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# Experimental study for improving sound absorption of a composite helical-shaped porous structure using carbon fiber

Bo-Seung Kim [a], Sung-Jin Cho [b], Dong-ki Min [b], Junhong Park [b,*]

[a] Department of Mechanical Convergence Engineering, Hanyang University, Haengdang-Dong, Seongdong-Gu, Seoul 133-791, Republic of Korea
[b] Department of Mechanical Engineering, Hanyang University, Haengdang-Dong, Seongdong-Gu, Seoul 133-791, Republic of Korea

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ABSTRACT

A composite sound absorption structure constructed with fibrous layer and carbon fibers was proposed and its acoustic performance was experimentally studied. Proposed structure's sound absorption properties depended on the gap of the air cavity between fibrous layers. To increase the absorption efficiency, carbon fiber was applied between the gaps. The normal incidence sound absorption coefficients and specific acoustic impedance were measured with the two-microphone impedance tube method to determine the effects of the carbon fibers on the acoustic properties. Random incidence absorption coefficients were determined from the measured specific acoustic impedances of the proposed structures. The measured results were compared for various fractions of carbon fibers. Modified wave propagation equations with empirical density equations were suggested to predict the acoustic behavior of the proposed absorbers. After application of the carbon fibers, the composite helical-shaped sound absorber showed better sound absorption efficiency under both normal and random incidence conditions. This suggested that the carbon fibers introduced additional sound dissipation when properly distributed along the gap of the sound absorber.



## 1. Introduction

Porous sound absorbers are common solutions to reduce the noise-related problems. Porous structures absorb sound through inner tortuous layers and dissipate it into heat energy [1]. As there have been continued interests in enhancing the absorption efficiency of sound absorber while maintaining the thickness, composite sound and vibration absorbing structures are widely studied for noise reduction in various applications. Wu et al. [1] studied the damping and sound absorption properties of Al matrix composite foams. The particle of the porous material reinforced by Al matrix composite foams showed better damping and sound absorption properties than plain Al foams. Yang et al. [2] developed hybrid carbon fiber composite pyramidal truss sandwich panels with viscoelastic layers embedded in the face sheets. The insertion of a viscoelastic layer in the face sheets distinctly increased its damping loss factor without significantly changing the natural frequencies. Zhou et al. [3] proposed composite sound absorber composed of recycled rubber particles. Sound absorption capability of the proposed absorber was enhanced through impedance matching design of structure and combination of damping effect. Ruben et al. [4] showed acoustic properties of sound-absorbing materials made from fluff, both with and without resin. With the recycling of waste materials, sound absorbers were designed to reduce noise and environmental pollution. Sargianis et al. [5] studied about the sound and vibration damping properties of natural material-based sandwich composites. By using natural fiber based composite materials, it was possible to create sandwich beams with superior acoustic performance. For the composition of wood-based materials for sound absorption in the residential environment, Yang et al. [6] suggested rice straw–wood particle composite board. Composite boards made from the random cutting of rice straw and wood particles were recommended for absorbing sound in manufacturing processes. The sound absorption coefficients of the 0.4- and 0.6- specific gravity boards were larger than those of other wood-based materials. Rozil et al. [7] introduced sound absorber made of coconut coir fiber, and the results from the experimental tests demonstrated that it had good acoustic properties at low and high frequency bands. To increase the absorption efficiency of porous materials at low frequencies, Atalla et al. [8] studied non-homogeneous thin macro-porous materials, enhanced performances were obtained for non-homogeneous

* Corresponding author.
*E-mail addresses:* r32gtr@hanyang.ac.kr (B.-S. Kim), sjcho0407@hanyang.ac.kr (S.-J. Cho), dkmin@hanyang.ac.kr (D.-k. Min), parkj@hanyang.ac.kr (J. Park).

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materials than for homogeneous simple layered materials. For the construction of a sound and vibration reducing structure with a thin fibrous layer, Kim et al. [9] proposed a sound absorption structure made in a helical shapes and measured its acoustic and viscoelastic properties. Proposed sound absorber showed better absorption than conventional porous acoustic foams with the same thickness.

In this study, a composite sound absorbing structure made from fibrous thin layers in helical shape and carbon fibers was proposed. Helical-shaped sound absorbers were made by rolling long thin layers into helical shapes. Their acoustic properties depended on the adjustment of the lengths of these thin layers. Carbon fibers were applied to the air gaps of the proposed structures to increase the sound absorption efficiency. The normal incidence absorption coefficients were measured to quantify effects of the carbon fibers on the acoustic performance. The random incidence absorption coefficients were calculated from the measured specific acoustic impedances to evaluate the absorption performance of proposed structures in reverberant sound field.

## 2. Theoretical background of composite helical-shaped sound absorber

The internal geometry of sound-absorbing porous materials is complex, and direct calculation of the viscous and thermal interactions between the air and these materials is difficult to perform [10]. To calculate the representative values for helical-shaped sound absorber, simplified pore shapes model of slits was used. Fig. 1 shows the one-dimensional sound propagation for helical-shaped absorber. To predict the theoretical acoustic properties of composite absorber, the slit model and the empirical equation of fibrous materials was used.

For one-dimensional parallel-sided slit model as shown in Fig. 1, effective density ($\rho_{eff}$) and bulk modulus ($K$) from the slit model was obtained as [10]

$$\rho_{eff} = \rho_0\left(1+\sqrt{\frac{2}{i}}\frac{\delta}{d}\right), \quad K = \frac{\gamma P_0}{\gamma-(\gamma-1)\Big/\left(1+\sqrt{\frac{2}{i}}\frac{\delta}{Bd}\right)}, \qquad (1a,b)$$

where $d$ is the gap width between the layers, $P_0$ is atmospheric pressure and $\gamma$ is the specific heat ratio of air. $\delta$ is represented by $(2\eta/\omega\rho_0)^{0.5}$, where $\eta$ is shear viscosity, $\rho_0$ is density of air, $\omega$ is angular frequency of sound wave. $B$ is the square root value of Prandtl number.

When carbon fibers were applied to the fibrous layer, the air gap inside the helical absorber was expected to change. The air density of the inner composite structure changed due to the porosity of the structure of the carbon fiber, when the fibrous layer was coated with carbon fiber. To predict the acoustic behavior of the composite helical absorber, the air density between layers was predicted by using porosity and flow resistance. The effective density for the composite absorber ($\rho_{eff}$) was calculated as

$$\rho_{eff} = \rho_2\left(1+\sqrt{\frac{2}{i}}\frac{\delta}{2d}\right). \qquad (2)$$

$\rho_2$ is the density of the fibrous medium having carbon fibers and was calculated as [11]

$$\rho_2 = 1.2 + \left[-0.0364\left(\frac{\rho_0 f}{\sigma}\right)^{-2} - i0.1144\left(\frac{\rho_0 f}{\sigma}\right)^{-1}\right]^{-2}, \qquad (3)$$

where $f$ is frequency in Hz, and $\sigma$ is flow resistance.

If the materials having density $\rho_1$ (here, density of the mulberry paper) and $\rho_2$ were arranged alternately as shown in Fig. 1, sound wave passed through the medium having the smaller characteristic impedance. Flow resistance increased with the increasing amount of applied carbon fibers due to change in the porosity of the medium [12]. With Eqs. (1) and (2), the characteristic impedance $Z_c$ and the complex wave number $k$ for proposed composite absorber was estimated

$$Z_c = \sqrt{K\rho_{eff}}, \quad k = \omega\sqrt{\rho_{eff}/K}. \qquad (4a,b)$$

Consequently, the acoustic impedance $Z$ was calculated as $Z = Z_c \cdot \coth(ikh)$. The normal incidence absorption coefficient for $\alpha_n$ was calculated as

$$\alpha_n = 1 - \left|\frac{Z-\rho_0 c}{Z+\rho_0 c}\right|^2, \qquad (5)$$

where $c$ is the speed of sound.

## 3. Measurement and prediction of the normal incidence absorption coefficient

### 3.1. Measurement of acoustic properties

The two-microphone impedance tube method was used to measure the normal incidence absorption coefficients and specific acoustic impedances [13]. A loudspeaker was placed at one end of the tube to generate random sound from 20 to 6400 Hz. The diameter of the tube was 29 mm, and the distance between the microphones was 20 mm. Two pressure-field microphones (B&K Type 4187) were mounted along the wall of the tube, and the absorption and reflection wave coefficients were calculated with a FFT analyzer (B&K Type 3560). A mulberry paper coated with carbon fiber was rolled into a helical shapes, and multiple samples were produced with different lengths, $L$, and masses of carbon fibers, as shown in Fig. 2. Eight samples were tested, and their dimensions are shown in Table 1. For all samples, the thickness ($h$) and diameter were 0.01 m and 0.029 m, respectively. Samples 1 to 4 were produced only with mulberry paper so that the acoustic characteristics are compared with those of the composite helical-shaped sound absorber. Samples 5 to 8 were produced using different lengths of mulberry papers and amounts of carbon fiber (ACECA-NA1, ACE C&TECH, Korea). The unit cell of carbon fibers was 6 μm in diameter and 3 mm in length.

### 3.2. Measured and predicted normal incidence absorption coefficient

Measured normal incidence absorption coefficient of samples 1 to 4 are shown in Fig. 3. The density of the fibrous medium, $\rho_0$, and the sound absorption efficiency increased with the decreasing distance between layer. The flow resistivity of samples 1 to 4

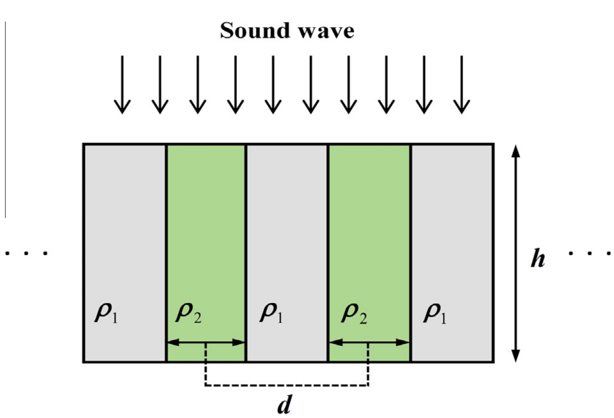


**Fig. 1.** One-dimensional sound wave propagation analysis of the composite helical-shaped absorber.