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PARAMETRIC INVESTIGATION OF TESLA VALVE-INSPIRED ACOUSTIC METAMATERIALS FOR TUNABLE LOW-FREQUENCY SOUND ABSORPTION IN CEMENTITIOUS COMPOSITES

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Abstract

Low-frequency noise remains a major challenge in urban environments, where conventional acoustic absorbers often require excessive thickness or compromise structural integrity. This study investigates a Tesla-valve-inspired acoustic metamaterial embedded in high-strength mortar, focusing on the geometric mechanisms that govern its sound-absorption performance. A parametric analysis was conducted to evaluate the influence of coiling angle, channel (leaf) length, valve count, and Helmholtz neck diameter on acoustic behavior within the 200–2500 Hz frequency range. Numerical simulations were performed using the thermoviscous acoustics interface in COMSOL Multiphysics, coupled with the Johnson–Champoux–Allard (JCA) model, to account for viscous and thermal dissipation effects. The results show that the coiling angle controls the resonance frequency by increasing tortuosity and the effective acoustic path length. In contrast, channel length enables near-linear tuning of the resonance position. Increasing the number of valves introduces multiple resonant modes, resulting in broadband absorption. In contrast, the Helmholtz neck diameter selectively tunes mid- to high-frequency response. Experimental measurements with an in situ PU probe confirm the simulation trends, demonstrating strong agreement between numerical predictions and measured absorption behavior.

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1. Introduction

Environmental noise pollution has become a major global concern, particularly in densely populated urban areas where transportation and industrial activities generate persistent low-frequency noise [1]. Conventional sound-absorbing materials such as mineral wool, porous foams, and micro-perforated panels primarily dissipate acoustic energy through bulk porosity and material thickness [2]. Although effective at mid- and high-frequency ranges, their performance at low frequencies is limited unless the absorber thickness approaches a quarter of the acoustic wavelength, which is often impractical for structural applications.

Recent advances in acoustic metamaterials demonstrate that geometric manipulation of sound propagation can enable strong subwavelength absorption without excessive thickness [3]. Space-coiling and labyrinthine structures extend the effective propagation path of acoustic waves, enhancing resonance and energy dissipation within compact systems. However, many existing designs rely on polymeric materials or microfabrication processes, which limit their integration into load-bearing structures [4]. Tesla valve-inspired geometries provide a promising alternative, as their asymmetric, tortuous channels increase acoustic path length and enhance thermoviscous dissipation through repeated reflections and boundary-layer interactions [5].

Previous work demonstrated that embedding an asymmetric coiled-channel metamaterial inspired by the Tesla valve in high-strength mortar can significantly improve low-frequency sound absorption while maintaining compressive strength above 70 MPa [6]. However, the influence of geometric parameters on acoustic performance has not been systematically examined. This study, therefore, conducts a parametric investigation, combining numerical simulations and experimental validation to determine how key geometric parameters govern the resonance frequency, absorption bandwidth, and overall acoustic performance.

In this system, sound absorption is governed by resonance tuning, tortuous wave propagation, and thermoviscous dissipation. The coiled Tesla-valve-inspired channel increases the effective acoustic path length, shifting the resonance toward lower frequencies, while narrow passages enhance viscous and thermal boundary-layer losses. The coupled Helmholtz cavity further enhances localized resonance, enabling compact low-frequency absorption without increasing overall material thickness.

2. Methodology

2.1 Geometric parameters for parametric investigation

Four geometric parameters were considered in the parametric study: coiling angle (θ, °), channel length (L, mm), number of valves (N), and Helmholtz neck diameter (d, mm). These parameters directly influence the acoustic path length, viscous interaction area, and resonance behavior of the Tesla valve–inspired channel. A systematic naming convention was used to identify the configurations. In this notation, θ represents the coiling angle, Lx represents the leaf length in mm, Nx represents the number of repeated Tesla-valve leaves, and dx represents the Helmholtz neck diameter in mm. For example, 90-L14-N9 denotes a configuration with a 90° coiling angle, 14 mm leaf length, and 9 leaves, while 90-L14-N9-d4 denotes the same geometry with a 4 mm Helmholtz neck diameter.

Table 1. Parametric variables investigated in the Tesla valve metamaterial design.

Parameter	Notation	Range
Coiling angle	q-Lx-Nx	15°–105°
Channel length	q-Lx-Nx	7 –18 mm
Number of valves	q-Lx-Nx	3–18
Helmholtz neck diameter	q-Lx-Nx-dx	1 –8 mm

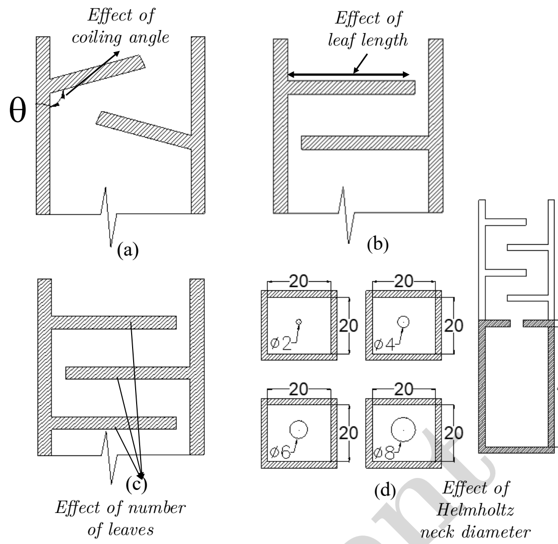


Figure 1. Geometric parameters used in the parametric study: (a) coiling angle, (b) channel length, (c) valve count, and (d) Helmholtz neck diameter. The Helmholtz neck is connected to the tortuous channel through an internal opening, allowing the incident wave to interact with both the coiled channel and the resonant cavity.

2.2 Numerical simulation

Acoustic performance was simulated using COMSOL Multiphysics. The thermoviscous acoustics interface was employed to resolve viscous and thermal boundary-layer losses in the narrow channels of the metamaterial structure. The surrounding mortar matrix was modeled using the Johnson–Champoux–Allard (JCA) formulation to capture the porous acoustic behavior of the cementitious material [7].

The simulation domain consisted of an air layer and a mortar layer containing the embedded metamaterial. The air domain was assigned a density of 1.21 kg/m³ and a speed of sound of 343 m/s. The mortar domain incorporated experimentally determined non-acoustical parameters, including porosity, airflow resistivity, and tortuosity.

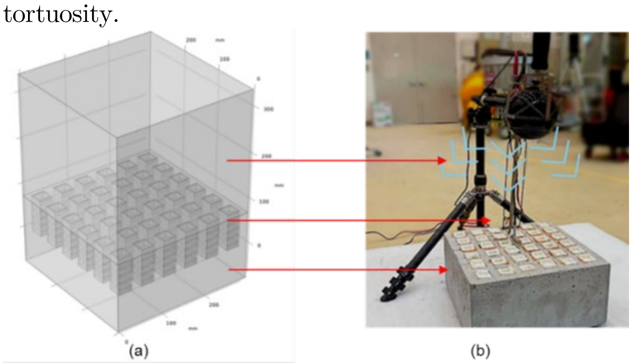


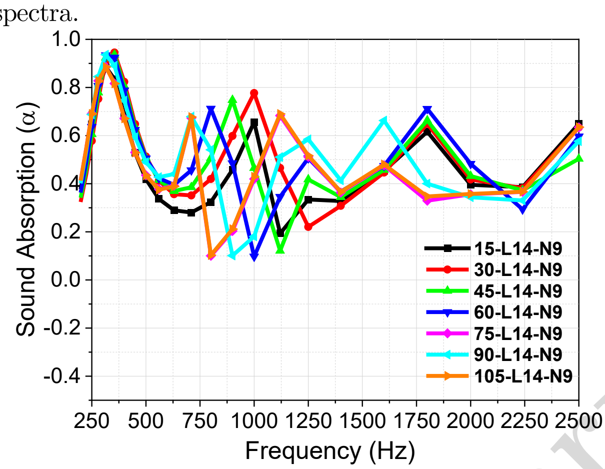
Figure 2. Numerical model used for thermoviscous acoustic simulation showing air domain, mortar layer, and embedded Tesla valve metamaterial geometry.

A plane-wave boundary condition was imposed on the incident side. At the same time, the rear surface was modeled as a rigid boundary to represent reflection from a backing wall. Perfectly matched layers were applied to the lateral boundaries to eliminate artificial reflections.

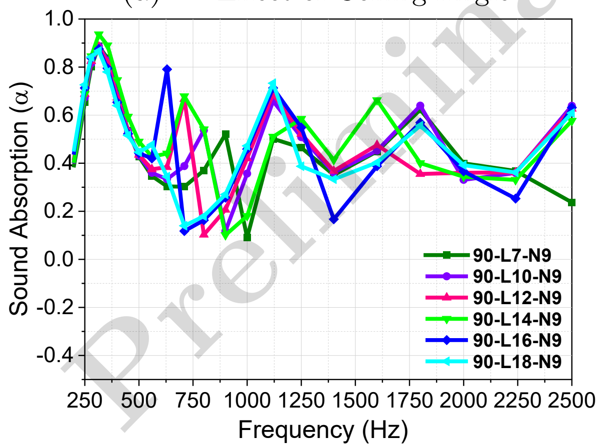
3. Results and Discussion

3.1 Parametric Study

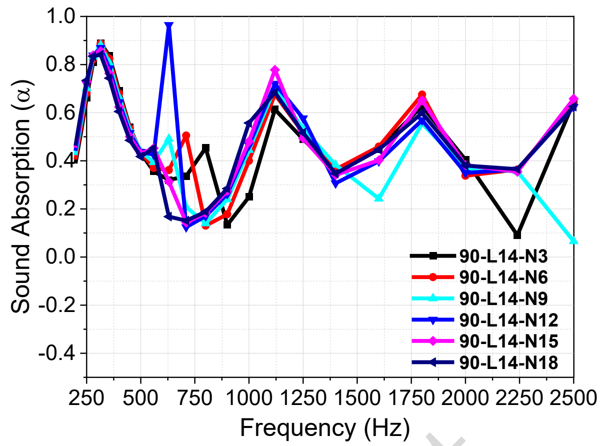
The acoustic performance of the proposed metamaterial was investigated using parametric simulations to understand how geometric parameters affect resonant behavior and overall sound absorption. Figure 3 presents the simulated results illustrating the effects of the coiling angle, channel length, valve count, and Helmholtz resonator neck diameter on the absorption spectra.



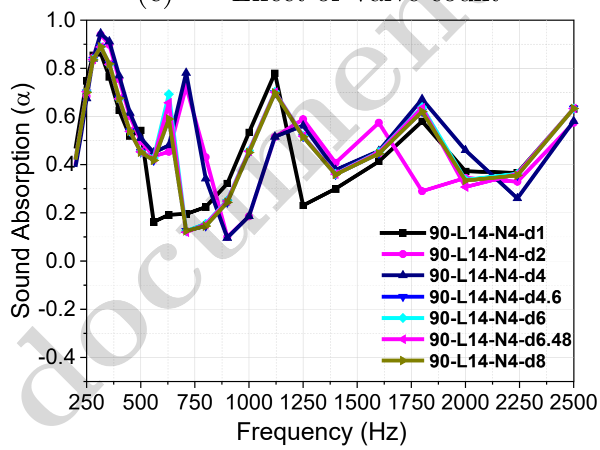
(a) Effect of Coiling Angle



(b) Effect of Channel length



(c) Effect of Valve count



(d) Effect of Helmholtz neck diameter

Figure 3 Parametric simulation results showing the effects of: (a) coiling angle, (b) channel length, (c) valve count, and (d) Helmholtz neck diameter on sound absorption spectra.

The coiling angle plays a critical role in controlling the tortuosity of the internal acoustic channel and directly affects the effective acoustic path length. As shown in Figure 3(a), increasing the coiling angle increases the propagation distance of sound waves within the channel, thereby lowering the resonance frequency according to the quarter-wavelength relation [8]. When the angle increases from 15° to 105°, the dominant absorption peak shifts progressively toward lower frequencies. This trend is consistent with space-coiling metamaterial theory, where geometric folding effectively increases the acoustic propagation path while maintaining a compact structural thickness.

In addition to the coiling geometry, the straight-channel length provides an important tuning mechanism for controlling resonance. As illustrated in Figure 3(b), increasing the channel length extends the effective propagation path while preserving the same turning geometry. The simulation results indicate a nearly linear shift of the resonance peak toward lower frequencies as the channel length increases. This behavior demonstrates that channel length can serve as a precise geometric parameter for targeting specific acoustic frequency bands without significantly altering the overall structural configuration.

The number of Tesla-valve segments also influences the acoustic response by modifying internal reflections and phase delays within the channel network. Although inspired by the asymmetric Tesla valve used in fluid transport, the present design is not intended to produce one-way acoustic behavior; instead, the asymmetric branches are used to increase path length, local impedance variation, and thermoviscous dissipation. The simulated results in Figure 3(c) show that increasing the valve count introduces additional internal reflections, which generate multiple standing-wave modes within the structure. As the valve count increases from 9 to 12, the absorber exhibits multi-mode resonance behavior, resulting in a broader absorption bandwidth with multiple peaks distributed across the measured frequency range.

Finally, the Helmholtz resonator incorporated in the hybrid design provides an additional mechanism for tuning mid- to high-frequency absorption. The resonance frequency of the Helmholtz cavity is governed by Eq. 1.

$$f_H = \frac{c}{2\pi}\sqrt{\frac{A}{V L_{\text{tot}}}} \quad (1)$$

where c is the speed of sound, A is the neck cross-sectional area, V is the cavity volume, and L_{tot} is the effective neck length [9]. As shown in Figure 3(d), decreasing the neck diameter increases viscous losses within the neck region. It produces sharper resonance peaks, while larger neck diameters broaden the absorption band but slightly reduce the peak absorption amplitude. This behavior demonstrates the capability of Helmholtz components to complement the Tesla valve geometry by extending the effective absorption range over a broader frequency range.

3.2 Experimental Validation

To validate the numerical predictions, metamaterial specimens with varying coiling angles were fabricated by embedding 3D-printed PLA inserts within high-strength mortar panels. Sound absorption performance was measured using an in-situ PU-probe surface impedance method in accordance with ISO 13472-1 [10]. The mortar panel had dimensions of 300 × 300 × 300 mm.

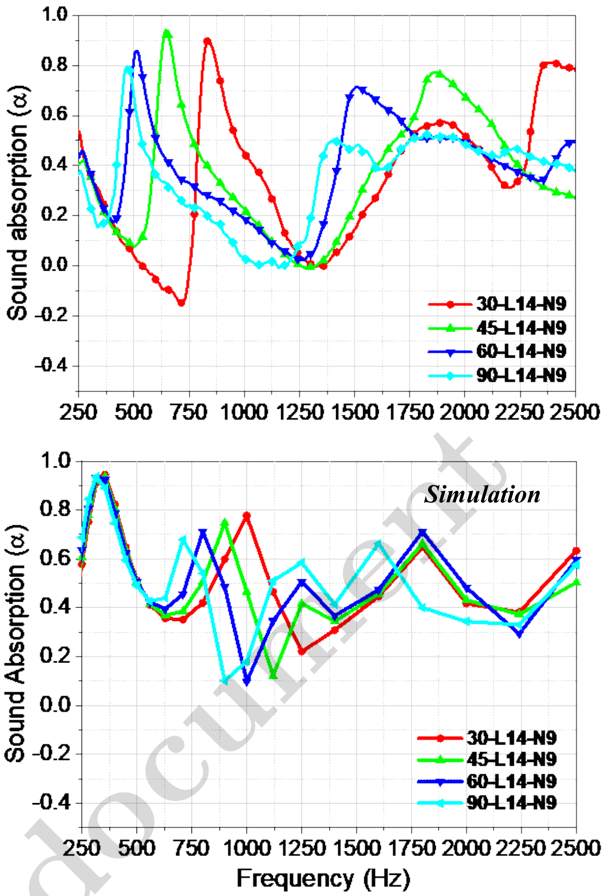


Figure 4. Experimental sound absorption coefficients comparison with simulated results for asymmetric coiled channel specimens with varying coiling angles.

For example, both simulation and experiment show that increasing the coiling angle shifts the main absorption region toward lower frequencies, confirming the role of the effective acoustic path length in tuning the resonance. Minor differences in peak magnitude and resonance position are attributed to fabrication tolerance, surface roughness, imperfect specimen mounting, and simplified boundary assumptions in the numerical model. Increasing the coiling angle shifts the resonance peak toward lower frequencies, confirming that the geometric tuning mechanisms identified in the simulations are consistent with measured acoustic behavior. The slightly negative absorption values observed in limited frequency ranges are not physical material responses but rather measurement artifacts arising from phase mismatch, edge leakage, imperfect mounting, and uncertainty in the in-situ PU-probe surface impedance method.

4. Conclusions

This study presented a parametric investigation of Tesla valve–inspired acoustic metamaterials embedded in cementitious matrices, demonstrating that geometric parameters strongly govern resonant behavior and acoustic dissipation.

Increasing the coiling angle from 15° to 105° extended the effective acoustic path length. It shifted the dominant resonance from approximately 830 Hz to 420 Hz (≈49% reduction), enabling strong low-frequency absorption within a compact structure. Increasing the channel length from 30 mm to 70 mm (≈133% increase) shifted the resonance by about 300–350 Hz (≈35–40% change), providing precise frequency tuning. Increasing the valve count from 9 to 12 (≈33% increase) transformed the absorber from a single-resonance response to a broadband multi-mode response across the 200–2500 Hz range. In addition, increasing the Helmholtz neck diameter from 4 mm to 10 mm (≈150% increase) shifted the resonance by ≈200–300 Hz (≈20–30%) while modifying the absorption bandwidth.

Experimental measurements confirmed the numerical predictions, with peak absorption coefficients ranging from $\alpha \approx 0.90$ to 0.95. These results provide practical design guidelines for developing load-bearing cementitious acoustic metamaterials with broadband sound absorption capability.

5. Acknowledgment

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