nodes of hollow aluminum shell (2% of surface area covered)
- Comparative studies showed anti-nodes to be optimal patch placement
- Same method applied to circular annular plates with similar reductions

**Active Patch Investigations**
- Representative experimental setup
  - Aluminum plate, disturbance from shaker
  - Piezoelectric patch to attenuate noise by destructive interference
- Significant reduction observed in sound pressure and accel.
  - Phase between disturbance and control signals varied
  - Reduction observed at different frequencies & for different patches

**Future Work**
- Mode Shape Characterization
  - Use roving-hammer-type test
  - Correlate with FEA, use to optimize patch placement (antinodes)
- Control Algorithm Development
  - Unknown disturbance frequency determined from measurement
  - Phase is control variable to minimize sound
- More complex geometry
  - Curvature, features like ribs
  - True in-situ geometry → electric motor housing

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**Project Leaders:** Raj Singh (singh.3@osu.edu) and Jason Dreyer (dreyer.24@osu.edu)

*Project initiated by Hyundai Motor Company (R&D Division)*
Project # 43: Thermally Invariant Smart Composites

Technology Summary

- NiTi-Al composites are a lightweight alternative to iron-based thermally invariant materials like Invar.
- Tight part tolerance is required in aerospace components which undergo large temperature fluctuations.
- Ultrasonic Additive Manufacturing (UAM) enables the manufacture of gapless NiTi-Al composites below the melting temperature of the constituent materials.

Applications/Benefits

- Low fiber volume fraction is possible, which reduces cost and weight.
- NiTi-Al composites can be mounted with standard fasteners, are tough, and require no power to function.
- Composite is multifunctional:
  - Slows composite thermal response.
  - Provides stiffening with heating.
  - Can be activated passively or actively.

Plan

- Develop high fidelity models for composite design and analysis.
- Improve and understand interfacial coupling between NiTi fibers and Al matrix.
- Scale up technology with mechanized UAM process:
  - Automated tape feed.
  - CNC subtractive stage and laser etching.
  - Fixtures for laying out of fibers.

Project Leader: Marcelo Dapino (dapino.1@osu.edu)
Project initiated by MIT Lincoln Laboratory.
**Problem Statement**

- The objective of this Smart Vehicle Concepts Center project is to develop flexible, self-powered, multi-functional tire sensors.
- We are interested in measuring tire physical properties, log tire history, and generate real-time information on tire condition and tire-road interactions.
- Research focus is PVDF (polyvinylidene fluoride) sensors and energy harvesters.

- As a first step we developed a tire revolution counter.
- We propose electrode patterning to measure various tire properties (revolutions, temperature, load, wear) with the same PVDF sensor.

**Background**

- Smart sensors and devices can add significant value to tires.
  - Safety: Real-time notification of tire condition and tire-road interactions can improve safety by providing accurate parameter estimation to the vehicle electronic stability control (ECS) system.
  - Performance: Historical monitoring of tire data can be used to improve tire design, modeling, and fabrication.
  - Operating costs: Tire condition monitoring is important in commercial vehicles where tires are the single largest maintenance cost item and may be retreaded multiple times.

**Prediction of Measured PVDF Voltage**

- Rectangular shape (Length: L/2, L, 2L)
  
- Stepped shape

**Flexible, Self-Powered, RFID Based Sensors**

**Objective:** Develop autonomous, self-powered, radio frequency identification (RFID)-based smart tire sensors (STS) that log the tire history within the tire and generate real-time information on tire condition and tire-road interactions.

**Energy Harvester**

- Energy harvesting to power data processing and writing to memory.

**System Architecture**

- Compatibility and optimization of components for system performance.
- Multifunctional elements that reduce cost and weight by using fewer components.

**Tag Antenna**

- Reliable reading regardless of tire construction and condition.
- Robust structure to withstand rubber curing, retreading, vehicle running/stopping.

- Receiving sensor input from multiple sensors.
- Processing of sensor data.
- Memory to store data.
- Energy harvesting circuitry.

**PVDF Sensor Output during Drum Tests**

**Drum tests:**
- PVDF sensors bonded to a truck/bus tire innerliner.
- Tested various bonding methods.
- Tested under typical vehicle speeds and loaded tire radius conditions.

**Drum test results:**
- Sensor successfully demonstrated without failure.
- Revolutions counted by sensor and algorithm matched data from a pulse tachometer.

**Prediction of measured voltage (3 sec for 1 rev)**

- Decreasing stepped shape.
- Increasing stepped shape.

**PVDF Output Voltage**

Example of PVDF sensor output.

PVDF output voltage

Detected number of revolutions: 35 rev.

Revolutions based on pulse tachometer: 35 rev.

**Power**

- Sensor 1
- Sensor 2
- Sensor n

RFID Tag Chip and other IC components.

**RFID Tag Chip**

- Receiving sensor input from multiple sensors.
- Processing of sensor data.
- Memory to store data.
- Energy harvesting circuitry.

** Sensors**

- Reliable sensing of different tire phenomena.
- Reliable algorithms to interpret sensor data.
- Robust structure and mounting to withstand operating conditions.

**Project Leader:** Marcelo Dapino (dapino.1@osu.edu) and Leon Headings (headings.4@osu.edu)

Project initiated by Bridgestone.
**Project # 45: Morphing Panels for Aerodynamic Performance**

**Problem Statement**
- Objective: Investigate morphing panels for improved aerodynamic performance at high vehicle speeds (150+ mph)
- Methodology:
  - Identify vehicle body shapes for aerodynamic drag reduction and examine smart material technologies to create appropriate shape changes
  - Propose shape morphing body concepts to reduce overall aerodynamic drag
  - Develop models and laboratory demonstrations to test the selected approaches and provide a basis for future development

**Background**
- There is growing interest in the use of morphing materials in both land and air vehicle applications to enhance aerodynamic performance
- Morphing vehicle structures must be lightweight and durable over a wide range of operating conditions
- Morphing panels can be used to improve aerodynamic performance by reducing drag and generating downforce at high speeds
- A variety of smart materials, composites, and devices can be used to create morphing structures for different applications

**UAM Active Hinge with SMA Ribbons**
- UAM active hinge concept using SMA ribbons
  - SMAs embedded in Al matrix are trained in a 180 degree folded shape for shape memory effect by heating shape set temperature of around 500 °C for 25 min and quenching in cold water
  - By applying electrical current through the two Al plates, SMAs actuate to fold the plate when heated above the transformation temperature
- 2.25"x4.5" active hinge panels with nine embedded SMA ribbons

The panels are activated by ~23 A drawn from the battery. If the SMA wires are electrically isolated and connected in series, activation current will be reduced to less than 1 A.

**Actuator Technologies and Morphing Panel Concepts**
- **Actuator technologies**
  - **Short-term:** Torsional SMAs
    - Objective: Develop welding methods for joining NiTi alloys to common structural materials and enhance thermal dynamic response
  - **Mid-term:** Electro-hydraulic actuators driven by smart materials
    - Objective: Develop lightweight and small scale electro-hydraulic actuators driven by smart materials such as magnetostrictive or piezoelectric materials in order to actuate UAM panels
  - **Long-term:** Shape memory polymer composites
    - Objective: Develop morphing shape memory polymer (SMP) composites with shape fixity and shape recovery
- **Morphing panel concepts**
  - **UAM panels and hinges**
    - Objective: Develop morphing panels and hinges by joining dissimilar materials, smart materials, polymers, or electronics
  - **UAM origami structure**
    - Objective: Develop morphing structure by joining multiple UAM panels with integral smart hinges

**Active Hinge with SMA Torque Tube**
- Shape memory alloy torque tube hinge concept
- 304 stainless steel
- SMA tube
- Cartridge heater
- Hinge
- NiTi / 304 SS NiTi / 304 SS Ni filler
- Applied 222 in-lb torque
- (Critical finish torque of TIG weld: 201 in-lb)

Both ends of 6" SMA tube are welded to 2.5" 304 stainless steel (with Ni filler) by orbital TIG welding

Thermal dynamic response can be enhanced by using a cartridge heater with larger diameter and filling the tube with a highly conductive material

**Project Leader:** Marcelo Dapino (dapino.1@osu.edu)

Project initiated by Toyota Technical Center
Motivation

- Need for a paint-on light source that can be used for aesthetic purposes in automotive applications
- Paint-on light to be coated on outer body surface of automobiles
- Mechanoluminescence (ML) of inorganic phosphors prime candidate

Problem Formulation

- ZnS:Mn film
- PZT (disks/sheets)
- Metal substrate

- ML - light emission induced by mechanical action
- ZnS:Mn film - ZnS:Mn particles in a matrix (epoxy binder)
- ZnS:Mn particles - micro and nano-sized particles
- Binder – Transparent, efficient in stress transfer, adhesive

Methods

Wet chemical method – ZnS:Mn nanoparticles

\[ \text{Zn(C}_2\text{H}_3\text{O}_2)_2 + \text{Na}_2\text{S} + \text{PVP} \rightarrow \text{PVP-ZnS} + \text{NaC}_2\text{H}_3\text{O}_2 \]

- Easy control over dopant concentration.
- Particles synthesized are in nanoscale.
- Control over particle size achieved
- PVP found to increase PL emission

Experimental Results

- Chemical composition of ZnS nanocrystals has been confirmed.
- ML has not been observed yet from the nanocrystals
- Micro-particles are to be considered in the future

Project Leader: Vishnu Baba Sundaresan (sundaresan.19@osu.edu)
Project initiated by Honda R&D
**Project Overview**

- **Motivation**: reduce driveline/gear vibration
- **Objective**: study magnetostrictive systems in relation to stiffness tuning, vibration damping, and energy harvesting
- **Expected Outcomes**:
  - Better understanding of multifunctionality
  - User-friendly FE module for 3D simulation

**Background**

- NASA is investigating piezoelectric-based solutions
- Available magnetostriction models are for expert users and have computational issues
- Galfenol and Terfenol-D offer the potential for
  - Improved energy harvesting and damping
  - Robust and reliable stiffness tuning

**Plan**

**Sub-project 47A:**
- Model stiffness switching (0 – 1 kHz)
- Design, build, and test magnetostrictive variable-stiffness components
  - Benchmark against NASA's variable spring

**Sub-project 47B:**
- Model 2D/3D electromagneto-mechanical behavior of harvester/damper

**Sub-project 47C:**
- Design and build vibration ring and circuitry
- Test prototypes up to 2.8 kHz

**Plan (cont.)**

- Design and build vibration ring and circuitry
- Test prototypes up to 2.8 kHz

**Sub-project 47C:**
- Improve material model solution procedure and numerical inversion for
  - Elimination of singularities
  - Faster and more robust convergence
- Integrate system models directly into commercial FE software
**Technology Summary**

- Metal matrix composites (MMCs) consisting of matrix and reinforcing material
  - Matrix: Al or Mg
  - Reinforcement: Al$_2$O$_3$, carbon fiber, or SiC
- Functional grading can be manufactured using ceramic preforms and squeeze casting under high force and low velocity
- A need exists for understanding mechanical and thermal properties along the gradient

**Applications / Benefits**

- MMCs can be tailored to achieve low density, high stiffness, improved wear characteristics, and enhanced high-temperature strength
  - Functionally graded composites offer tunable properties through selective reinforcement
    - Withstand specified thermomechanical loading conditions in specific areas
  - Applications include brake rotors and armor

**Approach**

- Micro and Macro characterization on coupon specimens to determine microstructure and mechanical properties
  - Multi-scale modeling of coupon specimens using RVE approach in Comsol
  - Development of structural level model using hierarchical finite element approach

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**Project Leaders:** Marcelo Dapino (dapino.1@osu.edu) and Soheil Soghrati (soghrati.1@osu.edu)  
**Project initiated by REL Inc.**

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Technology Summary

- Fiber Bragg Grating (FBG) sensors can be used for real-time strain sensing
- Sensors are needed to monitor internal strains of metallic structures
- Ultrasonic Additive Manufacturing (UAM)
  - Low temperature process for rapid prototyping of 3D metallic structures
  - Gapless joining of dissimilar metals
  - Sensing fibers can be seamlessly embedded into metals (e.g., Al 6061) with UAM

Applications / Benefits

- FBG sensors are small, noninvasive, immune to electromagnetic interference, and can be multiplexed
  - UAM process does not alter FBGs
    - No thermal loading
    - No deformation of the glass core
    - Embedded with commercial coatings
  - In-situ embedded sensing
    - Smart maintenance
    - Minimize downtime
    - Monitoring in harsh environments

Results

- Process developed for embedding FBGs
- Accurate and repeatable strain tracking from embedded FBGs
  - Measurements during both tensile and cantilever bending testing
  - No slip between acrylate coating and matrix
  - Strain tracking at elevated temperatures
  - Dynamic response
- Improvements to temperature threshold of sensor coating as a result of embedment

Project Leaders: Marcelo Dapino (dapino.1@osu.edu)
Project Initiated by Moog Inc.
Project #51: Ultrasonic Additive Manufacturing for Automotive Structures

**Purpose:**
Enable lightweight vehicle structures via UAM

**Research Objectives:**
- Understand the cause for the knockoff in x-tensile (in-plane) strength resulting from the UAM process
- Develop weld parameters that can reduce or eliminate the knockoff

**Methodology:**
- Investigate process-property relationships through Design of Experiments study
- Prior pilot study focused on feasibility of welds
- DOE study focused on x-tensile testing
- FEA models developed to guide the experiments and assists with data analysis

**DIC Testing and Modeling:**
- Digital image correlation (DIC) used to measure 2D and 3D strain fields
- Permits local and global measurements

**Ultrasonic Additive Manufacturing:**
- 3D printing technology based on ultrasonic metal welding
- Low-temperature process
- Dissimilar metal parts and integrated structures
- Successive application of metal tape builds part
- Periodic machining shapes part and maintains uniform welding surface

**DIC System Set up for Tensile Test:**
- Computer with DIC
- 2 Camera System
- DIC System set up for tensile test.

**Project Leaders:**
Marcelo Dapino (dapino.1@osu.edu) and Leon Headings (headings.4@osu.edu)
Pproject initiated by Honda R&D and Battelle Memorial Institute
**Motivation**

- Thermoelectric processing of polymer composites has been demonstrated by Sundaresan and coworkers as a way to 3D print structural composites
- Develop matrix libraries and particulate additives for thermoelectric processing of piezoelectric polymer composites
- Develop nozzle designs and extrusion modes for 3D printing

**Problem Formulation**

- Surlyn (E/MAA) + PZT-5H has been shown to demonstration ionic aggregation of polymer and poling of piezoelectric phases respectively
- New material compositions, nozzle designs and extrusion process parameters for 3D printing will be studied through this project

**Methods**

- Multiphysics modeling of thermoelectric extrusion of thermoplastic ionomers and piezoelectric work will be performed
- The model will be used to identify the influence of the following process parameters
  - Extrusion speed
  - Process temperature
  - Soak time
  - Electrical field

**Background Work**

- DSC shows the effect of thermoelectric processing in E/MAA
  - Narrowing of enthalpy peaks is representative of uniform dispersion of ionic groups, and this construct can be extended to other thermoplastic ionomers
Project #54: Magnetic Additively-Manufactured Structural Hybrid (MASH)

Magnetic gears - challenges

- Specific torque (torque/mass) is lower than aerospace gearing
  - Structures have conflicting requirements in terms of strength, mass, and magnetic properties
  - Flux lost to the structure reduces torque coupling
- Efficiency is reduced at high speed due to eddy currents in the structures
- Typical laminated metals have limited geometry
- Permeable ceramic (ferrite) is brittle / hard to machine

New magnetic materials are needed...

![Photography of constructed magnetic gear](image)

<table>
<thead>
<tr>
<th>Resistivity [$\mu\Omega \cdot cm$]</th>
<th>Tensile strength [MPa]</th>
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<tr>
<td>$10^1$</td>
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</tr>
<tr>
<td>$10^3$</td>
<td>400</td>
</tr>
<tr>
<td>$10^5$</td>
<td>800</td>
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<tr>
<td>$10^7$</td>
<td>1200</td>
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</table>

Features of new magnetic composites:
- Lightweight
- Strong magnetic coupling
- Low eddy current loss
- Robust and reliable
- Easy to manufacture
- Self-contained

<table>
<thead>
<tr>
<th>Performance Target</th>
<th>Permalloy 80 (cold rolled)</th>
<th>Metglas</th>
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</thead>
<tbody>
<tr>
<td>CoFe</td>
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<tr>
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<tr>
<td>NiZn ferrite</td>
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</tbody>
</table>

Approach – fabrication of MASH

Ultrasonic additive manufacturing or soft magnetic material powder consolidation

- Magnetic materials (high permeability / high resistivity) will be embedded in structural material (high tensile strength)
- Flux paths within the structures will maximize power transfer between rotors without excessive mass

Research plan

Part A: Investigation of Magnetic Gear Configurations
- Modeling of magnet gears

Requirements of MASH
- Machinability
- High magnetic permeability
- Geometry limitation
- High mechanical strength
- Low eddy current loss

Part B: Survey of Material Candidates for MASH
- Characterize stress-dependent magnetic properties
- Fabricate MASH
- Evaluate magnetic and mechanical properties of MASH

Part C: Development of Magnetic Gear
- Magnetic gear demonstrator

Project Leaders: Marcelo Dapino (dapino.1@osu.edu) and Zhangxian Deng (deng.92@osu.edu)
Project Initiated by NASA Glenn
Background and Objectives:

**Objective:** to predict the mechanical behavior of fiberglass insulations packs fabricated by Owens Corning in compression and upon unloading.

Fiberglass insulations are categorized as soft materials with randomly packed fibers that constitute a highly complex microstructure.

Simulating the mechanical behavior requires synthesizing the microstructure and capturing the contact friction forces between the fibers.

**Approach**

Developing a new microstructure reconstruction algorithms to create realistic image-based models of the fiberglass pack by checking the intersection between NURBS curves representing the fibers morphologies (shape and diameters are extracted from imaging data).

Abaqus is employed to simulate the deformation response of the fibers and characterize the force-deflection response of the pack.

**Applications and Benefits**

The proposed microstructure reconstruction algorithm is highly transformative and can be implemented for synthesizing a variety of material microstructures including nano-enhanced and particulate composites.

This computational study enables characterizing the effects of fibers volume fraction, shapes, and diameter on the mechanical behavior of the insulation pack, which can be used in the design of packs with improved properties to minimize the damage during the shipping and installation tasks.