Bio-Inspired Complexity in Engineered Metamaterials: Nonlinear Dynamics for Vibration Control and Monitoring

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ABSTRACT:
Complexity is a defining trait of biological systems: robustness, adaptability, and sensitivity emerge from nonlinear interactions across scales rather than from any single “perfect” component. High-performance mechanical structures—lightweight designs under high-cycle loading and harsh environments—face a similar reality: small perturbations can trigger resonance shifts, instabilities, and intermittent responses, making vibration control and condition monitoring inherently nonlinear.

This lecture takes a bio-inspired point of view: instead of merely suppressing complexity, we architect it into matter through metamaterial structures, using geometry as a functional design parameter. Architected sandwich concepts with high-performance skins and 3D-printed metamaterial cores enable tailored wave propagation and vibration filtering via topology-driven mechanisms (auxetic response, localization and bandgap-like effects) and intentionally nonlinear stiffness characteristics. Here, nonlinearity becomes an opportunity: amplitude-dependent dynamics can redirect energy, increase stability margins, and generate diagnostic signatures that are most informative when the structure is most stressed.

Experiments on representative sub-structures under resonant and broadband excitation include thermo-mechanical tests, showing how temperature variations shift effective stiffness/damping and modify resonance locations, instability thresholds, and nonlinear indicators—capturing operational variability in service. The key is a coupling: metamaterial architectures that mitigate vibrations can simultaneously enhance damage observability, enabling structures that are lighter, and more self-informative.