

ADDITIVELY MANUFACTURED TPU ACOUSTIC METAMATERIALS FOR HIGH-FREQUENCY NOISE MITIGATION IN DENTAL ROTARY INSTRUMENTS

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ABSTRACT

Noise generated by high-speed dental turbines represents a persistent challenge in dental clinics, affecting both patient comfort and the occupational well-being of medical staff. This study investigates the potential of additively manufactured thermoplastic polyurethane (TPU) acoustic metamaterials for high-frequency noise mitigation in dental applications. A layered metamaterial panel based on periodic hexagonal unit cells is proposed and numerically evaluated as a compact and frequency-selective acoustic treatment. A vibro-acoustic simulation framework is employed to assess the sound transmission loss (STL) performance of the proposed metamaterial in comparison with a solid TPU panel of equivalent thickness. Two configurations are analysed: a reference case without acoustic treatment and a modified case in which the TPU-based metamaterial is integrated onto the head of a dental rotary bur. Overall, the findings highlight the effectiveness of compact TPU-based acoustic metamaterials as a promising solution for targeted noise mitigation in dental environments. The proposed approach combines acoustic efficiency, design flexibility, and compatibility with additive manufacturing, thereby facilitating its potential integration into dental equipment and clinical noise control strategies.

KEYWORDS: panoramic dental radiography; metallic restoration detection; computer vision; image processing

1. Introduction

Noise pollution represents a significant challenge in medical environments, where excessive acoustic disturbances can negatively affect patient comfort, staff performance, and the accuracy of medical procedures. Hospitals and clinical facilities are characterized by complex acoustic conditions generated by medical equipment, ventilation systems, alarms, and human activity.

In recent years, acoustic metamaterials have emerged as a promising solution for advanced noise control due to their ability to manipulate sound propagation beyond the limitations of conventional materials [1-4]. By exploiting engineered subwavelength structures, metamaterials enable [5] the targeted attenuation of specific frequency bands,

offering new opportunities for noise mitigation in sensitive medical settings.

This work investigates the potential of metamaterial-based solutions for noise reduction in the medical industry, focusing on their underlying principles, design considerations, and applicability in real-world clinical environments. Traditional noise mitigation strategies in medical facilities typically rely on passive absorbers, barriers, or architectural modifications. While effective to a certain extent, these approaches often require substantial space, provide broadband but limited attenuation, and lack adaptability to varying noise sources.

Medical environments impose strict constraints related to hygiene, safety, compactness, and compatibility with existing equipment. Consequently, there is a strong demand for compact, lightweight, and frequency-selective noise mitigation solutions

that can be seamlessly integrated into medical devices and infrastructures.

Metamaterials address these requirements by enabling tailored acoustic responses, including negative effective mass density or bulk modulus, which allow for efficient attenuation of low-frequency noise that is otherwise difficult to suppress. This capability makes metamaterials particularly attractive for medical applications such as diagnostic rooms, intensive care units, and operating theatres [9-11].

Noise exposure in dental clinics represents a well-recognized occupational and patient-related issue, with potential implications for comfort, concentration, and long-term auditory health [6-8]. Modern dental procedures rely heavily on high-speed rotary instruments, among which the dental turbine is the predominant source of acoustic disturbance [9-14]. During clinical operation, dental turbines generate elevated sound pressure levels, typically ranging from 75 to 85 dB(A), with dominant spectral components located in the high-frequency range where human auditory sensitivity is maximal.

Prolonged exposure to such noise has been associated with increased stress levels in patients and cumulative auditory fatigue among dental professionals [14-18]. Moreover, the tonal and high-frequency nature of turbine-generated noise contributes to heightened discomfort, making effective noise mitigation strategies particularly relevant in clinical settings [17].

Conventional noise reduction approaches in dental clinics primarily involve passive acoustic treatments, equipment enclosures, or architectural modifications. While these solutions can provide partial attenuation, they are often bulky, broadband in nature, and difficult to integrate into compact clinical settings. In addition, standard acoustic materials typically exhibit limited performance in the high-frequency regime unless significant thickness is employed, which is impractical for many dental applications.

Recent advances in acoustic metamaterials offer new opportunities for targeted noise mitigation. By exploiting engineered microstructures and local resonance phenomena, metamaterials enable frequency-selective attenuation and enhanced damping within compact form factors. In this context, thermoplastic polyurethane (TPU) has emerged as a promising material due to its intrinsic viscoelastic damping properties, mechanical flexibility, and compatibility with additive manufacturing technologies.

This work investigates the potential of a TPU-based acoustic metamaterial, designed as a layered structure with stacked hexagonal unit cells, for reducing turbine-generated noise in dental clinics. A

numerical vibro-acoustic simulation framework is employed to evaluate the sound transmission loss (STL) through the proposed structure, with a specific emphasis on the clinically relevant 3–6 kHz frequency band. The study aims to demonstrate that compact, additively manufactured TPU metamaterials can provide effective and application-oriented noise mitigation solutions for dental environments.

2. Experimental procedure

This study adopts a multidisciplinary methodology combining acoustic theory, numerical simulation, and metamaterial design to investigate noise mitigation solutions for medical environments. In particular, the proposed approach integrates computational fluid dynamics (CFD)-based acoustic simulations with the structural modeling of hexagonal layered metamaterial cells, enabling detailed analysis of sound-structure interaction in the case of a dental rotary bur.

The methodology consists of the following main steps:

The acoustic metamaterial is modeled as a stacked arrangement of hexagonal unit cells, selected for their structural symmetry, efficient space-filling properties, and mechanical stability. The primary noise source considered in this study is the high-speed dental turbine, which is known to generate elevated sound pressure levels with dominant spectral components in the high-frequency range. Based on reported clinical measurements, the turbine produces sound pressure levels of approximately 75 dB(A), with pronounced peaks in the 5 kHz frequency band.

Accordingly, the objective of the simulation is to evaluate the effectiveness of a TPU-based metamaterial structure in attenuating airborne noise within the 1–8 kHz frequency range, with a specific emphasis on the clinically relevant 3–6 kHz band. The metamaterial is positioned on the dental rotary bur head (Fig. 2).

The proposed noise mitigation solution consists of a TPU-based acoustic metamaterial panel, designed as a layered structure composed of stacked hexagonal unit cells. This geometry was selected due to its structural symmetry, high porosity control, and capability to induce local resonances and enhanced damping effects.

The geometry consists of elongated hexagonal unit cells arranged in a longitudinally periodic lattice within a rectangular domain (Fig. 1). Key geometric parameters, including unit cell dimensions, wall thickness, and repetition pitch, are explicitly defined to enable fine-tuning of the effective mechanical and vibro-acoustic properties. Such structures are suitable for finite element analysis, parametric optimization,

and the additive manufacturing of lightweight functional components.

The TPU material is modeled as a viscoelastic polymer with frequency-independent elastic properties for the baseline simulations. Density, Young's modulus, and Poisson's ratio are defined based on manufacturer datasheets for medical-grade TPU 95A commonly used in additive manufacturing. Structural damping is introduced via a loss factor to capture the inherent energy dissipation characteristics of TPU.

To evaluate sound transmission through the metamaterial panel, a vibro-acoustic simulation framework is employed. The study investigates two scenarios: (i) a reference configuration without a metamaterial panel and (ii) a configuration in which the proposed metamaterial is integrated onto the head of the dental rotary bur.

This coupled formulation enables the assessment of both airborne sound transmission and structure-borne vibration effects, which are critical for accurate STL prediction.

The numerical simulations are implemented using Altair SimLab.

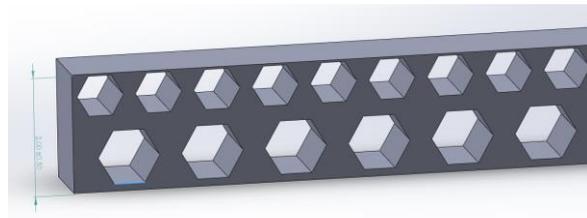


Fig. 1. Metamaterial structure

Comparing the two simulation results, a clear improvement in noise mitigation performance is observed in the second configuration. In the first image, the acoustic pressure field exhibits an extended region of elevated sound pressure levels, with high-intensity zones propagating farther from the dental turbine along the main emission direction. This indicates a more efficient transmission of acoustic energy into the surrounding air domain.

In contrast, the second image shows a noticeable reduction in both the magnitude and spatial distribution of the acoustic pressure field. High sound pressure level regions are more confined to the vicinity of the source, and the transition toward lower pressure levels occurs at a shorter distance from the turbine. Based on the colour scale and the contraction of the high-intensity regions, an estimated reduction of approximately 6–10 dB in peak sound pressure level is achieved in the second case.

This reduction is accompanied by a significant decrease in the directional propagation of the acoustic wave, suggesting enhanced dissipation and absorption

of acoustic energy. The observed behavior is consistent with the presence of an acoustic treatment that introduces additional damping and scattering mechanisms, leading to faster attenuation of the sound field. Overall, the comparison demonstrates that the second configuration provides a more effective noise mitigation solution, resulting in a substantial reduction of turbine-generated noise under identical simulation conditions.

This parametric analysis enables the identification of optimal design configurations that maximize noise attenuation in the target frequency band while maintaining minimal panel thickness.

Acoustic propagation through and around the metamaterial structure was investigated using CFD-based simulations, employing the linearized Navier–Stokes equations coupled with acoustic wave formulations. The simulations model the interaction between incident acoustic waves and the hexagonal metamaterial layers, allowing for the evaluation of pressure fields, velocity distributions, and sound transmission loss. Appropriate boundary conditions were applied to represent reflective, absorptive, or open acoustic environments typical of medical facilities.

3. Results and discussions

The modal analysis performed on the TPU-based metamaterial panel revealed multiple vibration modes within the targeted frequency range. In contrast to the solid TPU reference panel, the hexagonal layered configuration exhibited a higher density of local resonance modes between 3 and 6 kHz. These modes are primarily associated with the deformation of the hexagonal cell walls and inter-layer coupling effects.

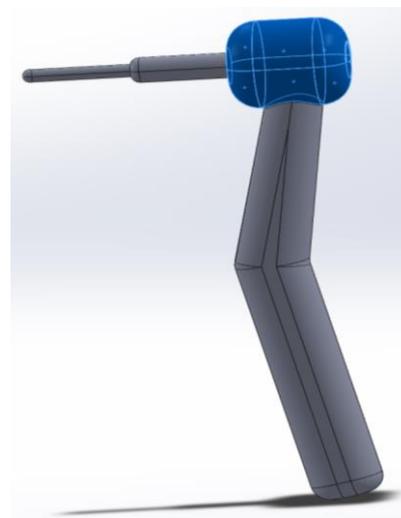


Fig. 2. Placement of the metamaterial

The presence of these localized resonances indicates an increased potential for energy dissipation through viscoelastic damping, which is expected to enhance acoustic attenuation within the corresponding frequency bands.

Figure 3 illustrates the simulated sound transmission loss (STL) as a function of frequency for both the solid TPU panel and the TPU metamaterial panel with stacked hexagonal cells. The solid TPU panel exhibits a gradual increase in STL with frequency, consistent with mass-law behavior, but provides limited attenuation within the critical 3–6 kHz band.

In contrast, the TPU metamaterial panel demonstrates a pronounced improvement in STL performance. Distinct attenuation peaks are observed within the 3–6 kHz range, coinciding with the identified structural resonance frequencies. In this band, the metamaterial panel achieves an STL increase of approximately 8–15 dB compared to the solid TPU reference, varying on the specific unit cell dimensions and number of layers.

The results highlight the frequency-selective nature of the proposed metamaterial design. While both configurations provide comparable attenuation at lower frequencies, the hexagonal layered structure exhibits superior performance in the high-frequency range associated with dental turbine noise.

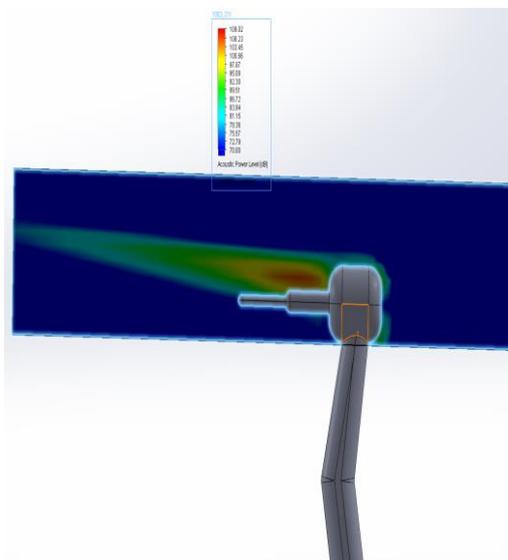


Fig. 3. Sound level in case of no panel

This behavior confirms that the attenuation mechanism is not solely governed by panel mass but is strongly influenced by the engineered geometry of the metamaterial. The stacked hexagonal cells act as locally resonant elements, inducing bandgap-like behavior and enhancing sound energy dissipation within targeted frequency intervals.

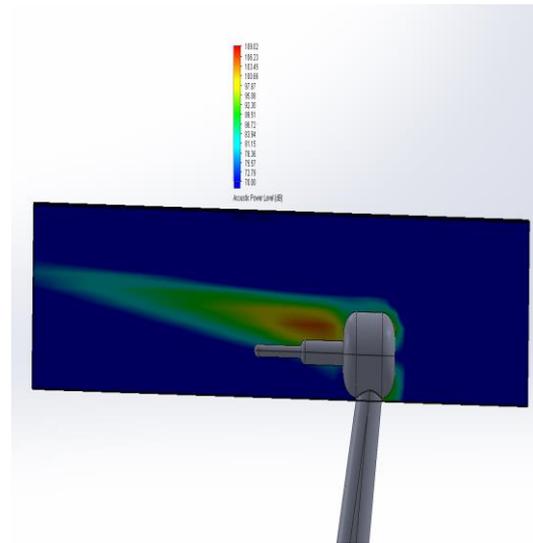


Fig. 4. Sound level distribution in case panel is applied

A parametric analysis indicates that the acoustic performance of the metamaterial panel is sensitive to the geometric characteristics of the hexagonal cells. Increasing the unit cell size or the total panel thickness shifts the STL peaks toward lower frequencies, whereas reducing these parameters shifts attenuation peaks to higher frequencies.

The results demonstrate that through appropriate tuning of the hexagonal cell dimensions and layering strategies, the metamaterial panel can be optimized to specifically target the dominant spectral components of dental turbine noise.

These findings suggest that compact TPU metamaterial panels can outperform conventional polymer-based acoustic treatments in dental environments, particularly for high-frequency noise mitigation. The results obtained from the vibro-acoustic simulations demonstrate that the proposed TPU-based metamaterial panel provides a significant improvement in sound transmission loss compared to a solid TPU panel of equivalent thickness. This improvement is particularly evident within the 3–6 kHz frequency band, which corresponds to the dominant spectral components of dental turbine noise and the region of maximum human auditory sensitivity.

The enhanced STL performance can be primarily attributed to the engineered hexagonal layered geometry, which introduces local resonance phenomena and increases structural compliance at targeted frequencies. Unlike conventional homogeneous panels, where sound attenuation is largely governed by the mass law, the metamaterial configuration enables frequency-selective attenuation through resonance-driven energy dissipation and the viscoelastic damping of the TPU material.

The modal analysis supports this interpretation by revealing a higher density of structural modes in the metamaterial panel within the critical frequency range. These modes facilitate stronger vibro-acoustic coupling, resulting in increased sound energy absorption and reduced acoustic transmission. The observed attenuation peaks align well with the predicted resonance frequencies of the hexagonal unit cells, confirming the effectiveness of the design strategy.

From an application perspective, the ability to achieve an additional 8–15 dB STL improvement without increasing panel thickness or mass is particularly relevant to dental environments, where space constraints and ergonomic considerations are critical. The use of TPU further enhances applicability, as the material offers favourable damping properties, mechanical flexibility, and compatibility with additive manufacturing processes.

Nevertheless, the results should be interpreted within the context of the study's limitations. The simulations assume idealized boundary conditions and linear material behavior, which may differ from real clinical settings. Furthermore, the current analysis focuses on airborne noise transmission and does not explicitly address structure-borne vibration pathways through dental equipment. These aspects warrant further investigation through experimental validation and extended modeling.

Overall, the findings indicate that TPU-based acoustic metamaterials represent a promising and practical solution for mitigating high-frequency noise generated by dental turbines, offering significant advantages over conventional polymer-based acoustic treatments in terms of efficiency and design flexibility.

4. Conclusions

This study investigated the potential of a TPU-based acoustic metamaterial for mitigating noise generated by high-speed dental turbines, which represent one of the primary acoustic disturbances in dental clinics. A vibro-acoustic simulation framework was employed to evaluate the sound transmission loss of a layered hexagonal metamaterial panel and to compare its performance to a conventional solid TPU panel of equivalent thickness.

The numerical results demonstrate that the proposed metamaterial configuration provides a substantial improvement in acoustic attenuation, particularly within the 3–6 kHz frequency range most relevant to turbine-generated noise and human auditory sensitivity. Compared to the solid TPU reference, the metamaterial panels achieved an additional 8–15 dB increase in STL without increasing panel thickness or mass.

The enhanced performance is attributed to the combined effects of local resonance phenomena induced by the hexagonal cell geometry and the intrinsic viscoelastic damping properties of TPU. These mechanisms enable frequency-selective noise mitigation beyond the limitations of conventional mass-based acoustic treatments.

Overall, the findings confirm that compact, additively manufactured TPU metamaterials represent a promising solution for noise reduction in dental environments. The proposed approach offers a balance between acoustic efficiency, design flexibility, and practical applicability, making it suitable for integration into dental equipment housings, liners, or localized acoustic barriers. Future work will focus on experimental validation, optimization for manufacturing constraints, and extending the approach to multi-source noise mitigation scenarios within clinical settings.

Despite the promising results obtained in this study, several limitations must be acknowledged. First, the analysis is based exclusively on numerical vibro-acoustic simulations performed under idealized boundary conditions. While these simulations provide valuable insights into the noise mitigation potential of the proposed TPU metamaterial, real dental environments exhibit more complex acoustic characteristics, including reverberation, equipment-induced structural vibrations, and variable source–receiver configurations.

Future work will therefore concentrate on experimental validation using additively manufactured TPU prototypes and controlled acoustic measurements in laboratory or simulated clinical environments. Parametric optimization studies will be extended to include a wider range of geometric configurations, material properties, and manufacturing constraints. Furthermore, the integration of adaptive or multi-material designs may enable tuneable and broadband noise mitigation tailored to diverse dental equipment and operational conditions.

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