Smart Vehicle Concepts Center (SVC) Projects

THE OHIO STATE UNIVERSITY

National Science Foundation (NSF) Industry-University Cooperative Research Center (IUCRC)

Smart Vehicle Concepts (SVC)

Center Director:

Marcelo Dapino

dapino.1@osu.edu

Department of Mechanical
and
Aerospace Engineering
The Ohio State University

www.SmartVehicleCenter.org

https://svc.osu.edu

SVC Companies	Status
American Axle and Manufacturing	Former Member
Advanced Numerical Solutions	Former Member
Army Research Laboratory	Former Member
Autoliv	**Current Member**
Battelle Memorial Institute* **	**Current Member**
BorgWarner	Former Affiliate
Bridgestone Americas Tire Operations, LLC	Former Member
Eaton Innovation Center	Former Member
Edison Welding Institute	Former Member
Ford Motor Company	Former Member
F.tech R&D *	Former Member
Goodyear Tire & Rubber	Former Member
Honda R&D Americas Inc. *	**Current Member**
Hyundai-Kia Motors *	Former Member
LMS Software	**Invited Observer**
MES, Inc.	**Invited Observer**
MIT Lincoln Laboratory	Former Member
Moog Inc.**	**Current Member**
MSC Software	**Invited Observer**
NASA Glenn Research Center **	**Current Member**
Owens Corning	Former Member
Parker Hannifin	Former Member
REL, Inc.	Former Member
Romax	**Invited Observer**
Solidica	Former Member
Tenneco, Inc.	Former Member
The Boeing Corporation	Former Member
Tokai Rubber	Former Member
Toyota Research Institute, Inc. *	**Current Member**
Transportation Research Center, Inc. *	Former Member
YUSA	Former Affiliate

**Multiple memberships* ***Member and Invited Observer* ****Pending*

Smart Vehicle Concepts Center (SVC)

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Cooperative Center Concept – IUCRC

- 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 on **smart materials and structures** applied to ground and aerospace vehicles
- Build an **unmatched base of research**, engineering education, and technology transfer with emphasis on improved vehicle performance
- Prepare **next-generation engineers** who posses both theoretical and experimental expertise applicable to auto and aero vehicles

Membership Fee Structure

The Ohio State University

- $40K/year – Full membership (one vote per full membership; access to all Center projects)
- $14K/year – Affiliate (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

Center Year	2017	2018	2019	2020	2021-22
Membership Fee (a)	$40K	$40K	$40K	$40K	$40K
Project Fee (b)	$12K	$14K	$16K	$18K	$20K
Admin Fee (c)	$5.2K	$5.4K	$5.6K	$5.8K	$6K
Cost of Solo Membership (a + b + c)	$57.2K	$59.4K	$61.6K	$63.8K	$66K

Industrial Advisory Board

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

SVC Core Faculty

Prof. Marcelo Dapino
Expertise: Smart materials; Nonlinear coupled systems; Design; Control

Prof. Jen-Ping Chen
Expertise: Computational fluid dynamics; CFD simulation and coding; Turbulence modeling; Turbomachinery

Prof. Hanna Cho
Expertise: Nonlinear NEMS/MEMS; AFM cantilever dynamics; Multi-functional ferroelectric material energy systems; Nano- and bio-science

Prof. Ardeshir Contractor
Expertise: Solar energy; Smart grids; Electric mobility; Renewable energy storage; Materials for energy conversion

Prof. Vicky Doan-Nguyen
Expertise: Synthesis; In-situ structural characterization; Smart materials; Advanced materials for energy storage/conversion

Prof. David Hoelzle
Expertise: Learning/adaptive control systems; Additive manufacturing processes; Microsystems for mechanobiology research; Dynamics systems analysis

Prof. Raj Singh
Expertise: Noise & vibration control; Geared systems; Nonlinear dynamics; DSP

Prof. Soheil Soghrati
Expertise: Advanced FEM; Modeling multiscale response of advanced/bio-materials and structures

Prof. Vishnu Sundaresan
Expertise: Piezoelectric materials; Active polymers; Bio-derived materials

For further details: https://svc.osu.edu/membership

www.SmartVehicleCenter.org

New Research Matrix for Phase III

Thrust	Interfacial Mechanisms	Safety, Comfort, and Health Monitoring	Adaptive Noise, Vibration, and Harshness (NVH)	Emerging Vehicle Technologies
	Characterization, constitutive modeling, system integration (sensors, actuators, dynamic simulation)	Machine and material diagnostics, human-machine interface, strain energy management	Active noise and vibration control, adaptive structures, system integration	Vehicle electrification, autonomous vehicles, lightweighting
PAST Relevant Projects	40A, 40E, 40F, 55	46, 58, 58A, 58B	45, 52, 57, 57B	51A, 54B, 56
CURRENT Relevant Projects	60	49, 63	57C	51B, 51C, 51D, 51E, 54, 61, 61B*, 62, 64*
Typical Sponsors	Honda R&D, TRC, R&D, Tenneco, Ford, NASA Glenn, Owens Corning	Autoliv, Bridgestone, Honda R&D, Moog	Honda R&D, TRC, Tenneco, NASA Glenn, Toyota, Parker Hannifin, CVG	NASA Glenn, Honda R&D, Battelle, TRC

**new project*

Project #1: Electro-Hydrostatic Actuation and Sensing (E-HAS)

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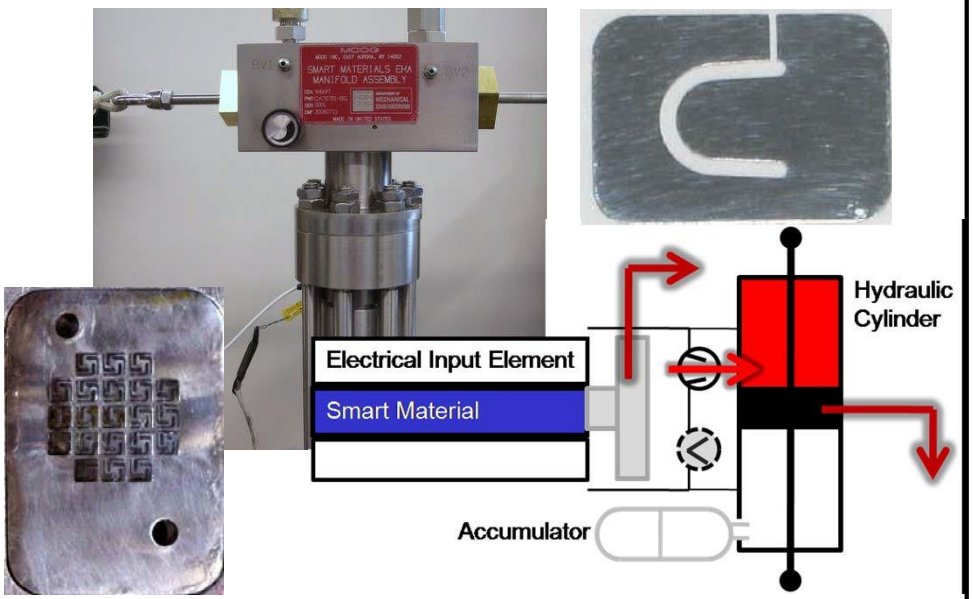
Technology Summary

- 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

Project leader: Marcelo Dapino (dapino.1@osu.edu)
Project Initiated by Moog Inc.

Project #3: Design Tool for Smart Engine Mounting Systems

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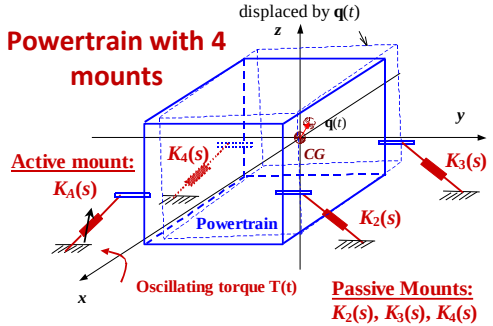
Motivation:

- Powertrain mounts affect the dynamic noise and vibration behavior of a vehicle
- Motion control and vibration isolation can be better obtained via smart mounting systems
- Improvements in torque roll axis decoupling of powertrains are possible with passive and active mounts

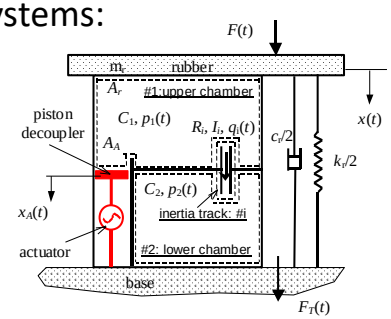


Hydraulic or rubber mount

Methods:

Develop multi-physics, multi-domain mathematical models for passive and smart mounts/mounting systems:

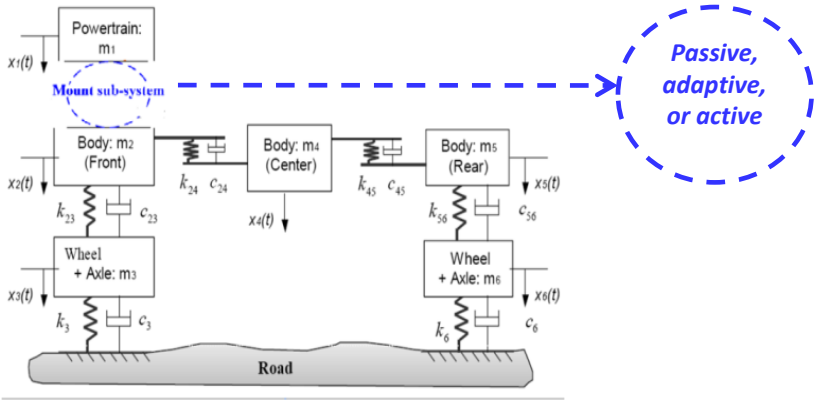
- **Nonlinear modeling of mounts**
  - Passive/adaptive/active mounts
  - Comparative evaluation studies
  - Mount characterization
- **Vehicle system studies**
  - Quarter/half/full vehicle models
  - Modal analyses
  - Forced response studies
- **Powertrain system analyses**
  - 3 or 4 mounts (with 1 or more smart)
  - Torque roll axis (TRA) decoupling methods
  - Transient analysis



Electromagnetic active mount concept

Problem Formulation:

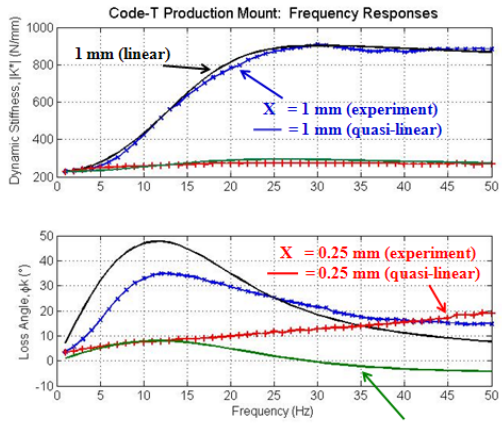
1. Model and characterize passive and smart mounts in the context of vehicle systems
2. Develop new dynamic design tools for mounting system
3. Specify components based on desired vehicle responses



Half vehicle model

Recent Results:

- Hydraulic engine mount with multiple inertia tracks
  - Quasi-linear modeling (nonlinear damping)
  - Broadband mount response achieved
- Electro-magnetic active mount
  - Actuator dynamics
  - Evaluated using half vehicle model
- Improve methods for torque roll axis decoupling



Comparison of linear and quasi-linear passive mount models

Project Leader: Raj Singh <singh.3@osu.edu>

Project Initiated by: Transportation Research Center (TRC)

Project #20: Development of an Interfacial Force Sensing System (Sub-Project #20C: Characterization of Pump Bearing Surfaces)

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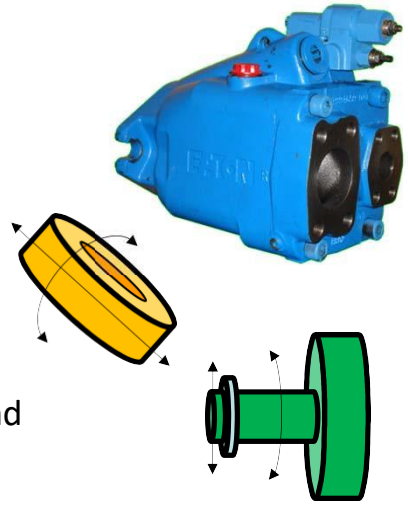
Motivation

- 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

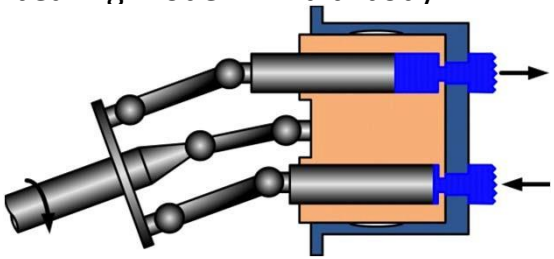


Goals and Expected Benefits

- 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

http://www.auto-bearings.cn

Project Leaders: Raj Singh (singh.3@osu.edu) and Jason Dreyer (dreyer.24@osu.edu)
Project Initiated by Eaton Corporation

Project #22: Material Database Compilation and Material Selection Tool

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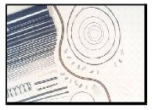
Motivation:



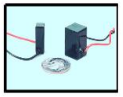
Shape Memory Alloys

Carbon Nanotubes

Dielectric Elastomer

Smart Materials and Elastomers have significantly variable properties and are highly non-linear.

In order to determine the best material for the application, key properties must be highlighted in the same context and tools must be developed to determine the best material for a given performance envelope.

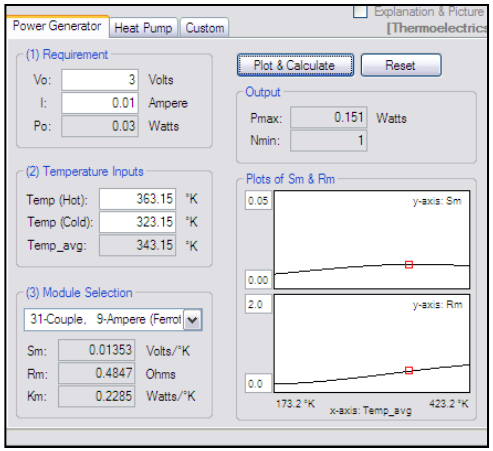


Electroactive Ceramics

Ionic / Electronic Conducting Polymers

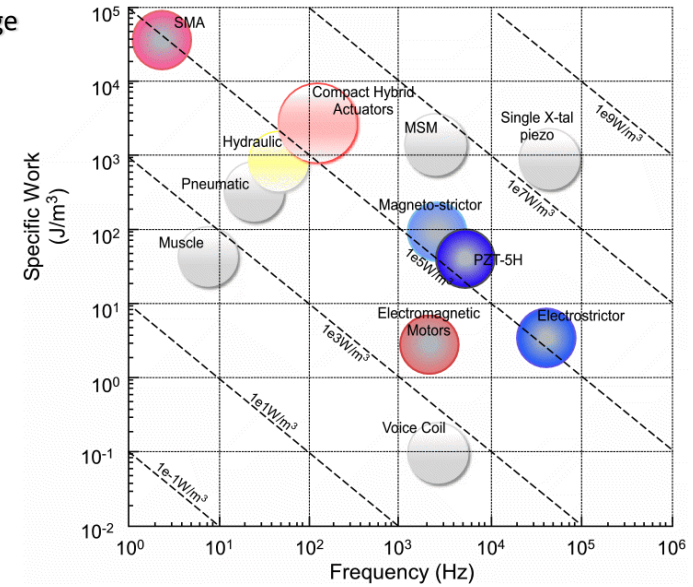
Project Goals:

- Extensive literature survey
- Compilation of the data into an easy to use format
- Development of a GUI based tool to utilize the data
- Development of design tools based on the GUI format
- Materials Testing and verification

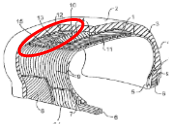


Design Considerations:

- Materials have a number of applications that range the space of
  - Force
  - Stroke
  - Bandwidth
  - Size
  - Weight
- Must consider
  - Hysteresis
  - Creep
  - Non linear stress-strain phenomena
  - The “illities”



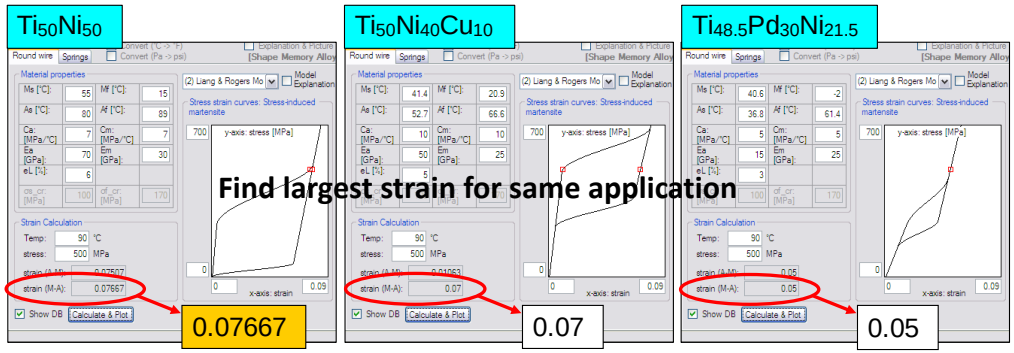
Example for SMA Application:



Metal reinforcing strap

“Metal straps are made of a shape-memory material which can be a metal alloy such as NiTi, NiTiX (where X is Fe, Cu, or Nb),...” [US patent No.: US 6,401,779 B1]

temperature value A_s: about 40 ˚C ~ 90 ˚C
temperature value A_f: about 60 ˚C ~ 120 ˚C
value of maximum stress at temperature A_f: 400 ~ 600 MPa



Project Leader: Greg Washington washington.88@osu.edu, Project Initiated by: Goodyear

www.SmartVehicleCenter.org

Project #31A: Ultrasonic Friction Control

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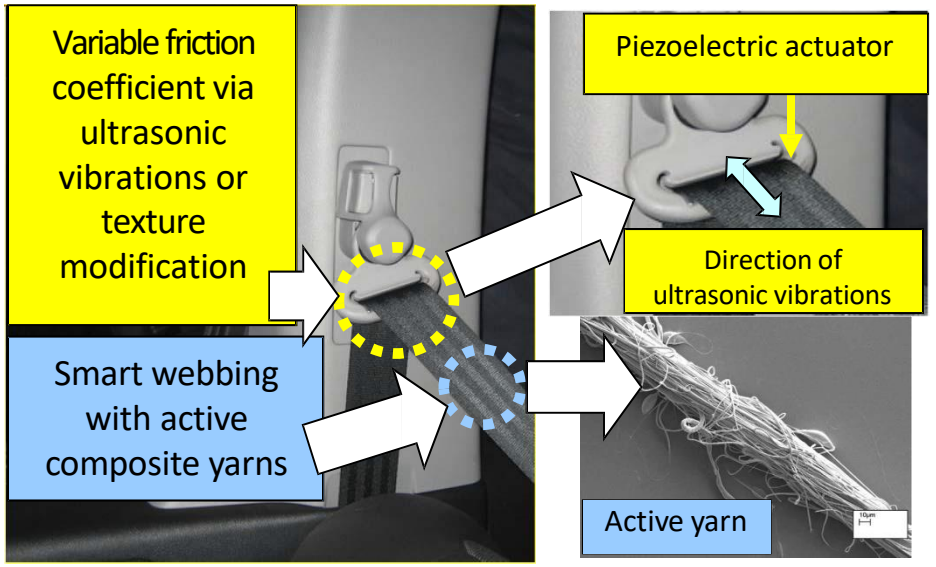
Technology Summary

- **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

Project #31B: Non-Contact Measurement, Visualization, and Analysis of Smart Dynamic Systems

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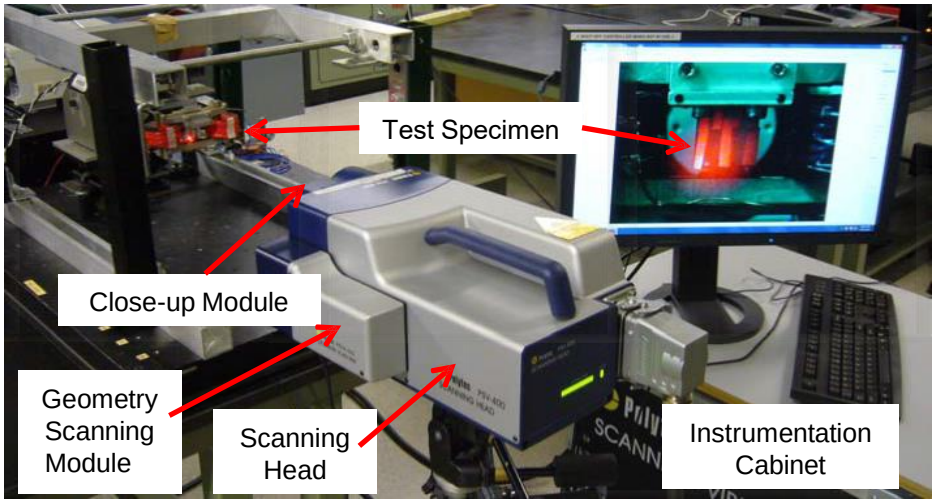
Laser Vibrometer

Features:

- **Non-contact out-of-plane velocity measurement**
- Scans to **measure vibration of entire structure**
- **"Small" and "large" structures** (mm^2 to m^2 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



Dynamic Testing of UAM Al-Galfenol Composites

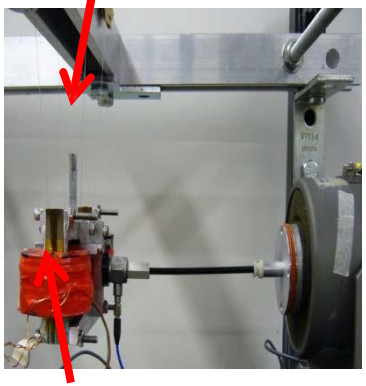
Experimental setup

- 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

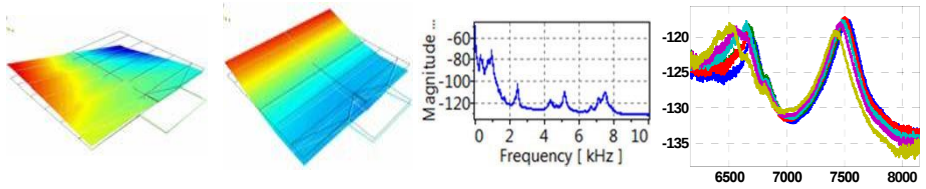
- Composite response expected to be nonlinear; **complex models required to extract full beam response from single point measurement**
- Ability of fixture to produce cantilever condition unknown
- **Many single point measurements required**

Circuit hung as pendulum with fishing wire



magnetic circuit with cantilevered composite

Typical Data



Composite mode identification

In-depth data processing

Bias Field at 0 Stress (kA/m)	Mode 1 (1st Bending)		Mode 2 (1st Torsion)		Mode 3 (2nd Bending)		Mode 4 (2nd Torsion)	
	Frequency (Hz)	Percent Difference (%)	Frequency (Hz)	Percent Difference (%)	Frequency (Hz)	Percent Difference (%)	Frequency (Hz)	Percent Difference (%)
0	949.22	------	2456.3	------	5166.4	------	7515.6	------
1.13	948.44	0.08	2448.4	0.32	5160.2	0.12	7506.3	0.12
4.51	946.88	0.25	2451.6	0.19	5149.2	0.33	7501.6	0.19
8.95	950	0.08	2441.4	0.61	5118.8	0.93	7474.2	0.55
13.5	946.09	0.33	2434.4	0.90	5108.6	1.13	7463.3	0.70
17.8	946.09	0.33	2422.7	1.38	5096.1	1.37	7410.2	1.41

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

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

Project Initiated by Honda R&D

www.SmartVehicleCenter.org

Project #31C: Ultrasonically-Assisted Metal Forming

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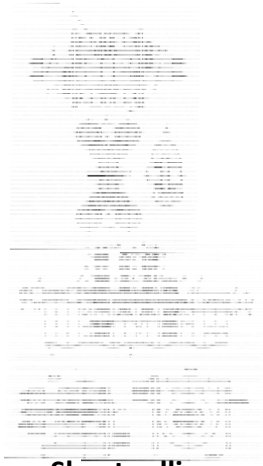
Background and Objective

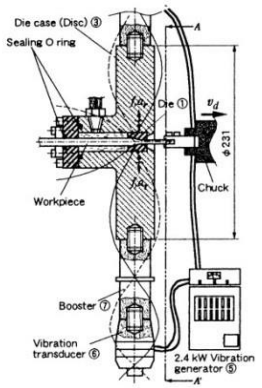
Objective: Develop 3D model for ultrasonic lubrication under speed and stress conditions found in metal forming processes

- **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

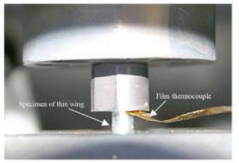
Examples of Ultrasonic Metal Forming



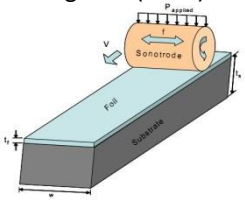
Sheet rolling
Severdenko et al. (1974)



Wire drawing
Murakawa et al. (2001)

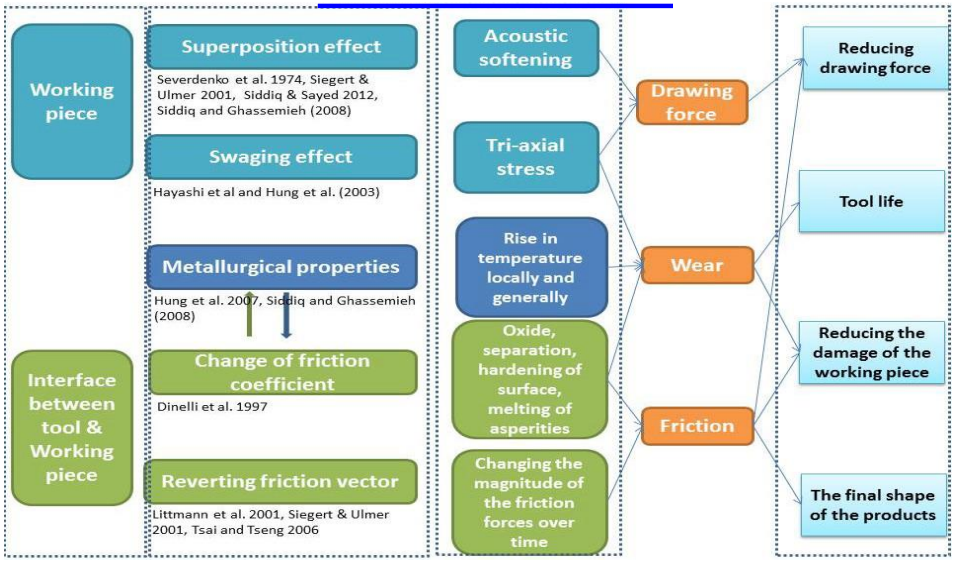


Hung et al (2007)

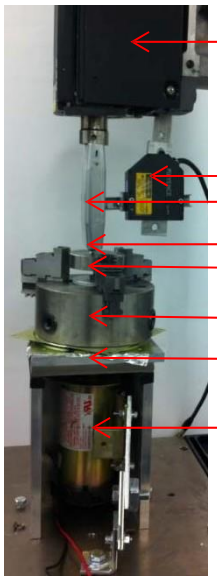


Compressing
Siddiq and Ghassemieh (2008)

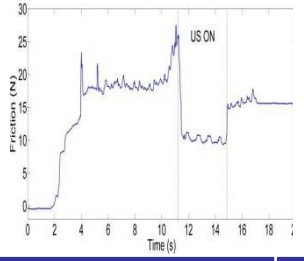
Literature Review

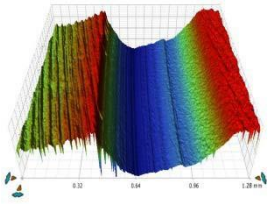


Experiments



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





Friction without US	22.88 - 27.52 N
Friction with US	9.93 - 10.71 N
Friction reduction	56.8 - 61.1%

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

Project Initiated by Honda R&D

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Project #40: Modeling & Characterization of Passive & Adaptive Bushings & Mounts (Sub-Project #40A: Rubber Bushings)

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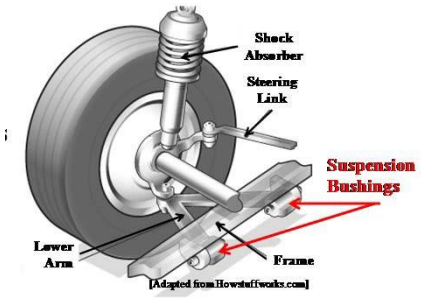
Motivation

➢ **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

Provide some analytical insight into an empirical world

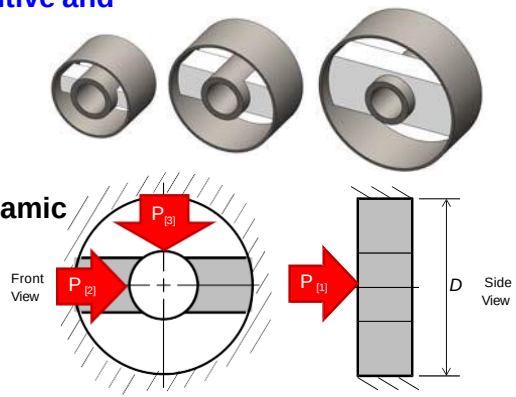


Experimental Component Study

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)

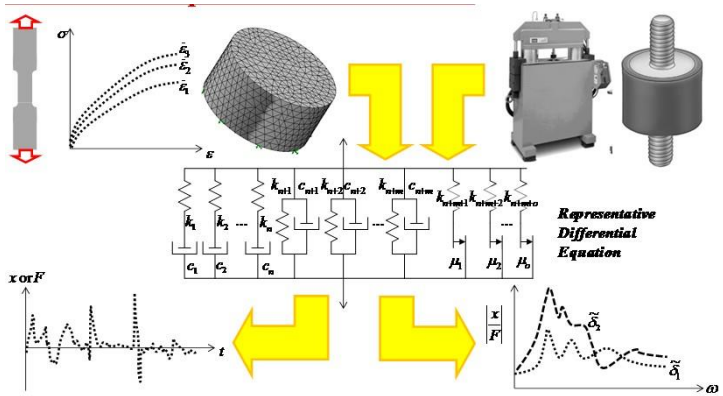
- ✓ 3 Different size specimens
- ✓ 9 Material compositions
- ✓ 3 Loading directions



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

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

Project #40: Modeling & Characterization of Passive & Adaptive Bushings & Mounts (Sub-Project #40B: Hydraulic Bushings)

THE OHIO STATE UNIVERSITY

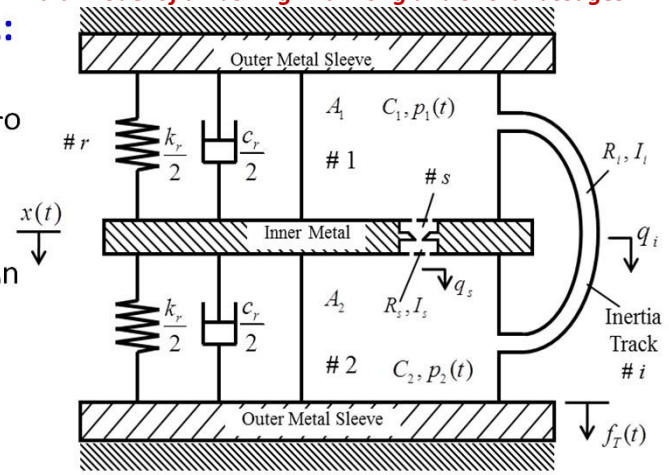
Motivation:

- 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

Fluid Model of a Bushing with Long and Short Passages



Research Plans:

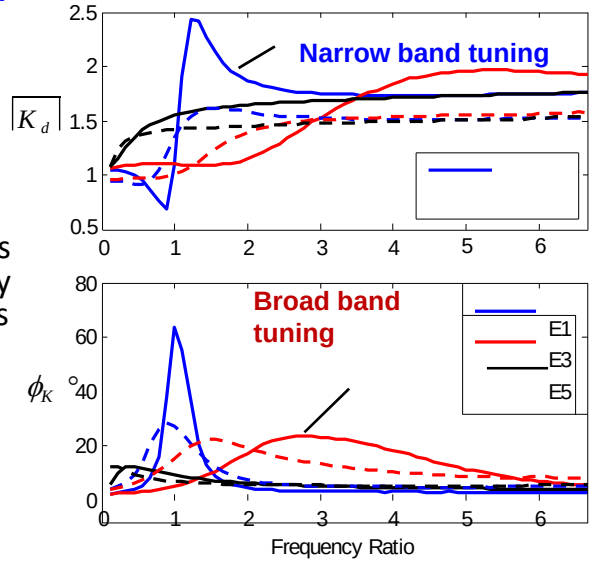
- Develop linear models of hydro bushings with two flow passages
- Investigate static and dynamic properties of production bushings
- Conduct experimental studies on a new prototype and validate linear models in frequency domain
- Conduct time domain experiments and analysis
- Develop quasi-linear (spectrally-variant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

New prototype device

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

Dynamic Stiffness Measurements of the prototype



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

Project #40: Modeling & Characterization of Passive & Adaptive Bushings & Mounts (Sub-Project #40C: Subframe Dynamics)

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Motivation:

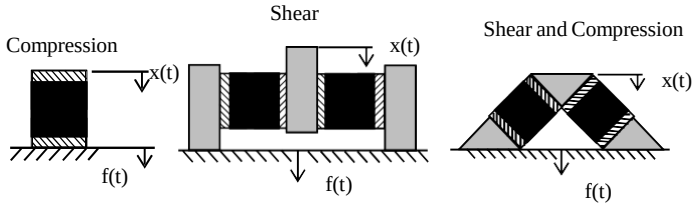
Automotive elastomeric joints are used extensively to accommodate relative movement between metal parts and absorb shocks. Subframes are formed in complicated shapes that must be lightweight, high strength and compact. Subsystem designs must balance the competing needs for:

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

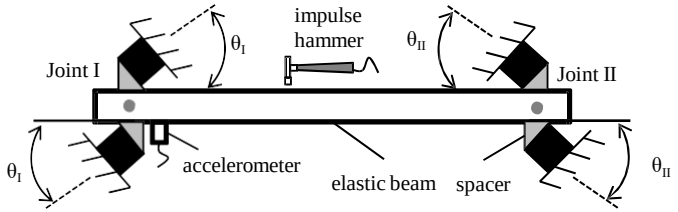
www.hondanews.com

Benchmark Stiffness Coupling Experiments:

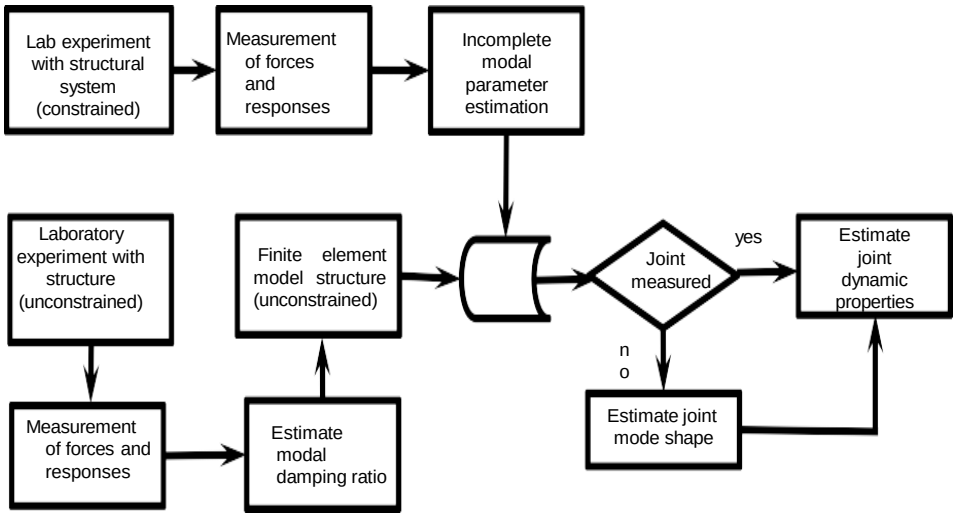
Direct Joint Measurements



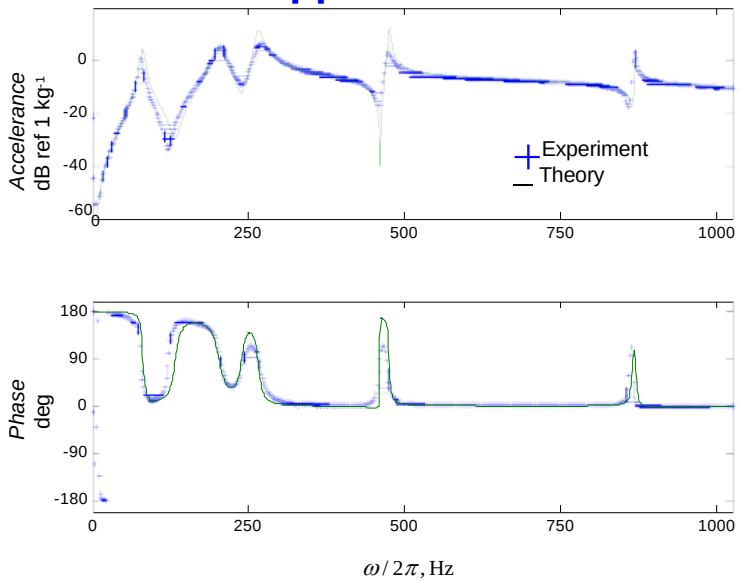
Joint Identification Using Inverse Method



Joint Identification Using Inverse Method:



Recent Results: Elastic Beam with Viscoelastic Supports



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

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Project #40: Modeling & Characterization of Passive & Adaptive Bushings & Mounts (Sub-Project #40D: Hybrid Modeling Methods)

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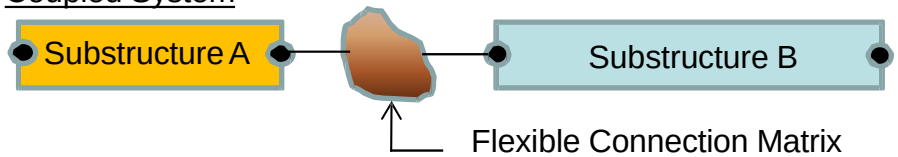
Motivation:

- 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.

FRF Based Substructuring:

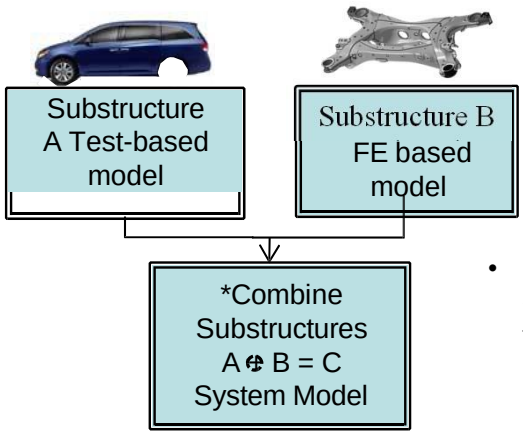
Uncoupled System

Coupled System



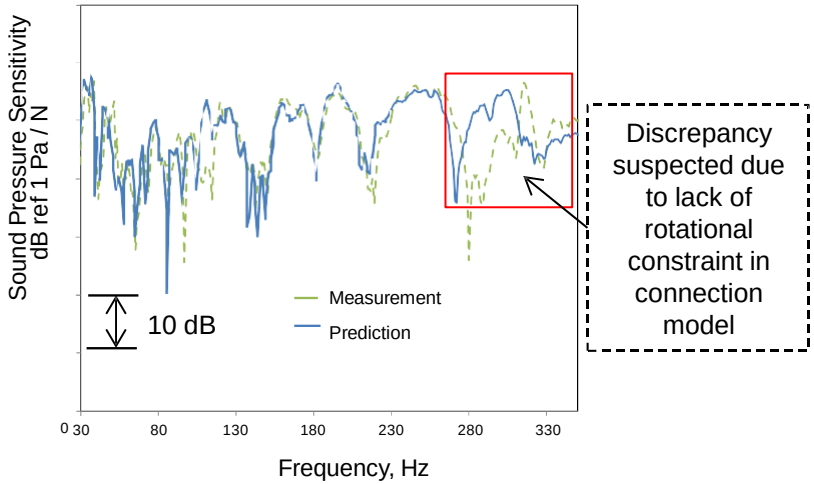
$$\begin{bmatrix} \mathbf{H}_{C_{rr}} & \mathbf{H}_{C_{rs}} & \mathbf{H}_{C_{rt}} \\ \mathbf{H}_{C_{sr}} & \mathbf{H}_{C_{ss}} & \mathbf{H}_{C_{st}} \\ \mathbf{H}_{C_{tr}} & \mathbf{H}_{C_{ts}} & \mathbf{H}_{C_{tt}} \end{bmatrix} = \begin{bmatrix} \mathbf{H}_{A_{rr}} & \mathbf{H}_{A_{rs}} & 0 \\ \mathbf{H}_{A_{sr}} & \mathbf{H}_{A_{ss}} & 0 \\ 0 & 0 & \mathbf{H}_{B_{tt}} \end{bmatrix} - \begin{bmatrix} \mathbf{H}_{A_{rs}} \\ \mathbf{H}_{A_{ss}} \\ -\mathbf{H}_{B_{ts}} \end{bmatrix} \left[\mathbf{H}_{A_{ss}} + \mathbf{H}_{B_{ss}} + [K_s]^{-1} \right] \begin{bmatrix} \mathbf{H}_{A_{rs}} \\ \mathbf{H}_{A_{ss}} \\ -\mathbf{H}_{B_{ts}} \end{bmatrix}^T$$

Problem Formulation:



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

Recent Results:



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

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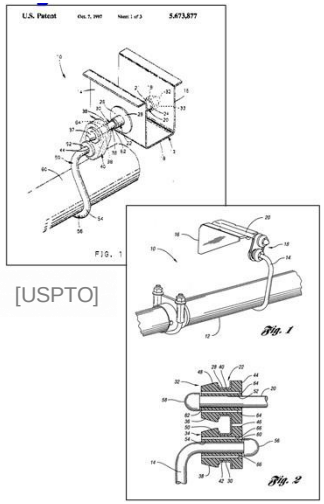
Project #40: Modeling & Characterization of Passive & Adaptive Bushings & Mounts (Sub-Project #40E: Automotive System Isolation)

Motivation:

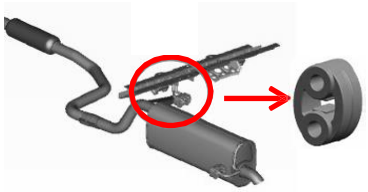
- Exhaust hangers are widely used to isolate exhaust structure and powertrain vibration
- Many features of exhaust hanger and isolation systems are described in 5500+ patents but no analytical or scientific justifications are provided
- Very few scholarly articles on this topic are available



[USPTO]

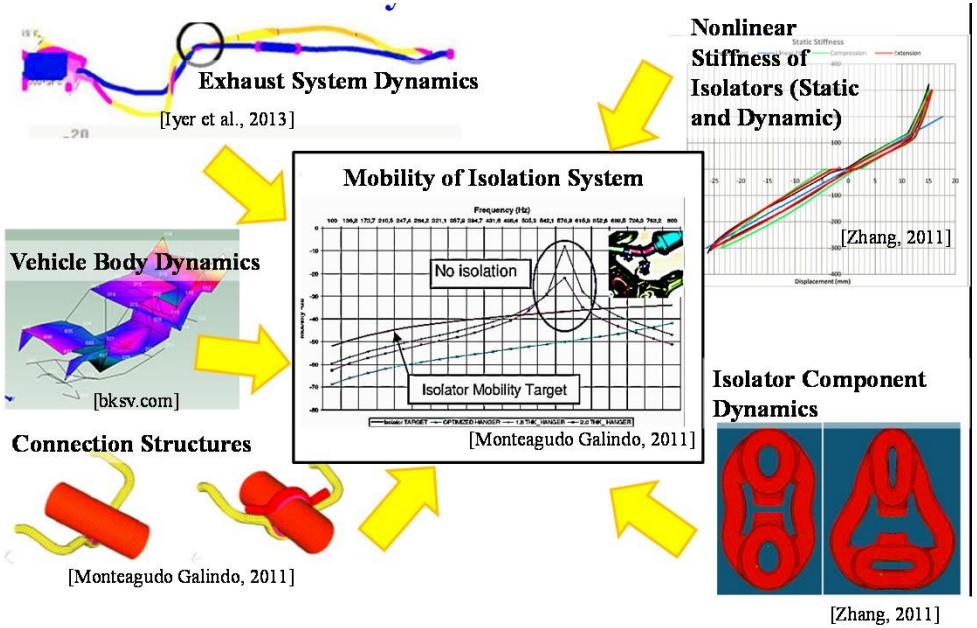
Project Goals:

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



[Figure adapted from Monteagudo Galindo, 2011 and tenneco.com]

Elements of Dynamic Performance:



Technical Issues:

- ❑ **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

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

Project #40: Modeling & Characterization of Passive & Adaptive Bushings Mounts (Sub-Project #40F: Inverse Identification Method for Radiator Mounts)

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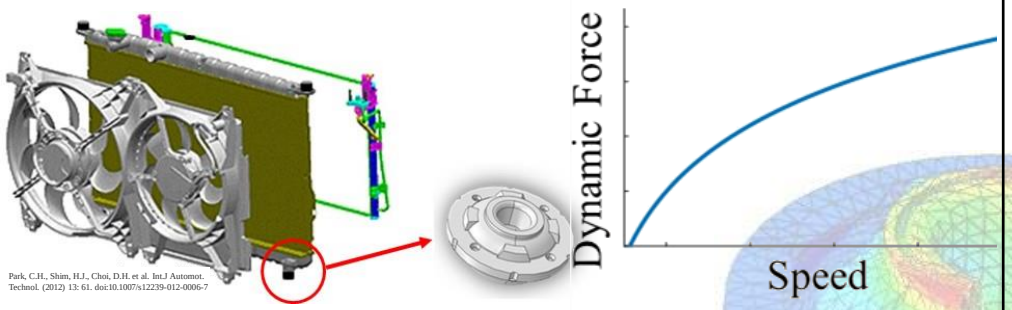
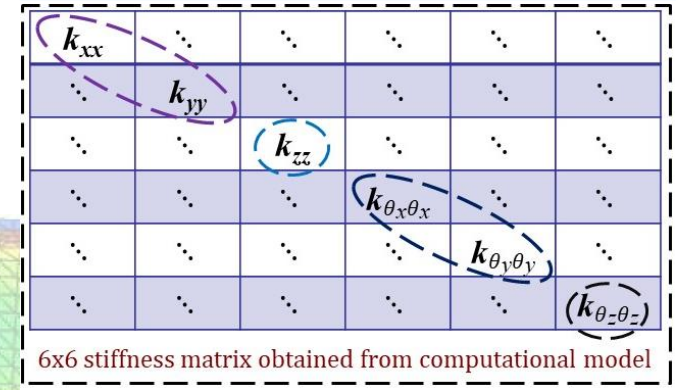
Industry Need, Context, and Relevance

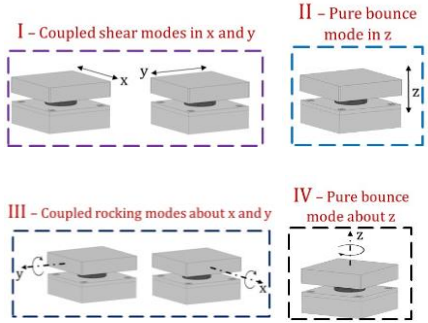
- Improved understanding should strengthen isolator design methodology and specifications for higher speed cooling fans



Goals

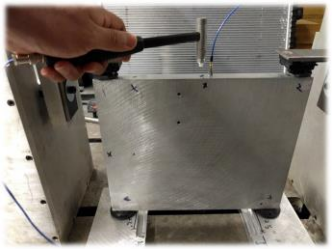
1. **Characterize the multi-dimensional stiffness matrix of elastomeric isolators using the inverse identification method**
2. **Develop refined computational models for the dynamic analysis of a radiator-fan mounting system**





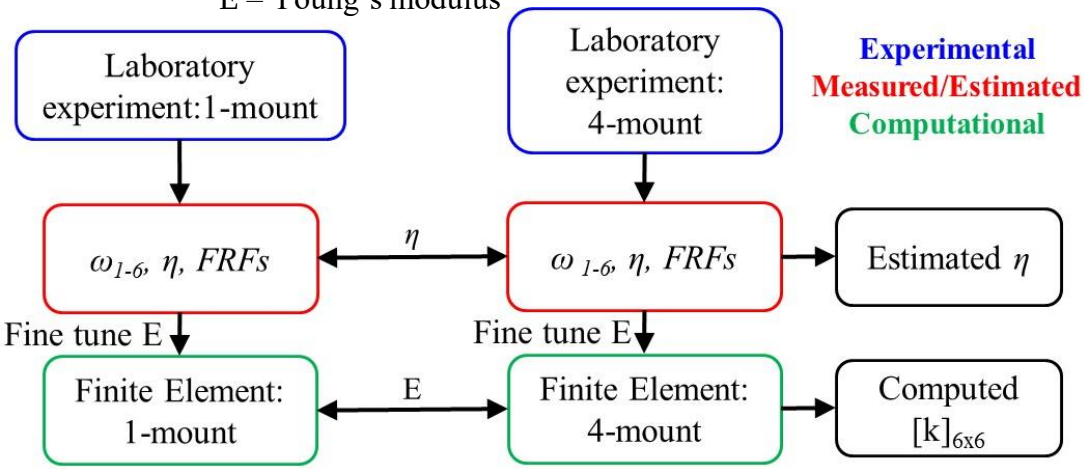
Scope and Assumptions

- Focus on 6 rigid body modes
- Linear system theory (small displacements) for noise and vibration studies
- Dynamic force excitation
- Frequency-independent stiffness (with structural damping)



Approach (Research Methods)

Key: ω – Natural frequency; η – Loss factor; E – Young's modulus; *FRFs* – Frequency response functions; $[k]_{6x6}$ – Stiffness matrix of dimension 6



Project Leader: R. Singh (OSU)

Project Mentor: Yi Zhang (Ford Motor Company)

Project #42A: Enhanced Methods for Reducing Powertrain Vibration Transmitted through the Mounts

THE OHIO STATE UNIVERSITY

Motivation

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

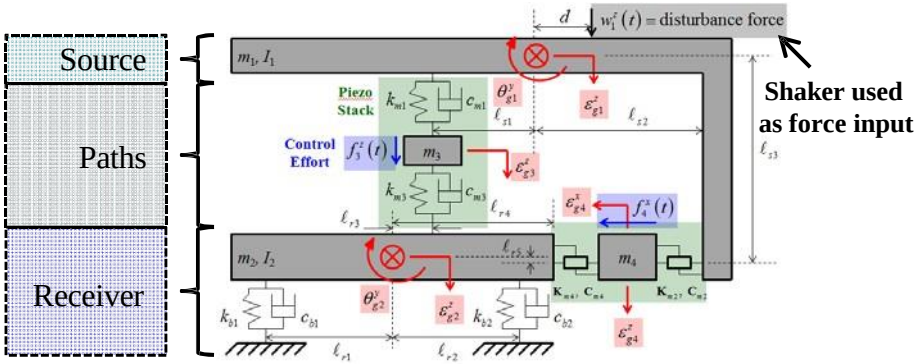
Source(s) (Powertrain, Transmission)	↔	Path(s) (Mounts)	↔	Receiver(s) (Sub-frame, chassis)
Design likely fixed		Flexibility in design		Design likely fixed

Motivation to enhance mount designs for NVH control.

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.

Problem Formulation



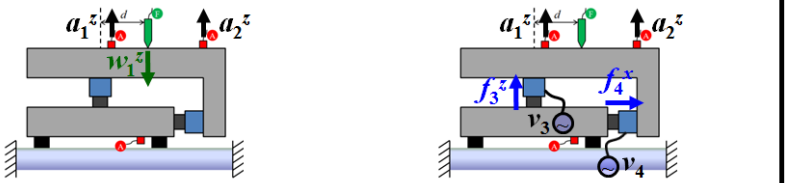
1. Conceptual experiment constructed for feasibility study of active mounts.
2. Active mounts are piezoelectric stacks, modeled with discrete masses.

Focus is on motion control of the source mass

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

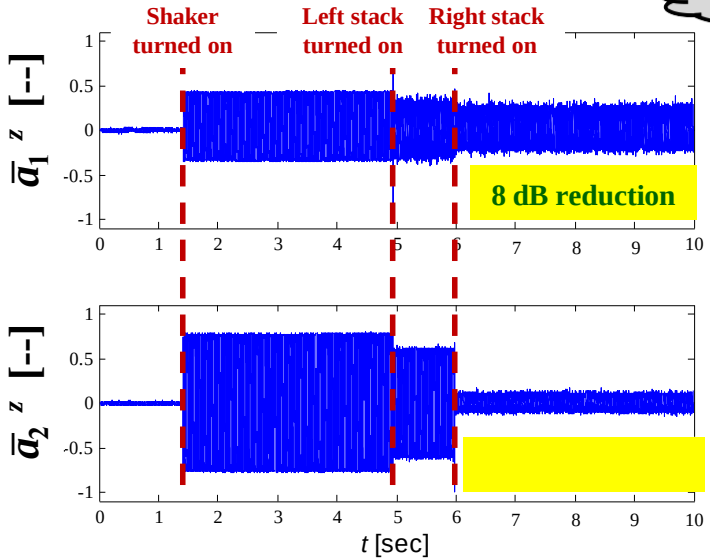


STEP #3: Apply the calculated control effort(s) using the piezo stack(s)

STEP #4: Adjust the phase(s) and magnitude(s) for best results

Control effort(s) calculated using model

Experimental Results



Remarks

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

Experimental results are similar to simulated results

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

THE OHIO STATE UNIVERSITY

Motivation

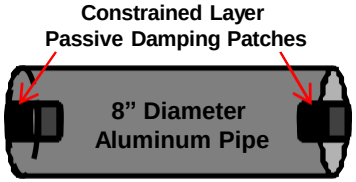
- **New noise sources seen in hybrid and electric vehicles**
- **Characteristics of motor noise**
  - Modulated sounds (with multiple sidebands)
  - Strong directivity
- **May excite structural resonances at high frequencies**
- **Psycho-acoustic perception issues**

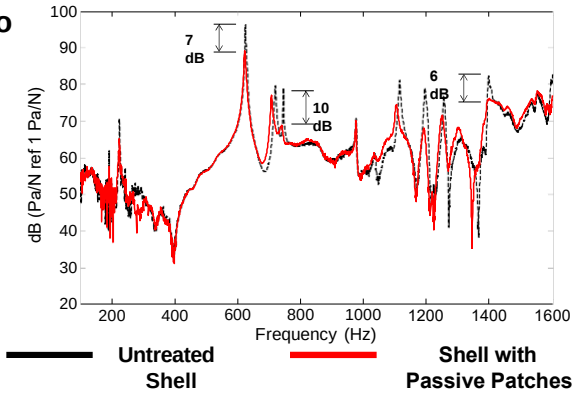
Objectives

- **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

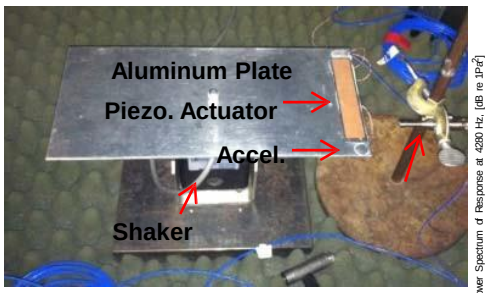
- **Passive damping patches placed on structural anti-nodes of hollow aluminum shell (2% of surface area covered)**
- **Comparative studies showed anti-nodes to be optimal patch placement**
- **Same method applied to circular annular plates with similar reductions**

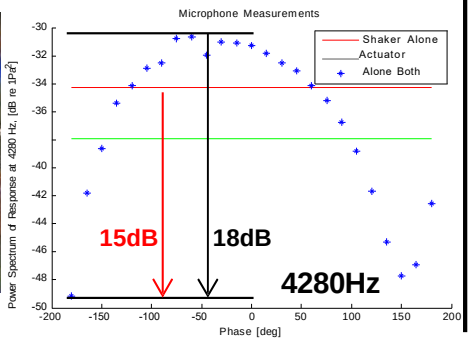




Active Patch Investigations

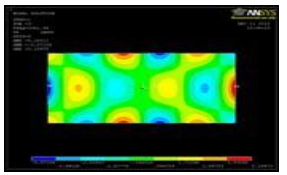
- **Representative experimental setup**
  - Aluminum plate, disturbance from shaker
  - Piezoelectric patch to attenuate noise by destructive interference
- **Significant reduction observed in sound pressure and accel.**
  - Phase between disturbance and control signals varied
  - Reduction observed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

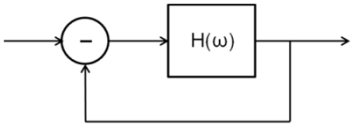




Future Work

- **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





From http://www.123rf.com

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

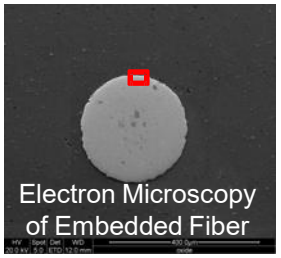
Project initiated by Hyundai Motor Company (R&D Division)

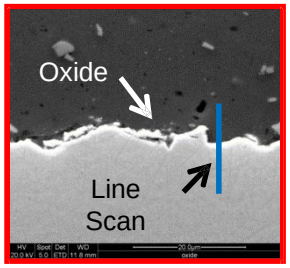
www.SmartVehicleCenter.org

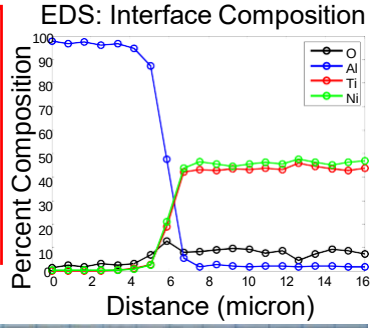
Project #43: Thermally Invariant Smart Composites

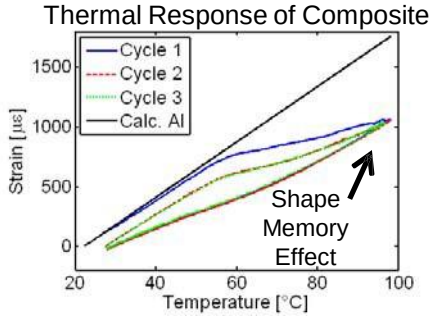
Technology Summary

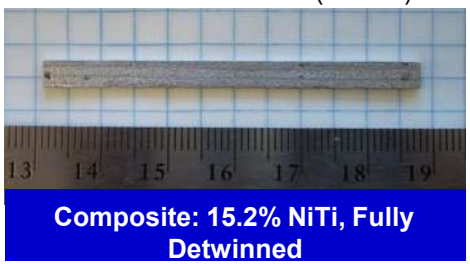
- NiTi-Al composites are a light weight alternative to iron based thermally invariant materials like Invar
- Tight part tolerance is required in aerospace components which undergo large temperature fluctuations
  - Ultrasonic Additive Manufacturing (UAM) enables the manufacture of gapless NiTi-Al composites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

Project #44: Smart Condition Detection and Monitoring

THE OHIO STATE UNIVERSITY

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

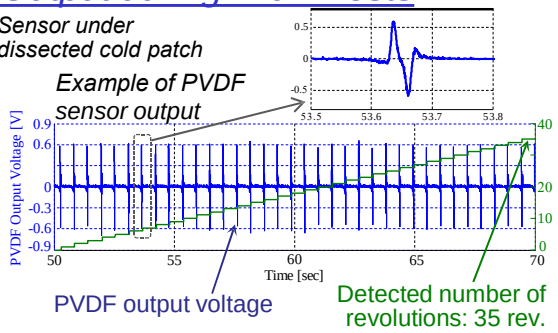
Background

- 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

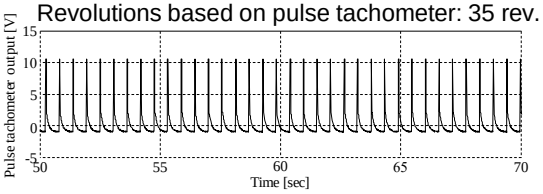
PVDF Sensor Output during Drum Tests

Truck tire

Sensor under dissected cold patch



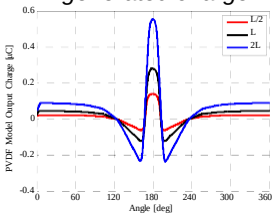
- Drum tests:
  - PVDF sensors bonded to a truck/bus tire innerliner
  - Tested various bonding methods
  - Tested under typical vehicle speeds and loaded tire radius conditions
- Drum test results:
  - Sensor successfully demonstrated without failure
  - Revolutions counted by sensor and algorithm matched data from a pulse tachometer



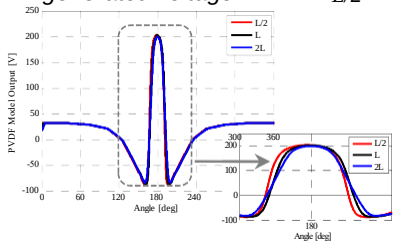
Prediction of Measured PVDF Voltage

➢ Rectangular shape (Length: L/2, L, 2L)

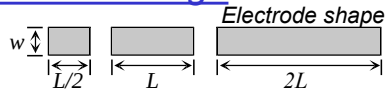
Prediction of generated charge



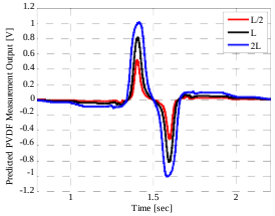
Prediction of generated voltage



Electrode shape

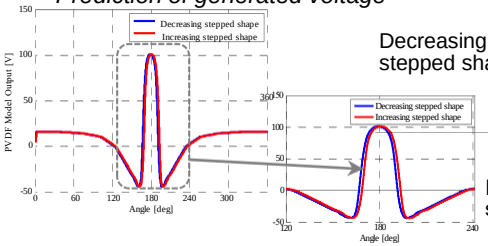


Prediction of measured voltage (3 sec for 1 rev)

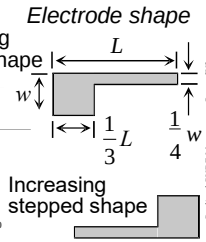


➢ Stepped shape

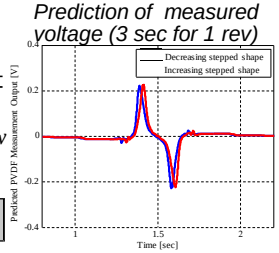
Prediction of generated voltage



Electrode shape



Prediction of measured voltage (3 sec for 1 rev)



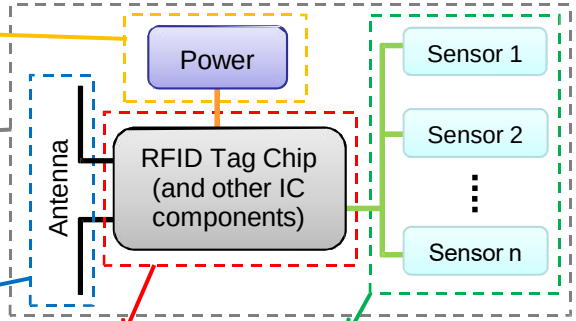
Flexible, Self-Powered, RFID Based Sensors

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



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

THE OHIO STATE UNIVERSITY

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

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

UAM Active Hinge with SMA Ribbons

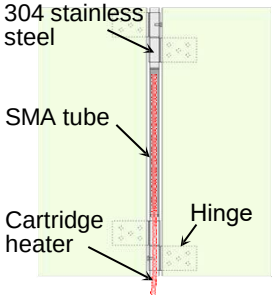
- UAM active hinge concept using SMA ribbons
  - SMAs embedded in Al matrix are trained in a 180 degree folded shape for shape memory effect by heating shape set temperature of around 500 ºC for 25 min and quenching in cold water

  - 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

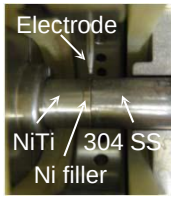
The panels are activated by ~23 A drawn from the battery. If the SMA wires are electrically isolated and connected in series, activation current will be reduced to less than 1 A.

Active Hinge with SMA Torque Tube

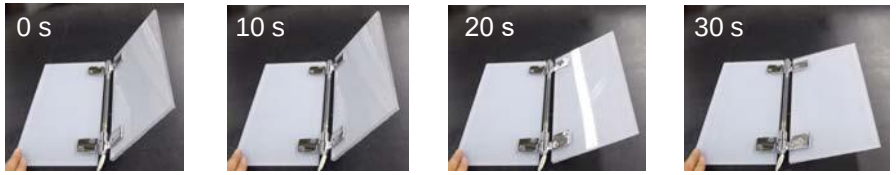
- Shape memory alloy torque tube hinge concept



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



Applied 222 in-lb torque
(Critical finish torque of TIG weld: 201 in-lb)



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)

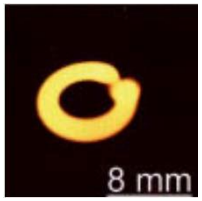
Project initiated by Toyota Technical Center

Project #46: Mechanoluminescent Paintable Light Sources for Automotive Applications

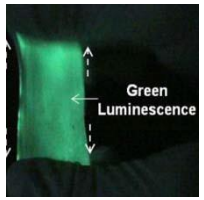
THE OHIO STATE UNIVERSITY

Motivation

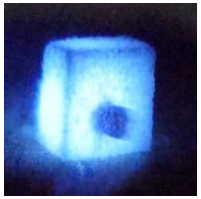
- Need for a paint-on light source that can be used for aesthetic purposes in automotive applications
- Paint-on light to be coated on outer body surface of automobiles
- Mechanoluminescence (ML) of inorganic phosphors prime candidate



Yellow light from ZnS:Mn phosphor
Appl. Phy. Lett. 74, 1236 (1999)

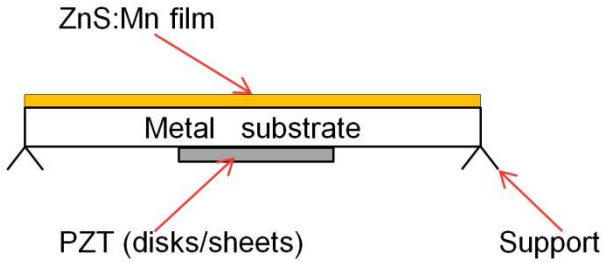


Green light from ZnS:Cu in PDMS
Appl. Phy. Lett. 102, 051110, (2013)



Blue light from a sugar cube on collision with bullet

Problem Formulation



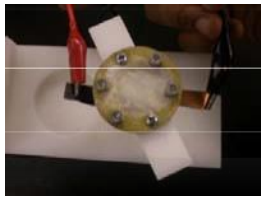
- ML - light emission induced by mechanical action
- ZnS:Mn film - ZnS:Mn particles in a matrix (epoxy binder)
- ZnS:Mn particles-micro and nano-sized particles
- Binder – Transparent, efficient in stress transfer, adhesive

Methods

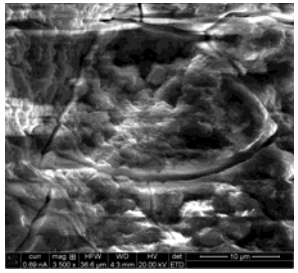
Wet chemical method – ZnS:Mn nanoparticles

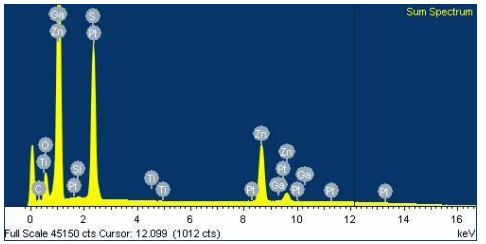
$Zn(C_2H_3O_2)_2 + Na_2S + PVP \rightarrow PVP\text{-}ZnS + NaC_2H_3O_2$

- 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

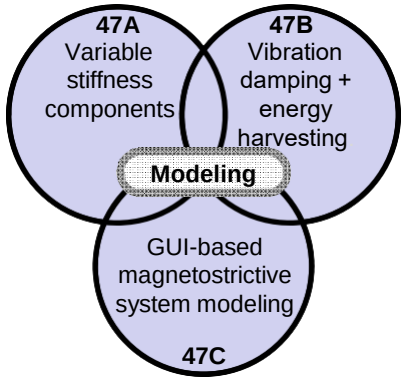
Project Leader: Vishnu Baba Sundaresan (sundaresan.19@osu.edu)

Project initiated by Honda R&D

Project #47: Multifunctional Magnetostrictive Systems – Experiments and Computer Simulation

Project Overview

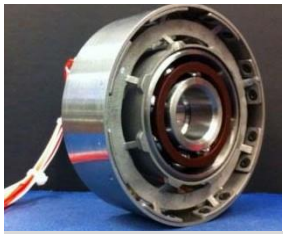
- Motivation: reduce driveline/gear vibration
- Objective: study magnetostrictive systems in relation to stiffness tuning, vibration damping, and energy harvesting



- 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


NASA's vibration ring

- Galfenol and Terfenol-D offer the potential for
  - Improved energy harvesting and damping
  - Robust and reliable stiffness tuning

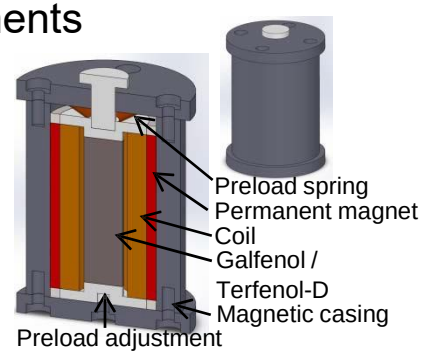
Plan

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:

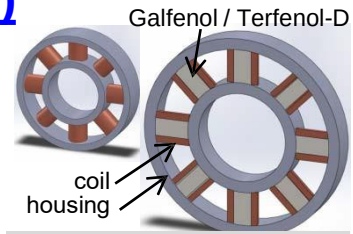
- Model 2D/3D electro-magneto-mechanical behavior of harvester/damper



Variable spring concept

Plan (cont.)

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



Vibration ring concept

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

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

Project initiated by NASA Glenn and Honda R&D

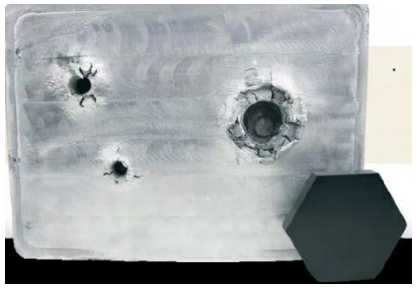
Project #48: Stress Field Development During Load Transfer in Functionally Graded Metal Matrix Composite Macro Interfaces

THE OHIO STATE UNIVERSITY

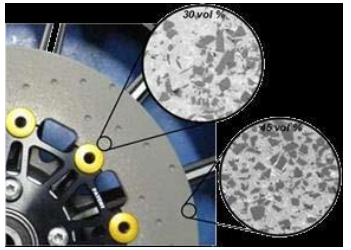
Technology Summary

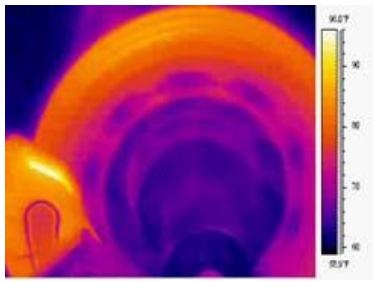
- Metal matrix composites (MMCs) consisting of matrix and reinforcing material
  - −Matrix: Al or Mg
  - −Reinforcement: Al_2O_3, carbon fiber, or SiC
- Functional grading can be manufactured using ceramic preforms and squeeze casting under high force and low velocity
- A need exists for understanding mechanical and thermal properties along the gradient

Ceramic preforms



Armor application





Brake rotor application

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

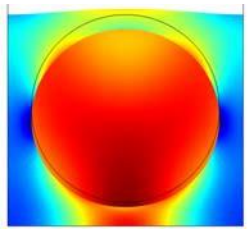
•Applications include brake rotors and armor

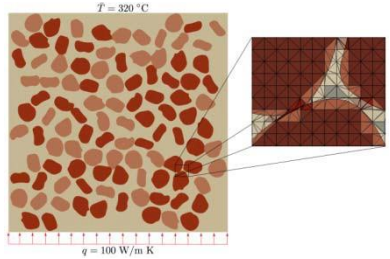
Approach

- 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





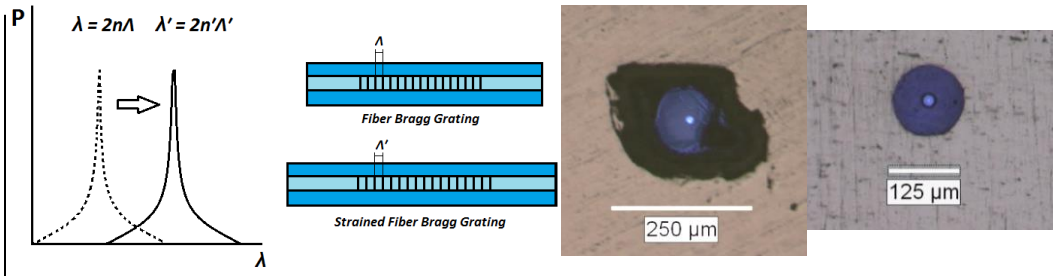
Project Leaders: Marcelo Dapino (dapino.1@osu.edu) and Soheil Soghrati (soghrati.1@osu.edu)
Project initiated by REL Inc.

Project #49: Embedded Fiber Optic Sensors for Structural Health Monitoring

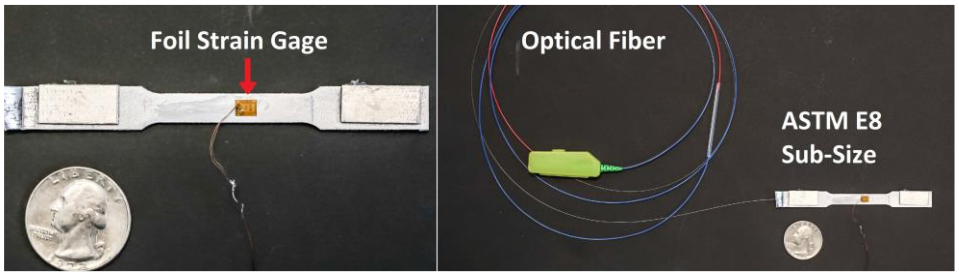
THE OHIO STATE UNIVERSITY

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



Strain Measurement **Embedded Fiber Optics**



Comparative Tensile Testing

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

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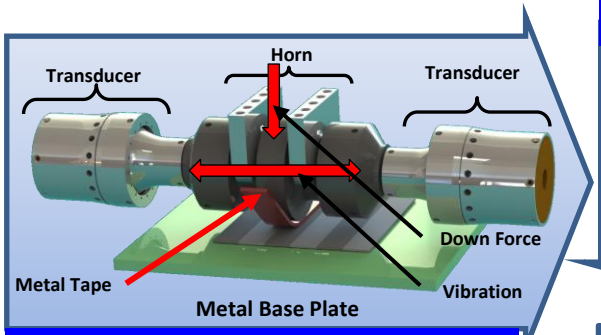
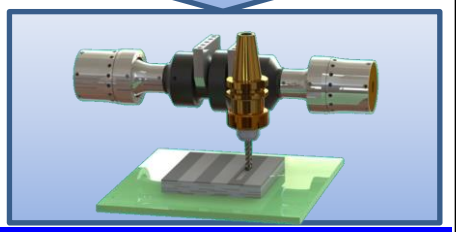
Ultrasonic Additive Manufacturing:



Ultrasonic welding system with rolling horn welds metal tape to base plate

Successive application of metal tape builds part



Periodic machining shapes part and maintains uniform welding surface

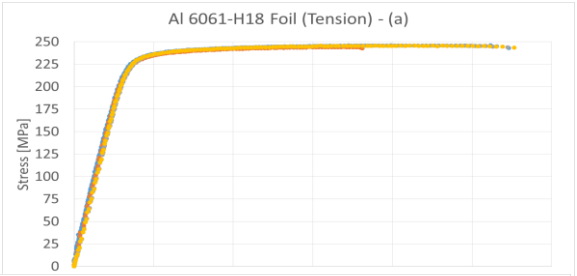
- 3D printing technology based on ultrasonic metal welding
- Low-temperature process
- Dissimilar metal parts and integrated structures

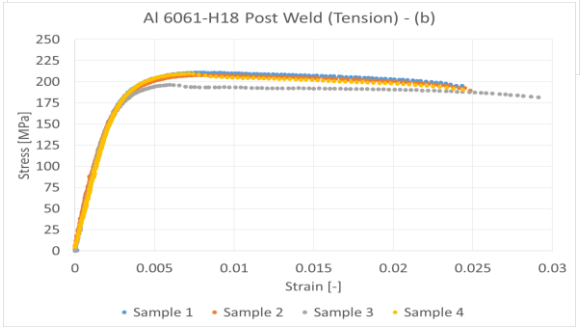
Purpose:

Enable lightweight vehicle structures via UAM

Research Objectives:

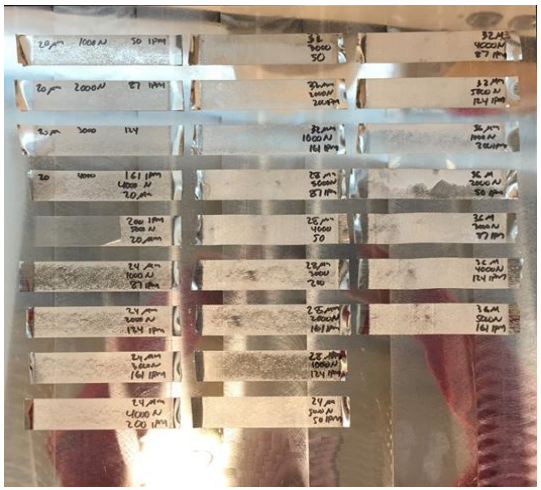
- Understand the cause for the knockoff in x-tensile (in-plane) strength resulting from the UAM process
- Develop weld parameters that can reduce or eliminate the knockoff

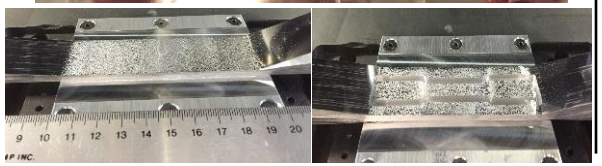




Methodology:

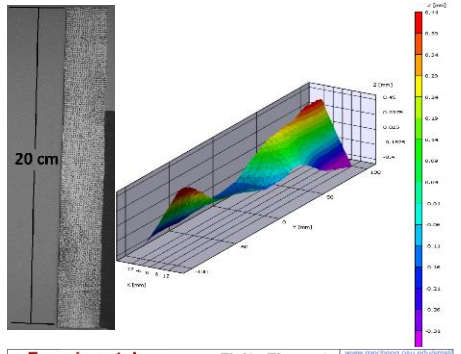
- Investigate process-property relationships through Design of Experiments study
- Prior pilot study focused on feasibility of welds
- DOE study focused on x-tensile testing
- FEA models developed to guide the experiments and assists with data analysis

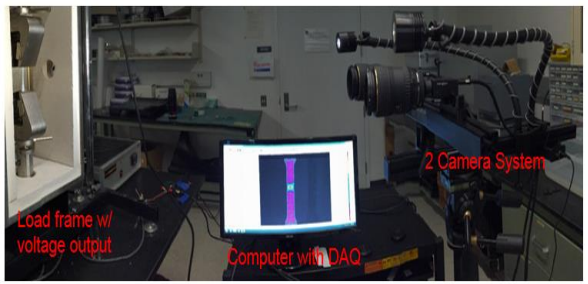




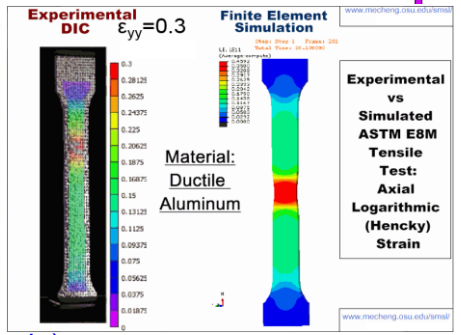
DIC Testing and Modeling:

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





DIC system set up for tensile test.



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

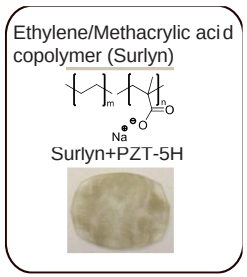
Project Initiated by Honda R&D and Battelle Memorial Institute

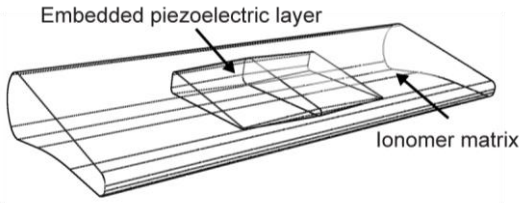
Project #52: Multifunctional Structural Polymer Composites for Vehicle Electrification

THE OHIO STATE UNIVERSITY

Motivation

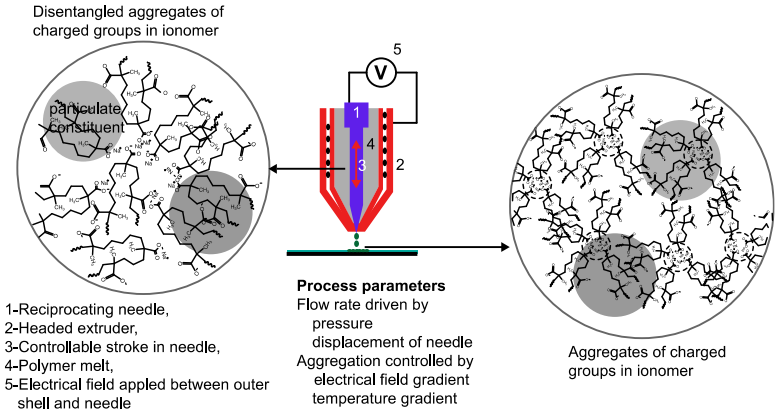
- Thermoelectric processing of polymer composites has been demonstrated by Sundaresan and coworkers as a way to 3D print structural composites
- Develop matrix libraries and particulate additives for thermoelectric processing of piezoelectric polymer composites
- Develop nozzle designs and extrusion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

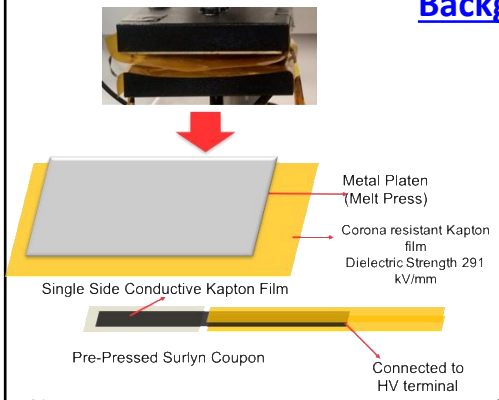


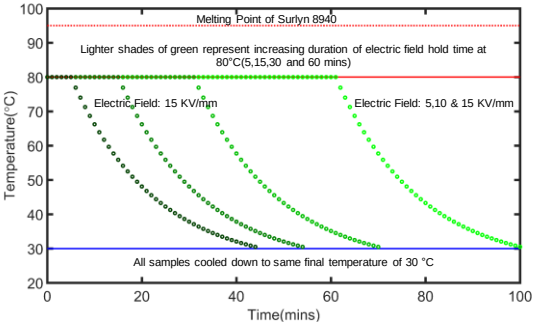
Methods

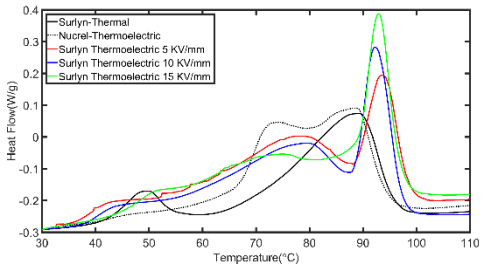
- Multiphysics modeling of thermoelectric extrusion of thermoplastic ionomers and piezoelectric work will be performed
- The model will be used to identify the influence of the following process parameters
  - Extrusion speed
  - Process temperature
  - Soak time
  - Electrical field

  on the following parameters
  - Build strength
  - Layer thickness
  - d_{33} coefficient
  - Interfacial adhesion (piezoelectric and polymer phase)

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 Leader: Vishnu Baba Sundaresan (sundaresan.19@osu.edu)
Project initiated by Parker Hannifin

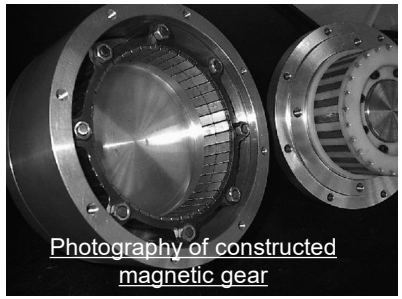
www.SmartVehicleCenter.org

Project #54: Magnetic Additively-Manufactured Structural Hybrid (MASH)

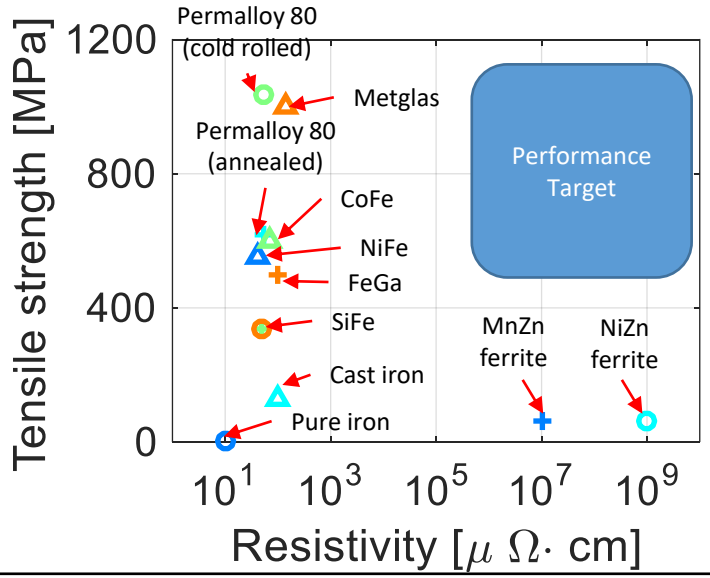
THE OHIO STATE UNIVERSITY

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


Photography of constructed magnetic gear

New magnetic materials are needed…



Features of new magnetic composites:

- Lightweight
- Strong magnetic coupling
- Low eddy current loss
- Robust and reliable
- Easy to manufacture
- Self-contained

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

Material candidates I

Characterize stress-dependent magnetic properties

Material candidates II

Fabricate MASH

Material candidates III

Evaluate magnetic and mechanical properties of MASH

Material candidates IV

Part C: Development of Magnetic Gear

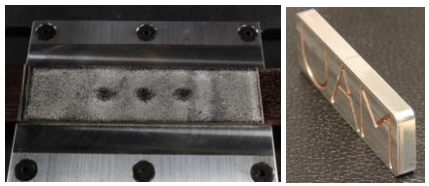
Magnetic gear demonstrator

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

9 kW SonicLayer 4000 Ultrasonic additive manufacturing (UAM) machine


3D printed structure with embedded magnetic features and circuits

Project Leaders: Marcelo Dapino (dapino.1@osu.edu) and Zhangxian Deng (deng.92@osu.edu)

Project Initiated by NASA Glenn

Project #55: Multiscale Finite Element Simulation of the Mechanical Behavior of Fiberglass Insulation Packs

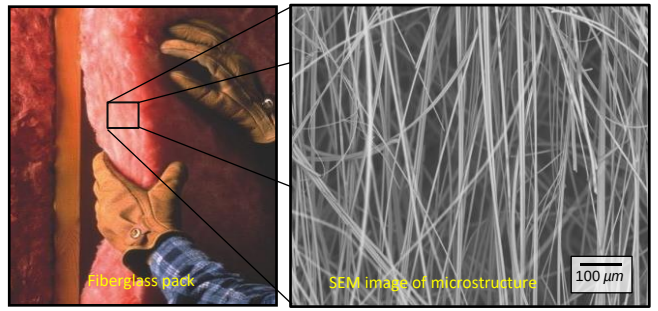
THE OHIO STATE UNIVERSITY

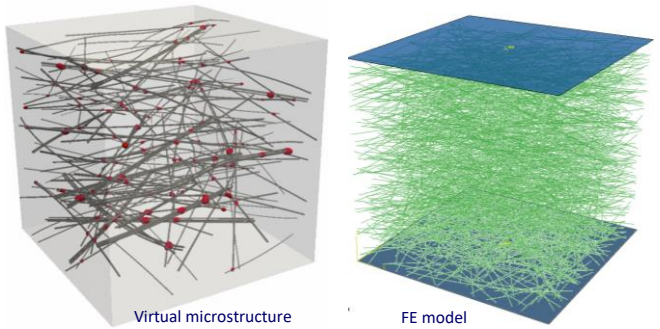
Background and Objectives

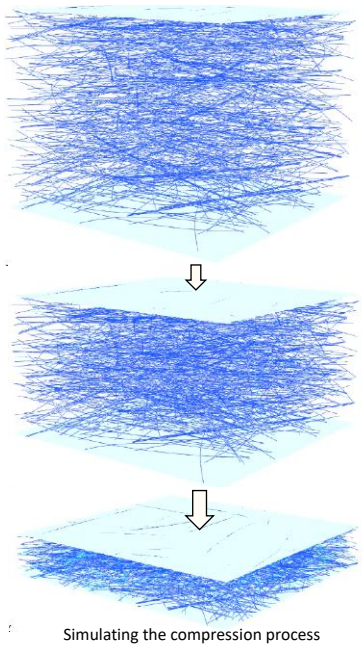
Objective: to predict the mechanical behavior of fiberglass insulation packs fabricated by Owens Corning subject to compressive loads.

Fiberglass packs: composed of nonwoven entangled glass fibers and a polymeric binder (total volume fraction: less then 2%)

Due to economic considerations, fiberglass packs are compressed to 10% of their original thickness for efficient shipping and handling







Approach

Develop a novel descriptor-based reconstruction algorithm to synthesize realistic 3D virtual models of the fiberglass pack.

Create reduced-order finite element (FE) models of fibers and the binder phase to simulate the deformation response

Calibrate with high fidelity FE results and study the impact of boundary conditions, size effects, and the binder on the mechanical behavior

Applications and Benefits

Novel algorithm for the automated reconstruction of the microstructure and converting that into an appropriate FE model

- Realistic virtual microstructure informed by imaging data

New reduced-order model for simulating the mechanical behavior taking into account all sources of physical and geometrical nonlinearity

- Computationally efficient micromechanical model
- Performing simulations with millions degrees of freedoms

www.SmartVehicleCenter.org

Project Leader: Soheil Soghrati (OSU)

Project Mentor: Andy Davis (Owens Corning)

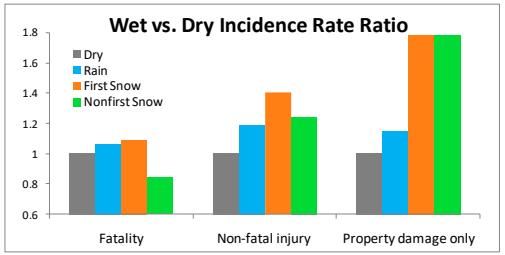
Project #56: Dynamic Friction Characterization of Icy Road Surfaces for Conventional & Automated Vehicles

THE OHIO STATE UNIVERSITY

Industry Need, Context, and Relevance

- Weather-related conditions associated with annual*
  - $42 Billion
  - 7000 fatalities & 800,000 injuries
- Improved traction technology may reduce these statistics
- Adaptive/predictive algorithms & reliable sensing needed for emerging autonomous tech

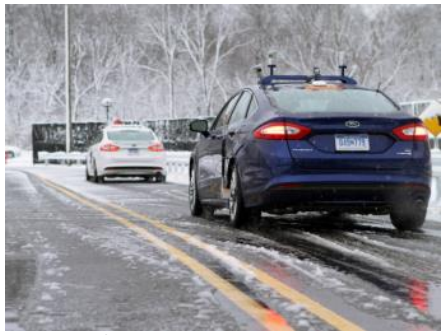
http://www.michiganautolaw.com



- Bridge laboratory and real-world experimental work
- Best practices and test strategies needed
- Broad applications to OEM, suppliers, regulatory agencies, etc.

* D. Eisenberg, K.E. Warner, Effects of snowfalls on motor vehicle collisions, injuries, and fatalities, *American Journal of Public Health* 95(1) (2005) 120-124.

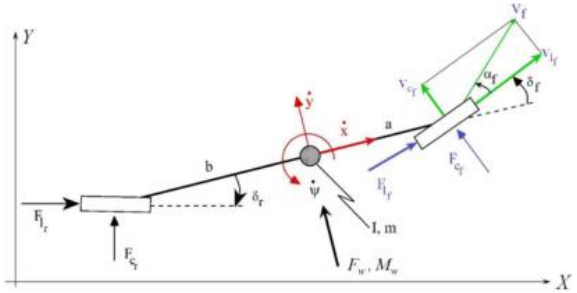
Broader Impacts – Automated Vehicles



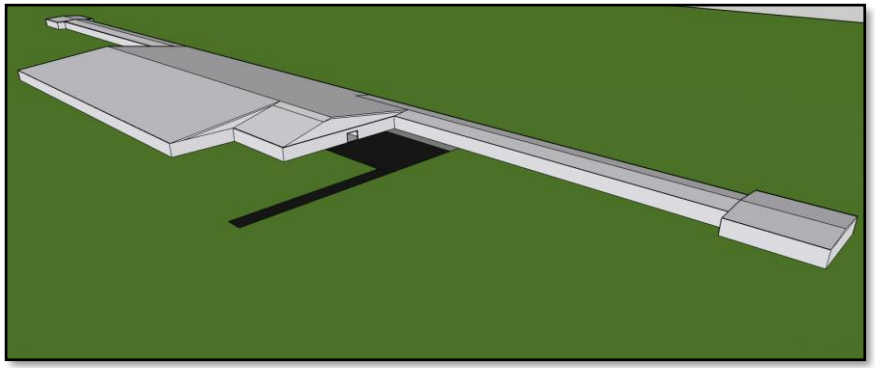
https://media.ford.com

- Emerging autonomous vehicle technology would require more reliable friction models.
- Adaptive or predictive steering algorithms rely on empirical friction models to ensure safe maneuvering
- Extreme conditions may surpass controller's ability to maintain on-road safety
- General lack of literature on autonomous vehicle performance in extreme winter conditions

P. Falcone, et al., Predictive active steering control for autonomous vehicle systems, *IEEE Transactions on Control Systems Technology* 15(3) (2007) 566-580.



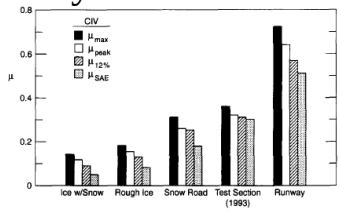
Selected Experimental Approaches



- Planned Indoor Winter Conditions Facility (IWCF)
- Controlled conditions allowing indoor simulated winter testing
- Laboratory, scaled, and full-scale experiments planned

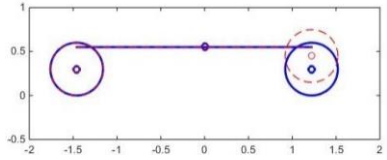
Modeling Approach

Dynamic friction

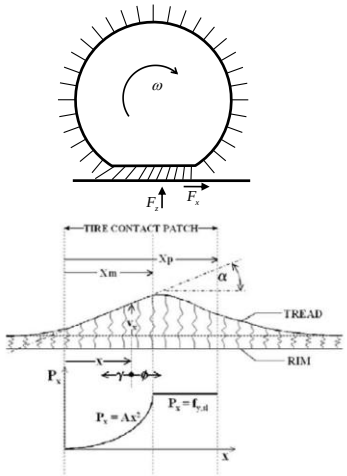


Shoop S, Young B, Alger R, Davis J, Effect of test method on winter traction measurements. *Journal of Terramechanics* 31.3 (1994) 153-161.

Vehicle Dynamics



Tires



Lacombe, James. "Tire model for simulations of vehicle motion on high and low friction road surfaces." *Proceedings of the 32nd conference on winter simulation*. Society for Computer Simulation International, 2000.

www.SmartVehicleCenter.org

Project Leader: R. Singh, L. Fredette (OSU) **Project Mentor: A. Mathers, R. Burton (TRC)**

Project #57: Flexible Piezoelectric Sensors for Vehicle Applications

THE OHIO STATE UNIVERSITY

Problem Statement

The goals of the project are:

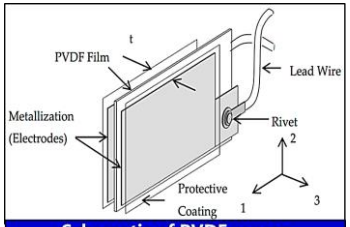
- Measurement of static and dynamic aerodynamic pressure in a representative small-scale vehicle structure
- Measurement of internal pressure in an inflatable structure
- Development of ideas to use flexible piezoelectric materials as advanced vehicle sensors or actuators

Background

- There is a growing interest to track real time air pressure in order to assess and control the aerodynamic performance of vehicles
- Conventional pressure transducers, besides their high cost, typically cannot be distributed. Due to their fixturing for flush mounting, they produce significant distortion of pressure fluctuations in the dynamic range.

Features of Flexible Piezoelectric Materials

- Flexible piezoelectric sensors are lightweight, non-invasive, and inexpensive; hence they are suitable for measurement of quasi-static and dynamic pressure measurements on the order of several kHz.
- A piezoelectric material of primary interest is polyvinylidene fluoride (PVDF), which is 10x more sensitive to stress inputs and 40x more compliant than conventional pressure and PZT transducers
- The primary focus will be on expanding the frequency range of pressure measurement into static regimes



Schematic of PVDF sensor
(source: www.measspec.com)

(a) Standard wind tunnel test vs (b) PVDF films on a scaled aircraft model

Significance

Research Gaps

- Direct measurement of static signals
- Development of compensators to mitigate environmental effects, such as temperature and electromagnetic interference
- Understanding of mechanical and sensing performance in harsh environments

Opportunities

- Design concepts like electrode patterning to tailor sensitivity and minimize signal processing requirements
- Integration into micro-systems and wireless technologies
- Investigation of new fabrication processes like 3D printing, film forming and electrospinning

Research Plan

Task A: Literature Survey

- Survey the literature on smart sensors for pressure measurement, PVDF and related technologies. Survey and compare different methods to measure air pressure during wind tunnel testing.
- Address key research questions in terms of ability of PVDF to measure static pressure and its sensitivity to environmental effects.

Task B: Sensor Modeling and Design

- Characterize PVDF, effect of shape, material, thickness etc. Develop multiphysics models of PVDF sensing systems to guide and supplement the characterization effort.
- Investigate new manufacturing and processing techniques. Characterize and analyze process-property relationships.

Task C: Experimental Validation

- Benchmark PVDF for pressure measurement against a commercial pressure sensor
- Develop and demonstrate a method to measure static pressure. Demonstrate use in a small scale wind tunnel setup to measure static pressure.
- Demonstrate internal pressure measurement in an inflatable structure

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

Project Initiated by Toyota Technical Center

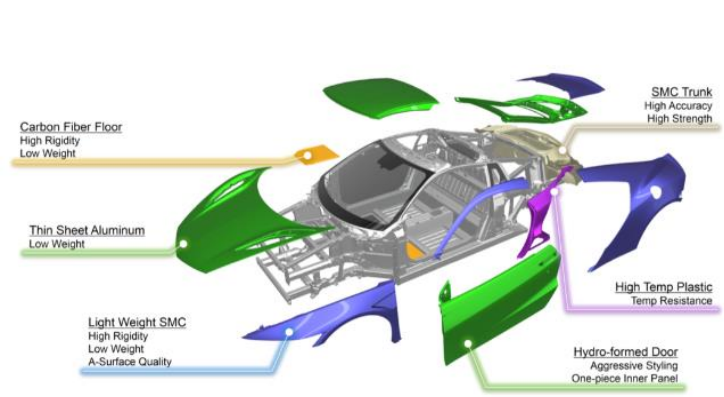
www.SmartVehicleCenter.org

Project #58: Architecture for Mechanoluminescent Sensors and Sensing Systems

THE OHIO STATE UNIVERSITY

Industry Need, Context and Relevance

Address challenges in health monitoring of multi-material components made of carbon fiber reinforced plastics (CFRP) in automotive and structural components

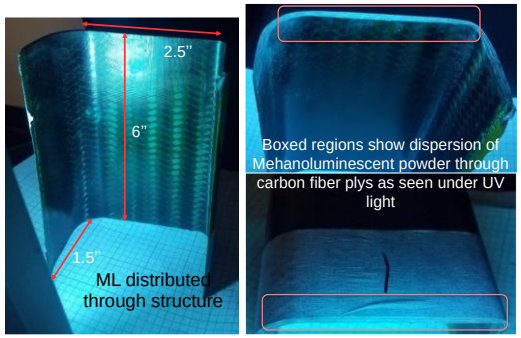


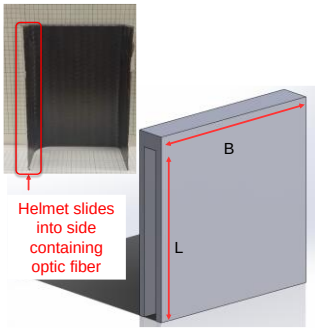
http://news.honda.com/newsandviews/article.aspx?id=8900-en

Project Goals and Objectives

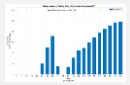
Experimental and in-field detection technique to report

(a) distribution of internal stress in the matrix and around the fibers,
(b) detecting the onset of damage, crack propagation
(c) extent of failure that will lead to abrupt structural damage, and
(d) machine learning to detect percentage life left in structure



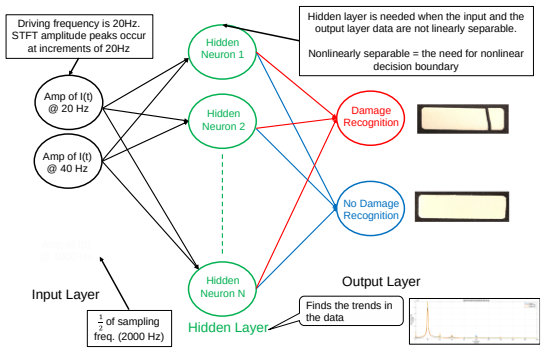


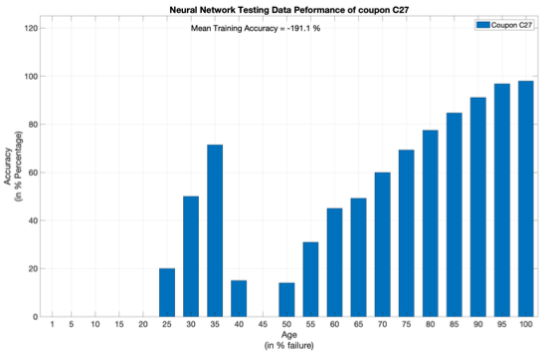
Approach (Research Methods)

Task No	Task Name	Status	Comment	Thumbnail
1	Fabrication of Mechanoluminescent CFRP	Complete	Prepared at NASA	ML-CFRP
2	Sample preparation for crush testing	Complete	Machined at OSU	Machining
3	Instrumentation for Crush testing	Partially complete	Designed and prepared at OSU	Helmet with sensors
4	***Crush testing at OSU (Dr. Seidt's lab)***	***Not started***	***Will be coordinated by Dr. Hery, Misganaw***	
5	Machine learning algorithm for SHM	Complete	B.E. (Hons) thesis in May 2020 (Ahmed Mohamed)	Algorithm for SHM 

Results

Fabrication of test samples, instrumentation for load characterization, machine learning for health determination





Project Leader: T. Hery, V. Sundaresan (OSU) **Project Mentor: Duane Detwiler et al (HRA)**

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Project #60: Distributed Programmable Actuation Platforms

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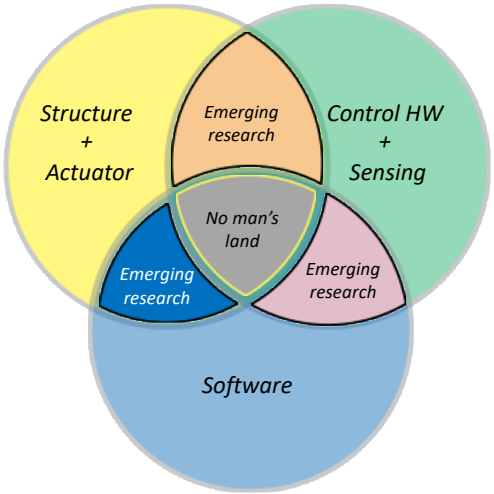


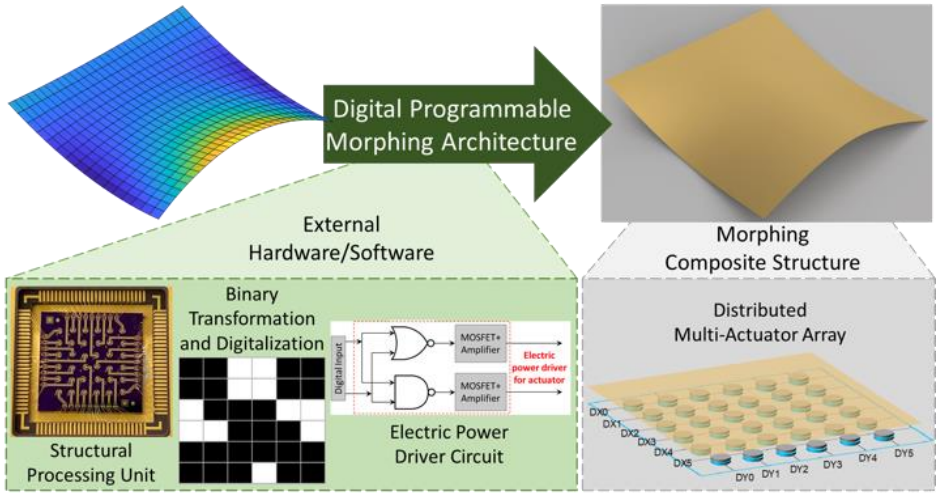
Industry Need, Context and Relevance

Morphing structures require integration of structure, actuator, sensing and computation into one entity. Some of the key limitation of contemporary approaches is the modular nature of these components.

This research program will focus on the abstraction of various subsystems at material level and lead to the development of a distributed programmable actuation platform for automotive and aerospace applications.

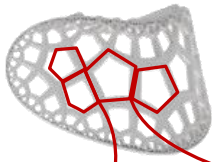
Project Goals and Objectives

Create materials library for (i) structural logic gate-based distributed actuator array for morphing, (ii) demonstrate morphing using digital inputs.

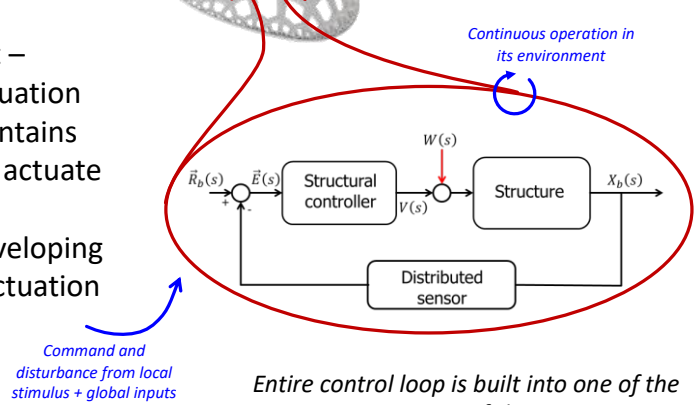


Approach (Research Methods)

This research has led to the development of a spatially discretized and distributed actuation platform.
Each discretized unit – referred to as an actuation element – AXEL – contains sense, compute and actuate functions.
We are currently developing digital logic-based actuation platform



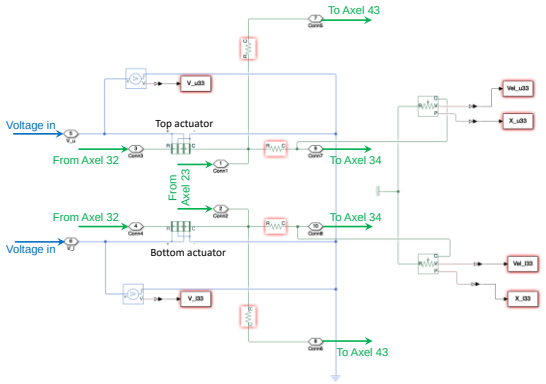
and expand this to neuromorphic structures in years 2, 3



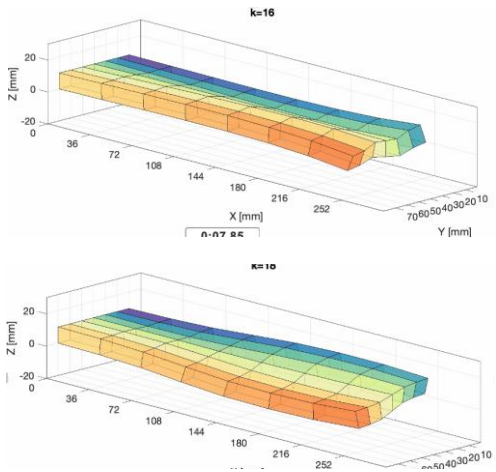
Entire control loop is built into one of the repeating units of the structure

Results

Structural logic circuit leading to device driver (akin to GPUs)



Dynamic simulation of discretized actuation platforms



www.SmartVehicleCenter.org

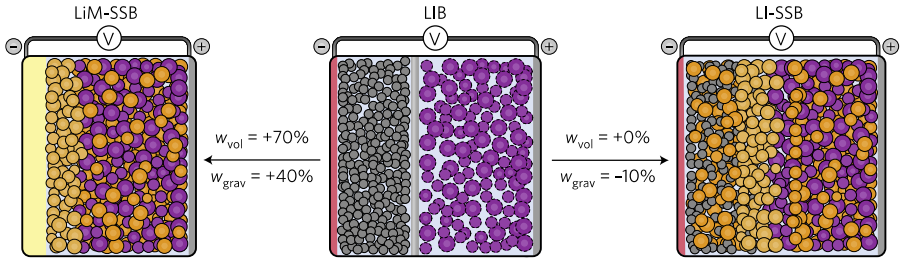
Project Leader: T. Hery, V. Sundaresan (OSU)

Project Mentor: Umesh Gandhi, Shailesh Joshi (Toyota)

Project #61: Dynamic Self-reforming Lithium/Solid Electrolyte Interface for Solid-state Battery

THE OHIO STATE UNIVERSITY

Industry Need, Context and Relevance

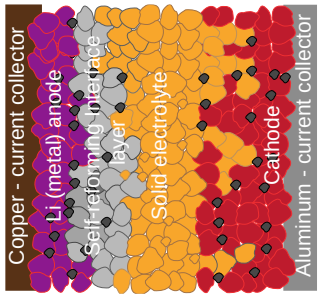


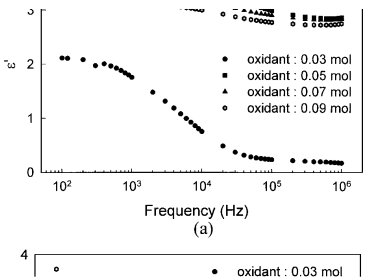
Nature Energy (1), 16141 (2016)

This research program will focus on the abstraction of various subsystems at material level and lead to the development of a distributed programmable actuation platform for automotive and aerospace applications.

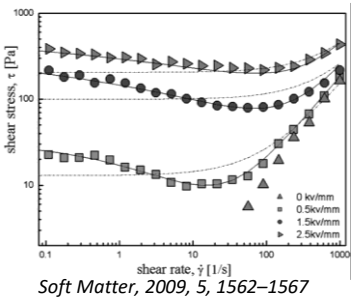
Project Goals and Objectives

Architecture of self-reforming interface in LIM-SSB





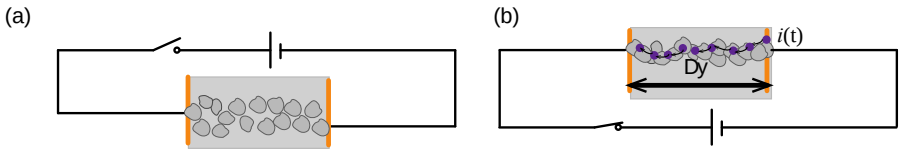
J. Mat. Sci., 37 (2002) 5051– 5055



Soft Matter, 2009, 5, 1562–1567

Prepare a self-reforming anode/solid electrolyte interface layer by (a) electropolymerization and transferred to SE, (b) chemical polymerization and cast with SE and investigate ionic conductivity at various C-rates.

Approach (Research Methods)



Current flow = 0

PPy or PANI particles disperse and have poor continuity

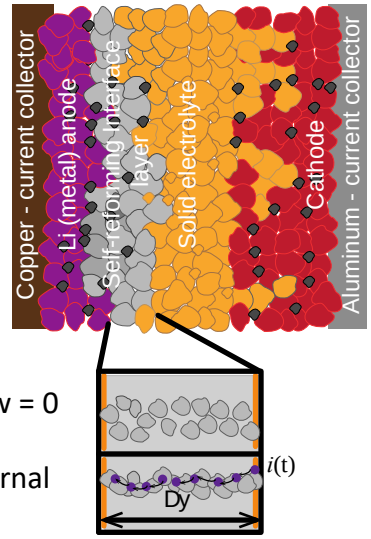
Current flows when external circuit is closed

PPy or PANI particles align along the applied field and exhibit higher conductivity

Long-term stability requires an interface that can form, reform and dynamically align along the interface.
Conducting polymers, especially, PPy(DBS), PANI, Melanin, etc., exhibit electrorheological properties.

Preliminary Results

- Multiphysics model for solid-state interface at anode/solid electrolyte being formulated in COMSOL®
- Effect of viscous binders and filler compounds on ionic conductivity at the interface will be investigated
- Impact on C-rate on ionic conductivity will also be studied and compared to experimental data



Current flow = 0

Current flows when external circuit is closed

www.SmartVehicleCenter.org

Project Leader: T. Hery, V. Sundaresan (OSU) **Project Mentor: Chris Brooks(HRA)**

Project #62: Nanostructured Materials for High-Energy Density Batteries

THE OHIO STATE UNIVERSITY

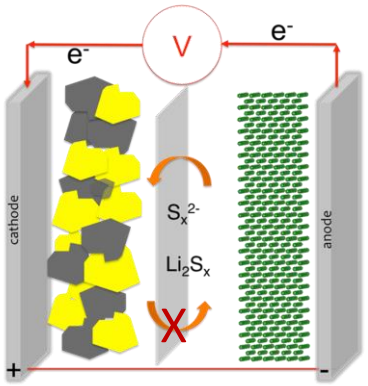
Industry Need, Context, Relevance

- Li-S batteries offer high capacity of 1672 mAh/g vs. 272 mAh/g for cobalt-oxide based cathodes.
- Sulfur (S) composite cathodes offer a sustainable materials solution ($150/ton for S) as compared to cobalt oxide-based intercalation cathodes ($10,000/ton).

Project Objectives

Overall goal: Develop synthesis methods for a library of metal nanostructures (spheres, wires) as structural additives to sulfur composite electrodes.

Prevent deleterious polysulfide dissolution



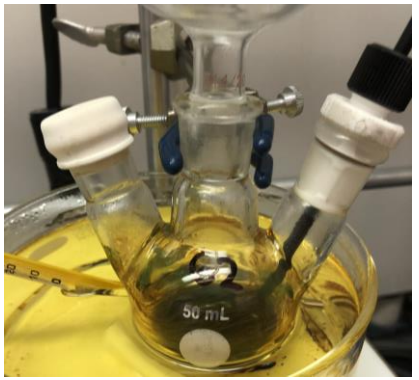
Research Plan

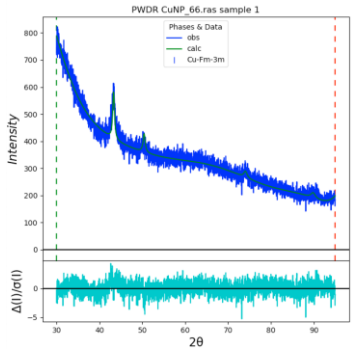
Task 1: Synthesis of copper nanowires for suppression of lithium polysulfide shuttling.

Task 2: Chemical and Structural characterization of metal nanowires for a synthetic feedback loop.

Task 3: Electrochemical testing of lithium-sulfur cells.

Preliminary Results/Applications





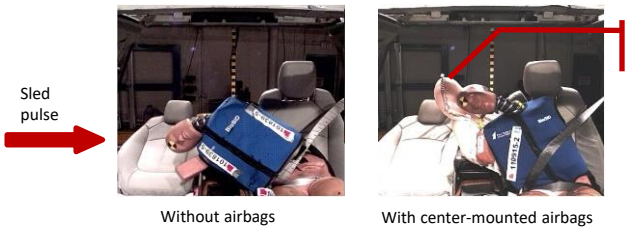
Achieved phase pure nanoparticles with diameter = 7.5 nm – 15 nm

Project #63: Smart Restraint System

Motivation

Current needs: Conventional three-point seatbelts fail in certain types of side impact cases in current vehicle designs

Center-mounted airbags are ineffective because they float when deployed



Without airbags

With center-mounted airbags

https://phys.org/news/2011-10-motors-center-mounted-airbags-video.html

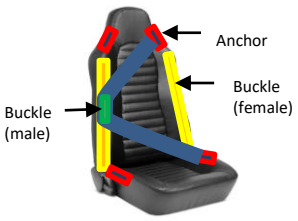
Future needs in autonomous vehicles

Reconfigurable or "smart" restraints are required to address challenging safety conditions arising from the occupant's variable seating position and orientation

www.mercedes-benz.com/en/innovation/research-vehicle-f-015-luxury-in-motion/

Concepts

Reconfigurable seatbelts: Develop versatile buckle-free restraining mechanisms for reconfigurable seats

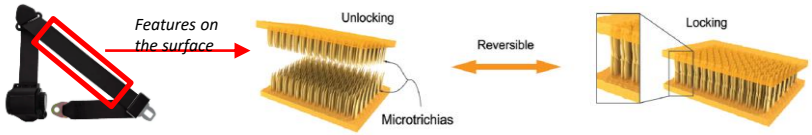


Variable anchor locations

Variable mounting heights

Belt-belt and belt-seat mounts

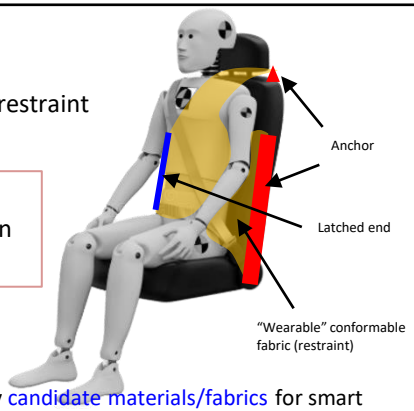
Reversible fastening mechanisms: Develop smart embedded latches/buckles that have extremely high shear strength but can be peeled off with a nominal normal force



Methodology

Novel restraining mechanisms: Develop alternative restraint designs outside the belts-and-buckle paradigm

> *Example*: "wearable" restraint that forms part of the seat and can be worn like a garment by the occupant



Computational study

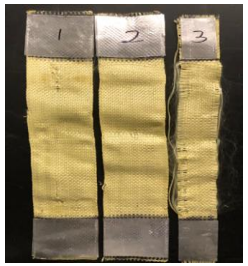
- Finite-element (FE) studies and experiments to identify candidate materials/fabrics for smart restraints (e.g., woven hybrid fabrics such as Kevlar + shape memory alloy)
- Feature-based analytical modeling: Calculation of homogenized material properties of a latch array (e.g., an array of Velcro hooks)
- FE study to quantify and compare the performance of smart restraints in various mounting configurations (e.g., reduced-order system model, full-body crash simulations)

Current Work

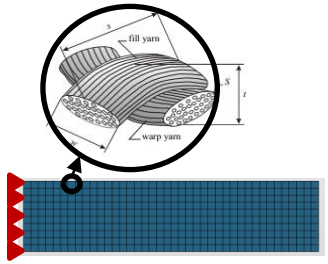
Tensile tests & simulation of a candidate fabric: **Kevlar 49**

ISO 13934-1 Textile Tensile
Rate of elongation: 20 mm/min
Gauge length: 200mm
Width: 50mm, 25mm
Textured aluminum end tab is used to prevent slipping

Tests

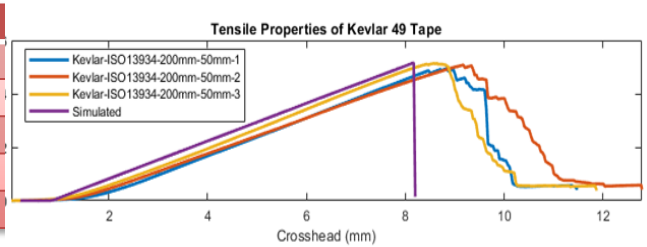


Simulation



Properties	Value
Weight	5 oz./yd2
Fiber	Kevlar 49,1140 Denier
Thickness	0.010 inches
Weave	plain
Count	17 x 17

Comparison



Project Leader: Prof. Marcelo Dapino, Dr. Leon Headings, Prof. Sheng Dong (OSU)
Project Mentor: Ryan Hahnlen, Skye Malcolm (Honda R&D Americas), Bengt Pipkorn (Autoliv)

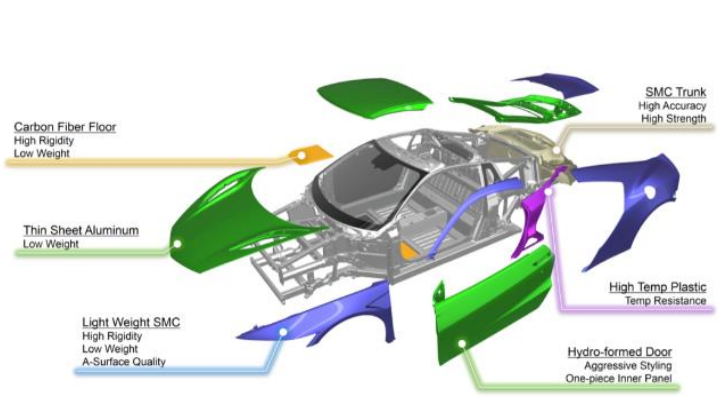
www.SmartVehicleCenter.org

Project #58: Architecture for Mechanoluminescent Sensors and Sensing Systems

THE OHIO STATE UNIVERSITY

Industry Need, Context and Relevance

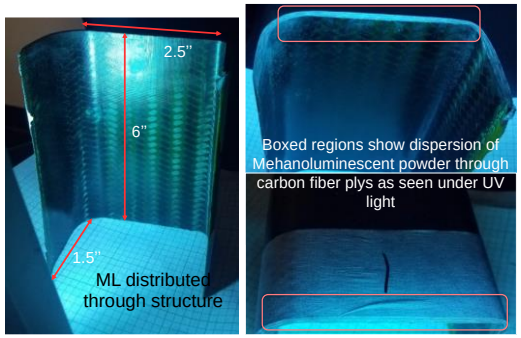
Address challenges in health monitoring of multi-material components made of carbon fiber reinforced plastics (CFRP) in automotive and structural components

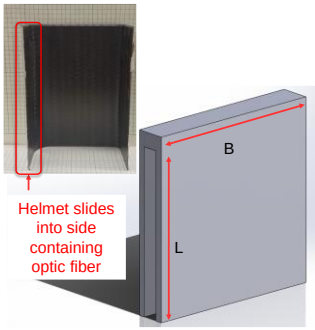


http://news.honda.com/newsandviews/article.aspx?id=8900-en

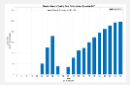
Project Goals and Objectives

Experimental and in-field detection technique to report
(a) distribution of internal stress in the matrix and around the fibers,
(b) detecting the onset of damage, crack propagation
(c) extent of failure that will lead to abrupt structural damage, and
(d) machine learning to detect percentage life left in structure



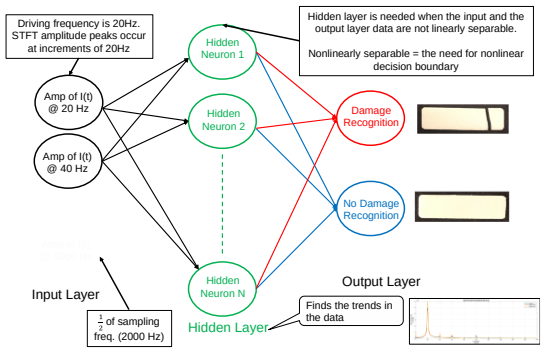


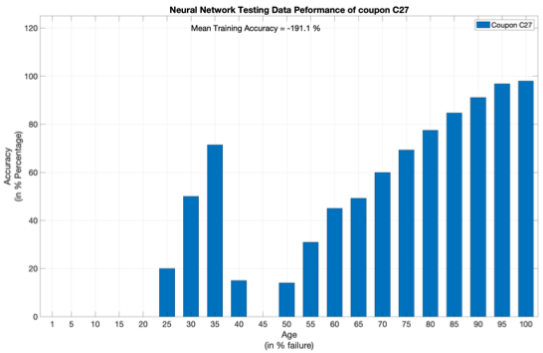
Approach (Research Methods)

Task No	Task Name	Status	Comment	Thumbnail
1	Fabrication of Mechanoluminescent CFRP	Complete	Prepared at NASA	ML-CFRP
2	Sample preparation for crush testing	Complete	Machined at OSU	Machining
3	Instrumentation for Crush testing	Partially complete	Designed and prepared at OSU	Helmet with sensors
4	***Crush testing at OSU (Dr. Seidt's lab)***	***Not started***	***Will be coordinated by Dr. Hery, Misganaw***	
5	Machine learning algorithm for SHM	Complete	B.E. (Hons) thesis in May 2020 (Ahmed Mohamed)	Algorithm for SHM 

Results

Fabrication of test samples, instrumentation for load characterization, machine learning for health determination





Project Leader: T. Hery, V. Sundaresan (OSU) **Project Mentor: Duane Detwiler et al (HRA)**

www.SmartVehicleCenter.org

Project #60: Distributed Programmable Actuation Platforms

THE OHIO STATE UNIVERSITY

Motivation

- Demonstrating distributed programmable structural logic for generating dynamic shape changes, leading towards structural computing
- Versatile and scalable distributed actuation realized using COTS materials and implementation of digital logic using electronic circuit

Summary

- Simscape model of 7 × 7 array of spatially distributed actuators built and simulated different input configs
- Fabrication and characterization of a 2×2 distributed programmable actuation platform prototype
- Prospective design concepts already underway for a larger prototype and associated drive electronics

Objectives

- Develop the digital logic and the electronic circuit to support that in simulation environment
- Building a fully characterized mechanical model of the programmable structure along with the digital logic in Simulink
- Selection of fabrication materials for the structure and the actuators
- Fabrication and characterization of the distributed programmable actuation platform

Next Steps

- Design a single bimorph followed by a 2 × 2 prototype using the new design process
- Fabrication of the larger prototype – 10 × 10 array planned
- Characterization of the larger prototype

www.SmartVehicleCenter.org

Project Leader: Navni Verma, Vishnu Baba Sundaresan (OSU) Project Mentor: Dr. Shailesh Joshi (Toyota Motor Engineering & Manufacturing, North America)

Project 61: Dynamic Self-Reforming Interfaces for Solid-State Batteries

THE OHIO STATE UNIVERSITY

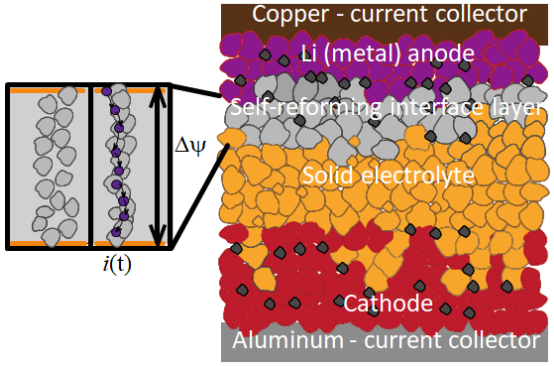
Industry Need, Context, and Relevance

- Realization of a rechargeable lithium metal battery needed to meet increasing demand for electric vehicles.
- Lithium metal batteries with high energy density allow for decreased battery pack size and weight in electric vehicles.

Project Objectives

Overall goal: Enhancement of lithium metal and solid electrolyte interface for long-term stability and high-energy density battery.

Self-reforming interface from conducting polymers that will continuously reform and maintain interface.



Research Plan

Task 1: Electrochemical testing of baseline lithium metal solid-state half-cells.
Task 2: Fabrication and characterization of conducting polymer or conducting polymer composite for use as self-reforming interface.
Task 3: Electrochemical testing half-cells and full cells with self-reforming interface.

Preliminary Results/Applications

- Baseline lithium metal solid-state half-cells have demonstrated early failure under low assembly and operating stack pressure.
- Free-standing conducting polymer film fabricated from polypyrrole doped with dodecylbenzenesulfonate and characterization ongoing.

Project #62: Nanostructured Materials for High-Energy Density Batteries

THE OHIO STATE UNIVERSITY

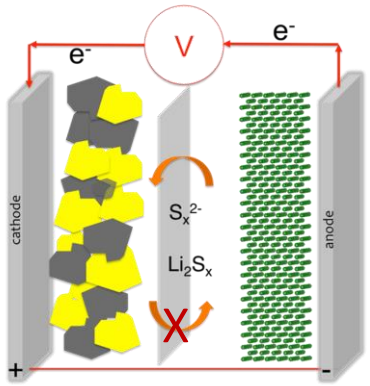
Industry Need, Context, Relevance

- Li-S batteries offer high capacity of 1672 mAh/g vs. 272 mAh/g for cobalt-oxide based cathodes.
- Sulfur (S) composite cathodes offer a sustainable materials solution ($150/ton for S) as compared to cobalt oxide-based intercalation cathodes ($10,000/ton).

Project Objectives

Overall goal: Develop synthesis methods for a library of metal nanostructures (spheres, wires) as structural additives to sulfur composite electrodes.

Prevent deleterious polysulfide dissolution

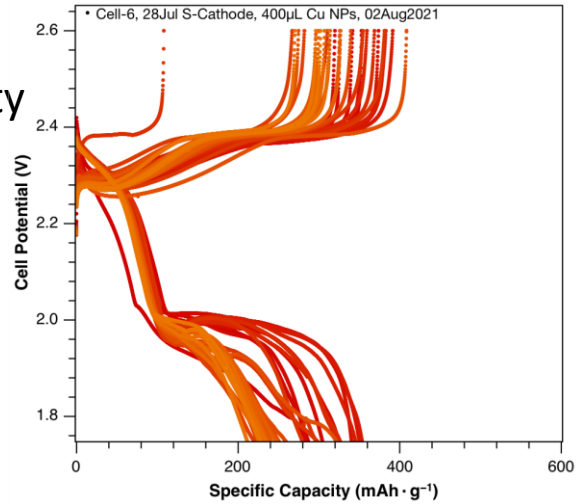


Research Plan

Task 1: Synthesis of copper nanowires for suppression of lithium polysulfide shuttling.
Task 2: Chemical and Structural characterization of metal nanowires for a synthetic feedback loop.
Task 3: Electrochemical testing of lithium-sulfur cells.

Results/Applications

Galvanosatic cycling captures lower capacity fade with addition of Cu additives.



Project Leader: Vicky Doan-Nguyen (OSU)

Project Mentor: Christopher Brooks (Honda)

Project #63: Smart Restraint System

Motivation

Current needs: Conventional three-point seatbelts fail in certain types of side impact cases in current vehicle designs

Center-mounted airbags are ineffective because they float when deployed

Without airbags

With center-mounted airbags

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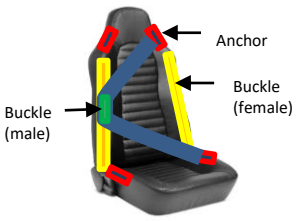
Future needs in autonomous vehicles

Reconfigurable or "smart" restraints are required to address challenging safety conditions arising from the occupant's variable seating position and orientation

www.mercedes-benz.com/en/innovation/research-vehicle-f-015-luxury-in-motion/

Concepts

Reconfigurable seatbelts: Develop versatile buckle-free restraining mechanisms for reconfigurable seats

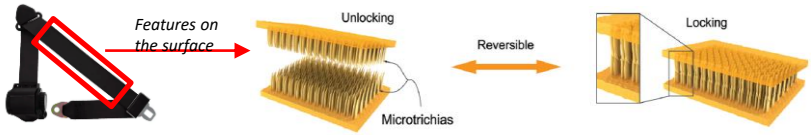


Variable anchor locations

Variable mounting heights

Belt-belt and belt-seat mounts

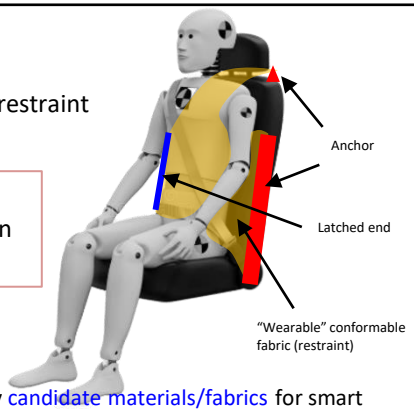
Reversible fastening mechanisms: Develop smart embedded latches/buckles that have extremely high shear strength but can be peeled off with a nominal normal force



Methodology

Novel restraining mechanisms: Develop alternative restraint designs outside the belts-and-buckle paradigm

> *Example*: "wearable" restraint that forms part of the seat and can be worn like a garment by the occupant



Computational study

- Finite-element (FE) studies and experiments to identify candidate materials/fabrics for smart restraints (e.g., woven hybrid fabrics such as Kevlar + shape memory alloy)
- Feature-based analytical modeling: Calculation of homogenized material properties of a latch array (e.g., an array of Velcro hooks)
- FE study to quantify and compare the performance of smart restraints in various mounting configurations (e.g., reduced-order system model, full-body crash simulations)

Current Work

Tensile tests & simulation of a candidate fabric: **Kevlar 49**

ISO 13934-1 Textile Tensile
Rate of elongation: 20 mm/min
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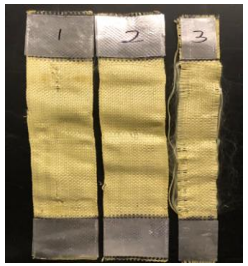
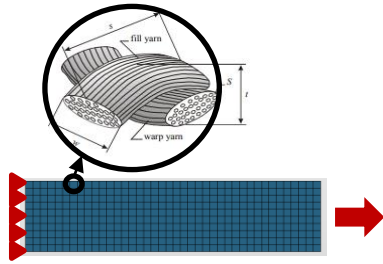


Simulation



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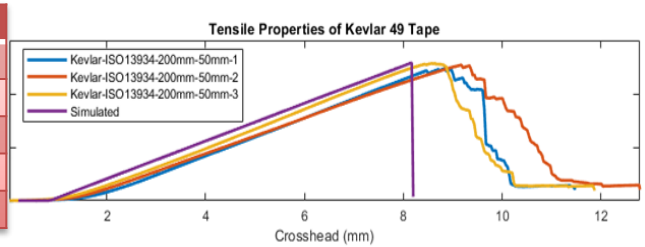


Project Leader: Prof. Marcelo Dapino, Dr. Leon Headings, Prof. Sheng Dong (OSU)
Project Mentor: Ryan Hahnlen, Skye Malcolm (Honda R&D Americas), Bengt Pipkorn (Autoliv)

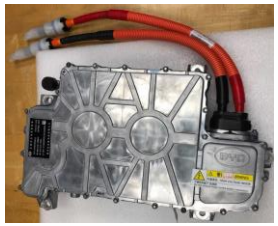
Project #64 : Heat generation and heat dissipation analysis for EV inverters

THE OHIO STATE UNIVERSITY

Motivation

- Aluminum die cast components used significantly in electric vehicle powertrain – covering shells for battery, inverters, power converters, e-motor, transmission etc.
- MES seeks to develop a deeper understanding and build their technical knowledge of thermal characteristics of EV components.
- Drive design changes in die-cast components – specifically inverter & battery housings

Cascadia inverter



BYD inverter

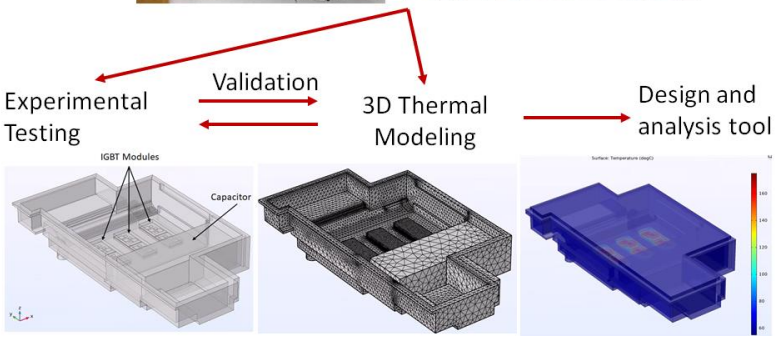
Project Goals

Develop understanding of thermal behavior and design features of EV inverter housings to guide design and manufacturing process

Objectives

1. Develop three-dimensional physics-based numerical models to simulate heat dissipation through inverter housings
2. Develop understanding of heat generation characteristics of IGBT modules using experimental testing
3. Develop a combined experimental and numerical framework for investigation of different inverter designs

Approach



Research Plan

- Literature review for thermal packaging studies of inverter modules
- Develop 3D thermal modeling framework for analysis of heat dissipation through inverter housings
- Develop power loss models to predict power dissipation from IGBT-diode pairs
- Conduct parametric studies to predict heat dissipation under different operating conditions, housing materials and thickness
- Experimental testing of BYD and Cascadia inverters for validation of numerical models and thermal data

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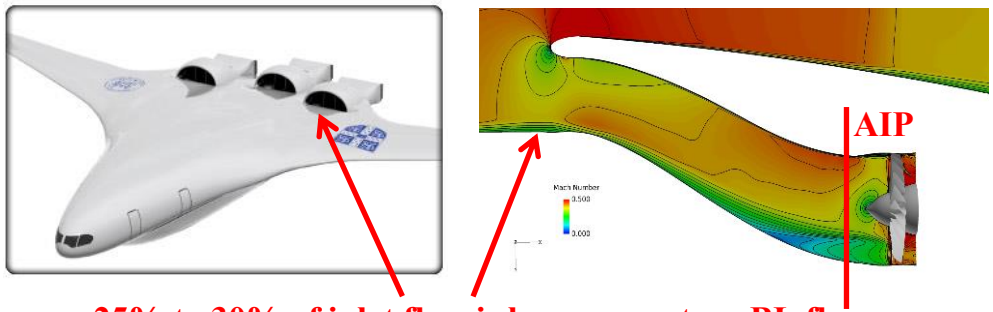
Project Leaders: Ardeshir Contractor (contractor.15) and Navni Verma (verma.55@osu.edu)

SVC Seed Grant: Aeromechanic Analysis and Optimization of Boundary Layer Ingestion Turbomachinery

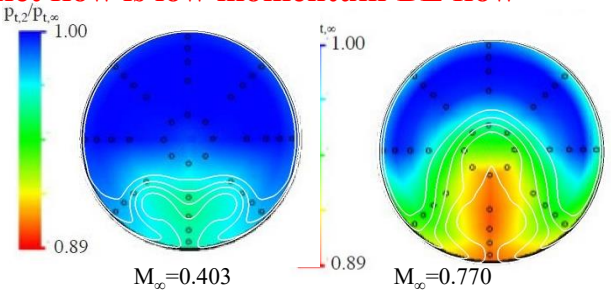
THE OHIO STATE UNIVERSITY

Motivation

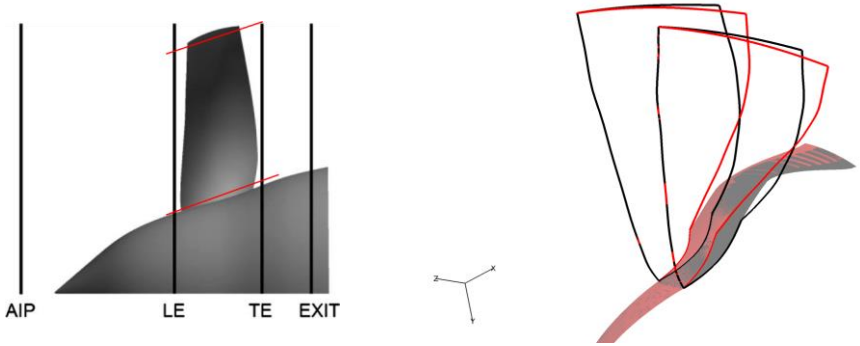
- NASA subsonic transport system metrics: Fuel Burn Reduction N+1 (2015) 33%, N+2 (2020) 50%, N+3 (2025+) 70%
- 3-5% fuel reduction by ingesting boundary layer (BL) flow
- Non-uniform BL ingestion and inlet geometry create flow distortions that negatively impact engine performance and structural integrity
- A need to study inlet/fan interaction through CFD simulation to understand fan response to inlet distortion to mitigate aero and aeroelastic challenges



Total pressure distortion upstream of compressor

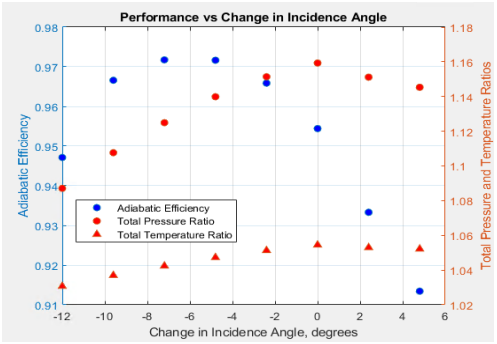


Optimizing efficiency of 3D fan using hub and tip twist angles and chord length



Preliminary results show significant efficiency improvement over baseline design used in original study

Case	$P_{T,ex}/P_{T,in}$	% Dif. from Base	η	% Dif. from Base
Base	1.2071	0.00%	0.8918	0.00%
Case 1 (3D)	1.1680	-3.29%	0.9362	4.86%
Case 2 (3D)	1.1723	-2.92%	0.9352	4.75%
Case 3 (3D)	1.1378	-5.91%	0.9444	5.73%
Case 4 (3D)	1.1890	-1.51%	0.9077	1.76%
Case 4.1 (3D)	1.1355	-6.11%	0.9443	5.72%



Optimization performed at design condition of baseline geometry

Optimizing the geometry of the blade allows for increased overall performance and longer life for the blade

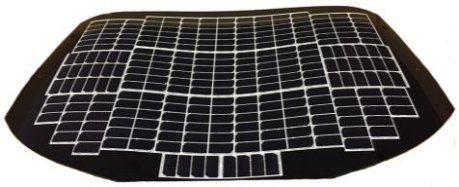
Project Leader: Jen-Ping Chen (chen.1210@osu.edu)

SVC Seed Grant: Analytical Model For Vehicle Integrated Photovoltaic Systems

THE OHIO STATE UNIVERSITY

Motivation

- Develop a computational research tool that serves as a platform to analyze the performance of vehicular integrated photovoltaic (VIPV) systems in various automotive formats and drive cycle applications
- For automotive manufactures, the model provides support for evaluation and design of VIPV systems
- For photovoltaic manufacturers and solar research centers, model provides analytical ability to support research in high efficiency cells for automotive applications



Project Goals

Study interplay between 4 sub-systems of model:

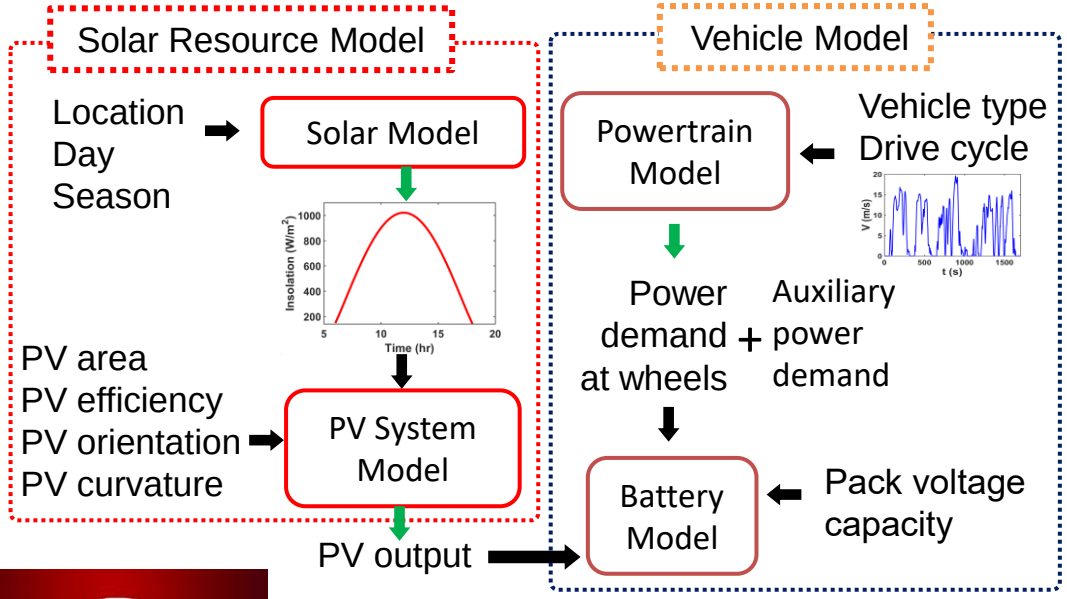
Solar Insolation
- location, season, time
- 3D curved roof shapes
- changing PV orientation

PV Energy Conversion
- cell type
- cell interconnection

Charging & Power Delivery
- battery charging interval
- battery capacity
- auxiliary power demand

Powertrain & Drive Cycles
- vehicle formats – car, utility van, bus, truck
- different drive patterns

Approach



Research Plan

- Account for curvature effects of vehicle roofs on insolation
- Include dynamic vehicle load and higher order model for battery sub-system
- Model integration of PV in fuel cell electric vehicles and option of PV energy supply for ancillary or refrigeration systems
- Analyze vehicle integrated PV as solution to anti-idling regulations
- Explore higher efficiency cells –
  - Interconnection, stringing and form-factors for high yield
  - Performance analysis
  - Economics and life-cycle analysis

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Project Leaders: Ardeshir Contractor (contractor.15) and Navni Verma (verma.55@osu.edu)

SVC Seed Grant: Solution Processing of Thermochromic Vanadium Dioxide Smart Windows

THE OHIO STATE UNIVERSITY

Industry Need, Context, Relevance

- Need to efficiently regulate temperature of internal environments with smart windows
- Impact on energy efficiency can be up to 42%[1] of total energy consumption for residential cooling and heating
- Need rapid synthesis methods to reduce processing time
- Need control over optical transmittance for smart windows applications

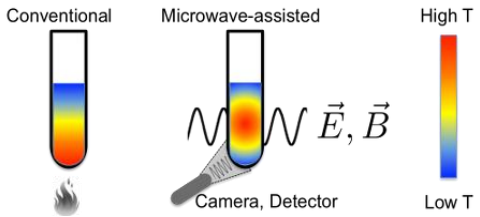
[1] S. Selkowitz 2010

Project Objectives

- Reduce typical synthesis of bulk materials from *days* to *minutes*
- Develop solution-processable low-temperature method for coating procedure

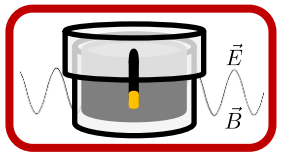
Research Plan

- Control microwave-assisted heating conditions to achieve phase purity of targeted materials

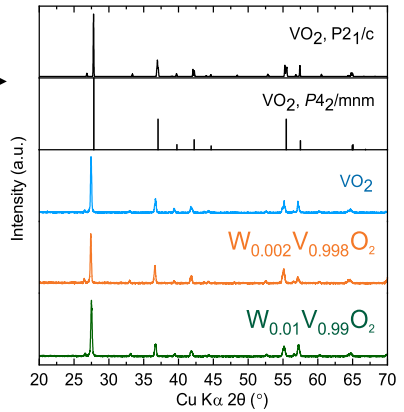


- Characterize phase purity of products and transition temperature
- Translate microwave-assisted heating conditions to solution-phase synthetic methods to control nanostructured morphology

Preliminary Results/Applications



Achieved phase purity



Preliminary results show phase purity of bulk smart materials. Next steps include film deposition and controlling opacity.

$A_xV_{1-x}O_2$

Vary x to control transition temperature

Project Leader: Vicky Doan-Nguyen (doan-nguyen.1@osu.edu)

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SVC Seed Grant: Integrated Hyperdamping Material Systems for Vibration, Noise, and Shock Attenuation

The Ohio State University

LSVR:
Advancing basic and applied science in vibrations, acoustics, mechanics, and smart materials.

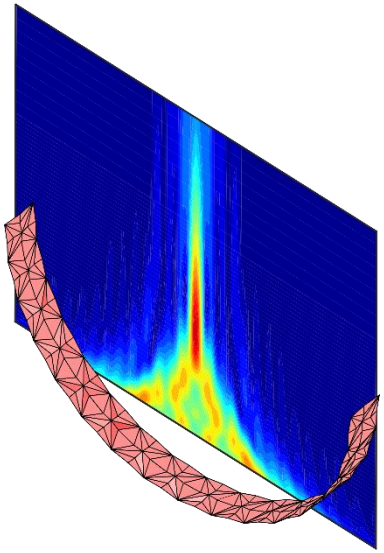
Director:
Prof. Ryan L. Harne

Thanks to our many industry, federal, and defense sponsors!

Research Student Team

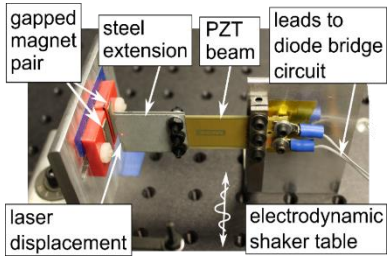
Origami-Inspired, Foldable Acoustic Arrays for Deployable Medical Ultrasound Devices:

Acoustics, wave physics, mechanics, design



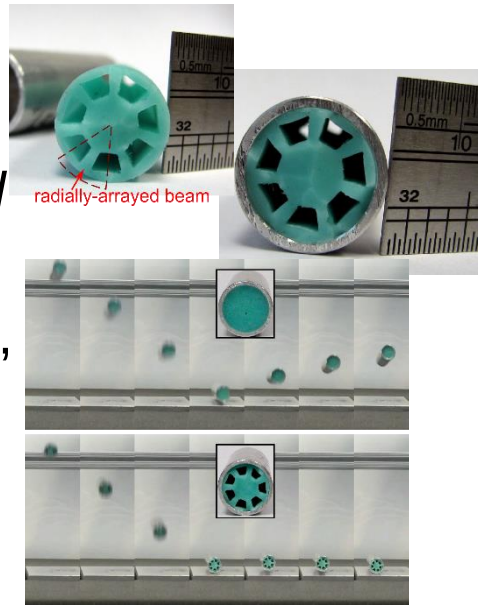
Understanding, Predicting Response of Multistable Structures Operating in Extreme Environments:

Analytical dynamics, energy harvesting, hypersonic multiphysics



Lightweight Material Systems to Control Shock, Vibration, and Sound:

Structural mechanics, materials science, design and manufacturing



Project Leader: Ryan Harne (harne.1@osu.edu)

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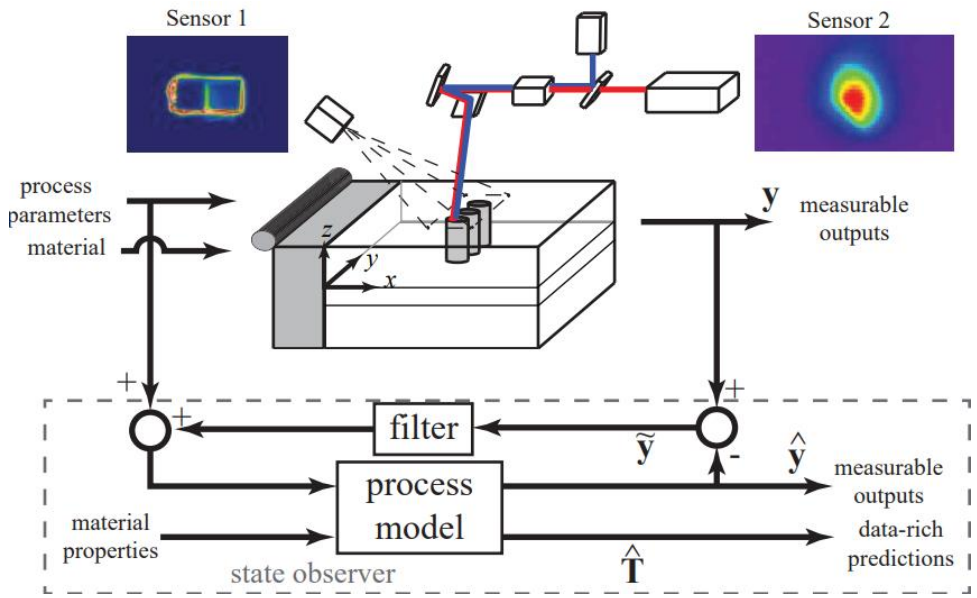
SVC Seed Grant: Validating state estimator-generated predictions of internal temperatures within Powder Bed Fusion

THE OHIO STATE UNIVERSITY

Objective: Estimating mid-build temperature fields in the metal PBF process using an Ensemble Kalman Filter. Estimated temperature fields can be correlated with process defects and features of interest, thus advancing in-situ PBF quality control.

Description of Effort:

- Theoretic analysis and numerical implementation of state estimators on a class of large-scale linear time-varying systems.
- Kalman filtering in the absence of *a priori* knowledge of system noise statistics.



Benefits of proposed technology: In-situ PBF quality control would save practitioners substantial time, money, and effort. This proposed technology is a substantial advancement of this as-yet-unrealized goal.

Challenges: PBF modeling generates large systems that present obstacles to practical computation, and prohibit several common control theory. Variability in part geometry challenges theoretical analysis by limiting *a priori* knowledge of the system structure.

Maturity of technology: This technology is still being tested in simulation, with initial experimental results to be delivered by year's end.

Project milestones:

- 2021: Gathering of experimental data, initial Ensemble Kalman Filter validation, development of feedback control algorithm environment.
- 2022: Ensemble Kalman Filtering algorithm hits performance targets, theoretical analysis complete.
- 2023: Completion of feedback control simulation environment.

Proposed funding: DAGSI grant C.N. RX9-OSU-20-5-AFRL2

Program cost:

- 2021: $80,000
- 2021: $81,000
- 2023: $82,000

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Project Leader: Nathaniel Wood (OSU)

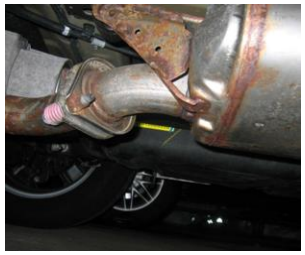
Project Mentor: David Hoelzle (OSU)

NSF REU Project: Investigation of Metal Corrosion by In-situ Electrochemical Force Microscopy

THE OHIO STATE UNIVERSITY

Motivation

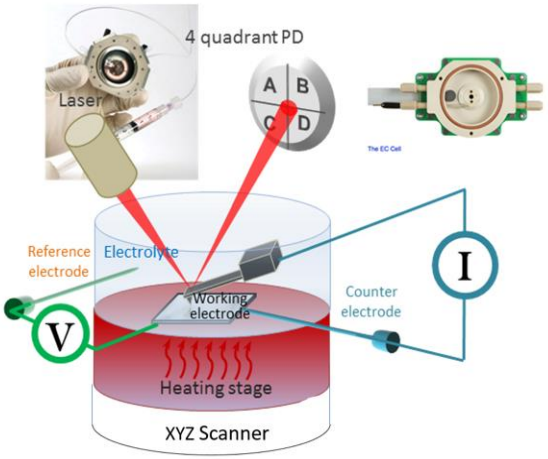
- Corrosion is a serious problem significantly affecting the lifetime of vehicles and thus automobile industry. For example, Toyota Motor Corporation has agreed to pay up to about $3.4 billion in 2016 to settle claims that certain of its trucks and sport-utility vehicles lacked proper rust protection, leading to premature corrosion of vehicle frames [1].



Rust in 2011 Toyota RAV 4 in muffler (carcomplaints.com)

- To date, the macro-scale electrochemical measurements have reveals the effect of electrochemical potentials, temperatures, solution conditions, timescales, and other factors on the global corrosion process for various metallic materials, while the local properties and conditions are trivialized.

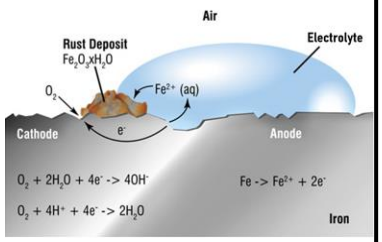
In-Situ Electrochemical Force Microscopy



- ✓ Nanoscale characterization
- ✓ In-situ measurement:
  - In liquid; In electrolytes
  - Temperature control
  - Electrical input/output
- ✓ Measuring the potential dependence of corrosion current
- ✓ Local electrochemical behavior

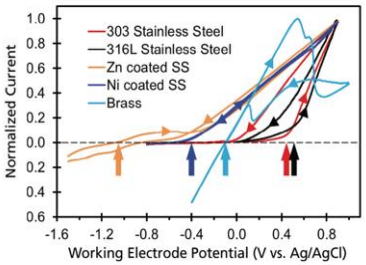
Background and Objective

- Localized corrosion accounts for 70 percent of material failures, and these failures are catalyzed by varying particular abnormalities affecting the metallic surface [2].
- Water (electrolyte) comes in contact with the surface of metal, while in the presence of air. With these three parts in contact, the metal becomes polarized and electrons flow through the metal, ultimately creating a mas build up of iron oxide, commonly known as rust.
- Nanoscale corrosion studies depend on the ability to mimic the real-world conditions that promote corrosion in a shorter time scale.
- By leveraging the PI's expertise in AFM, we aim to investigate the corrosion process of various metallic alloys frequently used in automobile production by employing the state-of-the-art in-situ Electrochemical Force Microscopy (EFM) based on Atomic Force Microscopy (AFM).

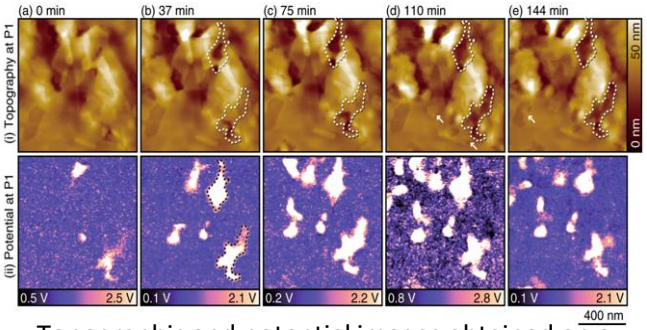


Project Leader: Hanna Cho (cho.867@osu.edu)

Typical Data



Cyclic voltammograms of various metallic samples [3]



Topographic and potential images obtained on a stainless steel sample in a 10 mM NaCl solution via Electric Potential Microscopy [4]

[1] https://www.wsj.com/articles/toyota-in-3-4-billion-settlement-over-corrosion-in-some-trucks-and-suvs-1478972740
[2] http://www.npl.co.uk/upload/pdf/beginners_guide_to_corrosion.pdf
[3] https://www.oxford-instruments.com
[4] Honbo, K., Ogata, S., Kitagawa, T., Okamoto, T., Kobayashi, N., Sugimoto, I., Shima, S., Fukunaga, A., Takatoh, C., and Fukuma, T., Visualizing Nanoscale Distribution of Corrosion Cells by Open-Loop Electric Potential Microscopy, ACS Nano 10 (2), 2575-2583 (2016).

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NSF REU Project: Self-stiffening, lightweight structural materials for energy-efficient transportation systems

THE OHIO STATE UNIVERSITY

Industry Need

- **Advanced lightweight materials** offers great potential to boost the fuel economy of vehicles, especially important for electric and hybrid vehicles.
- A 10% reduction in vehicle weight can result in a 6%-8% fuel economy improvement.
- Current efforts are mainly devoted to replacing cast iron and traditional steel components with lightweight materials
  - high-strength steel
  - magnesium (Mg) or aluminum (Al) alloys
  - carbon fiber reinforced composites

Project Objectives

We propose a new material design inspired by the structure and processes of bone tissue to improve upon current processes with a more complex material design that provides lightweight, self-stiffening structural materials for energy-efficient transportation systems.

Transduction Mechanism: Piezoelectricity

Transduce the force input to electrical signals to control mineralization

Stiffening Mechanism: Mineralization

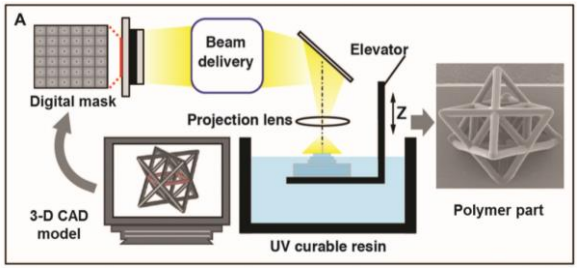
A soft polymer template is locally reinforced by stiff mineral

Template: 3D Printed Metamaterial

Complex microstructures to encode local force distributions

Diverse geometries and scales

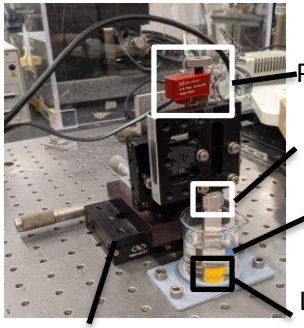
Research Plan



Lee, H. et al. *Science*, vol. 344, pp. 1373

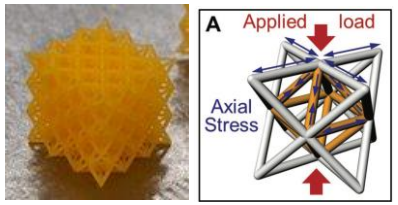
Projection micro-stereolithography (PμSL) is used to 3D print piezoelectric lattice structures.

This material undergoes cyclic, periodic loading over time in a mineral solution, which facilitate the mineralization of the lattice.

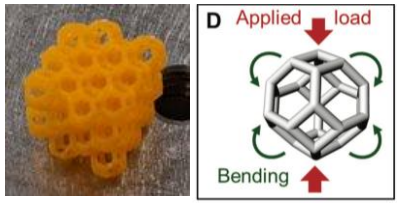


Results and Future Works

Stretch-dominated octet-truss



Bend-dominated Kelvin form



- We successfully fabricated two different types of piezoelectric lattice structure, that can vary the type of force loading.
- We will optimize the polymer composition to maximize the piezoelectric effect during loading.
- Based on the first results, we will further optimize the lattice structure to provide an effective base template for the self-stiffening mechanism.

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Project Leader: Hanna Cho (cho.867@osu.edu)

Project Mentor: Sajan Patel