CLEMSON
MECHANICAL ENGINEERING






RESEARCH PORTFOLIO

Clemson University Department of Mechanical Engineering

THE ULTRASONIC SCRUBBER

Phanindra Tallapragada, Dept. of Mechanical Engineering, Clemson University, Clemson, SC

Problem Statement - Fish-like swimming robots do not effectively utilize the hydrodynamics of the vortex wake due to challenges in modelling. This reduces efficiency of motion and agility and increases the sensing, control/actuation and onboard computational effort.

Innovation – Simplified models of robot-fluid interaction by identifying

- Nonholonomic constraints in swimming.
- These models informed novels forms of propulsion through internal momentum wheels.
- Showed passive degrees of freedom improve agility with little active sensing and feedback control

Significance of the Innovation –

- Highly reduced order models of robot-fluid interaction, that still capture the effects of unsteady wake.
- Physics based rigid body terrestrial surrogate models of fish-like swimming.
- Leads to simple, fast control algorithms for efficient propulsion and increased agility.

Technical/Research Accomplishments –

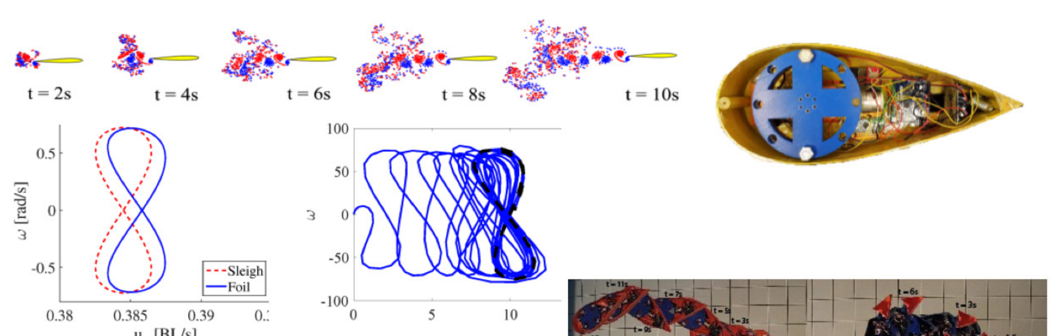
- Developed a common framework of nonholonomic constraints for both swimming and terrestrial locomotion.
- Showed the existence of low dimensional attractors in locomotion and demonstrated the utility of such attractors to determine common control laws for tracking a trajectory for a fish-like swimming robot and a terrestrial nonholonomic robot.
- Demonstrated the role of unactuated degrees of freedom in improving the agility of a swimmer.

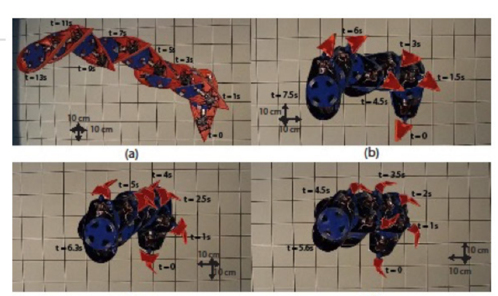
Key Outcomes –

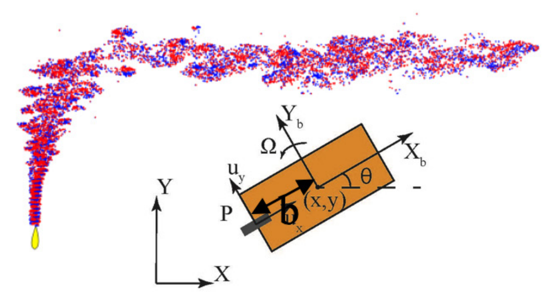
- Simplified, highly reduced models of swimming that nevertheless model all the key hydrodynamic effects on a swimmer.
- The framework developed will allow the modeling, analysis and efficient control of morphologically more complicated bioinspired swimming robots.
- Showed that unactuated degrees of freedom can be used as a means of embodied sensing and control minimizing onboard real time computation and active feedback control.

Applications –

- Small scale agile, versatile and reconfigurable underwater and surface swimming robots.
- Underwater structural inspection.
- Monitoring and sampling of water bodies.
- Pipeline inspection.
- Efficient unmanned unconventional ground vehicles to traverse unstructured environments.







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Website: ptallap.people.clemson.edu

Contact: Prof. Phanindra Tallapragada ptallap@clemson.edu

NONLINEAR META-MATERIALS BY DESIGN

Lonny Thompson, Department of Mechanical Engineering, Clemson University, Clemson, SC

Problem Statement - Design of meta-materials with prescribed novel by manipulating underlying architectures at multiple geometric and time scales properties operating in both linear and nonlinear regimes is challenging due the requirements of linearization for analysis and computation. The development of advanced manufacturing techniques, like additive manufacturing, has enabled a significant increase of the design space for producing materials with novel architected microstructures designed to operate in nonlinear regimes**.**

Innovation –

- Generalization from two-dimensional to three-dimensional structures, including instability by design together generalized hybrid origami folding techniques for novel meta-material properties
- Use multiple scales (>2) concurrently, including hierarchical scales
- Multiple-field properties, multi-physics (mechanical/thermal/electrical)
- Inclusion of non-linear finite strain effects (geometrically nonlinear)
- Inclusion of non-linear material behavior

Significance of the Innovation –

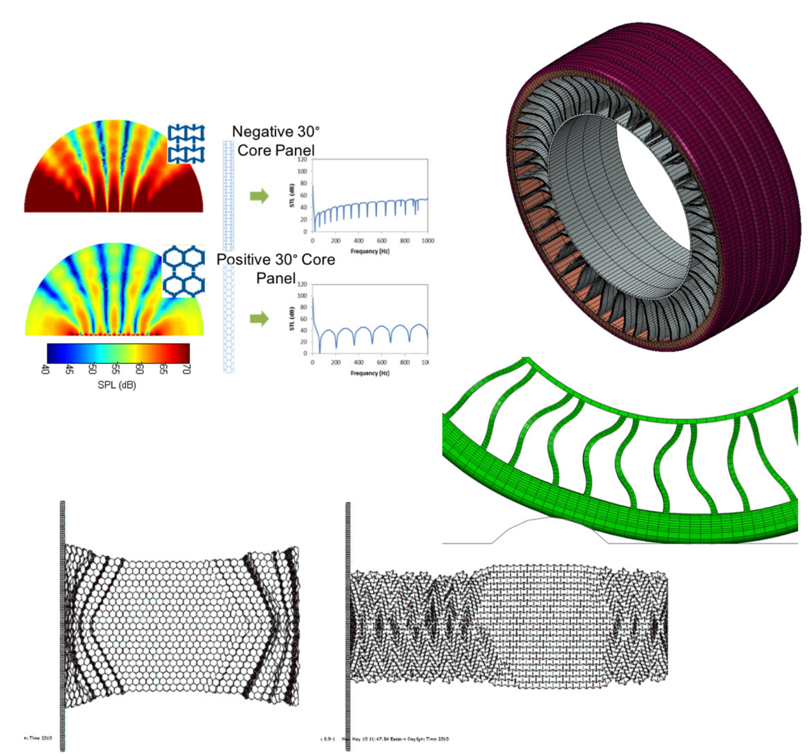
- Discrete and macro homogenization framework for metamaterials exhibiting both local and global field variables allows accurate micro behavior for metamaterials with changing fields such as found in bi-stable periodic lattice structures
- Meta-materials with microstructures consisting of bi-stable elements undergoing large geometric transformations upon reaching a critical buckling state provide different effective behavior compared to the initial state which can be exploited for shape morphing, hybrid origami folding, and acoustic wave-frequency filtering, and energy absorption
- Macro continuum equivalent representations for micro discrete structure retains local properties of the lattice with significantly reduced number of variables than those required for detailed models.

Key Outcomes –

- Multiple stability modes, design of bi-stable structures for enhanced acoustics and energy absorption, shape morphing and soft robotics
- Multi-Physics: coupled mechanical/thermal/electrical
- Mechanical metamaterials exhibiting novel behaviors

Applications – Cross-Disciplinary –

- Soft robotics,
- Lightweight structures and components
- Manufacturing processes and tools
- Stealth acoustics, Acoustic filtering and vibration isolation
- Impact energy absorbing structures and components
- Energy harvesting



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Website: https://cecas.clemson.edu/~lonny/

Contact: Prof. Lonny Thompson lonny@clemson.edu

ACOUSTIC META-MATERIALS

Lonny Thompson, Department of Mechanical Engineering, Clemson University, Clemson, SC

Problem Statement - Design of engineered acoustic meta-materials with orders of magnitude improvement in attenuation, stealth, frequency filtering, and vibrational energy harvesting capabilities are needed to produce the next generation of devices and structures.

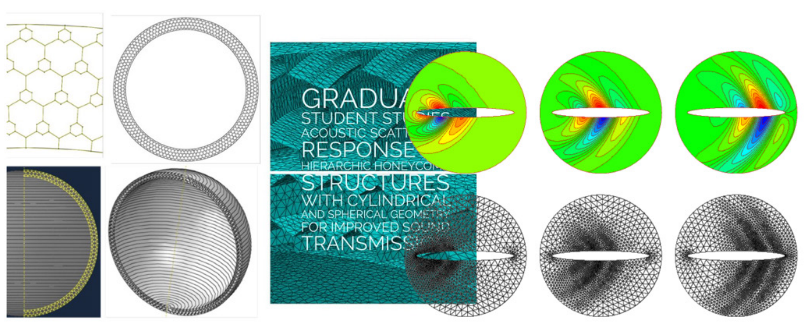
Innovation –
- Use of hierarchical scales and design of nonlinear and bi-stable structures for enhanced acoustics and energy absorption
- Space and time adaptive discontinuous Galerkin Least Squares finite element methods developed for efficient solution allows for wide range of multi-frequency solutions
- Generalized finite elements for acoustics with intrinsic wavenumber-frequency behavior for improved accuracy
- Parallel program distributed across multiple-processors for large-scale computational solutions
- Exact non-reflecting boundary conditions for exterior acoustic problems

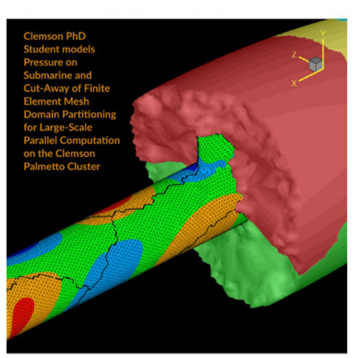
Significance of the Innovation –
- Acoustic scattering from geodesic and other novel lattice structures with multiple geometric scales provides spatial wavelength filtering
- Harnessing multi-material additive manufacture leads to significant improvements in acoustic properties by design

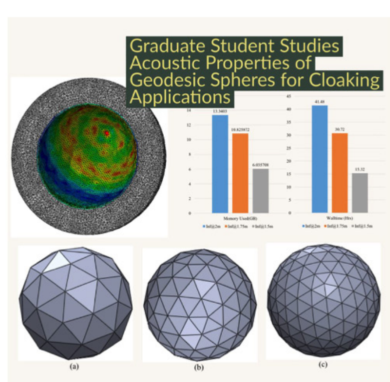
Key Outcomes –
- New innovations in design and control of wave directionality, attenuation, frequency filtering, stealth

Applications – Cross-Disciplinary –
- Stealth acoustics
- Acoustic filtering and vibration isolation
- Impact energy absorbing structures and components
- Structural Acoustic Energy harvesting
- Attenuation across barriers

Applications –
- Small scale agile, versatile and reconfigurable underwater and surface swimming robots.
- Underwater structural inspection.
- Monitoring and sampling of water bodies.
- Pipeline inspection.
- Efficient unmanned unconventional ground vehicles to traverse unstructured environments.







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Website: https://cecas.clemson.edu/~lonny/

Contact: Prof. Lonny Thompson lonny@clemson.edu

ASYMPTOTIC HOMOGENIZATION FOR META-MATERIALS

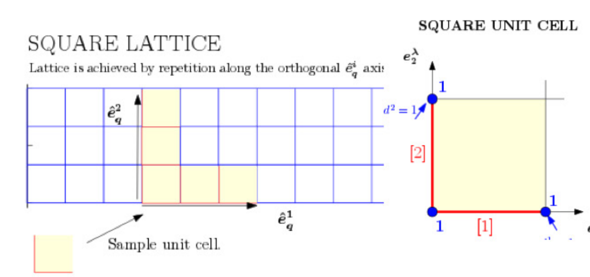
Lonny Thompson, Department of Mechanical Engineering, Clemson University, Clemson, SC

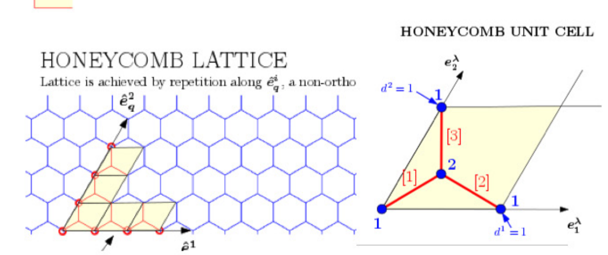
Problem Statement - Macro continuum equivalent representations for micro discrete structure retain local properties of the lattice, significantly reducing the number of variables than those required for detailed models. For architected metamaterials with high-contrast micro-properties, classical homogenization methods cannot capture the essential micro-behavior at the macro-level. For high-contrast materials, generalized continuum field equations including second-gradient models are obtained which require high-order continuity in computational solutions.

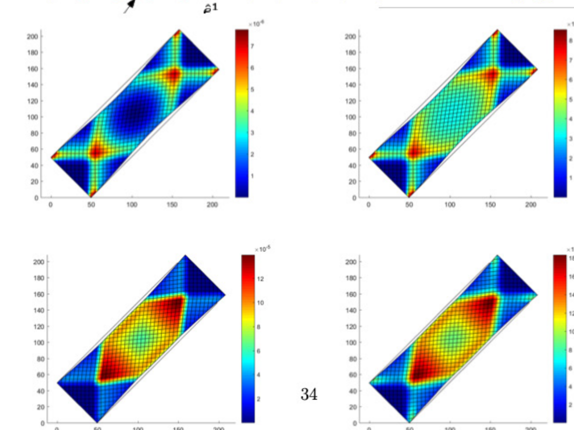
Innovation –
- Asymptotic homogenization models for high-contrast lattices assembled by extensible and continuous fibers that exhibit bending stiffness and interconnected by internal pivots. The pivots constrain the beam fibers to share the same displacement at their connections, however, when modeled as idealized pivots with zero torsional resistance, the intersecting fibers are allowed to rotate independently.
- Analytical and computational asymptotic homogenization methods are developed to derive the leading order continuum field equations with respect to asymptotic geometric scale parameters without using conventional approaches which assume the model a-priori and which can lead to inconsistencies.
- Finite element methods are developed that ensure continuity of derivatives across boundaries as required for second-gradient and micromorphic field equations of the leading order.

Significance of the Innovation and Key Outcomes –
- Different asymptotic orders for torsional stiffness are introduced within an asymptotic homogenization of the discrete micro-beam model at the pivots, in order to systematically identify leading order continuum field equations and associated homogenized material properties.
- The homogenized material properties are orthotropic and exhibit highly anisotropic behavior with respect to different coordinate rotations.

Applications – Cross-Disciplinary –
- Inclusion of micro-scales in macro-scale computational methods at the continuum model level.
- Consistent homogenized material properties at macro-scale, automation, and identification of appropriate model beyond classical elasticity found in commercial finite element codes.







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Website: https://cecas.clemson.edu/~lonny/

Contact: Prof. Lonny Thompson lonny@clemson.edu

DESIGN OF ACOUSTIC WAVELENGTH-FREQUENCY RELATIONSHIPS FOR META-MATERIALS

Lonny Thompson, Department of Mechanical Engineering, Clemson University, Clemson, SC

Problem Statement - For lattice structures, the periodic unit cell used for Bloch wave analysis is not unique. In previous research, when different unit cells and basis directions are chosen differently, the frequency- wavenumbers where not directly compared. Scaling and basis vector transformations for different unit cell basis directions are needed with respect to a common reference physical basis to make direct comparisons of the frequency directional behavior for wave vector components.

Innovation –

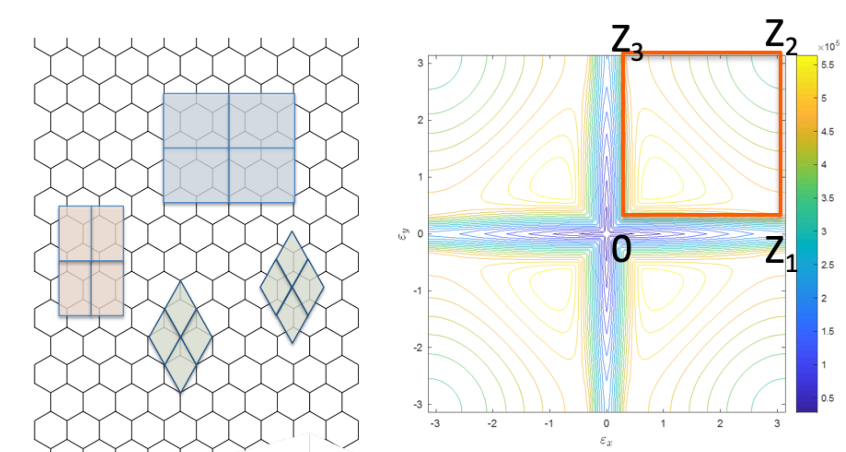
- For two- and three-dimensional Bloch wave analysis, both orthogonal and nonorthogonal periodic lattices are considered for both in-plane and out-of- plane bending free-wave propagation allowing for an expanded design space
- Examine wave propagation in lattices for wave vectors decomposed in covariant and contravariant (dual) basis in curvilinear coordinates allows new topologies to be designed and evaluated
- Specialize curvilinear coordinates to common separable coordinates including cylindrical, spherical, elliptical for novel geometric designs within common systems
- Identification of stopping bands and filtering within frequency ranges for stealth and attenuation applications
- Include energy absorption and damping effects for full descriptions of wave behavior

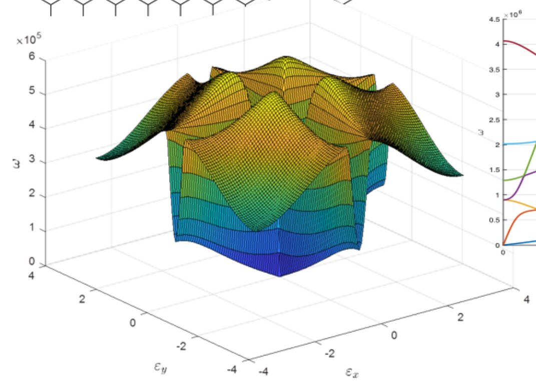
Significance of the Innovation and Key Outcomes –

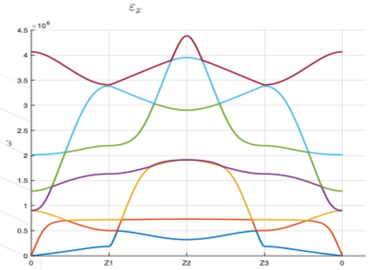
- Evaluation of phase velocity variation in terms of frequency and direction of propagation for complex lattice structures
- Identification of stopping bands and filtering within frequency ranges
- Include energy absorption and damping effects
- Anisotropy by design for controllable acoustic directionality

Applications – Cross-Disciplinary –

- Acoustic waveguides with engineered high-contrast geometric and mass scales distributed through the lattice by design to produce controllable anisotropic acoustic wave directionality which can be exploited for waveguiding or acoustic-focusing
- Identification and design of stopping bands and filtering within frequency ranges for stealth







K-space Diagram

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Website: https://cecas.clemson.edu/~lonny/

Contact: Prof. Lonny Thompson
lonny@clemson.edu

INVERSE MATERIAL CHARACTERIZATION WITH SURROGATE MODELS

Cameron J. Turner, Department of Mechanical Engineering, Clemson University, Clemson, SC

Problem –

- Advances in materials result in materials with complex nonlinear, anisotropic behaviors with dependencies on many manufacturing parameters
- Existing design methods presume a knowledge of the actual as-built material properties
- Simulation-based approaches are unable to currently predict the properties of these materials with accuracy
- Methods to experimentally obtain the properties are expensive

Innovation –

- Use surrogate models to replace the computationally expensive operations in the analysis with surrogate models allowing experimental data to be converted into as-built material models

Significance of the Innovation –

- Computational run times reduced by up to 10^6
- Allowed experimental costs to be reduced by incorporating the results into the control loop

Technical/Research Objectives –

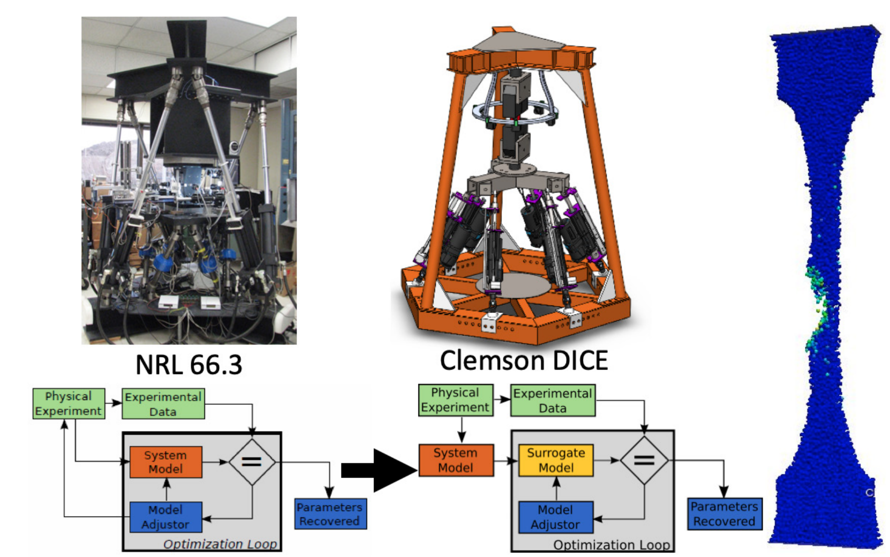
- Design a next generation 6DOF Material Test Apparatus for polymer materials
- Assist NRL in the design of a next generation 6DOF Material Test Apparatus for metal and ceramic materials
- Assist NRL in the design of a next generation 6DOF Material Test Apparatus for fatigue testing
- Design a surrogate model to support inverse material testing
- Determine the relationships between design/manufacturing parameters and material behaviors
- Develop models that enable predictive design based on manufacturing parameter decisions

Work Plan/Expected Outcomes –

- Design and fabricate test apparatus at Clemson and NRL
- Calibrate, Verify and Validate system performance
- Conduct testing
- Develop models and design tools from data

Applications –

- Characterization of the as-built properties of engineered materials such as Composites and Additively Manufactured Materials
- Basis for understanding how to control the manufacturing process to achieve a material behavior (Designing the Material for the Product)
- Manufacturing Process Control



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Contact: Prof. Cameron J. Turner
cturne9@clemson.edu
(864) 656-2413