

Research Paper

Broadband Vibration-Isolating Metamaterial for MRI-Induced Vibrations

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Magnetic resonance imaging (MRI) is an important diagnostic tool in the medical field. Vibrations originating from the gradient coils of an MRI system lead to loud operational noise. This study explores a numerical investigation of elastic metamaterial designed for the attenuation of MRI-induced vibrations that could radiate as sound at the air-structure interface. Elastic metamaterials with embedded resonators can significantly attenuate wave propagation by opening a local resonance bandgap. In this study, the wave propagation properties of two elastic metamaterial models are analysed. The resulting dispersion diagrams are studied using a parametric analysis to investigate the influence of different geometric features on bandgap generation. The metamaterial models are analysed using finite element analysis (FEA) to investigate their wave attenuation performance. A frequency analysis of the multicellular model shows a high transmission loss corresponding to the bandgaps in the calculated dispersion diagrams. The results reveal that the optimised metamaterial model shows an overlap of 72.3 % with the vibration frequency range of the MRI scanner, while the frequency analysis of the multicellular arrangement reports a transmission loss of up to 115.7 dB. These results demonstrate the potential of such elastic metamaterials for targeted vibro-acoustic control and provide a framework for designing structures for wave attenuation in sensitive acoustic environments.

Keywords: elastic metamaterials, local-resonance bandgap, vibro-acoustic coupling, magnetic resonance imaging (MRI), MRI noise, wave attenuation.



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1. INTRODUCTION

The magnetic resonance imaging (MRI) is a very important tool in medical diagnosis without the use of harmful ionising radiation (BRUNO *et al.*, 2019; REDA *et al.*, 2021; LANDINI *et al.*, 2018). For generating images, an MRI system utilises a static magnetic field, a dynamic magnetic field gradient, and radiofrequency pulses. The interaction of the static magnetic field and the gradient field leads to the generation of a Lorentz force, setting the gradient coil into vibration. This vibration propagates to the scanner surface, and its vibro-acoustic coupling with the surrounding air generates the typical MRI noise (ZHANG *et al.*, 2025; LEO, D'ORAZIO, 2025; HEDEEN, EDELSTEIN, 1997; MANSFIELD *et al.*, 1998; MOELKER *et al.*, 2003). Literature has reported sound pressure levels reaching up to 133 dB, which may induce anxiety, fear, and a potential temporary loss of hearing (MOELKER, PATTYNAMA, 2003; HUTTER *et al.*, 2018; ARAWADE, PIECHOWICZ, 2024a; 2024b). Furthermore, this vibration also propagates through the structure and reaches the scanning zone, reducing the quality of images with blurring and other unknown artifacts (GALLICHAN *et al.*, 2010; FUHRER *et al.*, 2019; FROLLO *et al.*, 2007). Generally, MRI noise and vibrations are present in the frequency range of 300 Hz to 3000 Hz, with major peaks observed between 1000 Hz and 2000 Hz. Many approaches have been explored to reduce the generation and propagation of the MRI vibration and noise, such as modifying the input electric current pulses to the gradient coil, gradient coil modification, and active and passive noise control (MCJURY, 2022; KANAL *et al.*, 1992; AL-MEER, 2022; LI *et al.*, 2011; LEE *et al.*, 2017; LASOTA, MELLER, 2020).

In addition to these system-level approaches, significant industrial efforts have been directed towards vibration isolation and structural decoupling of MRI equipment from its surroundings. AMC MECANOCAUCHO offers their Vibrabsorber + Sylomer® mounts, which effectively minimise vibration propagation¹. Kinetics Noise Control offers precision isolation systems, including elastomeric isolators, to mitigate airborne and structure-borne noise². Unisorb Installation Technologies (2025) presents engineered isolation materials, such as IB-500™ blocks for minimising vibrations³. International Design Engineering (IDE) delivers both passive and active vibration isolators to enhance MRI imaging performance⁴. Additionally, acoustic panels and floating ceiling and wall treatments are also commonly employed in the MRI rooms to absorb airborne noise and enhance the room acoustics^{5,6}. Despite these developments, most existing solutions focus on isolating the MRI scanner or treating the room and do not directly suppress vibro-acoustic couplings at the panel. This highlights the need for strategies that address vibration attenuation at the source.

Metamaterials are artificial materials that possess specially tailored properties that natural materials do not have (KUMAR *et al.*, 2022; WEI *et al.*, 2025; WU *et al.*, 2025; ZHANG, ZHAO, 2025). Metamaterials are explored for various counterintuitive properties, such as frequency bandgaps (MIAO *et al.*, 2025; LIU *et al.*, 2025), cloaking (AHMAD *et al.*, 2025; FU *et al.*, 2025), negative refraction (RUKS *et al.*, 2025; ZHOU *et al.*, 2025), negative mass density (HAO *et al.*, 2025; WANG *et al.*, 2025), and a negative Poisson's ratio (LI, 2025; SHUNSHUN, ZHAO, 2025). Mechanical metamaterials are a class of metamaterials having properties designed to regulate the propagation of elastic waves. Literature shows that their properties are highly influenced by structural parameters instead of solely the composition of the constituent materials (CHUA *et al.*, 2025; HE *et al.*, 2024). Elastic metamaterials are composed of periodic composites of two or more materials with dissimilar mechanical properties, leading to the generation of elastic bandgaps in wave dispersion. Elastic waves cannot propagate within the frequency range of a bandgap and therefore this property of elastic metamaterials makes them important for potential applications in vibration isolation and damping.

The methods to obtain a bandgap over a specific frequency range are mainly classified as the Bragg scattering effect and the local resonance mechanism (KAINA *et al.*, 2013). Phononic crystals-based metamaterials having scatterers embedded in a host material utilise the principle of Bragg scattering for wave propagation control. In this method, wave reflection and interference within the periodic structure lead to the formation of a frequency-dependant bandgap, restricting wave propagation at specific frequencies (CHUANG *et al.*, 2020; LIU, ZHU, 2019). Phononic crystals show a bandgap when the structural periodicity is on the order of the wavelength, where the bandgap characteristics typically depend upon the lattice arrangement, scatterer size, and the impedance contrast between the constituent materials in the unit cell (QI *et al.*, 2018; XIANG *et al.*, 2020). These cellular structures show a high strength-to-mass ratio, which is favourable in different applications requiring robust and broad bandgaps (WEN *et al.*, 2020; WICKELER, NAGUIB, 2020). Phononic crystals are primarily suitable for high-frequency applications because of the requirement of destructive interference of waves between the periodic cells. In the case of low- to mid-frequency range vibration control, using Bragg scattering phononic crystals becomes impractical due to the requirement of a larger structural size (ZHAO *et al.*, 2024). The local resonance metamaterial based on a periodic structure was first introduced by LIU *et al.* (2000), achieving subwavelength bandgaps using local resonance in the structure. Locally resonant metamaterials work on the principle of negative indexes, where the frequency-dependant properties become negative in the tuned frequency range. In this negative property region, the local resonators oscillate with maximum potential, which provides restoring forces opposing the incoming excitation, and thus elastic/acoustic waves cannot propagate through the structure (LEE, WRIGHT, 2016; LEE *et al.*, 2022). The resonating units have been reported as spring-mass systems, Helmholtz resonators, mass-on-membrane resonators, and other configurations (HU *et al.*, 2019; LI *et al.*, 2022; PEIRÓ-TORRES *et al.*, 2019; NAIFY *et al.*, 2010). Through the modification of design parameters such as mass, stiffness, damping, and

¹<https://www.mecanocaucho.com/en/news/magnetic-resonance-en/> (access: 26.10.2025).

²<https://kineticsnoise.com/precision/isolation> (access: 26.10.2025).

³<https://unisorb.com/industries/medical-equipment/> (access: 26.10.2025).

⁴https://www.ideworld.com/en/active_vibration_isolation.html (access: 26.10.2025).

⁵<https://www.acousticalsurfaces.com/blog/soundproofing/soundproofing-a-noisy-mri-scanner/> (access: 26.10.2025).

⁶<https://faradayshielding.com.au/acoustic-wall-panels-2/> (access: 26.10.2025).

geometry, local resonance metamaterials can be tuned to attenuate specific targeted frequencies (FAN *et al.*, 2021; HU *et al.*, 2021). Local resonance metamaterials show smaller lattice cells with low- to mid-frequency bandgaps, highlighting their potential in multiple applications of structural monitoring, vibration isolation, and noise mitigation (MA, SHENG, 2016; PIRES *et al.*, 2022). Generally, they show narrow bandgaps, and research is actively underway to optimise locally resonant metamaterials to produce wide bandgaps.

Despite extensive research in the field of metamaterials, very few studies have explored their potential to control the vibration and noise generated by MRI systems. This work explores the inverse design of a locally resonant elastic metamaterial specifically targeting the vibration frequencies generated by the gradient coils of an MRI scanner that propagate and couple to the acoustic field at the air-structure interface. The local resonance mechanism is selected because it enables the formation of bandgaps within the target low- to mid-frequency range using subwavelength unit cells, resulting in a compact design suitable for the confined geometry of the MRI system. Dispersion relation analysis is employed to characterise the intrinsic wave propagation behaviour of the periodic cell and identify the subwavelength-resonance-induced bandgaps that govern the attenuation behaviour. The study investigates the influence of constituent materials and geometric parameters on bandgap generation and vibration attenuation performance by using the finite element method (FEM). By designing the bandgap to correspond with the MRI system vibration spectra, this investigation presents a systematic methodology for designing metamaterials for targeted vibro-acoustic control in sensitive medical environments.

2. MODEL AND METHODS

This section mainly presents the geometric structure of the locally resonant elastic metamaterial and introduces the method for evaluation of dispersion of its characteristic curves and transmission loss spectrum of the elastic metamaterial using the solid mechanics module of the numerical simulation software COMSOL, followed by a material compatibility analysis.

2.1. DESIGN OF THE ELASTIC METAMATERIAL

The study focuses on a 2D elastic metamaterial having periodic arrangement in the $X - Y$ plane and a uniform structure in the out-of-plane direction. The inclusion material is considered to be an isotropic hard solid periodically embedded in a soft matrix material. The unit cell forms a square lattice structure with a lattice constant a , representing the distance between two adjacent unit cells. The diameter of the inclusion is denoted by d_1 . The study includes analysis of two models: the first model consists of a hard solid inclusion in a single soft matrix, while the second model consists of a hard inclusion wrapped in an additional layer of soft elastic material and embedded together in the soft matrix. The thickness of this soft wrapping layer is denoted by w . The proposed geometric models and their corresponding unit cells are shown in Fig. 1.

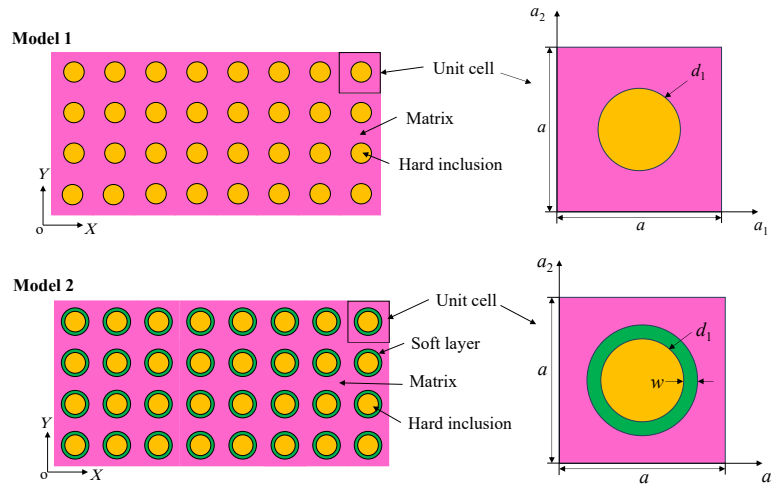


FIG. 1. Structural schematic of the elastic metamaterial presenting configuration of metamaterials models and their unit cell geometries.

The geometry of the metamaterial layer is defined by the initial geometric parameters of the unit cell presented in Table 1. In this study, in addition to a non-magnetic nature, chemical inertness and corrosion resistance are critical attributes that are required for the constituent materials to ensure suitability for application in an MRI environment. Therefore, the proposed metamaterial uses tungsten as the solid inclusion, a silicone (polysiloxane) polymer as the host elastic matrix, and soft rubber as the wrapping layer. The mechanical material properties considered for the numerical model are presented in Table 2.

TABLE 1. Geometric parameters in the model.

Parameter	Value [mm]
Lattice constant of unit cell – a	5
Diameter of hard inclusion – d_1	3
Thickness of the soft wrapping layer – w	0.2

TABLE 2. Material properties in the model.

Material	Density [kg/m ³]	Modulus of elasticity [GPa]	Poisson's ratio
Tungsten	18 950	360	0.28
Silicone	1080	4.5E-03	0.46
Rubber	1300	1.175E-04	0.47

In an MRI system, the gradient coil system is usually cylindrical with a radius of approximately $R \approx 300$ mm. In this study, the maximum size of the metamaterial unit cell is constrained to below $a = 8$ mm. This yields a curvature parameter $a/R = 0.026$. This small ratio indicates a weakly curved configuration, for which the structure can be locally approximated as planar at the scale of the unit cell. Consequently, the plane wave hypothesis employed in the dispersion analysis remains valid for the considered frequency range. In addition, the silicone host has a low elastic modulus, which allows it to conform to the cylindrical geometry of the MRI bore with negligible curvature-induced stress at the unit cell scale. Considering these conditions, the mechanical excitation of the metamaterial layer base can be approximated as locally uniform, and curvature effects are not expected to significantly influence the local resonant bandgap characteristics.

2.2. FEA

To characterise the intrinsic wave propagation behaviour of the periodical metamaterial presented in models 1 and 2, a dispersion relation analysis is performed using an eigenfrequency formulation. This approach enables the identification of subwavelength bandgaps associated with the locally resonant unit cell, within which wave propagation is restricted. By solving the Bloch–Floquet eigenvalue problem for a single unit cell, the dispersion relations are obtained independently of finite size and boundary effects, providing the fundamental basis for prediction of vibration attenuation. The theoretical background and conceived method for the calculation of the dispersion diagram are explained in this section (SUN *et al.*, 2022; HUANG *et al.*, 2021; LI *et al.*, 2023; YANG *et al.*, 2023; TANG *et al.*, 2024). The direct basic vectors in orthogonal Cartesian coordinates are $a_1 = a(1, 0)$ and $a_2 = a(0, 1)$. In the reciprocal space, these vectors are defined as follows:

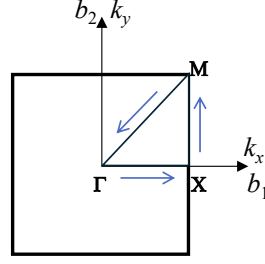
$$b_1 = \frac{2\pi}{a}(1, 0); \quad b_2 = \frac{2\pi}{a}(0, 1). \quad (1)$$

The finite element analysis (FEA) enables the evaluation of the dispersion diagram by solving the extreme values of the multi-order eigenfrequencies in the first Brillouin zone. The square lattice of unit cells exhibits $1/8$ symmetry, and the corresponding irreducible Brillouin zone (IBZ) with key points of highest symmetry Γ , X , and M are shown in Fig. 2.

Wave propagation in the linear elastic, periodic lattice media is expressed by the following governing equation:

$$-\rho\omega^2 \mathbf{u} = (\lambda + \mu)\nabla(\nabla \cdot \mathbf{u}) + \mu\nabla^2 \mathbf{u}, \quad (2)$$

where $\mathbf{u}$ is the displacement vector, ω is the angular frequency, ρ is the density, ∇ is the Hamilton operator, and λ and μ are the Lamé constants of the constituent materials.

FIG. 2. Illustration of IBZ Γ -X-M in the square lattice unit cell.

According to Bloch–Floquet theory, an infinite structure with a lattice constant can be substituted by a unit cell for the basic calculation. The Bloch–Floquet theorem defines the displacement field of periodic media as

$$\mathbf{u}(\mathbf{r}, t) = \mathbf{u}(\mathbf{r})e^{i\omega t}, \quad (3)$$

where t is time and $\mathbf{r} = (x, y)$ is the position vector.

The displacement vector $\mathbf{u}(\mathbf{r})$ can be expressed as

$$\mathbf{u}(\mathbf{r}) = U(\mathbf{r})e^{-i\mathbf{k}\cdot\mathbf{r}}, \quad (4)$$

where $U(\mathbf{r})$ is the eigenvalue amplitude and $\mathbf{k} = (k_x, k_y)$ is the Bloch wave vector. The displacement $\mathbf{u}(\mathbf{r})$ is also periodic, consistent with the lattice vector $\mathbf{R}$ (Bravais lattice vector), which is expressed as

$$\mathbf{u}(\mathbf{r} + \mathbf{R}) = U(\mathbf{r}). \quad (5)$$

Thus, the displacement u satisfies the following relation:

$$\mathbf{u}(\mathbf{r} + \mathbf{R}) = e^{i\mathbf{k}\cdot\mathbf{r}}\mathbf{u}(\mathbf{r}). \quad (6)$$

This relation is applied as a boundary condition to the outer edges of the unit cell in the x - and y -directions. Combining the governing equation with these boundary conditions yields a standard eigenvalue problem:

$$(\mathbf{K} - \omega^2\mathbf{M})\mathbf{q} = \mathbf{F}, \quad (7)$$

where $\mathbf{K}$ is the stiffness matrix, $\mathbf{M}$ is the mass matrix, and $\mathbf{q}$ and $\mathbf{F}$ are the generalised displacement and force vectors, respectively. The formulated eigenvalue problem is solved numerically by using an eigenfrequency analysis in COMSOL Multiphysics. The dispersion relation is calculated by sweeping the Bloch wave vector $\mathbf{k}$ along the boundaries of the IBZ. The FEM of the metamaterial cell for evaluation of dispersion relations was discretised by using a free triangular mesh. The mesh density was defined based on the smallest geometric feature of the model. Particularly, for model 2 with the thin wrapping layer of soft rubber around tungsten, a minimum of two finite elements were ensured across the thickness of the layer. A mesh refinement study was performed to ensure numerical accuracy, confirming that the results are insensitive to a further increase in mesh density.

To maintain the applicability of the elastic metamaterial in an MRI system for attenuating the vibration produced by the gradient coil, the size of the metamaterial was limited to 40 mm in the Y -direction. A parametric analysis was performed to investigate the influence of the geometric features in model 1 and model 2. The lattice constant a was varied from 5 mm to 8 mm, the diameter d_1 of the hard inclusion was varied from 3 mm to 7.5 mm, and the thickness w of the rubber layer was varied from 0.1 mm to 0.7 mm. Furthermore, the bandgap coverage (BGC) percentage was calculated to investigate the suitability of the metamaterial for attenuating MRI vibrations, according to the following expression:

$$\% \text{ BGC} = \left(\frac{\sum_{j=1}^M \max \left(0, \left(\min \left(f_{d2}, f_{g2}^{(j)} \right) - \max \left(f_{d1}, f_{g1}^{(j)} \right) \right) \right)}{f_{d2} - f_{d1}} \right) \times 100, \quad (8)$$

where f_{d1} and f_{d2} are the lower and upper limits of the desired bandgap, respectively, M is the total number of bandgaps in the desired frequency range, and $f_{g1}^{(j)}$ and $f_{g2}^{(j)}$ are the lower and upper limits of the j -th obtained bandgap, respectively.

A frequency-domain analysis was performed to evaluate the transmission loss (TL) of a finite number of elastic metamaterial cells, validating the band structure obtained from the eigenfrequency analysis. In the 2D $X - Y$ model, the TL is evaluated along the radial Y -direction, corresponding to the direction normal to the MRI panel surface. The FEA model used to calculate TL is shown in Fig. 3. Both models were meshed with free triangular elements, with the mesh setup and refinement checks consistent with those performed in the dispersion analysis. A harmonic displacement excitation with a frequency ranging from 0 Hz to 3000 Hz was applied as the input to the first cell of the elastic metamaterial, and the output was measured at the end of the last cell. The TL is calculated as

$$TL = 20 \log_{10} \left(\frac{P_{in}}{P_{out}} \right), \quad (9)$$

where P_{out} is the output displacement and P_{in} is the input displacement. An artificial domain known as a perfectly matched layer (PML) was considered on the input and output sides of the model. The TL was calculated for a number of iterations by varying the geometric parameters of the model 1 and model 2 elastic metamaterials.

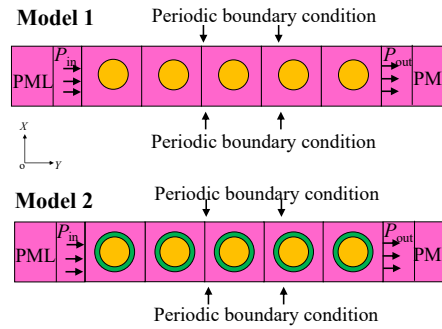


FIG. 3. FEA setup for evaluation of transmission loss in the Y -direction through a multicellular arrangement of metamaterial cells.

2.3. MRI COMPATIBILITY ANALYSIS OF SELECTED MATERIALS

While Subsec. 2.1 and Subsec. 2.2 presented the mechanical necessity of the selected materials for achieving specific wave propagation characteristics, it is also crucial to verify their electromagnetic compatibility for integration into an MRI scanner. This section analyses the electromagnetic characteristics of the constituent materials to ensure they do not disturb the imaging process. Properties such as magnetic susceptibility and electrical conductivity are particularly important to determine whether the structure might perturb the static magnetic field, influence the gradient field distribution, or induce currents during MRI operation. In the presented metamaterial models, the primary components are tungsten rods acting as inertial resonators, silicone serving as the host matrix, and a soft rubber wrapping layer functioning as an additional layer around the tungsten rods specifically in the second model.

2.3.1. INFLUENCE OF MAGNETIC SUSCEPTIBILITY ON FIELD HOMOGENEITY

Tungsten is a paramagnetic material with a volume magnetic susceptibility of approximately $\chi_v \approx 76 \times 10^{-6}$, calculated from the reported mass susceptibility of $\chi_{mass} = 4 \times 10^{-9}$, m^3/kg , (ENGHAG, 2008) and an industrial-grade density of $18\,950 \text{ kg/m}^3$. The silicone has volume diamagnetic susceptibility of $\chi_v = -8.03 \times 10^{-6}$ for RTV 615 silicone, which is comparable to that of water and biological tissues (WAPLER *et al.*, 2014). Soft rubber is a diamagnetic material and shows a volume susceptibility on the order of $\chi_v \approx -1 \times 10^{-5}$ (CALLISTER, RETHWISCH, 2020). As a result, the overall magnetic contrast introduced by the elastomeric components is minimal.

As discussed by Schenck, the localised susceptibility-mismatch-induced magnetic field distortion ΔB decays with distance s according to an inverse-cubic relation: $\Delta B \propto 1/s^3$, where s is the scalar distance from the

susceptibility inclusion (SCHENCK, 1996). Given the relatively weak susceptibility contrast of tungsten compared to ferromagnetic materials and the peripheral placement of the metamaterial relative to the scanning volume, any field distortion decays substantially before reaching the isocentre, resulting in a negligible influence on the global field homogeneity and the linearity of the gradient within the scanning volume. For context, the volume magnetic susceptibility of tungsten is approximately half that of titanium alloys commonly used in MRI-conditional implants (KAJIMA *et al.*, 2020; CHIBA *et al.*, 2019).

2.3.2. INFLUENCE OF ELECTRICAL CONDUCTIVITY AND EDDY CURRENTS

In an MRI system, the dynamic magnetic fields from the gradient coils are known to induce eddy currents responsible for heating, electromotive forces, and torques on conductors and imaging artifacts. Tungsten is an electrically conductive material and could, in principle, support induced eddy currents when exposed to time-varying gradient magnetic fields. The magnitude of the eddy currents and the heating effects in a typical MRI environment strongly depends on the geometry, location, and orientation of the conductor (BUCHLI *et al.*, 1988; STROUD *et al.*, 2019; LEE *et al.*, 2024).

The tungsten rods are oriented parallel to the main magnetic field, which minimises magnetically induced displacement and torque. Conversely, time-varying transverse gradient magnetic fields are perpendicular to the rod axis and may induce eddy currents within the conductor. However, these currents are expected to remain localised and limited in magnitude due to the design features of the metamaterial. Each tungsten rod is encapsulated by the dielectric silicone in model 1, while model 2 has an additional layer of dielectric rubber wrapped around the tungsten rods. This configuration prevents electrical continuity between adjacent tungsten inclusions, consequently minimising the possibility of large-scale conduction loops and resulting eddy-current heating. Additionally, the relatively small diameter of the tungsten rods minimises the effective loop area exposed to changing magnetic flux, further reducing the eddy-current amplitudes.

Considering the radiofrequency (RF) pulses during an MRI scan, the RF field couples with the conductor in the MRI scan bore and induces heat at the tips of the conductor. This heating effect is maximised when the length of the conductor corresponds to half of the RF excitation wavelength in the MRI medium, a phenomenon known as the antenna effect (MATTEI *et al.*, 2008; WINTER *et al.*, 2021). Taking advantage of the 2D design of the metamaterial, the length of the tungsten rods can be explicitly controlled to make them electrically short compared to the RF wavelength at clinical field strength, thereby minimising their ability to resonate with the RF field. Furthermore, the rods are embedded in dielectric material, ensuring galvanic isolation from the scanner and the subject. The isolation limits the RF-induced eddy-current pathways and prevents conduction loops.

Based on the above considerations, the selected materials support the assumption that the proposed structure introduces negligible perturbation to the MRI magnetic field and minimal eddy-current generation, while producing effective vibration control through the local resonance mechanism.

3. RESULTS AND DISCUSSION

This section presents the band structures of elastic metamaterial model 1 and model 2 calculated using the method mentioned in the previous section. The mechanisms of bandgap formation and the parametric influences on these characteristic are thoroughly investigated. Furthermore, the TL is evaluated through a frequency-domain analysis as an indicator of reduced vibro-acoustic coupling.

3.1. BANDGAP CHARACTERISTICS AND VIBRATION MODES

Initially, the first eight eigenfrequencies were considered for the calculation of the dispersion curves. The dispersion relations obtained from the eigenfrequency analysis of model 1 in its initial configuration ($a = 5$ mm, $d_1 = 3$ mm) are shown in Fig. 4. The dispersion relations of model 1 notably show a complete bandgap highlighted in the grey region, where the upper limit of the eigenfrequency solutions was observed to be above 11 000 Hz. As per requirements of the application in an MRI scanner, the bandgap should appear within the frequency range

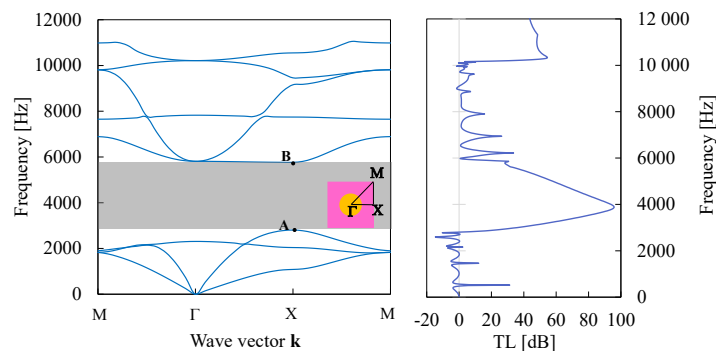


FIG. 4. Dispersion diagram of elastic metamaterial model 1 presenting the identified bandgap shaded in the grey region, with points A and B representing the lower and upper limits of the bandgap, accompanied by the TL spectrum.

of 300 Hz to 3000 Hz. To assess the validation of the dispersion curve characteristics of the initial configuration of model 1, the TL characteristics were evaluated in the frequency range from 0 Hz to 12 000 Hz, as depicted in Fig. 4.

It is evident that the dispersion curves of model 1 exhibit a single ultrawide complete bandgap spanning from 2804.4 Hz to 5765.7 Hz between the 3rd and 4th eigenfrequency bands. The attenuation peak exceeds 76 dB within the bandgap, with an average TL exceeding 58 dB within this forbidden band. The vibration attenuation region in the TL spectrum roughly corresponds to the attenuation region of the bandgap observed in the dispersion curve, providing a strong validation for the accuracy of the calculated dispersion diagram. The overall BGC concerning the MRI vibration range of model 1 was found to be 7.24 % for the given configuration. The vibration modes corresponding to points A and B, indicating the lower and upper limits of the bandgap in model 1, are shown in Fig. 5. The colour of the model surface indicates the amplitude of the vibration, where red indicates the maximum displacement and blue corresponds to the minimum displacement.

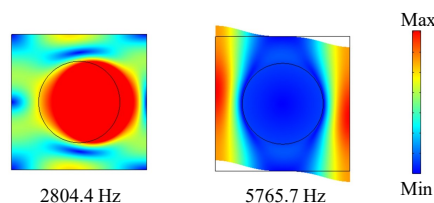


FIG. 5. Vibration modes of bandgap in model 1 at points A and B shown in the dispersion diagram.

Model 2 of the elastic metamaterial was analysed using a similar configuration of unit cell of model 1 ($a = 5$ mm; $d_1 = 3$ mm) and a thickness of soft wrapping layer of $w = 0.2$ mm. To maintain consistency in the methodology, the analysis was limited to first eight eigenfrequencies, and the dispersion relation was calculated and plotted

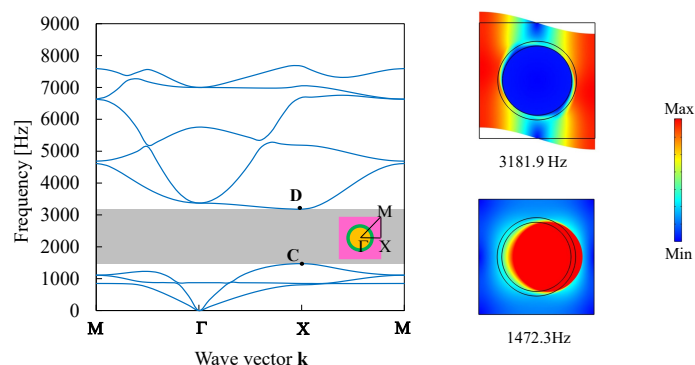


FIG. 6. Dispersion diagram of elastic metamaterial model 2 depicting the bandgap shaded in the grey region, along the bandgap vibration modes at points C and D.

as shown in Fig. 6. Model 2 also shows a single wide complete bandgap starting at 1472.3 Hz and closing at 3181.9 Hz. The presence of the soft layer around the hard inclusion shifted the bandgap to lower frequencies. The vibration mode shapes corresponding to the opening and closing of the bandgap at points C and D are presented in Fig. 6. The BGC calculated for the analysed configuration of model 2 was found to be 56.57%.

3.2. PARAMETRIC ANALYSIS OF METAMATERIAL MODELS

After identifying bandgaps closer to the desired frequency range, the influence of the geometric parameters on both elastic metamaterial models was explored. The diameter d_1 of the hard inclusion was varied from 3 mm to 0.5 mm less than the lattice constant a with an incremental step of 0.5 mm. During the subsequent analysis, the lattice constant parameter a was varied from 5 mm to 8 mm, with an incremental step of 1.0 mm. The variation in the obtained bandgap characteristics of model 1 are shown in the Fig. 7.

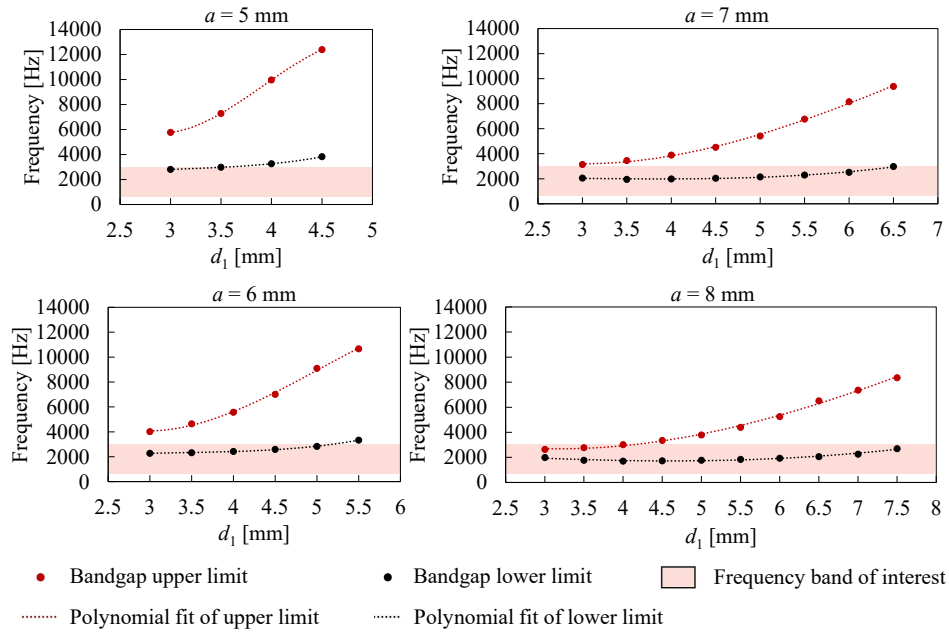


FIG. 7. Bandgap characteristics of metamaterial model 1 for different diameters of inclusion in unit cell with lattice constants, depicting the overlap with the frequency range of interest.

The results from the parametric analysis highlight that the bandgap characteristics are significantly influenced by the inclusion diameter and the lattice constant of the metamaterial. As observed in Fig. 7, the upper limit of the bandgap showed a significant increase with an increase in the diameter of the hard inclusion, resulting in a widening of the bandgap. The lower limit of the bandgap also presented a gradual increase corresponding to the increase in the diameter of the hard inclusion. Model 1 with the configuration $a = 5$ mm, $d_1 = 4.5$ mm presented the widest bandgap spanning from 3820.7 Hz to 12 389.6 Hz. Increasing the diameter in the other configurations having lattice constants of $a = 6$ mm, 7 mm, and 8 mm revealed a similar trend in the upper and lower limits of the bandgap frequencies. Importantly, an increase in the lattice constant a shifts the bandgaps downward in the dispersion diagrams. The minimum lower limit of the bandgap was observed to be 1708.6 Hz, with a corresponding upper limit of 3017.7 Hz for the configuration of $a = 8$ mm, $d_1 = 4$ mm in model 1.

Model 2 of the elastic metamaterial was analysed to investigate the influence of geometric parameters on the bandgap characteristics. As in the case of model 1, the lattice constant was similarly varied from 5 mm to 8 mm with a step of 1 mm, and the diameter of the hard inclusion was changed from 3 mm with a step of 0.5 mm, keeping the thickness of the soft wrapping layer at 0.2 mm. The results from the parametric analysis of model 2 are presented in Fig. 8. An increase in the inclusion diameter d_1 , shows a significant increase in the upper limit of the bandgap but a small decrement in the lower limit of the bandgap, leading to a widening of the overall bandgap width. The widest bandgap was observed for the configuration of $a = 5$ mm, $d_1 = 4.5$ mm, $w = 0.2$ mm

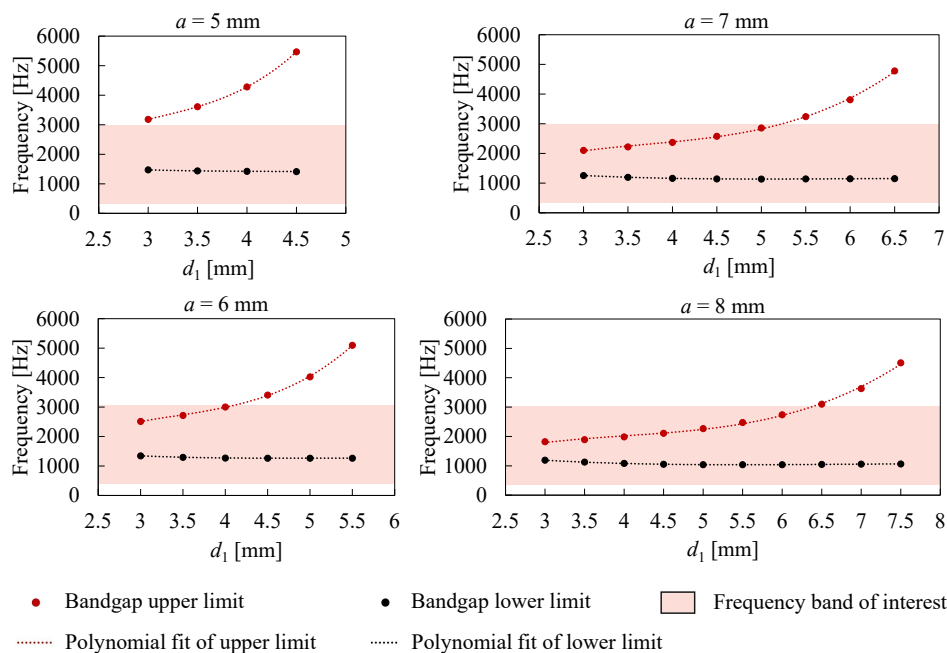


FIG. 8. Bandgap characteristics of metamaterial model 2 with 0.2 mm thick rubber layer for varying diameters of inclusion in unit cell with lattice constants, depicting the overlap of the bandgaps with the frequency range of interest.

in the range of 1413.9 Hz to 5466.7 Hz. Meanwhile, the bandgap with the minimum lower limit of 1034.9 Hz and a corresponding upper limit of 2472.4 Hz was obtained for the configuration of $a = 8$ mm, $d_1 = 5.5$ mm, $w = 0.2$ mm in model 2.

A comprehensive analysis of the parametric studies for model 1 and model 2 was conducted to investigate their performance concerning the attenuation of MRI system vibrations, as shown in the Fig. 9. The performance factor was calculated as the % BGC according to Eq. (8). It was revealed that metamaterial model 1 exhibits a maximum BGC of 47.83% for the configuration of $a = 8$ mm, $d_1 = 4$ mm. In model 2, the maximum BGC of 72.35% was achieved with the configuration of $a = 8$ mm, $d_1 = 6.5$ mm, $w = 0.2$ mm, which was consequently selected as the optimum model for subsequent investigations. Comparing the corresponding plots in Fig. 7, Fig. 9, and Fig. 10, the presence of rubber layer is essential to shift the bandgap into the lower frequency range.

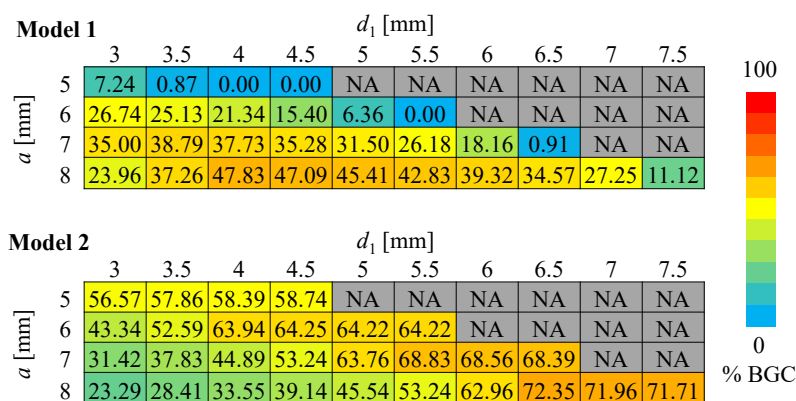


FIG. 9. BGC percentage (% BGC) calculated for different configurations of metamaterial model 1 and model 2 with a wrapping rubber thickness of $w = 0.2$ mm for the desired frequency range of 300 Hz to 3000 Hz.

As the configuration of metamaterial model 2 with an inclusion diameter of $d_1 = 6.5$ mm and a lattice constant of $a = 8$ mm led to the maximum % BGC, it was selected for further evaluation to investigate the influence of the rubber wrapping layer thickness on the bandgap characteristics. The results from the analysis are depicted

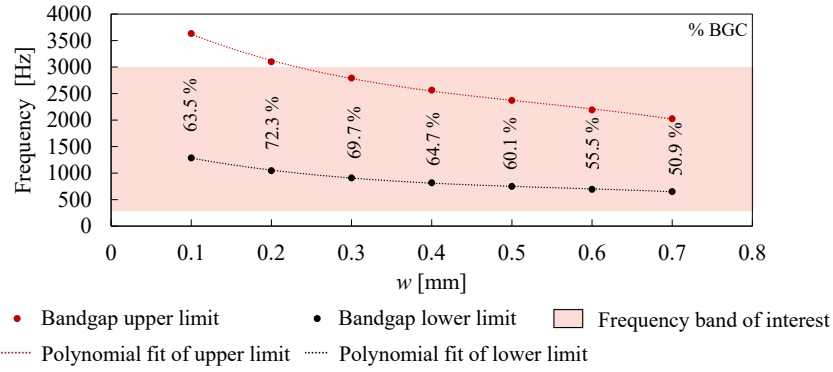


FIG. 10. Bandgap characteristics obtained by varying the wrapping layer thickness w in model 2 with a resonator diameter of $d_1 = 6.5$ mm and a lattice constant of $a = 8$ mm.

in Fig. 10. The thickness of the wrapping layer was varied from 0.1 mm to the 0.7 mm with the incremental step size of 0.1 mm. As the layer thickness increased, the bandgap shifted to lower frequencies, though this compromised the bandgap width. The maximum BGC of 72.3% was observed for the configuration with a 0.2 mm wrapping layer thickness. Furthermore, an increase in thickness resulted in a gradual reduction of the BGC from the maximum of 72.3% to a minimum of 50.9%. The lowest frequency associated with the opening of the bandgap was found to be 650.6 Hz for model 2 with the configuration of $a = 8$ mm, $d_1 = 6.5$ mm, $w = 0.7$ mm.

The polynomial fit equations of the upper and lower limits of the bandgap, derived from the complete parametric analysis of model 1 and model 2, are presented in Appendix.

3.3. FREQUENCY DOMAIN ANALYSIS OF THE OPTIMUM MODEL

The unit cell of model 2, exhibiting the maximum BGC of 72.3% identified in the previous section, was considered for analysing the influence of the number of unit cells on the elastic wave propagation phenomenon. The TL curves were plotted for arrangement of three, four, and five cells, as shown in Fig. 11. A harmonic input displacement of 0.5 mm was applied to the left edge of the first cell, and the response displacement on the opposite side of the last cell was analysed to calculate the TL in the model. The results showed that the position of bandgap characteristics concerning the frequency range remained identical, but the vibration attenuation performance (TL) increased with an increase in the number of cells. Also, the results of the displacement propagation in the five-unit-cell model for frequencies inside and outside the bandgap is shown in Fig. 11. It can be clearly seen that in the bandgap region, the wave cannot propagate to the other side of the metamaterial.

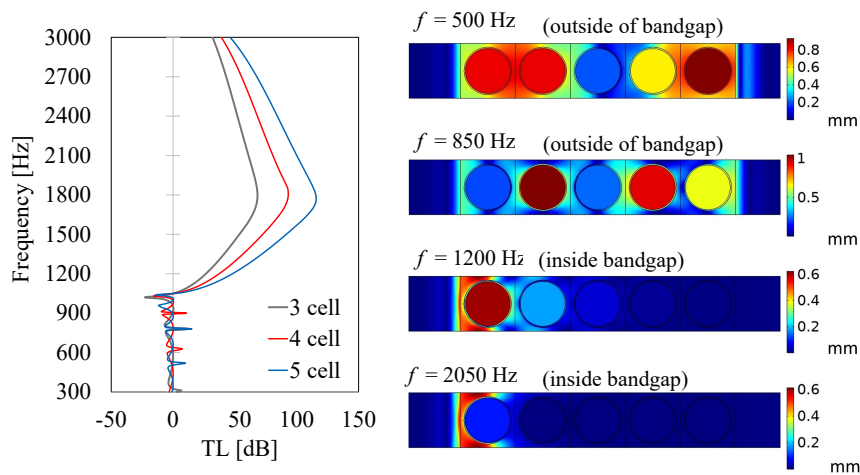


FIG. 11. Transmission loss characteristics calculated for the composite system of elastic metamaterial model 2 with arrangement of three, four, and five unit cells using the configuration ($a = 8$ mm, $d_1 = 6.5$ mm, and $w = 0.2$ mm), along with the displacement wave propagation in metamaterial model 2 with five-unit cells at different input frequencies.

This study demonstrates that a high contrast in the physical properties of the constituent materials can produce local resonance bandgaps in mid-range frequencies, specifically from 300 Hz to 3000 Hz, advancing conventional metamaterial designs that require unit cell sizes of few centimetres to target a similar frequency range (GAO *et al.*, 2023; YIN *et al.*, 2024). Material selection was challenging due to MRI-specific and medical requirements. Model 2, with its optimum configuration, achieved a BGC of 72.3 % and high TL within bandgaps, suggesting potential for reducing vibro-acoustic coupling at the air-structure interface. Although the optimum model covers a high-noise frequency zone, frequencies below the bandgap may still contribute to noise. Hence, it is important to explore more configurations to fully cover the MRI noise spectrum. Currently, the weight of the identified metamaterial is high due to the large fill fraction of the high-density inclusion. Future work will focus on enhancing the attenuation capabilities of the elastic metamaterial while ensuring it to be lightweight and non-magnetic, and fully compatible with the MRI environment.

4. CONCLUSION

In summary, two models of an elastic metamaterial composed of a soft silicone matrix, a rubber layer, and hard tungsten cylindrical inclusions were analysed for targeted vibration attenuation in the MRI gradient coil frequency range. It was found that the both models show bandgaps in the desired frequency range. However, the BCG of model 1 was very low compared to that of model 2. As observed in model 1, the bandgap shifted to lower frequencies with an increase in the inclusion diameter, but it could not achieve a BGC higher than 47.83 %, with the bandgap opening at 1708.6 Hz. Conversely, the optimum configuration of model 2 demonstrated a BGC of up to 72.3 %, with a lower bandgap opening frequency at 1046.6 Hz.

The characteristics of the presented elastic metamaterial are highly dependent on its geometric parameters. The parametric analysis revealed that larger inclusion diameters, larger lattice constants, and an increased thickness of the soft layer shift the bandgap towards lower frequencies, though this narrows the bandgap width. A frequency-domain analysis demonstrated significant TL within the forbidden bands, validating the vibration attenuation performance. These results suggest that further studies should focus on increasing BGC through exploring multi-material configurations for enhanced performance.

Overall, this numerical study highlights the capability of elastic metamaterials to attenuate MRI-induced vibration. Additionally, the high TL achieved in the bandgap suggests that the presented elastic metamaterial may provide a means to reduce vibro-acoustic coupling in MRI systems.

APPENDIX

Trendline equations of the bandgap limits in model 1 from the parametric analysis.

Configuration	Upper limit of the bandgap	Lower limit of the bandgap
$a = 5 \text{ mm}, d_1 \in [3, 4.5]$	$f_{g2} = -1864.1d_1^3 + 21880d_1^2 - 79995d_1 + 99160$	$f_{g1} = 222.27d_1^3 - 2111.4d_1^2 + 7011.1d_1 - 5227.6$
$a = 6 \text{ mm}, d_1 \in [3, 5.5]$	$f_{g2} = -277.3d_1^3 + 4202.4d_1^2 - 17597d_1 + 26525$	$f_{g1} = 80.29d_1^3 - 818.66d_1^2 + 2903.8d_1 - 1239.3$
$a = 7 \text{ mm}, d_1 \in [3, 6.5]$	$f_{g2} = -53.57d_1^3 + 1181.9d_1^2 - 5653.8d_1 + 10967$	$f_{g1} = 23.636d_1^3 - 197.09d_1^2 + 462.25d_1 + 1780.1$
$a = 8 \text{ mm}, d_1 \in [3, 7.5]$	$f_{g2} = -20.172d_1^3 + 591.54d_1^2 - 3166.2d_1 + 7421.9$	$f_{g1} = 4.7403d_1^3 + 30.757d_1^2 - 582.69d_1 + 3286.3$

Trendline equations of the bandgap limits of model 2 from the parametric analysis.

Configuration	Upper limit of the bandgap (f_{g2})	Lower limit of the bandgap (f_{g1})
$a = 5 \text{ mm}, w = 0.2 \text{ mm}$ $d_1 \in [3, 4.5]$	$f_{g2} = 361.56d_1^3 - 3308.8d_1^2 + 10883d_1 - 9448.6$	$f_{g1} = -20.277d_1^3 + 253.14d_1^2 - 1070.6d_1 + 2953.3$
$a = 6 \text{ mm}, w = 0.2 \text{ mm}$ $d_1 \in [3, 5.5]$	$f_{g2} = 156.2d_1^3 - 1586.6d_1^2 + 5809.9d_1 - 4857.8$	$f_{g1} = -10.95d_1^3 + 164.3d_1^2 - 818.35d_1 + 2618.9$
$a = 7 \text{ mm}, w = 0.2 \text{ mm}$ $d_1 \in [3, 6.5]$	$f_{g2} = 77.66d_1^3 - 864.36d_1^2 + 3479.1d_1 - 2667.8$	$f_{g1} = -6.4297d_1^3 + 113.04d_1^2 - 648.65d_1 + 2359.7$
$a = 8 \text{ mm}, w = 0.2 \text{ mm}$ $d_1 \in [3, 7.5]$	$f_{g2} = 43d_1^3 - 519.71d_1^2 + 2277.3d_1 - 1526.4$	$f_{g1} = -4.1224d_1^3 + 82.899d_1^2 - 536.63d_1 + 2164.7$
$a = 8 \text{ mm}, d_1 = 6.5 \text{ mm}$ $w \in [0.1, 0.7]$	$f_{g2} = -7708.7w^3 + 12277w^2 - 8101.6w + 4317$	$f_{g1} = -3417.4w^3 + 5814.9w^2 - 3762.6w + 1604.1$

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORS' CONTRIBUTIONS

Swapnil Arawade conceptualized the study, wrote the original draft of the manuscript, conducted the formal analysis, and interpreted the results. Janusz Piechowicz supervised the study, contributed to the interpretation of the results, reviewed and edited the manuscript, and acquired the funding. All authors reviewed and approved the final manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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