Design of smart quasiperiodic nonlinear topological metastructures for vibration energy harvesting and sensing

Position type	PhD thesis		
Location(s)	FEMTO-ST Institute, Department of Applied Mechanics (Besançon - France)		
Supervisor(s)	Najib Kacem (UMLP), Valentin Calisti (UMLP), Noureddine Bouhaddi (UMLP)		
Start date	01/10/2026	**Duration**	3 years
Salary	About 2300 euros/month (gross salary)		
FUNDING	Ministère de l'Enseignement supérieur, de la Recherche et de l'Espace		

Job description

1. Context

Space (mode) localization in periodic structures is a fundamental phenomenon in engineering science, characterized by the confinement of vibrational energy within a limited spatial region due to the exponential decay of wave amplitudes. In linear periodic systems, such localization arises when **weak coupling** between substructures is combined with structural mistuning, as exemplified by **Anderson localization**, where material imperfections lead to wave attenuation and energy trapping. In contrast, **nonlinear periodic systems** can exhibit strong localization even in the absence of defects. Under weak coupling conditions, these systems support **Nonlinear Normal Modes (NNMs)**, including soliton-like excitations, also referred to as intrinsic localized modes or discrete breathers, which are highly stable and play a central role in energy transport mechanisms. Seminal contributions, such as the Fermi–Pasta–Ulam–Tsingou experiment and the derivation of the Korteweg–de Vries equation, have demonstrated the persistence of energy localization in nonlinear lattices. These phenomena have since been extensively explored in engineering systems, including coupled oscillators and granular media, revealing complex dynamics governed by nonlinear wave propagation and energy confinement.

Within the research activities of the DSMART team in the Department of Applied Mechanics at FEMTO-ST Institute, the experimental work has primarily demonstrated the feasibility of vibration energy harvesting based on Anderson localization, as well as its effectiveness in enhancing VEH performance in terms of frequency bandwidth and harvested energy. It has also shown the nucleation of solitary waves in a metastructure based on magnetic coupling, and how tuning disorder can improve the stability of nonlinear energy localization. On the theoretical side, it has been established that topological metamaterials provide a powerful framework for **highly sensitive and robust inertial sensing**. In particular, gyroscopic metamaterials exploit acceleration-induced modifications of the band structure, where variations in edge-state bandwidth enable sensing mechanisms that outperform conventional approaches while remaining robust to defects. In parallel, valley phononic metamaterials have been proposed for **three-axis sensing**, where acceleration drives energy localization and rotation induces measurable phase shifts. Through interface engineering, these systems achieve independent multi-axis measurements with very low cross-sensitivity.

Despite these advances, the **integrated design of quasiperiodic nonlinear topological metastructures** capable of simultaneously achieving optimized vibration energy harvesting and sensing functionalities remains an open challenge. Addressing this gap requires further investigation into the coupled roles of nonlinearity, disorder, and topology in shaping wave localization and energy transfer.

2. Objective

The principal goal of this thesis consists in the design of a novel class of **disordered nonlinear topological metastructures** specifically engineered to enhance and control energy localization. The core objective is to exploit the interplay between nonlinearity, disorder, and topology to achieve superior performance in vibration-based applications. To this end, the study will focus on: (i) introducing **tunable coupling mechanisms** to regulate inter-element interactions and maximize localization intensity for improved energy harvesting and sensing; (ii) incorporating **tunable nonlinearities** to enable the controlled generation of solitons and multi-soliton states, thereby extending localization phenomena beyond the classical Anderson framework; and (iii) designing **controlled disorder** to enhance localization robustness, facilitate soliton nucleation, and improve energy control efficiency.

Furthermore, the project will integrate **topological optimization at multiple scales**, encompassing both the unit-cell level and the overall structural configuration, to systematically tailor the metastructure dynamic response. In parallel, **higher-order asymptotic homogenization techniques** will be employed to derive effective nonlinear wave equations, enabling a reliable description of large-scale behavior while incorporating the effect of complex interactions at the unit-cell levels. Indeed, the real system exhibits intricate small-scale features, such as geometry, nonlinearities, and disorder, that strongly govern its global response. A central challenge is therefore to establish a rigorous link between scales, namely: **how microscale complexities shape and control large-scale wave dynamics and energy localization**.

Ultimately, these advanced metastructures are envisioned as multifunctional systems capable of simultaneously harvesting vibration energy and performing sensing tasks, thereby establishing a new paradigm for efficient, adaptive, and robust energy management in engineered structures.

3. Positioning and integration within FEMTO-ST

The use of solitons has been widely explored in fields such as optics and acoustics, where their remarkable properties for energy localization and robust wave propagation are well established. Extending these concepts to nonlinear mechanics, particularly for vibration-based energy harvesting and sensing through the collective dynamics of quasiperiodic topological metastructures, represents a highly innovative and forward-looking research direction. Such an approach opens new avenues for exploiting nonlinear wave phenomena to enhance performance, adaptability, and resilience in engineered systems. However, its implementation is particularly challenging, as it involves multiple scientific and technical issues, including the need for advanced theoretical modeling, numerical simulations, and precise experimental validation. These challenges require a strong multidisciplinary framework, combining expertise in nonlinear dynamics, materials science, and system integration. Collaboration with other departments within FEMTO-ST Institute are envisaged to support the successful development and realization of the proposed devices.

4. PhD tasks

The PhD project will involve the implementation of higher-order asymptotic homogenization methods to accurately capture the complex behavior of the proposed metastructures across multiple scales, followed by the development of a multiscale topological optimization framework to achieve optimal structural and functional performance. In parallel, uncertainties quantification and qualification of key design parameters will be carried out to assess the robustness and reliability of the proposed solutions under variability and external perturbations. The project will also include the fabrication of quasiperiodic topological metastructures, enabling the confirmation of the phenomena involved (Proof-of-Concept) and the validation of theoretical and numerical predictions. Finally, the PhD student will focus on the device miniaturization and its co-integration with an advanced electronic circuit, paving the way for practical implementation in compact and efficient vibration energy harvesting and sensing systems.

Candidate profile

The candidates should have a master degree in applied mechanics, physics or applied mathematics. They have to prove their relevant knowledge in the following disciplines: vibrations, nonlinear dynamics and advanced numerical methods. The candidate must perform extensive computer simulations and data analysis. A disposition for both numerical and experimental works is required. Proficiency in English is important.

Application

The application consists of ONE pdf-file comprising:

- Curriculum Vitae with list of publications
- Short summary of the master's thesis
- Suggestion of two referees with contact details
- Provide detailed explanation justifying your choice for this PhD project

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