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Numerical Vibro-Acoustic Characterization of Aerospace Structures Made of Miura-Ori Origami Metamaterial

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Abstract The objective of this work is to define a method for evaluating the dynamic characteristics of a Miura-origami acoustic metamaterial panel. The metamaterial must be able to absorb the noise generated by an aircraft and shield the passenger cabin from it. The Miura-origami metamaterial is a periodic corrugated plate. The acoustic properties can be derived from the calculation of the dispersion curves, given the mechanical properties of the structure. The former are obtained using the Wave Finite Element Method, the latter using a Layer-Wise approach based on Carrera's Unified Formulation. The method is applied to a starting configuration of the metamaterial's unit cell.

Introduction

Acoustics, a branch of physics concerning the generation, propagation, detection, and conversion of sound waves, is playing an increasingly important role in modern engineering. With the advent of acoustic metamaterials (AMMs), the manipulation of complex sound and vibrations has become possible. Due to their distinctive engineering properties determined by the precisely structured geometries at the macro level, they have been artificially designed to address the noise and vibrations problem which cannot be solved with naturally occurring materials and are often used for efficient sound absorption and insulation as well as negative refraction, wave steering, and filtering.

AMM for aeronautical use has been developed in various studies [1, 2, 3], particularly for low-frequency noise, which is the primary source of noise in an aircraft. The advantage is the possibility of obtaining efficient, lightweight materials. In particular, AMM panels can be inserted into the cavity between the fuselage and the cabin as the core of a sandwich, replacing the traditional material [4, 5] (usually Nomex). In this case, the AMM must also guarantee a minimum level of mechanical strength. In this work, Miura-origami-shaped panels were chosen [6]. These materials are suitable for insertion into a sandwich and offer various production options for different materials, ranging from plastics to carbon fiber.

The presence of complete and partial bandgaps will be evaluated employing the wave finite element method (WFE) [7, 8]. The developed method enables the calculation of dispersion curves for periodic materials. The structure is described according to the Carrera's Unified Formulation (CUF) framework for beams, plates, and shells, which embeds a wide class of powerful refined 2D plate theories exploiting the finite element (FE) approximation

[9].

Among these, layer-wise (LW) approaches, that suppose the composite structure as made of independent layers so that it is possible to have a 3D description of the stress-strain state in the material, makes it possible to evaluate the power radiated by the plate in a given layer, so the one opposite to the layer on which the acoustic wave breaks. LW theories have also been proved to be able to model the vibro-acoustic behaviour of structures with low computational costs and high accuracy, particularly in the case of multilayer orthotropic materials, which gives the opportunity for future developments in the manufacturing and analysis of the Miura-Ori structure as a carbon fibre reinforced polymer (CFRP) composite material. Finally, numerical simulations will be validated against experimental results, conducted by impedance tube system and anechoic chamber.

In conclusion, the development and characterization of an acoustic origami-inspired metamaterial is proposed in this work in order to address the noise and vibration problem in aircraft cabins. The aim is to obtain an accurate evaluation of the dynamic behaviour of an ABS Miura-Ori plate, an origami-inspired acoustic metamaterial, parametrized according to the unit cell shown in Fig. 1.

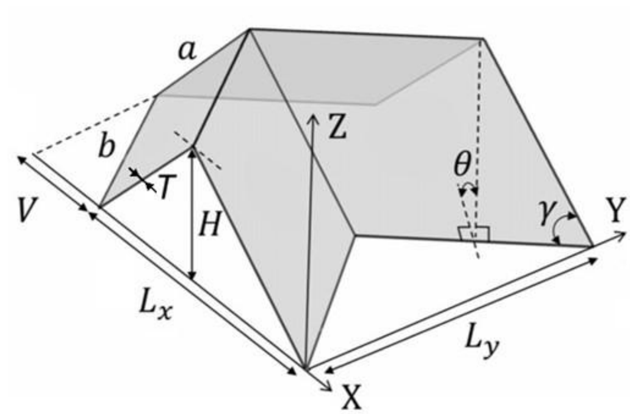

Figure 1: Periodic unit cell of the Miura-Ori plate.

Wave finite element and numerical approximation

The WFE is a powerful tool for understanding the energy transfer mechanism of a structure. This method has gained popularity in the study of infinite periodic structures, enabling the calculation of dispersion curves [10].

Considering a $x - y$ plate made of an infinite periodic repetition of unit cells with N degrees of freedom (DOFs) and assuming both forces and displacements are harmonic in time, the kinematic field is described in the frequency domain by the following relation:

$$(\boldsymbol{K} - \omega 2\boldsymbol{M})\boldsymbol{q} = \boldsymbol{F} \qquad \widetilde{\boldsymbol{D}}(\omega)\boldsymbol{q} = \boldsymbol{F} \tag{1}$$

with **K**, **M** being the $N \times N$ stiffness and mass matrices, and **q** and **F** the $N \times 1$ nodal displacement and external forces vectors. The angular frequency is ω. The mass and stiffness matrices are merged in the dynamic stiffness matrix $\widetilde{\boldsymbol{D}}$.

According to the Bloch's theorem, due to the periodicity of the medium and the equilibrium of the forces, the propagation of the free waves depends only on the reduced displacement vector $\widetilde{\boldsymbol{q}}$:

$$\boldsymbol{q} = \boldsymbol{R}\widetilde{\boldsymbol{q}} \qquad \boldsymbol{R}'\boldsymbol{F} = 0 \tag{2}$$

where **R** is the periodicity matrix and **R**′ is the conjugate transpose of **R**. Combining Eq. 2 in Eq. 1, the generalized dispersion eigenvalue problem is obtained:

$$\left(\boldsymbol{R}'\widetilde{\boldsymbol{D}}(\boldsymbol{\omega})\boldsymbol{R}\right)\widetilde{\boldsymbol{q}} = \boldsymbol{0} \tag{3}$$

in which $\widetilde{\boldsymbol{D}}$ is a function of the wave numbers k_x and k_y ($\lambda_x = e^{-jk_x\Delta x}$ and $\lambda_y = e^{-jk_y\Delta y}$, where Δ_x and Δ_y are the dimensions of the unit cell in x and y).

Solving the problem for λ_y with a direct approach (providing ω and λ_x), Eq. 3 becomes a quadratic equation:

$$\left(\boldsymbol{A_2}\lambda_y^2 + \boldsymbol{A_1}\lambda_y + \boldsymbol{A_0}\right)\widetilde{\boldsymbol{q}} = 0 \tag{4}$$

The full definition of the matrices for different finite elements is reported in [7, 8].

According to the CUF, the displacement vector **u** for a plate in the finite element approximation is written as:

$$\mathbf{u}(x,y,z,t) = F_\tau(z)N_i(x,y)q_{i\tau}(t), \quad 1 \le i \ge n_e, \quad 1 \le \tau \ge M \tag{5}$$

with $F_\tau(z)$ the thickness functions, $N_i(x,y)$ the Lagrangian finite element shape functions. The order of the shape function is defined by the number of nodes in the element, n_e (i is the nodal index in the element), while the order of the thickness depends on the number M which define the structural theory (τ is the nodal index through the thickness). The WEM has been already validated in [8] for different thickness functions. In this work, Lagrange polynomials are used.

Case study

In this work, the use of WEM is extended to a corrugated metamaterial plate. The unit cell, derived from [6], is shown in Fig. 1. As a case study, an ABS (Young modulus E =2.2 GPa, Poisson ratio ν = 0.35 and density ρ =1040 kg/m^3) cell is used for future experimental comparisons, with a thickness of 1.5 mm and dimensions as shown in Tab 1. The FEM analysis is made using 16 quadrangular elements with four nodes Q4 (four Q4 per face) and three nodes along the thickness (LW2). To manage the edges, the formulation in [11] is used, which allows for unconventional, distorted 3D elements (a combination of 2D FEM and 1D thickness functions). The periodic conditions are shown in Fig. 2. The problem has 19 independent nodes, with a total of 171 DOFs. Results are calculated from 0 Hz to 20000 Hz. The dispersion curves of the real part of the wave number are reported in Fig. 3 and Fig. 4 for k_x and k_y respectively.

Table 1: Dimension of the unit cell in Fig. 1. Lengths are in mm and angles in degrees.

L_x	L_y	V	H	T	a	b	θ	γ
59.9	52.5	26.7	26.5	1.5	40.0	40.0	60	42

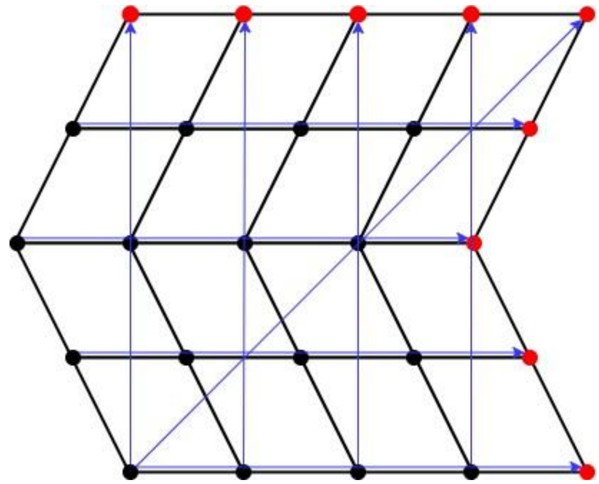

Figure 2: Periodic boundary conditions applied to the unit cell. Black nodes are independent, red dependent and the arrows show the dependency.

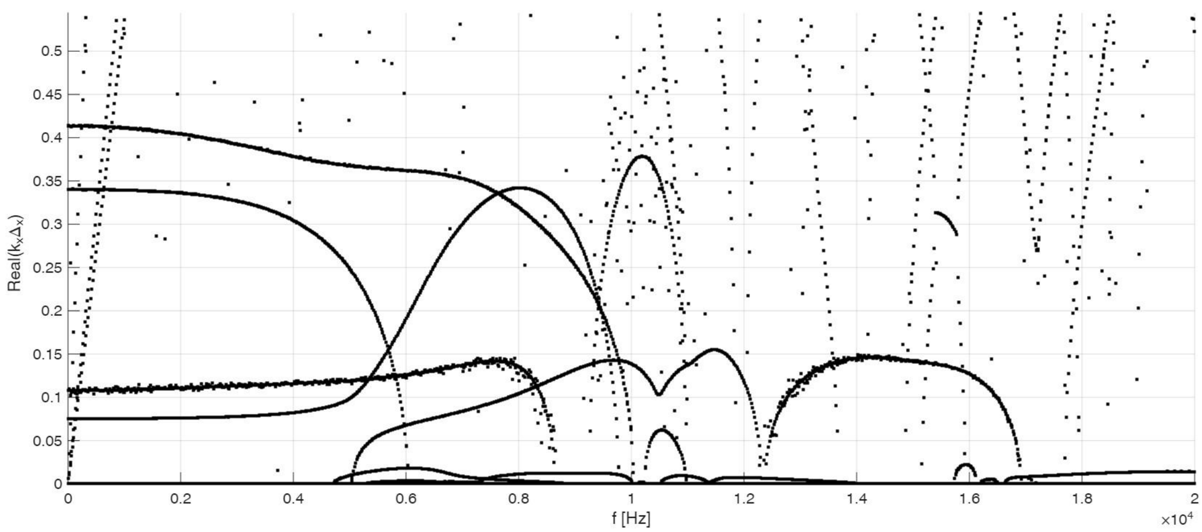

Figure 3: Real part of the dispersion curve in x.

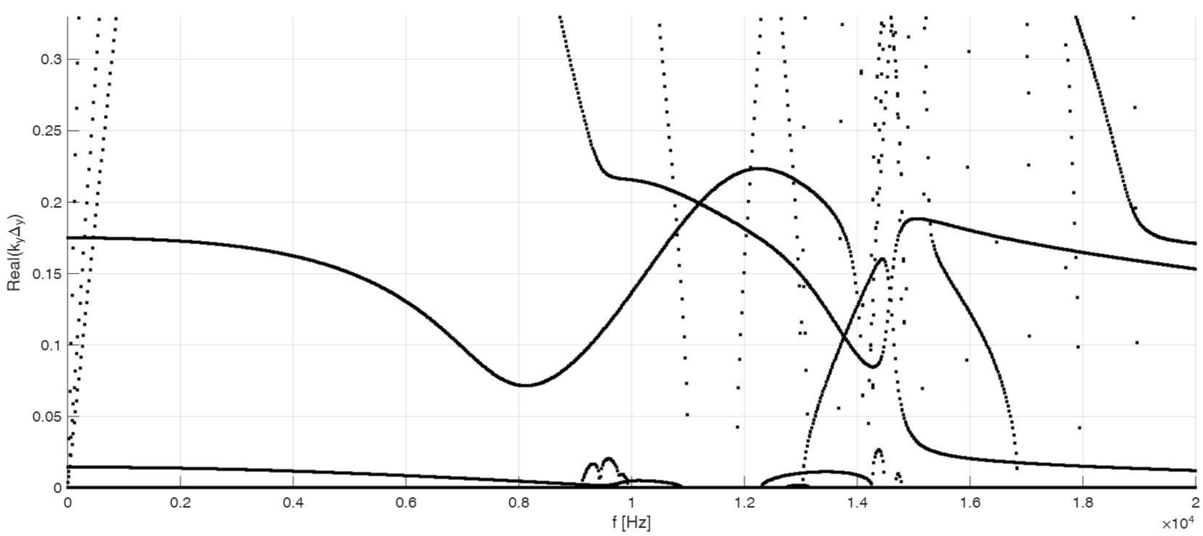

Figure 4: Real part of the dispersion curve in y.

Conclusions

Thanks to WFE, it is possible to calculate dispersion curves for a periodic material. In this work, we combine the potential of a LW approach with that of WFE to calculate dispersion curves for a corrugated metamaterial. A future development will be to calculate transmission loss based on the results obtained.

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