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Sound insulation effect of magnetorheological fluid as a function of magnetic field strength and direction

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ABSTRACT

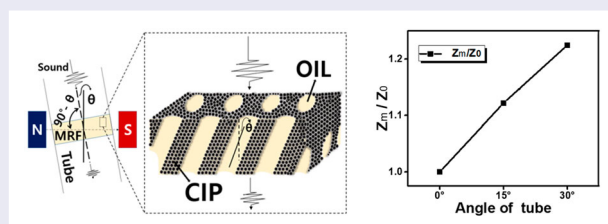
We developed a sound absorber using a magnetorheological fluid (MR-F) based on the density and alignment angle of carbonyl iron powder (CIP) chains by the controlling the magnetic field strength and direction. The magnetically arranged CIP lattice structure considerably influenced the sound transmission loss (STL). We used optical microscopy, energy-dispersive X-ray spectrometry, and X-ray diffraction to investigate the STL by varying the magnetic field strength from 0 to 40 mT and the angle from 0 to 30°. The STL was markedly increased (133%) owing to an ~10-fold increased density and the CIP alignment. These results were verified using the developed MR-F porous model.

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KEYWORDS

Magnetorheological fluid (MR-F); sound transmission loss (STL); carbonyl iron powder (CIP); impedance tube; porous model



IMPACT STATEMENT

Sound transmission loss was significantly increased by sound insulation effect of a magnetorheological fluid as a function of magnetic field strength and direction.

1. Introduction

Magnetorheological fluids (MR-Fs) have been widely studied as smart materials for controlling vibration [1–9]. Ferromagnetic microparticles, such as carbonyl iron powder (CIP), are distributed in carrier fluids. When a carrier fluid is subjected to an external magnetic field, the particles are magnetized and arranged to follow the magnetic field lines [1,2], thereby causing the MR-F to become quasisolid. Over the past few decades, various studies have been conducted on MR-Fs for damping applications owing to high MR-F responsiveness, sensitivity, and other excellent properties [3–9]. For example, Mohammadi et al. [10] proposed typical viscoelastic and viscoplastic models to simulate the fluid behavior in pre- and postyield regions. However, although the mechanical properties of MR/electrorheological fluids (ER-Fs) [11–21] have been studied, few studies have investigated

the noise response properties of sandwich and shell structures and the use of MR/ER-Fs as sound absorption materials [22–28].

In the sound insulation field, viscoelastic and honeycomb materials are commonly used for sound absorption [29–40]. For instance, Gohari et al. presented the vibroacoustic properties of simply supported cylinders fabricated using porous material interlayers [40] and found that such materials were mainly effective for improving sound transmission loss (STL) within a narrow band in the high-frequency range. J. Yan et al. [41] also reported that sound absorber material particle density was an important parameter affecting STL. In addition, viscoelastic materials such as MR/ER-F sandwich structures provide an opportunity to control structural sound transmission over a wide frequency range. Furthermore, theoretical finite element analysis [10,42,43] and modal

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loss factor analysis [44–48] have been conducted on viscoelastic sandwich plates.

However, no studies have been conducted to date on MR-F STLs rather than on the STLs of MR-F-coated materials [36]. In addition, no research has been conducted on CIP particle density sound absorption properties and CIP chain arrangement angles for different magnetic field strengths and directions, despite the important parameters affecting the STL [41].

Therefore, we investigated how the STL was affected by applying various magnetic field strengths and directions to an MR-F-based sandwich structure in a sound insulation impedance tube. Different magnetic field strengths and directions changed the CIP arrangement, such as the MR-F density and particle chain angles. CIP characteristics were analyzed using optical microscopy, energy-dispersive X-ray spectrometry (EDS), and X-ray diffraction (XRD) for different magnetic fields. The magnetic field intensity was analyzed using two-dimensional magnetic field simulation software (FEMM). In addition, the sound absorption was analyzed and compared for different CIP chain densities and angles at different frequencies. The experimental results were verified using the acoustic impedance parameter of the developed MR-F porous model.

2. Materials and methods

2.1. Magnetorheological fluid

The MR-F (MR-F-140CG, LORD Corporation) exhibited a magnetic field response time of less than 5 ms. The iron microparticles in the fluid were between 1 and 20 μm . To prevent errors due to the uneven CIP distribution, three consecutive methods were applied to prepare the MR-F. First, the sample was stirred continuously for 10 min with a glass rod. Then, the sample was mixed in a high-speed rotating disperser (COROB CLEVER mix 700) at 1500 rpm for 5 min. Finally, the sample was processed for 3 min using an ultrasonic processor (KFS-250N) at 100% output power (150 W) and a frequency of 20 kHz.

2.2. Magnetorheological fluid sandwich plate

The sandwich plate into which the MR-F was inserted was shaped into a hollow cylinder fabricated using 30-mm-thick, 98-mm-inner-diameter polylactic acid (PLA) by the 3D printer, like Figure 1. To prevent cuvette leakage, we coated the fabricated cuvette inner surface with polydimethylsiloxane and added deionized water to the coated cuvettes for 24 h to verify the cuvette seal. The detailed cuvette fabrication is described in the

Supporting Information. Subsequently, the hollow sandwich plate was filled with the MR-F.

2.3. Impedance tubes

The impedance tube was designed using two microphones in accordance with the ISO 10534–2 standard. This impedance tube was fabricated using 1000-mm-long, 100-mm-inner-diameter polyvinyl chloride, like Figure 1(a,b). The sound source was connected to one tube end. Two microphones were set up 650 and 800 mm from the sound source. The sandwich plate sample was placed in the middle of the two microphones, and the other tube end was filled with sound-absorbing cotton to prevent ineffective sound waves from reflecting in a closed environment. Finally, the sound source and microphone were connected to an Arduino control board, and the sound source frequency was controlled from 0 to 6000 Hz using a computer. The data were obtained using a microphone under various magnetic field conditions, like Figure 1(b).

2.4. Magnetic field device

To control the MR-F CIP arrangement inside the sandwich plate, two permanent magnet-based devices were manufactured, like Figure 1(b). Two 80-mm-wide, 30-mm-thick rectangular parallelepiped permanent magnets were used as the magnetic field source. The magnets were placed at both designed console ends, and the magnetic field was changed by controlling the distance between the magnets. The magnetic field was measured using a Gauss meter (HT20; Shanghai Hengtong Magnetics Technology Company, China). Prior to the experiment, the magnet position was adjusted to generate 19- and 40-mT fields. We also simulated the MR-F magnetic particle morphological arrangement in the sandwich structure for various magnetic field strengths and directions, like Figure 1(c).

3. Results and discussion

3.1. Optical microscopy analysis

The MR-F CIP particle arrangement was investigated using optical microscopy (OLUMPUS, BH2-UMA) for different magnetic field strengths and directions. Because an optical microscope uses reflected light, metal particles such as CIPs effectively absorb and scatter incident light. Particle-absorbed light can excite electron leaps, induce hot carrier generation, and cause photoluminescence [49]. The CIPs aligned by the magnetic field appeared as a column of bright spots of reflected light. In

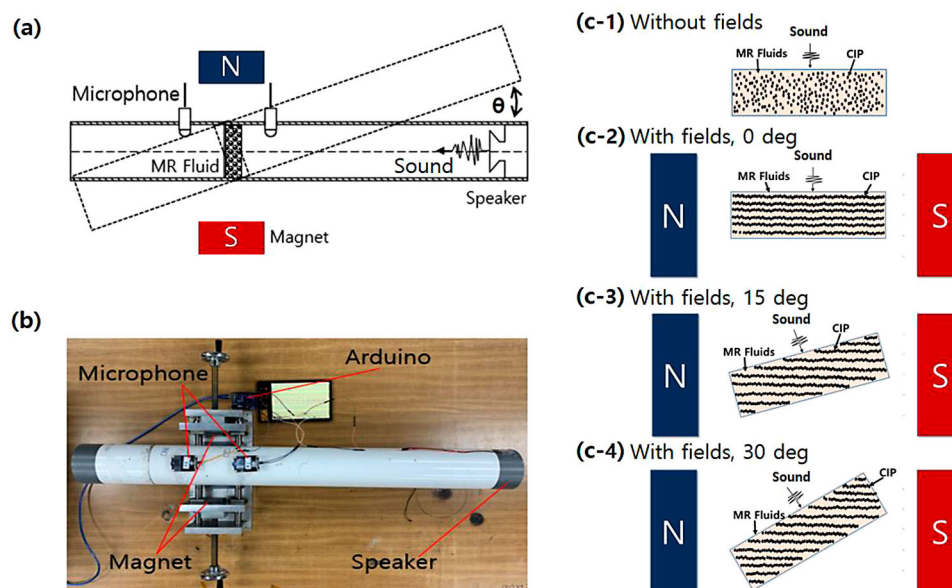


Figure 1. (a) Schematic of an impedance tube with a magnetic device. (b) Photograph of the experimental setup. (c) Conceptual figures of the arrangement of magnetic particles in sound absorbing sandwich structures for different magnetic field directions.

the MR-F oil near a bright CIP, on the other hand, most light was absorbed, thereby appearing relatively dark in the microscopic image, like Figure 2, because the incident light waves had been absorbed by the MR-F oil base [49]. When no magnetic field was applied, the CIP particles were uniformly distributed within the MR-F, like Figure 2(a). Clearly, the CIP particles that previously had been uniformly distributed were aligned along the magnetic field at 0° and 40 mT, as shown in Figure 2(b). Additionally, when the 40 mT magnetic field direction was changed, the CIP particles rearranged accordingly, as shown in Figures 2(c,d). These experimental results show that the magnetic field caused the CIP particles to form a column of iron rod-like chains uniformly distributed in the oil base.

3.2. CIP particle characterization

MR-F properties are influenced by the particle size and surface morphology [50,51]. Dry CIP samples were obtained by washing and heating, and the CIP particles were characterized using field-emission scanning electron microscopy (FE-SEM) and XRD, as shown in Figure 2. Clearly, the CIP particles were in the range $\sim 1\text{--}5\text{ }\mu\text{m}$. According to the EDS results, most CIP microparticle clusters consisted of Fe, and traces of C, O, Al, and Si were detected in the MR-F.

The CIP crystal structure and phases were also investigated using XRD, and CIP magnetization was studied at magnetic saturation [52], which can vary depending on the particle size, shape, and oxidation degree [53].

Magnetic resonance materials exhibit very high magnetic reversibility because they are easily magnetized and demagnetized when the magnetic field polarity is reversed. Figure 2(f) shows the CIP XRD peaks. Each peak was indexed, and the plane spacing was calculated for each index set. The peak intensity depended on the crystal structure, constituent element X-ray factor, elemental composition, and CIP preparation conditions. All the diffraction peaks indicated the formation of a body-centered cubic (BCC) (α)-iron structure exhibiting a lattice parameter of 0.286640 nm. The diffraction peak broadening revealed that the particles were composed of various nanograins.

3.3. Sound transmission loss and coefficient

To evaluate the MR-F for application as a sound absorber, the MR-F STL was investigated at different frequencies by changing the magnetic field strength and direction, as shown in Figure 3. When the MR-F was used as a sound insulator and no magnetic field was applied, the average STL was 12.47 dB, like Figure 3(a). In contrast, the STL increased in the overall frequency range when a 40 mT magnetic field was applied at 0°. With increasing magnetic field intensity, the average STL increased, reaching 15.75 and 16.68 dB at 19 and 40 mT, which were 26 and 33% higher, respectively, than the STL achieved when no magnetic field was applied. In particular, the STL difference measured at 4100 Hz and 40 mT, was up to 14 dB, depending on the magnetic field presence or absence.

These results suggest that an MR-F sound insulator can effectively generate impedance, which improves

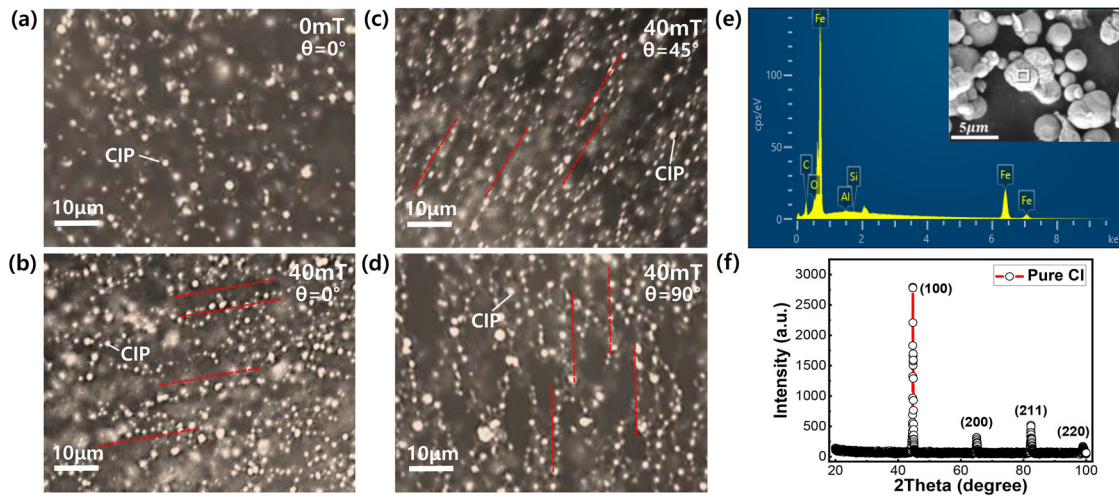


Figure 2. Optical microscope images of the microstructure of CIP as a function of different magnetic field strengths from (a) 0 to (b) 40 mT and directions of 0°, (c) 45°, and (d) 90°, respectively. (e) EDS spectrogram of prepared MR fluid samples, (f) XRD pattern of pure CIP.

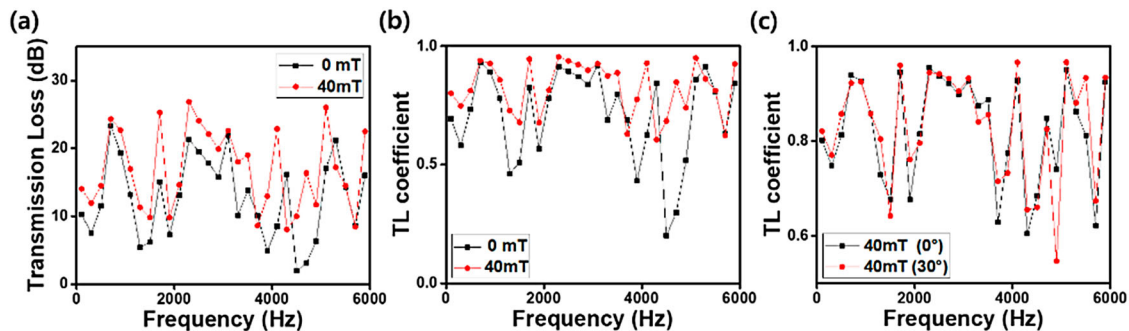


Figure 3. (a) Transmission loss and (b) transmission loss coefficient of an MR fluid as a function of frequency from 0 to 6000 Hz with different external magnetic field strengths at 0° and (c) the transmission loss coefficient at different applied magnetic field directions.

when a magnetic field is applied. The STL results were explained using a reference equation, as shown in Figure 3(b). The closer the data point was to 1, the higher the STL and the better the sound insulation. Furthermore, the STL coefficient clearly increased with increasing magnetic field strength.

Additionally, the impedance tube rotation angle increased in the horizontal plane in the range 0–30°, thereby slightly increasing the sound insulation. The average STL coefficient was 0.824, 0.829, and 0.832 at 0, 15, and 30°, respectively. The STL coefficient was higher at 30° in most frequency ranges.

In addition, the CIP particle density and compactness both increased with increasing magnetic field strength, as indicated by the data listed in Table S1. The particle density was analyzed by counting the number of particles forming CIP chains per unit area ($62 \times 12 \mu\text{m}$). The density proportionally increased by approximately 10 times from 18 ± 2 – $242 \pm 14\%$ at 0 and 40 mT, respectively. Although higher sound absorption material density is an important parameter for increasing sound loss [41], no previous studies have investigated how changing

the magnetic field strength and the applied MR-F angles affect the STL. In this study, the CIP particles adsorbed on the main chain aggregated into shorter or longer chains [54] with increasing magnetic field strength, thereby increasing the particle density and eventually increasing the STL.

However, with increasing applied angle in the same 40-mT magnetic field, although the density slightly decreased from 242 to 201% at 0 and 30°, respectively, the STL increased from 16.68–17.56 at 0 and 30°, respectively. These results indicate that the alignment angle of CIP chains is also an important parameter to determine the sound absorption performance, in addition to the density parameter.

3.4. Simulation analysis of the magnetic field

To explain these phenomena, we used two-dimensional FEMM software to analyze a simulated magnetic field intensity in the sandwich plate central plane. The experimental data are displayed in the three-dimensional diagram shown in Figure 4. The magnetic field intensity at

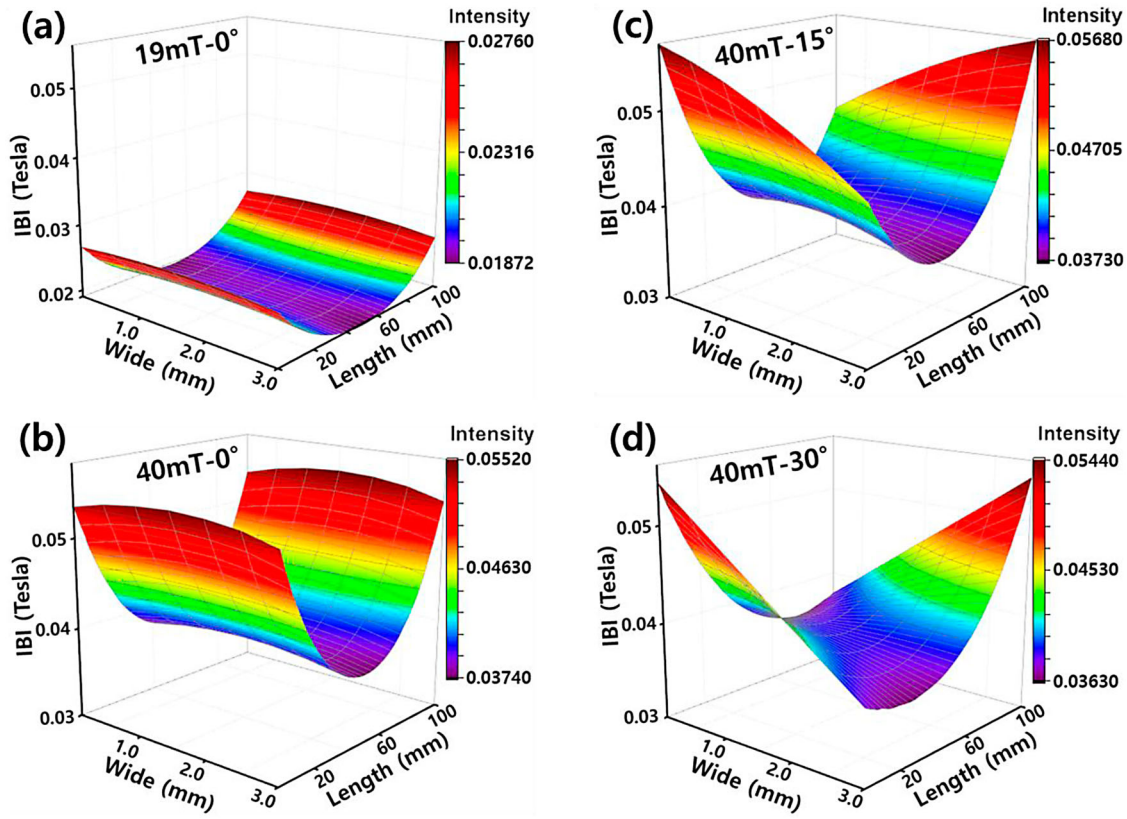


Figure 4. 3D analysis of magnetic field intensity according to magnetic field strength and direction.

the sandwich plate was calculated for various magnetic field strengths and directions.

The sandwich plate central plane was 30 mm thick, and rotating the impedance tube changed the distance between the central plane and the magnet. We set the magnetic field strengths to 19 and 40 mT at the sample center. The simulation results were consistent with the corresponding experimental ones obtained under the set conditions: the central magnetic field strength was 19 mT at the position closest to the magnet exhibiting the maximum magnetic field strength of 27.6 mT. The central magnetic field intensity was set at 40 mT, and the magnetic field intensity increased with decreasing distance from the magnet. The maximum intensity of 55.2 mT was reached at the sample edge (Figure 4(b)). The magnetic field intensities at 15 and 30° were simulated while the sandwich plate was rotated based on its central position, as shown in Figures 4(c,d). The results showed that both edge positions closest to the magnet exhibited the maximum magnetic field strengths of 56.8 and 54.4 mT, respectively. In addition, we calculated the total magnetic field strength through the entire central plane rather than at a specific point. The total magnetic field strength was 4346.4 mT, and the magnetic field lines were arranged into a tight single layer by the magnet. The total magnetic field strength decreased because

the distance between the magnets and the central plane slightly increased with increasing rotation angle. These results are like those wherein the CIP particle density decreased despite the STL slightly increasing, as listed in Table S1. Therefore, the MR-F porous analytical model for expressing acoustic impedance was established using the CIP chain density and angles, which were the main parameters for determining sound absorption.

3.5. Porous MR-F model analysis

Figure 5(a) shows the proposed porous MR-F model for CIP particles aligned in a magnetic field. CIP particles arranged in a lattice structure can be porously expressed according to the magnetic field. Because porous structure hole inclination angles considerably affect the acoustic impedance (Z) [55], the following formula was used to calculate the acoustic impedance (Z_m):

$$Z_m = \frac{\rho_0 c_0}{NA} \sqrt{1 + \frac{NA^2 R \cos(90^\circ - \theta)}{j\omega\rho}},$$

where ρ_0 is the oil density, c_0 is the sound velocity, N is the number of pores per unit area, A is the pore area, R is the resistance frequency dependence, $j\omega\rho$ is the density dependence, and θ is the impedance tube rotation

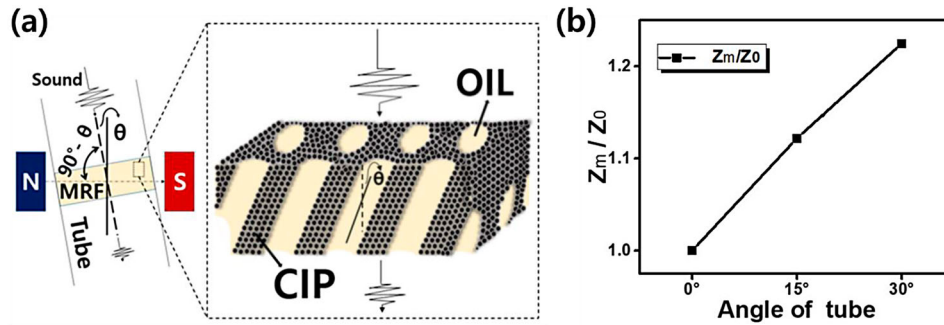


Figure 5. (a) Analytical porous model of an MR fluid with an applied magnetic field and (b) ratio of impedance to total magnetic field intensity at various magnetic field directions compared to 0° values.

angle. A detailed description is provided in the Supporting Information.

The calculated acoustic impedance was proportional to the rotation angle (θ). At each angle, the Z_m/Z_0 ratio was calculated based on impedance Z_0 at 0°, as shown in Figure 5(b). With increasing rotation angle, the impedance (Z_m) increased compared to Z_0 . In addition, the acoustic impedance increased until the rotation angle approached 90°. Although these results followed the same trend as the increased STL, the particle density and magnetic field strength both decreased at the central plane. In other words, the CIP chain angle was an important factor for determining the MR-F porous structure acoustic impedance in a magnetic field.

4. Conclusions

We investigated MR-F sound absorption. In particular, the STL was analyzed and compared under various conditions by changing the lattice structure wherein MR-F CIP particles were arranged according to the magnetic field intensity and direction. The CIP particle arrangement was observed using optical microscopy under a magnetic field, FE-SEM, EDS, and XRD. Additionally, we varied the magnetic field strength to investigate how the particle density affected sound reduction and found that the transmission loss considerably increased with increasing particle density. In addition, the CIP chain angle, which alignment changed according to the magnetic field direction, was an important parameter affecting sound absorption. The experimental results were consistent with those obtained using the developed porous MR-F analytical model.

Therefore, in MR-F-based sound insulation, not only the magnetic field strength can be controlled, which affects the transmission loss, but also the magnetic field direction can be varied. These findings can accelerate the development of nanoporous MR-F-based sound absorbers.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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