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Magnetorheological tunable auxetic structure for energy harvester mounting

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Abstract This paper presents a numerical analysis of a tunable sandwich structure with an auxetic and non-auxetic core filled with magnetorheological fluid. The proposed composite structure is intended for adaptive mounting systems used in vibration energy harvesting applications. The influence of the magnetic flux density and cellular core geometry on the static and dynamic properties of the structure was investigated using the finite element method implemented in COMSOL Multiphysics. The analysed structures were based on rotating geometries capable of exhibiting auxetic behaviour depending on geometric parameters. The magnetorheological fluid properties were modelled as a function of magnetic flux density, enabling active control of the effective stiffness of the composite. Numerical simulations included static analysis, eigenfrequency analysis, and frequency response analysis for magnetic flux densities ranging from 0.05 to 1 [T]. The obtained results demonstrated that increasing the magnetic flux density significantly modifies the dynamic response of the structure. The auxetic core exhibited higher stiffness sensitivity to magnetic field variations compared to the classical non-auxetic structure. The proposed concept enables adaptive tuning of structural dynamic properties and may improve the operational efficiency of vibration energy harvesters operating under variable excitation frequencies.

Keywords: auxetic, tunable, metamaterial, FEM, MR fluid, magnetorheological fluid, energy harvester.

1. Introduction

All machines and devices require a constant energy supply to operate, most commonly electrical energy. Conventional energy sources, such as batteries, do not perform well under all conditions and additionally have limitations such as limited lifespan and high replacement costs. In recent years, solutions have been developed to obtain energy not only directly from electrical sources, but also through the conversion of one form of energy into another. The most commonly converted forms are solar energy, biomass energy , and wind energy. Another possibility is the conversion of energy generated by the machine itself, which is not directly utilized to perform work. In most cases, the energy that is not transformed into useful work is dissipated in the form of vibrations. This method of conversion can be divided into three energy harvesting techniques [1]: piezoelectric (a piezoelectric element deforms due to machine vibrations, generating an electric charge), electromagnetic (motion between a magnetic field and a coil induces current flow in the circuit), and electrostatic (stored energy flows between capacitors, enabling the conversion of energy into electrical energy).For this reason, some machines are equipped with an energy harvester. This is a device used to convert unused kinetic energy into a form that can be reused by the machine. Most commonly, harvesters extract energy from the machine's vibrations and convert it into electrical energy used to power the machine's own systems [2, 3]. The analysis of the impact of parameters on the operation of harvesters was also presented in the studies [4, 5].

The main disadvantage of these devices is that they can operate only within resonant frequency ranges, which affects their efficiency. If the vibrations occur outside this range, the efficiency of the device becomes very low and the harvester will not perform effectively. Moreover, even if the machine initially operates at the harvester's resonant frequency, the frequency may change during operation, causing the harvester to no longer fulfill its function. One possible solution is to move the mass responsible for generating vibrations during operation [6], or to use a magnetorheological fluid [7].

The proposed adaptive structure may be particularly useful for vibration energy harvesters operating within low and medium frequency ranges. Typical piezoelectric and electromagnetic vibration harvesters are characterized by narrow operational bandwidths and high sensitivity to changes in excitation frequency. For example, the electromagnetic vibration energy harvester investigated by Ibrahim et al. [4]

operates in a frequency range below 100 Hz and utilizes tunable dynamic properties to improve energy conversion efficiency. Similarly, magnetorheological fluid-based vibration harvesters described by Sciuto et al. [7] demonstrated the possibility of adaptive resonance tuning through changes in magnetic field intensity.

Therefore, this study proposes a composite structure composed of a cellular material filled with magnetorheological fluid. Dynamic problems of elastic solids and sandwich panels were previously considered by many researchers. For structures such as composite sandwich plates, various models were proposed in papers [8-11].

In this paper the influence of the cellular structure geometry and the magnetic field on the vibrations of the structure was analyzed. The composite structure with variable properties can be used as a base for mounting a harvester, enabling the adjustment of dynamic properties through the influence of an external magnetic field and thereby ensuring higher harvester efficiency. The cellular structure of the composite is based on rotating unit cells, which, depending on specific values of geometric parameters, may exhibit auxetic properties.

Auxetic materials, characterized by a negative Poisson's ratio, are currently the subject of extensive research. Among others, the behavior of auxetic structures subjected to bending has been analyzed [12]. Due to their unique properties, numerous studies have focused on the dynamic properties of these materials [13], their resistance to impact loading [14], mechanical impedance [15], as well as applications in biomedical engineering [16].

In particular, the behavior of metamaterials, including auxetics with magnetic properties subjected to an electromagnetic field, has also been investigated [17]. Furthermore, the possibility of actively influencing and controlling the value of the metamaterial's Poisson's ratio by means of an external magnetic field has been considered [18, 19].

2. Modelling of the structure

2. 1. Geometrical model

In the analysed problem, the mechanical properties of a sandwich panel with an auxetic and non-auxetic core are investigated. The core consists of a solid pattern and voids filled with magnetorheological fluid (material) (Fig. 1). In Figure 1, the grey colour denotes fluid (magnetorheological fluid), and the purple colour denotes solid material (silicon). A two-dimensional geometrical model is used in analysis with dimensions $W \times H$ (width x height). Each of the two outer face sheets has height H_S. The core height is H_C.

The plane strain computational solid mechanics model is used [20]. Plane strain is a two-dimensional solid mechanics condition where all deformations occur in a single plane, and the strain in the perpendicular direction is zero. It is used to simplify complex 3D problems and is frequently applied to long, cylindrical objects or structures constrained along their length.

Dimensions of the sandwich panel are: width: $W = 1$ [m], height: $H = 0.135$ [m] ($H_C = 0.125$ [m] for core and $H_S = 0.005$ [m] for each sheet face), and depth: $D = 1$ [m] so that the area of the top and bottom surface $A = W \times D$. Properties of the used material are presented in Table 1. Geometry of the core was described by Mrozek and Strek [13].

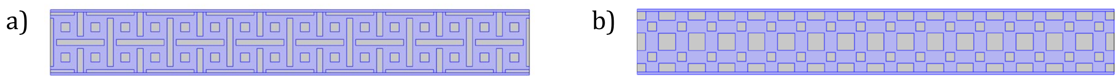

Figure 1. Geometry of sandwich panel with (a) auxetic structure,
(b) non-auxetic structure (classical rectangular structure).

2.2. Mathematical model

The analysed problem can be characterized by the governing equations of the motion of elastic structures under small deformations (displacements and total elastic strain energy), and dynamic properties (eigenfrequencies, frequency response for total elastic energy).

The Navier's equation of motion can be written in displacement formulation as:

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} - \nabla \cdot \mathbf{S} = \mathbf{F}_{\mathrm{V}}, \tag{1}$$

where: ρ is the density, $\mathbf{u}$ is the vector of displacements, $\mathbf{u} = [u, v, w] = [u_1, u_2, u_3]$, $\mathbf{S}$ is the stress tensor, $\mathbf{F}_{\mathrm{V}}$ is the volume force vector (e.g. gravity force).

The total stress **S** in Hooke's law (constitutive equation, relation between stresses and deformations) is:

$$\mathbf{S} = \mathbf{C} : \boldsymbol{\varepsilon}, \tag{2}$$

and the elastic strain tensor $\boldsymbol{\varepsilon}$ is:

$$\boldsymbol{\varepsilon} = \frac{1}{2}\left((\nabla\mathbf{u})^T + \nabla\mathbf{u}\right). \tag{3}$$

In the case of the isotropic linear material the elasticity matrix becomes as follows:

$$\mathbf{C} = \frac{E}{(1+\nu)(1-2\nu)}\begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix}. \tag{4}$$

The above relationship describing the material properties is based on Young's modulus and Poisson's ratio. This formulation is particularly important in the analysis of auxetic metamaterials. On the other hand, the properties of magnetorheological fluids are usually described using the shear modulus (G) and bulk modulus (K). Therefore, Equation (4) can also be expressed in terms of these parameters:

$$\mathbf{C} = \begin{bmatrix} K+\frac{4}{3}G & K-\frac{2}{3}G & K-\frac{2}{3}G & 0 & 0 & 0 \\ K-\frac{2}{3}G & K+\frac{4}{3}G & K-\frac{2}{3}G & 0 & 0 & 0 \\ K-\frac{2}{3}G & K-\frac{2}{3}G & K+\frac{4}{3}G & 0 & 0 & 0 \\ 0 & 0 & 0 & 2G & 0 & 0 \\ 0 & 0 & 0 & 0 & 2G & 0 \\ 0 & 0 & 0 & 0 & 0 & 2G \end{bmatrix}. \tag{5}$$

Relations between the Young's modulus, Poisson's ratio and shear and bulk modulus:

$$E = 2G\cdot(1+\nu),\ \nu = \frac{3K-2G}{2(G+3K)} \text{ and } G = \frac{E}{2(1+\nu)},\ K = \frac{E}{3(1-2\nu)}. \tag{6}$$

2.3. Properties of materials

In the paper [21], the authors investigated the behaviour of the MR within the framework of continuum mechanics. A two-dimensional asymmetric MR damper was investigated and analysed using the finite element method. Furthermore, the magnetic flux density was obtained through the MR fluid gaps in the 2-D MR damper. The magnetorheological fluid was modelled using an equivalent linear elastic approach with magnetic-field-dependent material properties.

The magnetorheological fluid shear modulus is assumed to be a function of the magnetic flux density. The shear modulus of magnetorheological material (fluid) data for Lord MRF-132AD MR fluid was calculated using Eq. (7) as shown in Figure 2, and it was characterized by a 4th order polynomial of the form [21, 22]:

$$G(B) = 6894.76\cdot(6.298\cdot B^4 - 25.824\cdot B^3 + 26.639\cdot B^2 - 0.438\cdot B\ ), \tag{7}$$

where B [T] is the value of the magnetic flux density and G is the shear modulus [Pa]. The range of the magnetic flux density used in computations ranged from 0.05 [T] to 1 [T].

Table 1. Properties of materials in sandwich panel.

Material	Density, ρ [kg/m^3]	Young modulus, E [Pa]	Poisson's ratio, ν [-]	Shear modulus, G [Pa]	Bulk modulus, K [Pa]
silicon	2329	170e9	0.28	6.6406E10	1.2879E11
MR fluid (0.05T)	4000	8.59e2	0.499	286.19	1e9
MR fluid (1T)	4000	1.38e5	0.499	46022.52	1e9

Magnetic flux density describes the magnetic field acting inside the material and is commonly used to characterize magnetorheological devices. Magnetic flux density is a vector measure of the strength and direction of a magnetic field.

It is important not to confuse magnetic flux density with magnetic field intensity (strength) (H) (measured in Ampere per meter [A/m]) represents the applied magnetising force from an external source or electric current. Magnetic flux density (or magnetic induction) represents the actual, resulting magnetic field inside a material or vacuum. These two quantities are related by the permeability (μ) of the medium through the equation: ($B = \mu H$), where permeability is the product of the permeability of free space (μ_0) and the relative permeability of the material (μ_r).

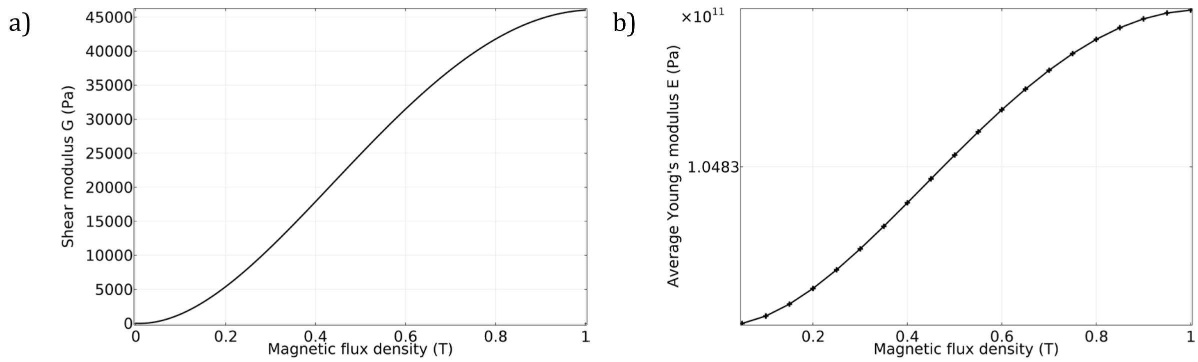

Figure 2. The functions of (a) the shear modulus of magnetorheological fluid, and (b) the effective value of Young's modulus of the sandwich Panel as a function of the magnetic flux density.

2.4. Finite element model

During the conducted analysis, three analyses were performed: steady state, eigenfrequencies and frequency response. In all steady state analyses, the vertical load at the top sheet face was applied. In dynamic analysis, the top wall was harmonically loaded with frequencies from 0 to 1000 [Hz]. In all cases, left and right boundaries are fixed, and the gravity volume force is applied.

Numerical computations were conducted by Comsol Multiphysics [20] with use of the finite element method [23]. Number of elements used in computations was: 6306 second-order triangle elements for auxetic structure (Figure 3a) and 6440 triangles with second-order Lagrange polynomial shape function for non-auxetic structure (Figure 3b):

Figure 3. Finite mesh elements for sandwich panel with (a) auxetic core, and (b) non-auxetic core.

A mesh convergence study was performed in order to verify the numerical stability of the obtained results. Further mesh refinement produced negligible changes (differences below 0.8%) in displacement and eigenfrequency values, confirming the adequacy of the adopted finite element discretization

2.5. Boundary conditions

Definition of boundaries of analysed samples:

- left boundary (LB): $x = 0$ and $y \in \langle 0, H \rangle$;
- right boundary (RB): $x = W$ and $y \in \langle 0, H \rangle$;
- bottom boundary (BB): $y = 0$ and $x \in \langle 0, W \rangle$;
- top boundary (TB): $y = H$ and $x \in \langle 0, W \rangle$.

Boundary conditions (BC) applied to the analysis of the mechanical properties of the structure with load applied at the top boundary are in the vertical y-direction:

- boundary (RB): fixed BC: $\mathbf{u} = \mathbf{0}$;
- boundary (LB): fixed BC: $\mathbf{u} = \mathbf{0}$;
- boundary (BB): free BC;
- boundary (TB): applied force: $\mathbf{S} \cdot \mathbf{n} = \mathbf{F}_A$, where $\mathbf{F}_A = \left[0, \frac{F_0}{A}\right]$.

Boundary conditions (BC) applied to the analysis of dynamic properties of the structure with load applied at the top boundary are in the vertical y-direction:

- boundary (RB): fixed BC;
- boundary (LB): fixed BC;
- boundary (BB): free BC;
- boundary (TB): harmonic excitation force BC: $\mathbf{S} \cdot \mathbf{n} = \mathbf{F}_A e^{i\phi}$, where $\mathbf{F}_A = \left[0, \frac{F_0}{A}\right]$, the value of $F_0 = 1\times10^6$ [N] and $\phi = 0$ [rad].

3. Results and discussion

Figures 4 and 5 present the numerical results obtained for sandwich panels with auxetic and non-auxetic cores filled with magnetorheological fluid. The analyses included static calculations, eigenfrequency analysis, and frequency response analysis for magnetic flux densities ranging from 0.05 [T] to 1 [T].

In general, the obtained results show that both the magnetic field intensity and the type of cellular structure strongly affect the dynamic behaviour of the analysed structures. In both cases, increasing the magnetic flux density caused a reduction in displacement and elastic strain energy. This is mainly related to the increasing stiffness of the magnetorheological fluid when subjected to an external magnetic field.

For the auxetic structure, the maximum total displacement decreased from approximately 0.5974 [mm] to 0.59738 [mm] as the magnetic flux density increased (Fig. 4a). The total elastic strain energy also slightly decreased, from about 182.12 [J] to 182.10 [J] (Fig. 4b). Although these changes are not very large, a much stronger effect can be observed in the natural frequencies. The first eigenfrequency increased from around 19 [Hz] to more than 240 [Hz] (Fig. 4c), which indicates a noticeable change in the effective stiffness of the structure. A similar relation was observed for the non-auxetic structure. The displacement and strain energy also decreased with increasing magnetic flux density (Fig. 5a-b). However, the changes in eigenfrequencies were significantly smaller. In this case, the first natural frequency increased from approximately 9 [Hz] to 112 [Hz] (Fig. 5c). This suggests that the classical cellular structure is less sensitive to changes in the magnetic field than the auxetic one.

Comparing both cases, it can be noticed that the auxetic geometry provides much wider tunability of dynamic properties. This behaviour is most likely related to the deformation mechanism of the rotating unit cells, which react more strongly to changes in the effective properties of the magnetorheological filling. The frequency response plots shown in Figures 4d and 5d are particularly important. For the auxetic structure, the frequency response is dominated by a relatively narrow resonance region with one major peak and several smaller local resonances (Fig. 4d). Compared to the non-auxetic structure, the response appears more ordered and concentrated within a narrower frequency range.

However, the non-auxetic structure exhibits several resonance peaks distributed over a much wider frequency range (Fig. 5d). In some regions, a strong increase in total elastic strain energy can be observed, especially for selected values of magnetic flux density. This might indicate the occurrence of local resonance effects and stronger vibration amplification.

Considering energy harvesting applications, both behaviours may be useful depending on the operating conditions. The broader resonance range observed for the non-auxetic structure could potentially increase the probability of matching external excitation frequencies. However, such behaviour may also lead to less stable operation and stronger local vibrations. In contrast, the auxetic structure shows a more controlled and predictable response, which may be advantageous in adaptive systems where stable tuning of resonance frequencies is required.

The obtained results also confirm that the magnetorheological fluid can effectively act as an active tuning medium. Increasing the magnetic flux density changes the effective shear modulus of the fluid, which directly affects the stiffness and dynamic response of the entire structure. As a result, the proposed system may be considered as a tunable mounting platform for vibration energy harvesters operating under varying excitation conditions.

The obtained results confirm that the auxetic structure provides a wider range of dynamic tuning compared to the classical cellular structure.

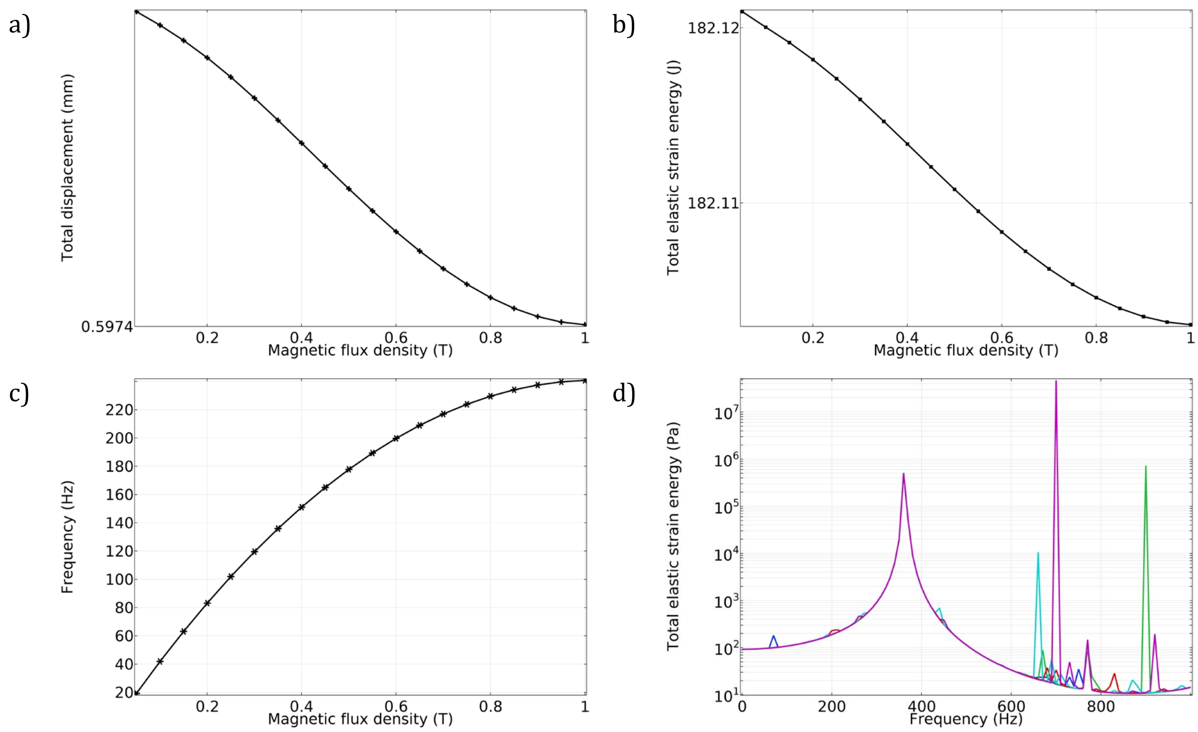

Figure 4. Numerical results for the sandwich panel with an auxetic core: (a) maximum displacement, (b) total strain energy, (c) first eigenfrequency, and (d) frequency response of the total elastic strain energy for different magnetic flux densities (mfd parameter).

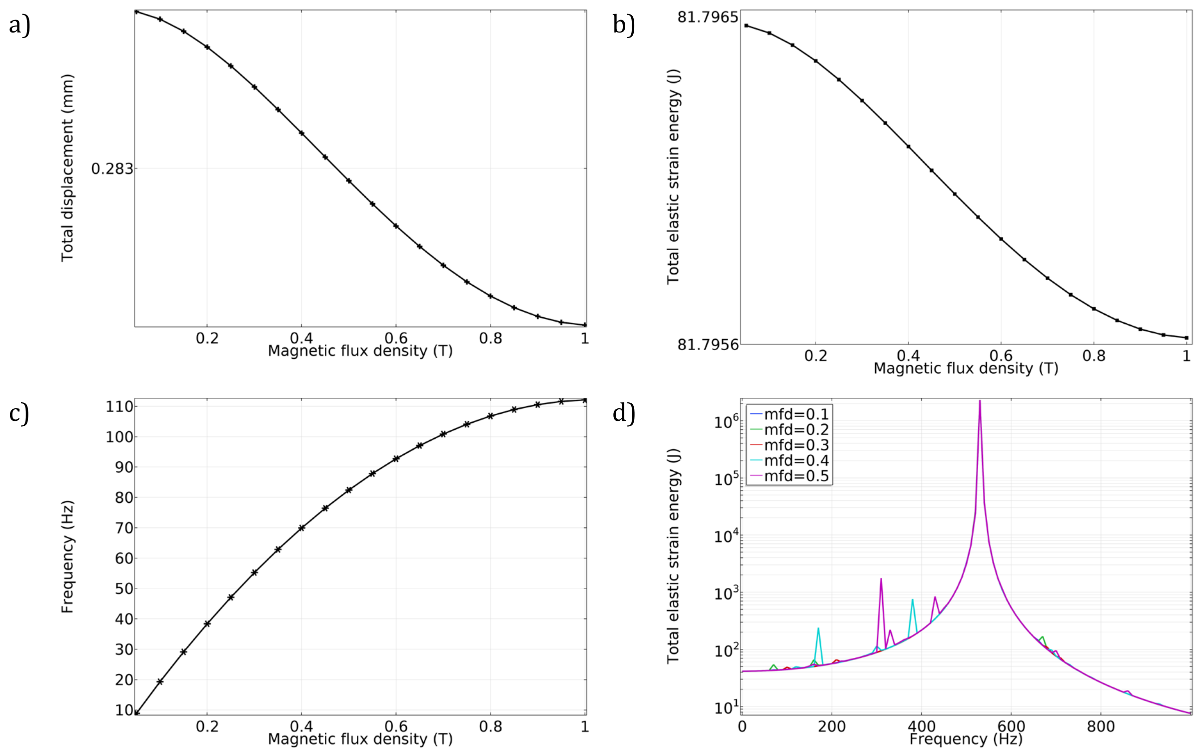

Figure 5. Numerical results for the sandwich panel with a non-auxetic core: (a) maximum displacement, (b) total strain energy, (c) first eigenfrequency, and (d) frequency response of the total elastic strain energy for different magnetic flux densities (mfd parameter).

4. Conclusions

The present study investigated the static and dynamic behaviour of sandwich structures with auxetic and non-auxetic cores filled with magnetorheological fluid. Numerical simulations performed using the finite element method demonstrated that the application of an external magnetic field significantly affects the mechanical and dynamic properties of the analysed structures.

An increase in magnetic flux density resulted in a decrease in total displacement and total elastic strain energy, accompanied by a substantial increase in the first natural frequencies. The auxetic structure exhibited a stronger sensitivity to changes in magnetic field intensity compared to the classical non-auxetic structure, indicating greater tunability of its dynamic response.

The obtained results confirm that the combination of auxetic cellular geometries with magnetorheological materials enables active control of structural stiffness and vibration characteristics. Such adaptive structures may be effectively applied as tunable mounting systems for vibration energy harvesters operating under varying excitation conditions.

It should also be noted that the present study is based on a simplified numerical model. In the performed analyses, damping effects were not included in order to focus primarily on the influence of the magnetic field and cellular geometry on the stiffness-related dynamic response of the structure. As a consequence, some resonance peaks obtained in the frequency response analysis may be sharper than those observed in real physical systems. Additionally, the proposed model has not yet been experimentally validated. The current work should therefore be treated as a preliminary numerical investigation intended to demonstrate the general behaviour and tunability of the proposed structure. More advanced modelling approaches, including damping effects, nonlinear material behaviour, and coupled multiphysics interactions, will be considered in future studies.

Further work will also include experimental investigations of physical prototypes in order to validate the numerical model and assess the practical applicability of the proposed magnetorheological auxetic structure in vibration energy harvesting systems.

Additional information

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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