

TECHNICAL WHITE PAPER

Uncertainty-Aware Design of Dynamic Metamaterials

Computational Strategies for Defense-Relevant Structural Systems

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Delivering Certifiable Metamaterial Performance Under Real-World Uncertainty

DARPA | AFRL | ARL | ONR | DOE | Defense & Aerospace Industry

Based on forthcoming research in Mechanical Systems and Signal Processing (Elsevier)

1. EXECUTIVE SUMMARY

Defense and aerospace platforms increasingly rely on engineered metamaterials for broadband vibration attenuation, acoustic signature management, and structural damping. Yet the path from a numerically optimized metamaterial design to a certified, deployable component remains blocked by a fundamental challenge: **manufacturing-induced geometric variability degrades performance in ways that conventional simulation tools cannot efficiently predict or bound.**

Dr. Rafael O. Ruiz and the Mechanist Lab at the University of Michigan-Dearborn have developed a computational framework that closes this gap. The flagship methodology combines Craig-Bampton substructuring, Support Vector Machine (SVM) boundary detection, and PCA-Kriging interpolation to predict the full frequency response of aperiodic metamaterial assemblies at speeds **5,000 to 8,000 times faster than direct finite element analysis**, while maintaining accuracy across geometric perturbations up to 50% of nominal dimensions. This work appears in *Mechanical Systems and Signal Processing* (Elsevier).

The methodology directly enables Monte Carlo uncertainty quantification, robust topology optimization, and digital twin workflows for defense structural applications, all previously computationally intractable at system scale.

Key Capability	Demonstrated Result
Computational speedup vs. direct FEA	5,000 to 8,000x after training
Resonance frequency prediction error	Below 0.5% (validated case)
Accuracy at 50% geometric perturbation	Below 11% MAPE (vs. 600x worse for LP)
Design space handled	Up to $\pm 50\%$ nominal geometry variation
PCA dimensionality reduction	30,000 matrix features to 6 latent variables

¹ MAPE: Mean Absolute Percentage Error, a standard measure of prediction accuracy across multiple frequency response samples. ² LP: Lagrange Polynomial interpolation, a conventional strategy for interpolating reduced mass and stiffness matrices that breaks down under large geometric perturbations.

2. THE PROBLEM: UNCERTAINTY IN DEFENSE-RELEVANT DYNAMIC SYSTEMS

Metamaterials engineered to attenuate vibration, control wave propagation, or isolate precision instruments are increasingly attractive for military platforms. Armored vehicles require vibration isolation for sensor payloads. Aircraft structures demand broadband damping without weight penalty. Naval vessels must manage acoustic signatures. Missile systems need shock attenuation at specific frequency bands. Additive manufacturing has made complex metamaterial geometries fabricable at scale.

The core problem is predictive reliability under manufacturing uncertainty. Additive manufacturing introduces stochastic geometric deviations at the substructure level. Tolerances in strut lengths, wall thicknesses, and core positions alter the resonant characteristics of individual unit cells. When assembled into a full structure, these deviations compound, shifting or eliminating designed-in bandgaps and attenuation zones entirely.

A compounding challenge is **digital certification**: the ability to monitor the additive manufacturing process in real time, predict the resulting structural behavior from in-process measurements, and flag potential performance degradation before a component reaches the field. Without uncertainty-aware computational tools, this certification pathway does not exist.

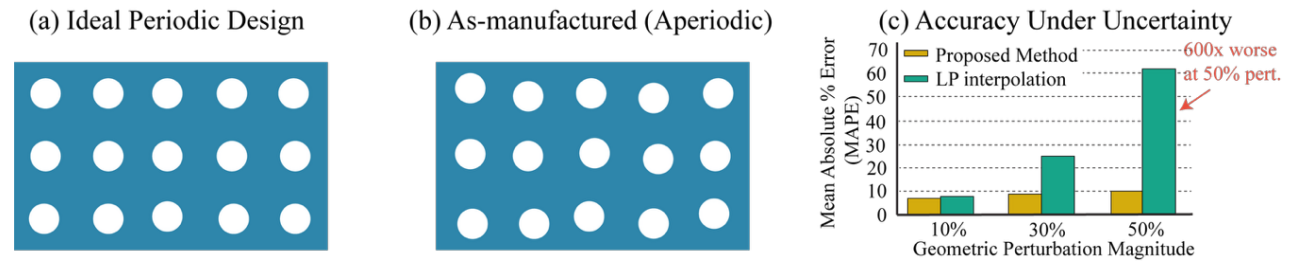


Figure 1. (a) Idealized periodic metamaterial; (b) as-manufactured structure with stochastic geometric deviations introduced by additive manufacturing tolerances; (c) prediction accuracy: the proposed surrogate maintains stable error across all perturbation levels, while LP^2 interpolation degrades dramatically (>600x higher MAPE¹ at 50% perturbation).

The simulation challenge is equally severe. Propagating uncertainty through a metamaterial assembly requires thousands to millions of frequency response evaluations. For a structure with modest complexity (10 to 15 substructures), each evaluation involves a full finite element solve requiring tens of seconds of CPU time. Monte Carlo uncertainty quantification at system scale is computationally prohibitive with current methods. Existing surrogate methods based on polynomial interpolation fail when geometric perturbations are large: mode crossing causes numerical instability that makes them unreliable across realistic manufacturing tolerance ranges of 30 to 50% of nominal geometry.

- **Reliability gap:** No rigorous way to bound metamaterial performance across manufacturing tolerances.
- **Certification gap:** Defense procurement requires performance bounds, not point estimates.
- **Digital certification gap:** No tool exists to predict field performance from in-process manufacturing data.
- **Optimization gap:** Robust design requires evaluating a stochastic parameter space. Without fast surrogates, this is intractable.

3. TECHNICAL APPROACH

The Mechanist Lab reframes uncertainty quantification as a surrogate modeling task at the substructure level. Instead of running expensive full-scale simulations for every geometric realization, the framework learns a compact, accurate map from substructure geometry to structural response using a modest training set. Three innovations make this possible where prior methods fail.

Innovation 1: Automated Detection of Numerically Stable Subregions

Classical matrix interpolation on Craig-Bampton reduced-order models fails when geometric perturbations cause mode crossing: structural mode shapes change order, making it impossible to maintain a consistent modal projection basis. The Mechanist Lab framework detects this failure automatically. Latin Hypercube Sampling explores the design space, and a Support Vector Machine classifier maps the numerically stable subregions where interpolation remains valid. This eliminates silent model failure, a critical property for defense-grade computation.

Innovation 2: Multi-Region PCA-Kriging Surrogate

Within each detected stable subregion, the framework trains a dedicated surrogate model. Principal Component Analysis reduces the high-dimensional Craig-Bampton matrix output (up to 30,000 entries per substructure) to a small number of latent features (typically 6 to 10), capturing over 99.8% of variance. A Kriging interpolation model maps geometric parameters to these latent features, enabling full frequency response reconstruction for any new geometry without additional FEA runs. A multi-class SVM routes new geometries to the appropriate regional surrogate automatically.

Innovation 3: Modular Substructure Architecture

The framework operates at the substructure level. Each unit cell is modeled independently, allowing the assembly of arbitrary aperiodic configurations from pre-trained surrogates. This modularity is directly suited to additively manufactured components, where each piece carries its own realized geometric uncertainty. The framework is compatible with ANSYS MAPDL and MATLAB, extensible to 3D geometries, material property uncertainty, and viscoelastic damping models.

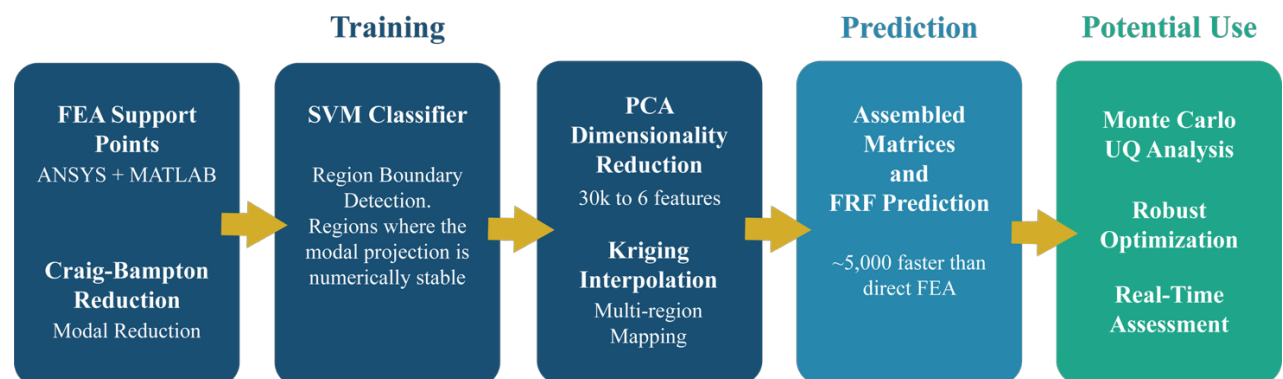


Figure 2. Three-phase computational framework. Phase 1 generates training data via FEA and Craig-Bampton modal reduction. Phase 2 uses Latin Hypercube Sampling with SVM classification to detect numerically stable parameter subregions. Phase 3 deploys PCA-Kriging surrogates per region, enabling predictions 5,000-8,000x faster than direct simulation.

4. KEY RESULTS AND DEMONSTRATED CAPABILITIES

The framework was validated on two canonical metamaterial benchmarks: a plate-core unit cell assembly (15 substructures, 3-parameter design space) and a beam-like structure with resonator-induced vibration attenuation bands (10 substructures, 2-parameter space, 50% nominal variation range). All experiments were performed on a 13th Gen Intel Core i5-13500 with 16 GB RAM, without parallel processing.

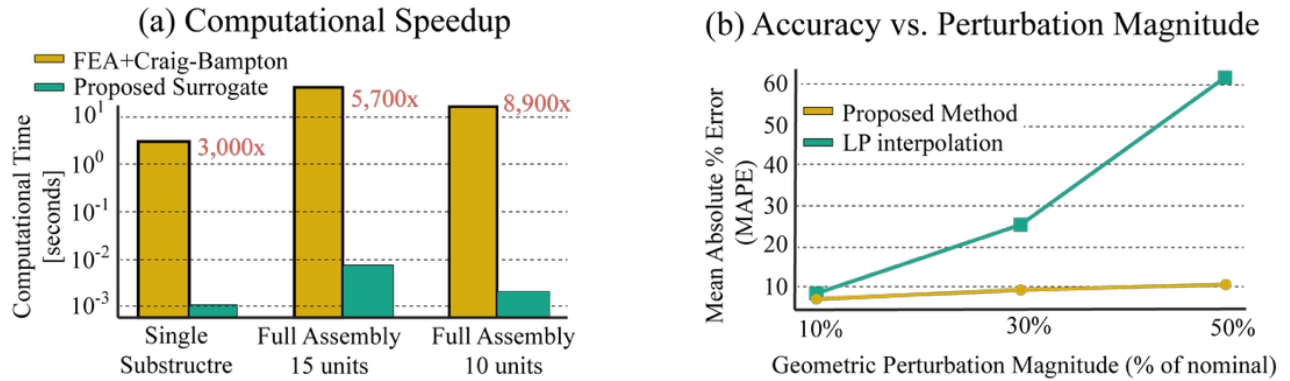


Figure 3. (a) Computational speedup of the surrogate framework vs. direct FEA with Craig-Bampton reduction. Speedups of 5,000-8,000x are achieved after training. (b) MAPE¹ vs. geometric perturbation magnitude: the proposed method maintains stable accuracy at all perturbation levels, while LP² interpolation degrades sharply beyond 10%.

Accuracy. In the single-region benchmark, resonance frequency predictions showed absolute errors below 0.5%. In the multi-region benchmark, the proposed method maintained MAPE below 11% at 50% geometric perturbation, over 600 times more accurate than LP interpolation at the same level. LP MAPE grows more than 4x from 10% to 50% perturbation; the proposed method shows negligible degradation.

Speed. After offline training, predictions are delivered 5,000 to 8,000 times faster than direct FEA. An assembly requiring 45 seconds of CPU time is evaluated in 8 milliseconds by the surrogate, making Monte Carlo uncertainty propagation with thousands of realizations feasible in minutes.

Generality. The framework handles arbitrary substructure topologies, geometry and material property uncertainty, and arbitrary assembly configurations. Extension to 3D structures and additive-manufactured experimental validation are the immediate next steps.

5. OPEN RESEARCH GAPS AND FUNDING OPPORTUNITIES

The current framework establishes a strong computational foundation. Several high-impact extensions are mature enough for funded research programs and directly align with priority areas across the defense and energy funding landscape.

Research Gap	Defense / DOE Relevance	Target Programs
Extension to 3D additively manufactured metamaterials and experimental validation on AM test articles	Structural armor panels, vibration isolation mounts for precision sensors and optics	ARO ERI, AFRL MURI, DARPA MTO
Real-time UQ for structural health monitoring and fatigue damage prognosis	Airframe and rotor system prognosis; shipboard structural monitoring	ONR, NAVAIR, AFRL S&T;
Digital certification of AM metamaterials: in-process monitoring, performance prediction, and degradation detection from manufacturing data	Certifiable additive manufacturing for mission-critical structural components	DARPA TRADES, AFRL AM, NRL
Robust topology optimization of metamaterials under manufacturing uncertainty	Next-generation lightweight protective and load-bearing structures	DARPA EQUIPS, AFOSR YIP
Multi-fidelity surrogate integration for full platform-level uncertainty analysis	Digital twin certification for autonomous and unmanned systems	DARPA ACTM, ARL ECI, DOE ASCR
Uncertainty propagation in piezoelectric metamaterial energy harvesters for GPS-denied environments	Self-powered sensors on UAVs, UGVs, and munition-embedded electronics	ARL, ERDC, DARPA ERI

Dr. Ruiz is actively seeking research partnerships and funding collaborations in these areas. The Mechanist Lab is equipped to serve as PI or co-investigator on programs requiring computational mechanics, uncertainty quantification, and stochastic simulation expertise. Collaboration with experimental groups for physical validation is a priority.

The tools are built. The gaps are real. The timing is right.

Program managers interested in UQ, metamaterial design, or computational dynamics are encouraged to reach out directly.

6. AUTHOR BIO AND CONTACT

Dr. Rafael O. Ruiz is an Assistant Professor of Mechanical Engineering at the University of Michigan-Dearborn, where he leads the Mechanist Lab (Computational Mechanics & Stochastic Engineering). His research focuses on uncertainty quantification, computational structural dynamics, surrogate modeling, and the design of metamaterials and piezoelectric energy harvesters.

Flagship publication: "Multi-Region Matrix Interpolation for Dynamic Analysis of Geometrically Perturbed Metamaterials" (with J. Pereira), forthcoming in *Mechanical Systems and Signal Processing* (Elsevier). Preprint: arxiv.org/abs/2511.03711. Related article on UQ in metamaterial vibration attenuation in *Journal of Sound and Vibration* (2025).

Fourth year of a tenure-track appointment. Actively developing externally funded research collaborations with defense agencies and industry partners.

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¹ MAPE = Mean Absolute Percentage Error. ² LP = Lagrange Polynomial interpolation (conventional matrix interpolation baseline). This white paper is based on research funded by Dr. Ruiz's startup package at the University of Michigan-Dearborn. Preprint: arxiv.org/abs/2511.03711. Dr. Ruiz welcomes inquiries from program managers, researchers, and industry partners.