Self-aware active metamaterial cell 3D-printed in a single process

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Abstract

Metamaterials are capable of attenuating undesired mechanical vibrations within a narrow band-gap frequency range; however, real-world applications often require adjustments due to varying loads and frequency content. This study introduces a self-aware, thermo-active metamaterial, 3D-printed in a single process using thermoplastic material extrusion. The adjustment of the natural frequency and band-gap region is achieved through resistive heating of conductive paths, which alters the stiffness of the base cell's resonator. Additionally, these conductive paths facilitate the detection of the resonator's excitation frequency and temperature, thereby eliminating the need for external sensors. This dynamic adaptability, experimentally demonstrated by achieving a band-gap tuning range from 505 Hz to 445 Hz with a 17°C temperature difference, highlights the potential of these metamaterials for

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applications in smart structures across the aerospace, civil, and automotive industries.

Keywords: metamaterials, 3D printing, thermo active, single process, piezoresistivity, material extrusion

1. Introduction

Metamaterials are intricately designed geometric structures that exhibit material properties not found in nature [1, 2]. These structures lead to tunable material characteristics such as negative or zero Poisson's ratios [3, 4, 5], effective Young's moduli [6], negative coefficients of thermal expansion [7, 8], and quasi-zero stiffnesses [9, 10]. The tunability of such properties makes metamaterials great candidates for applications in low-frequency vibration isolation [11, 12, 13], enhancement of sound transmission loss [14, 15, 16], or attenuation of elastic waves in structures [17, 18, 19, 20]. Ma et al. (2023) presented a tunable, locally resonant metamaterial that uses a chiral buckling structure to achieve vibration isolation at low frequencies. The design utilizes buckling to configure different stiffness levels that vary by up to an order of magnitude, resulting in different bandgap frequency attenuation ranges [12]. Similarly, Liu et al. (2024) presented a Kresling origami-inspired compression-twist coupled metamaterial structure that combines different unit cell designs to achieve bandgaps 350% wider than those of conventional Kresling structures at low frequencies [13]. In the field of sound transmission loss, Sal-Anglada et al. (2024) developed a multiresonant layered acoustic metamaterial that uses coupled resonances and a zero-stiffness response to create a triple-peak sound transmission loss effect [15]. Comandini et al.

(2023) investigated the sound transmission loss of 3D-printed Hilbert fractal acoustic metamaterials, providing an analytical formulation linking fractal patterns and acoustic cavity resonances to the maxima of the sound transmission loss [16]. For elastic waves attenuation, Hu et al. (2024) presented a 2D metamaterial wing model with bi-stable nonlinear resonators capable of dissipating transient vibrations, achieving a dissipation rate of over 75% [18]. Additionally, Li et al. (2024) demonstrated the tunable attenuation of longitudinal elastic waves in a metamaterial rod composed of piezoelectric semiconductor and piezoelectric materials, with a tuning capacitor exploiting the Bragg scattering effect [17].

Bragg-scattering [21] and local resonant metamaterials [22] are the two most common physical operation principles for elastic flexural wave manipulation [23]. Bragg-scattering metamaterials utilize periodic structures that create high impedance changes, causing the incoming and reflected waves to cancel out via destructive interference. For example, Geng et al. (2023) demonstrated this physical principle of flexural vibration suppression in pipes by periodically attaching sleeves to the existing pipe structure, thereby altering the effective cross-section of the pipe [24]. Bragg-scattering metamaterials are effective for wavelengths comparable to the metamaterial's base cell length, but less suitable for lower frequencies due to size constraints [25]. Conversely, local resonant metamaterials incorporate periodic local resonators, with their effectiveness relying not on the periodicity but on the resonators' spacing being much smaller than the target wavelengths [26]. When resonators induce a non-zero resultant force on the base structure, a Fano-type interference [27] is created around the resonators' frequencies, enabling attenuation in lower frequency ranges than those achievable with Bragg scattering, thus overcoming its limitations [28].

Local resonant metamaterials have been succesfully utilized for vibration attenuation [29]. Recently, the attenuation of flexural and longitudinal waves was presented by Li et al. (2024) with a spiral acoustic black-hole metamaterial, where the periodic cell consisted of a host structure and dual spiral resonators [30]. Similary, two-dimensional periodic additive acoustic black holes were proposed by Deng et al. (2024) to achieve vibration attenuation and high loss factor via local resonances [31]. Xu et al. (2024) explored the attenuation of torsional waves using a metamaterial shaft equipped with tunable local resonators possessing a quasi-zero stiffness. This effect is achieved through an arrangement of electromagnetic elements and a flexible rod connected in parallel, which collectively yield a quasi-zero stiffness effect [32]. Alternatively, Zhao et al. (2022) achieved band gaps through a carefully designed 3D chiral mechanical structure that converts longitudinal waves into transverse waves, resulting in attenuation of the longitudinal waves [33]. Yu et al. (2023) employed star-shaped re-entrant lattices and locally ruddershaped struts made from two-phase materials to not only attenuate the vibrations within a desired frequency range, but also to achieve an effective zero thermal expansion coefficient [34]. In contrast, Mazzotti et al. (2023) presented a non-self-similar hierarchical elastic metamaterial that couples local resonances with Bragg scattering and inertial amplification mechanisms to achieve broadband bandgaps at various frequency scales [35]. Bragg scattering and local resonances were also coupled with energy dissipation mechanisms using a two-dimensional square-lattice viscoelastic metamaterial presented by Mei et al. (2023) through a concept of spatiotemporal damping. Although the presented metamaterials exhibit exceptional performance, a common limitation is that the frequency range of the band gap becomes fixed once the design parameters are established.

Various physical principles can be used to alter a metamaterial's properties during operation, such as piezoelectric effect [17], magnetostriction [36, 37], electrodynamic force actuation [38] or temperature-dependent mechanisms [39]. Li et al. (2018) demonstrated broadband low-frequency wave attenuation using resonant metamaterials equipped with adaptive mechanical local resonators. the frequency-dependent stiffness of the resonators was achieved using piezoelectric sensors and actuators [40]. Gao et al. (2023) introduced broadband-gap active metamaterials with an optimal time-delayed control strategy [41]. Alternatively, Gorshkov et al. (2023) presented theoretical aspects of actively influencing the stopband in acoustic metamaterials using magnetorheological elastomers that change their stiffness when exposed to an external magnetic field [37]. Zhang et al. (2024) presented a magnetostrictive phononic crystal beam capable of dynamically manipulating longitudinal elastic waves through external magnetic, stress, and thermal loadings [36]. Jalšić et al. (2023) presented an active metamaterial cell capable of achieving non-reciprocal sound transmission by using concurrent velocity feedback loops with non-collocated sensor-actuator pairs, resulting in significant attenuation of vibration in one direction and increased transmission in the opposite direction over a wide frequency band. Temperature-dependent mechanisms offer another way to tune a metamaterial's properties. Li et al. (2019) proposed an electro-thermally tunable Hoberman spherical metamaterial. Utilizing a 3D-printed lattice and thermoelectric heaters, they successfully tuned band gaps by exploiting the Young's modulus-temperature relationship of glassy polymers with Joule heating [42]. Li et al. (2023) introduced a temperature-controlled quasi-zero-stiffness (TC-QZS) metamaterial beam utilizing shape-memory alloys (SMAs) for tunable, low-frequency, band-gap adjustment. By leveraging the negative-stiffness mechanism of an SMA and a nonlinear geometrical structure, they demonstrated a capability for broad-range frequency tuning with externally induced temperature changes [43]. Ma et al. (2023) introduced a thermally actuated metamaterial unit cell capable of reversible contact-driven snapping, enabling morphing structures that can sequentially snap into multiple locked configurations at predefined temperatures [44]. Zhang et al. (2024) introduced a topology-optimization strategy for designing elastic resonant metamaterials that enable thermally driven band-gap tuning to attenuate the flexural waves [39].

The complexity of metamaterial geometries often necessitates innovative fabrication methods, making additive manufacturing an ideal choice due to its ability to simplify multiple fabrication steps into a single process. Bilal et al. (2017) demonstrated the use of thermoplastic material extrusion (TME) in fully 3D printing two-dimensional phononic metamaterial plates with resonant cylinders, showcasing the production of local resonant band gaps [45]. Miranda et al. explored the creation of flexural wave band gaps in multi-resonator elastic metamaterial plates, employing 3D printing with photopolymer-jetting technology to study different lattice configurations [46, 47]. Mizukami et al. (2021) presented 3D-printed locally resonant carbon-fiber composite metastructures for the attenuation of broadband vibrations, utilizing TME with steel masses attached to resonators postprinting [48]. Lastly, Cai et al. (2022) presented a metamaterial beam designed for flexural wave attenuation, featuring compliant, quasi-zero-stiffness resonators partially fabricated with material extrusion [49].

TME enables the creation of smart functional structures beyond passive metamaterials. This is achieved by integrating electrically conductive components [50], sensor elements [51, 52], and actuation elements [53] in a single fabrication process. It can leverage various physical principles for sensory functions, including piezoresistive [54, 55, 56], piezoelectric [57, 58], and capacitive [59, 60], as well as for actuation purposes, such as dielectric [61], thermally active [62, 63], and electrothermal principles [64, 65].

Thermally active and electrothermal principles are frequently employed in the actuation of 3D-printed structures, as materials used in TME exhibit significant changes in Young's modulus, damping, and coefficient of thermal expansion (CTE) in response to temperature and 3D-printing parameters, as demonstrated by Krivic and Slavič (2023) [66]. Goo et al. (2020) showed that single thermoplastic material with programmed anisotropic thermal deformation properties can be used to achieve localized bending and therefore actuation [67]. Duan et al. (2022) demonstrated a 4D-printed structure exhibiting reversible deformation, facilitating the movement of a soft crawling robot. Locomotion was achieved with a bilayer structure, containing heating elements 3D-printed from conductive polyactic acid (CPLA) [68]. Similarly, Chen et al. (2023) utilized TME to create a quadruped robot with a shape-memory polymer, actuated by the electrothermal effect [69] and Wang et al. (2024) used electrothermal principle to actuate and control a 4D-printed origami, containing continuous fiber-reinforced composites [70]. Finally, Mostofizadeh et al. (2024) used 3D-printed lattice metamaterials with a conductive coating to achieve up to 94% stiffness reduction by applying electrical current, inducing structural softening [71].

Conductive polymers used in TME can exhibit piezoresistive properties [72, 73], a characteristic extensively studied by Arh et al. [74]. Arh and Slavič have explored its use in sensing, demonstrating CPLA's effectiveness in acceleration sensing across one and three axes [52, 75]. Additionally, Hainsworth et al. (2020) employed 3D-printed conductive PLA in a soft actuator designed to measure grip angles [76]. Furthermore, Palmieri et al. (2021) incorporated piezoresistive 3D-printed elements within structures for health monitoring, demonstrating the versatility and application breadth of 3D-printed piezoresistive materials [77]. It should also be noted that the conductive properties of 3D-printed electric pathways can significantly depend on the parameters of 3D printing [78, 79] and temperature [80, 81]. Dijkshoorn et al. (2024) demonstrated this dependency by fabricating a electric metamaterial direct current concentrator with tuned anisotropic electrical properties [82].

In this research, thermoplastic material extrusion is utilized to integrate electrothermal principles and piezoresistive sensing, fabricating an active, self-aware, locally resonant metamaterial cell. This cell is capable of adjusting its resonator natural frequency via the electrothermal principle and to detect the excitation frequency via the piezoresistive principle. The study primarily focuses on the design, manufacturing, and testing of a single metamaterial cell. The research is organized as follows: the necessary theoretical background is provided in Sec. 2, the design of the metamaterial cell is detailed in Sec. 3, the fabrication methods are described in Sec. 3.3, the experimental methods are outlined in Sec. 4, the results are presented and discussed in Sec. 5, and the capabilities of the metamaterial cell are further outlined in Sec. 5.4.

2. Theoretical Background

This section provides a concise overview of the theoretical foundations underpinning the study of locally-resonant metamaterials, which are designed to attenuate elastic waves within a specific frequency range of interest. It then delves into the principles of Joule heating, a mechanism by which the properties of metamaterials can be modified. Finally, the concept of piezoresistivity is introduced, highlighting its application in enabling metamaterials to possess self-awareness capabilities or to sense excitation frequencies.

2.1. Locally Resonant Metamaterials

Locally resonant metamaterials are composed of unit cells, each consisting of a base structure and an attached resonator. These metamaterials are capable of creating frequency-band-gap where free wave propagation is prohibited, enabling vibration and noise attenuation [29]. Arising from Fanotype interference between incoming and out-of-phase re-radiated waves by local resonators [28], these band gaps do not require periodicity for their formation; however, a sub-wavelength arrangement of local resonators is required [83]. It is essential for the natural frequency of the resonator, f_{res} , to be below the Bragg-interference-limit frequency, $f_{\lambda/2}$, to ensure the resonant band gap's formation [29]:

$$f_{\rm res} < f_{\lambda/2}.\tag{1}$$

At the frequency $f_{\lambda/2}$, local resonators are spaced at half the wavelength λ of the attenuation-targeted wave within the structure.

Primarily, the resonance frequency of the local resonator, $f_{\rm res}$, and the mass ratio, r_m , between the base structure and local resonator, influence the metamaterial's noise- and vibration-attenuation capabilities. The mass ratio is defined as [29]:

$$r_m = \frac{m_{\rm res}}{m_{\rm base}},\tag{2}$$

where $m_{\rm res}$ and $m_{\rm base}$ represent the masses of the resonator and base structure, respectively. An increase in the resonator frequency, while keeping the resonator mass constant, raises the center frequency of the band gap. Conversely, enlarging the mass ratio r_m without altering the resonator frequency broadens the band gap. For details the reader is referred to other literature, e.g.: [84, 85, 29].

2.2. Joule Heating

The band-gap frequency region can be modulated by exploiting the relationship between the Young's modulus and the temperature in glassy polymers with Joule heating [42]. Joule heating is a phenomenon where electric elements produce heat when they pass an electric current. For a direct electric current (DC), the heat generated in an element is equivalent to the electric power dissipated within that element [86]:

$$Q = P_{\rm el} = V I, \tag{3}$$

where Q denotes the heat generated in the electric elements, $P_{\rm el}$ is the electric power, V is the voltage drop across the electric element, and I is the electric current.

2.3. Piezoresistivity

Conductive materials used in thermoplastic material extrusion may demonstrate piezoresistive properties, whereby their resistance alters in response to mechanical strains within the material [74]. This property allows the measurement of mechanical strains within the material, provided that the conductive paths are appropriately designed. The piezoresistive effect can be quantitatively expressed using the Voigt-Kelvin notation as follows [52]:

$$\mathrm{d}\rho_i/\rho_{0i} = \xi_{ij}\varepsilon_j, \quad i, j = 1, \dots, 6.$$
(4)

Here, $d\rho_i/\rho_{0i}$ represents the change in relative resistivity, ξ_{ij} denotes the piezoresistive coefficients, and ε_j corresponds to the strains. Given the unidirectional deposition of material in thermoplastic material extrusion, the orthotropy can be assumed [87]. For more details on the piezoresistive effect in 3D-printed structures, the reader is referred to the research by Arh et al. [74].

3. Metamaterial Cell

This section introduces the concept and detailed design of an active metamaterial cell, designed to modulate its natural frequency and thereby alter its band-gap characteristics via Joule heating. Initially, the fundamental design and operational principles are discussed. This is followed by an examination of the metamaterial cell's design considerations for single-process 3D printing. The final part of the section provides an overview of the metamaterial cell's fabrication process.

3.1. General Active Metamaterial Cell Concept



Figure 1: Metamaterial cell design: a) active metamaterial cell, b) metamaterial cell's base structure, c) metamaterial cell's resonator (base structure removed) composed of inertial mass and 8 beam-like springs, d) metamaterial cell's beam-like spring, e) electric current flow direction through metamaterial cell

As shown in Fig. 1, the active metamaterial cell's design encompasses a base structure (Fig. 1 b)) and a resonator (Fig. 1 c)). The resonator is further composed of 8 beam-like springs (Fig. 1 d) and an inertial mass.

The band gap of the metamaterial is predominantly determined by the natural frequency of the metamaterial and the mass ratio between the metamaterial's resonator and the base structure [29]. In this research, the primary objective is the design of an active cell able to modify the natural frequency of the resonator (achieved by heating). Specifically, the resonator's beam-like springs are subjected to electric heating, targeting primarily the resonator's spring-like elements, thereby elevating their temperature. Given that the spring-like elements consist of polymer, their mechanical properties, notably stiffness, vary with temperature, experiencing a slight decrease for an increased temperature change. The change in stiffness results in a change of the resonator's natural frequency within the metamaterial, subsequently affecting the band gap's location in the frequency domain.

The electric resistance of the conductive parts of a 3D-printed metamaterial cell increase with temperature [88]. Utilizing the established resistancetemperature relationship enables an estimation of the metamaterial's temperature, particularly that of the beam-like springs, using electric resistance measurements. Thus, the metamaterial cell also has the ability to detect temperature.

Furthermore, the conductive paths are also employed to detect mechanical oscillations, notably those of the cell's resonator. Given that conductive polymer-based materials often exhibit piezoresistive properties [74], their resistance varies under mechanical loads. Mechanical load-based variations in the electric resistance are typical several orders of magnitude smaller than those resulting from temperature changes; however, these changes are usually on different time scales and therefore relatively easy to distinguish. By employing suitable frequency filtering, it becomes feasible to distinguish between the quasi-static (temperature) and dynamic (mechanical loads) components of resistance. This capability facilitates the measurement of the resonator's natural frequency, among other parameters.

3.2. Active Metamaterial Cell Shape Design For Single-Process 3D Printing

The base structure, shown in Fig. 1 b), incorporates relatively thick conductive electric paths to minimize the electric resistance and consequently reduce the heating of the metamaterial cell's base structure. Moreover, it is equipped with contacts designed for the electric interconnection of the metamaterial cells in the longitudinal direction, as suggested in Fig. 1 b). CPLA (conductive PLA) is used as the electrically conductive material, while PLA forms the base structure.

The beam-like springs, shown in Fig. 1 c) and d), are designed to enable heating across their full length with an approximately even distribution of heat. The electric current's direction is visible in Fig. 1 e). Additionally, the beam-like springs are used to sense the inertial mass displacement. With boundary conditions approximating those of a fixed-fixed beam, the conductive path is positioned to ensure either compression and neutral, or tension and neutral strains along the conductive path. Consequently, the conductive path adopts a "Z" shape to maintain consistent deformation characteristics, see Fig. 1 d). In the 3D-printing process for the beam-like springs, the lower non-conductive part also acts as a foundational bridge for adding subsequent layers, a process depicted in Fig. 2. The foundational layer anchors the beam-like spring to the inertial mass and the base structure, allowing the next layers to be deposited, following the proposed Z-shaped design. This method eliminates the need for any support structures during the fabrication of the beam-like springs.

The design of the resonator's inertial mass (see Fig. 1 c)), within the metamaterial cell focuses on maximizing the length of the beam-like springs and ensuring their effective attachment to the resonator's inertial mass. Simultaneously, it aims to maximize the mass within the limited space available. Two conductive sections are incorporated on the lower and upper parts of the inertial mass, facilitating electric interconnections between the springs. The central part of the inertial mass is non-conductive and serves as the mass of the resonator.



Figure 2: Beam-like resonator's springs fabrication: a) initial bridging layer with PLA, b) the rest of beam-like spring fabrication.

3.3. Cell Fabrication

The metamaterial cell's fabrication employed a 3D printer, Toolchanger by E3D, featuring four Hemera extruders (E3D), which enabled multi-material 3D printing without the undesired mixing of materials. G-code generation was performed using PrusaSlicer 2.7.1, see Fig. 3 a). The layer height was set to 0.2 mm for both the base structure and the resonator's mass, whereas a finer 0.1-mm layer height was chosen for the layers containing the resonator's beam-like springs. The extrusion paths had a width of 0.45 mm, with a printing speed of 80 mm/s. An infill of 100% was selected, aligned with the X and Y axes, accompanied by 2 perimeters. The heated-bed temperature was maintained at 60°C, and the printing temperatures for both PLA and CPLA were set to 215°C, using an extrusion multiplier of 0.95. Fig. 3 b) showcases the 3D-printed metamaterial.

Following the 3D printing, electric contacts to the metamaterial cell were established: a wire was soldered to a copper tape, followed by the application of conductive silver paint on the printed metamaterial cell, onto which the copper tape was then affixed. Subsequently, the connection was coated with superglue to secure the copper tape to the printed metamaterial. The completed electric contacting process is depicted in 3 c).

As the final step, the metamaterial is coated with black paint, as demonstrated in Fig. 3 d), to achieve a consistent emissivity factor across its surface, allowing more accurate temperature-field measurements. Additionally, a reflective sticker was added to the resonator's inertial mass for the laser vibrometer measurements. Following this preparation, the sample is ready for measurement.



Figure 3: 3D-printed metamaterial cell: a) g-code vizualization, b) after 3D-printing process, c) after electrically contacted, d) after black paint coating with reflective sticker for laser vibrometer measurement.

4. Experimental Methods

The experiment aimed to establish three characteristics of the active metamaterial cell: a) electric characteristics - electric resistance with respect to temperature, b) mechanical characteristics - first natural frequency with respect to the voltage applied across the metamaterial cell, and c) selfawareness, sensor characteristics - the excitation-frequency detection capability. All the metamaterial cell's properties were concurrently assessed within the same experimental framework, the setup and schematics of which are illustrated in Fig. 4 a) and Fig. 4 b), respectively.



Figure 4: Experimental setup: a) physical experiment, b) acquisition schematics of electric quantities, c) measurement sequence.

As depicted in the electric circuit in Fig. 4 b), the voltage across the metamaterial cell $(V_{\rm MM})$ and the supply voltage $(V_{\rm supply})$ are measured. The voltage across the shunt resistor can be deduced as $V_{\rm shunt} = V_{\rm supply} - V_{\rm MM}$. Utilizing the reference resistor $R_{\rm shunt} = 2660 \,\Omega$ and the calculated voltage

 $V_{\rm shunt}$, the electric current through the metamaterial cell is determined. Subsequently, the electric resistance of the metamaterial cell is calculated from the electric current and the voltage $V_{\rm MM}$. Additionally, the voltage across the metamaterial cell $V_{\rm MM}$ is filtered through a high-pass filter (cut-off frequency $f_c = 0.5$ Hz) and amplified with an instrumentation amplifier, with the output voltage labeled as $V_{\rm sensor}$. This method facilitates the measurement of minor resistance changes attributed to dynamic loads on the metamaterial, manifesting as subtle dynamic voltage fluctuations across the metamaterial, given that the reference resistor and metamaterial cell function together as a voltage divider.

Based on the voltage V_{sensor} , the dynamic component of the metamaterial cell's resistance can be computed. The relationship in the frequency domain between V_{sensor} and V_{MM} is [89]:

$$V_{\text{sensor}}(\omega) = V_{\text{MM}}(\omega) G \frac{\mathrm{i}\,\omega R_{\text{HP}} C_{\text{HP}}}{1 + \mathrm{i}\,\omega R_{\text{HP}} C_{\text{HP}}},\tag{5}$$

where V_{sensor} is the output measured voltage on the instrumentation amplifier, V_{MM} is the voltage across the metamaterial, G is the gain factor of the instrumentation amplifier, R_{HP} and C_{HP} are the resistance and capacitance of the high-pass filter with a cutoff frequency of 0.5 Hz, ω represents the angular frequency, and i is the imaginary unit. For the loads with frequency content well above the cutoff frequency of the high-pass filter, we can assume:

$$V_{\text{sensor}}(t) = V_{\text{MM, AC}}(t) G, \qquad (6)$$

$$V_{\rm MM}(t) = V_{\rm MM, \ DC} + V_{\rm MM, \ AC}(t), \tag{7}$$

where $V_{\rm MM, AC}$ is the dynamic part of the voltage, and $V_{\rm MM, DC}$ is the quasistatic part of the voltage across the metamaterial cell. Based on the shunt resistor R_{shunt} and the measured voltages V_{MM} and V_{supply} , the resistance of the metamaterial cell is:

$$R_{\rm MM}(t) = R_{\rm shunt} \frac{V_{\rm MM}(t)}{V_{\rm supply} - V_{\rm MM}(t)}.$$
(8)

In the context of detecting dynamic loads, we are only interested in the dynamic part of the resistance $R_{\rm MM, AC}$, identified as:

$$R_{\rm MM, AC}(t) = R_{\rm shunt} \frac{V_{\rm MM, AC}(t)}{V_{\rm supply} - V_{\rm MM, DC}},\tag{9}$$

assuming that $V_{\text{MM, DC}} \gg V_{\text{MM, AC}}(t)$. Considering Eq. (6), Eq. (9) is rewritten as:

$$R_{\rm MM, AC}(t) = G_{\rm total} V_{\rm sensor}(t), \qquad (10)$$

$$G_{\text{total}} = \frac{1}{G} \frac{R_{\text{shunt}}}{V_{\text{supply}} - V_{MM,DC}},\tag{11}$$

where G_{total} is the overall scaling factor that relates $R_{\text{MM, AC}}$ and V_{sensor} . From Eq. (11), it is evident that G_{total} varies with V_{supply} .

The metamaterial cell is heated by appliying the voltage $V_{\rm MM}$. The temperature field is observed using a thermal camera (FLIR A10). The temperature fields of the upper visible beam-like springs, the resonator's mass, and the base structure are monitored individually. The average temperature from each area is calculated, as depicted in Fig. 4 a).

To measure the natural frequency of the metamaterial cell's resonator, the metamaterial cell is clamped to a electrodynamic shaker (LDS V406) and subjected to a sinusoidal sweep from 100 Hz to 900 Hz, with an acceleration amplitude of approximately 4 g ($g = 9.81 \text{ m/s}^2$). During this process, the excitation acceleration a_{exc} is recorded using a reference accelerometer (DYTRAN 3097A2T), and the metamaterial cell resonator's response is measured with a laser vibrometer (Polytec VibroGo). Concurrently, all the electric values and the metamaterial cell's upper-surface temperature field are measured. Time-domain signals are filtered with an analog low-pass filter at Nyquist frequency of 12.8 kHz (sampling rate is 25.6 kHz) and then processed through a digital bandpass filter, with cutoff frequencies set between 100 and 900 Hz. Subsequently, the transmissivity T(f) is identified from the time-domain signals of the acceleration a_{exc} and the velocity v_{res} , using:

$$T(f) = \frac{S_{va}}{S_{aa}} \frac{1}{\mathrm{i}\,2\,\pi\,f},\tag{12}$$

where S_{va} is the cross-spectrum between the velocity of the mass v_{res} and the acceleration of the base structure a_{exc} , S_{aa} is the power spectrum of the acceleration of the base structure a_{exc} , and f is the frequency [90]. The resonator's natural frequency is determined from the amplitude spectrum T(f).

Utilizing the dynamic component of the metamaterial cell's resistance $R_{\text{MM, AC}}$ and the excitation acceleration a_{exc} , the frequency-response function K_R can be formulated:

$$K_R(f) = \frac{S_{Ra}}{S_{aa}},\tag{13}$$

where S_{Ra} represents the cross-spectrum between the change in resistance $R_{\rm MM, AC}$ and the acceleration $a_{\rm exc}$. The frequency response function K_R describes the metamaterial cell's dynamic resistance behavior $R_{\rm MM, AC}$ in response to vibrational excitation at various frequencies.

The measurement is conducted repeatedly at various supply voltages V_{supply} , ranging from 10 V to 60 V (resulting in different temperature con-

ditions in the metamaterial cell). The measurement procedure is depicted in Fig. 4 c). The metamaterial cell is subjected to three cycles of thermal loading, with a three-minute interval between consecutive measurements to allow the metamaterial cell's temperature field to stabilize.

5. Results and Discussion

This section presents and discusses three characteristics of the 3D-printed active metamaterial cell. First, it examines the relationship between the electric resistance and the temperature, indicating the cell's temperature-sensing capability. Next, attention is given to the mechanical properties, particularly how the natural frequency changes with applied voltage, demonstrating the cell's ability to adjust its band gap dynamically. Furthermore, the metamaterial cell's self-awareness or sensor features are discussed, highlighting its environmental interaction potential. Finally, the collective findings on these characteristics are analyzed to explain how they contribute to the active behavior of the metamaterial cell.

5.1. Electric Characteristics

Fig. 5 shows a clear relationship between the metamaterial's electric resistance and temperature, primarly attributed to the resistance change of the beam-like springs. After the first thermal cycle a slight decrease in resistance is observed. This phenomenon is attributed to the conductive components of the polymer aligning or forming enhanced electric connections in the presence of the electric field, particularly as the temperature approaches the glass-transition temperature T_g of PLA [91]. This proximity to T_g facilitates more facile movement of the molecular chains [66]. While heating the beam-like springs, a temperature increase is also experienced by the metamaterial's base structure and the resonator's inertial mass, with a maximum temperature difference of approximately 10°C. Consequently, the observed changes in electric resistance are not exclusively attributable to the springs but also, to some extent, to the base structure and mass. At room temperature, the total electric resistance of all the conductive paths within the metamaterial base structure and resonator's inertial mass is $1.2 \text{ k}\Omega$, while the overall electric resistance of the metamaterial cell is $6.4 \text{ k}\Omega$. Since beam-like springs account for approximately 81% of the total electric resistance of the metamaterial cell it is reasonable to assume that the predominant share of the electric resistance change is caused by the beam-like springs.

Electric resistance in beam-like springs can also be influenced by thermal strains arising from the different coefficients of thermal expansion (CTE) of PLA and CPLA, coupled with the different Young's moduli between PLA and CPLA. However, for the printing directions of beam-like springs (see Fig. 3), results from [66] and additional measurements indicate that the CTE of PLA is approximately 102 μ m m⁻¹K⁻¹, while the CTE of CPLA is approximately 108 μ m m⁻¹K⁻¹. This slight difference in CTE is unlikely to cause a significant increase in resistance due to thermal strains. Additionally, the measured Young's moduli of CPLA and PLA with respect to temperature did not differ significantly in the temperature range of interest (25°C-45°C).

The heatmap images in Fig. 5 reveal slightly uneven heating along the springs. Uneven heat generation is most likely caused by inconsistent Joule heating due to varying resistivity in the 3D-printed beam-like springs. This

variability arises from slight differences in printing parameters and slightly higher resistance between adjacent 3D-printed traces, a known issue in 3Dprinting using thermoplastic material extrusion [79, 80]. Regardless, as shown in Fig. 5, the metamaterial cell's electric resistance serves as a viable means to estimate the springs' average temperature. With an average temperature change of 17°C, the electric resistance of the metamaterial cell alters by approximately 2.6 k Ω , or 38% relative to the initial resistance at room temperature, which is consistent with the literature [81].



Figure 5: Electric characteristics of metamaterial cell: a) temperature field for selected measurements with shown averaging regions, b) average temperature of selected regions for each consecutive measurement, c) resistance of metamaterial for each consecutive measurement, d) relationship between resistance and average temperature of metamaterial cell's beam-like spring elements.

5.2. Mechanical Characteristics

The transmissivity T(f) (12) is shown in Fig. 6 a). It is observed that the natural frequency decreases with an increase in voltage $V_{\rm MM}$, and concurrently, the amplitude response at the natural frequency declines, likely due to enhanced mechanical damping at elevated temperatures. Increased damping at elevated temperatures is expected to broaden the stop-band frequency range and reduce the peak attenuation within the stop-band region [28]. The natural frequencies, extracted from the amplitude spectra, are presented as a function of voltage across the metamaterial cell in Fig. 6 c), for the 2nd and 3rd cycles. The relationship is fairly linear with an R-squared quality of fit of $R^2 = -0.978$. The decline is approximately 1.52 Hz/V, which, at an average temperature difference of 17°C, amounts to a change in the natural frequency of approximately 60 Hz.



Figure 6: Mechanical and sensor characteristics of metamaterial cell: a) transmissivity T(f) between inertial mass acceleration and base-structure acceleration - amplitude spectrum, phase spectrum and coherence, b) frequency-response function $K_R(f)$ between resistance $R_{\text{MM, AC}}$ and base structure acceleration a_{exc} - amplitude spectrum, phase spectrum and coherence, c) relationship between metamaterial cell's natural frequency f_0 and V_{MM} .

5.3. Self-Awareness, Sensor Characteristics

In Fig. 6 b), the frequency-response function K_R (13) between the measured dynamic part of the metamaterial's resistance $R_{\rm MM, AC}$ (10) and the excitation acceleration $a_{\rm exc}$ is displayed. At lower $V_{\rm MM}$, lower resonance peaks are observed in the K_R amplitude spectrum (Fig. 6), mirroring the behavior seen in the transmissivities T(f). With higher supplied voltages $V_{\rm MM}$, there is a noticeable increase in the resonance peaks despite a diminished mechanical response at resonance relative to lower voltages (see Fig. 6), suggesting an increased sensitivity to the mechanical excitation of the metamaterial cell at elevated temperatures. More examples of metamaterial cell's time-domain response to excitation are presented in Appendix A.

Fig. 6 b) illustrates that the coherence C_{xy} between the $R_{\rm MM, AC}$ and $a_{\rm exc}$ signals strengthens as the excitation frequency approaches the metamaterial cell's natural frequency, showcasing its effective natural frequency detection. In the sub-natural frequency region at lower V_{MM} (lower temperatures), the lower coherence indicates a decreased signal-to-noise ratio, as the measured signal levels decrease while noise levels remain constant. The drop in coherence at 450 Hz is likely due to electrical grid noise, with a base frequency of 50 Hz and higher harmonics, including 450 Hz, affecting the metamaterial cell's $R_{MM,AC}$ measurement. However, an increase in the correlation at elevated temperatures, including in the sub-natural frequency region, enhances the detection of excitation frequencies below the natural frequency, indicating improved performance across a broader frequency range. This enhancement is attributed to two factors: elevating the power-supply voltage increases the measured voltage V_{sensor} , but also increases the metamaterial cell's temperature, thereby heightening its sensitivity at elevated temperatures. Despite these variables, the metamaterial consistently demonstrates proficiency in detecting its natural frequency with the sensitivity K_R ranging from approximately $0.15 \,\Omega/g$ to $0.3 \,\Omega/g$.

5.4. Metamaterial Cell's Active Capabilities

The study demonstrates that applying a 40 V voltage difference or inducing an average 17°C temperature increase to the metamaterial cell leads to a shift in its natural frequency by approximately 60 Hz or approximately 12% of the initial natural frequency. This capability facilitates the precise adjustment of the metamaterial's band gap to the specific frequency range where vibration attenuation is desired. Upon incrementally increasing the voltage V_{MM} by approximately 8 V, an average frequency shift of approximately 12 Hz was observed within three minutes, serving as a conservative estimate for the system to reach steady state. This observation suggests that the metamaterial cell is capable of adjusting its frequency by at least 12 Hz within a period of 3 minutes or less. The response time can potentially be decreased by using different materials and implementing design changes. Despite its response time, the metamaterial design is well-suited for applications with gradually changing excitation profiles, such as those in turbine engines during aircraft cruising, machining operations in precision machinery, or scenarios where operational changes occur due to manufacturing inconsistencies or material aging.

Additionally, the metamaterial's ability to self-assess the excitation frequency enables the implementation of a feedback mechanism. Altough not shown in this research, this mechanism can adjust the applied voltage in response to changes in the metamaterial's properties over time, ensuring consistent performance despite the inherent variability in the mechanical and electrical characteristics of 3D-printed components.

The research further identifies the quasi-static electrical resistance com-

ponent of the metamaterial cell as an effective indicator of its average temperature. An average temperature change of 17°C alters the cell's resistance by approximately 38% relative to its initial value at room temperature (see Fig. 5 d)). This temperature-sensing capability is crucial for monitoring the proximity to the glass-transition temperature (T_g), at which point the material may undergo permanent deformation or alteration, especially under resonant conditions. Thus, temperature monitoring serves as a preventive measure against potential structural failure.

6. Conclusions

A thermo-active, self-aware metamaterial cell was introduced, fully realized through a single 3D-printing process with the capability to adjust its natural frequency. Adjustment is facilitated by resistive heating of the conductive paths within the resonator's beam-like springs, altering their stiffness and, consequently, the natural frequency. Such modulation enables the tailoring of the metamaterial cell's band-gap region. With a 40 V difference applied across the metamaterial cell or an average 17°C temperature increase, the natural frequency is observed to shift by approximately 60 Hz or 12%, exhibiting a close-to-linear relationship.

Additionally, the metamaterial cell possesses the capability to sense temperature fluctuations and prevent a temperature increase above the glasstransition temperature; an average temperature variation of 17°C in the beam-like springs results in an approximate 38% variation in the metamaterial cell's quasi-static resistance.

Furthermore, the metamaterial cell's excitation frequency can be mea-

sured using the same conductive paths via the piezoresistivity phenomenon, rendering the structure self-aware. When the excitation frequency is near its cell's natural frequency, the excitation acceleration of 1 g produces an approximately $0.15 - 0.3 \Omega$ change in resistance. Additionally, it was observed that the detection sensitivity increases with an increase in temperature.

Metamaterials made from the presented metamaterial cell, when appropriately controlled, can adapt their band-gap region in response to environmental changes. This feature has potential applications in aerospace, automotive, and civil engineering, where an adaptive response of the structures is essential to maintain a safe, vibration-free, and noise-free environment.

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Appendix A. Time domain metamaterial cell's response

Fig. A.7 shows time-domain response to a pure sine base acceleration excitation (see Fig. 4). The dynamic resistance $R_{AC,MM}$ is shown as a response at 400 Hz, metamaterial cell's natural frequency and 550 Hz.



Figure A.7: MM cell's dynamic resistance $R_{AC,MM}$ over time at different V_{MM} : a) response at 400 Hz, b) response at natural frequency, c) response at 550 Hz.

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