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The control of ultrasonic transmission by the metamaterials structure of electrorheological fluid and metal foam

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Abstract

A metamaterial structure formed by foamed metal and starch and oil-based electrorheological (ER) fluid is designed in this paper. Experiments show that the metamaterial structure exhibits a regulation effect on the amplitude and phase of the transmitted waves of 35–80 kHz ultrawideband ultrasonic waves in water. With the increase of the electric field, the transmission amplitude and phase of the ultrasonic wave increases, whereas the control ability of the same gradient electric field decreases. The amplitude of the transmission controlled by the metamaterial structure and electric field increases at first, and then decreases with the increase in volume fraction of the ER fluid. Thus, it is thought that the interaction between the microstructure produced by the rheological properties of the ER fluid and the porous foam metal affects the propagation of the acoustic wave.

Keywords: metal foam and ER fluid metamaterials structure, ultrasonic transmission, regulation

(Some figures may appear in colour only in the online journal)

Introduction

Porous materials are effective sound-absorbing materials. Foamed metals are a new type of porous material with abundant pores. Foamed metals not only overcome the shortcomings of traditional porous sound-absorbing materials, such as low strength, easy deliquescence, easy to accumulate dust, but also have high temperature tolerance and light weight. Since the introduction of foam metals, many researchers have studied the acoustic properties in the audible frequency range [1, 2], particularly on air absorption and rarely on water absorption [3, 4]. Results show that the structural parameters, such as pore size, porosity of the foamed metal and viscosity of the saturated fluid, affect the acoustic properties of foamed metal materials [5, 6].

Electrorheological (ER) fluid is an intelligent fluid that responds to electric field [7]. ER fluid is a suspension formed by the dispersion of micron-sized high-dielectric-constant particles into a low permittivity and low conductivity carrier oil. Under the action of electric field, the particles in ER fluid rapidly form chains or columnar structures along the direction of the electric field. This structure change induces variations in many physical properties, such as shear stress, elastic modulus and viscosity [8, 9]. ER fluids can be rapidly and reversibly converted between liquid and solid-like solid state with good performance under electric field, and the transformation speed is fast and instantaneously controllable. These characteristics allow the wide use of ER fluids in vehicle engineering, mechanical engineering and other fields [10]. Similarly, changes in the microstructure and physical properties of ER fluids also affect the propagation of sound waves. Guicking [11] studied the change of acoustic velocity in ER fluid, and Duan [12] measured the change of acoustic impedance in ER fluid. Ding [13] studied acoustic propagation properties of ER fluids. Tang et al studied the sandwich layer between flexible electrode and ER fluids at the 80–160 Hz frequency range of the sound transmission spectrum [14, 15]. Most previous studies focused on the parameters, such as acoustic velocity and impedance of audible
single-frequency sound waves, whereas the acoustic spectrum characteristics of ER fluids are seldom studied.

Electromagnetic metamaterials not only have been greatly developed in recent years [16–18], but also facilitates a series of singular phenomenon that conventional materials cannot do naturally [19–22]. In terms of local resonance, acoustic metamaterials have been largely developed, such as the similarities to the properties of electromagnetic metamaterials and the realization of negative refraction, tablet focus, super resolution imaging, and acoustic invisibility cloak [23, 24]. Due to the phase coupling between the structure of hollow tube ‘super atom’ and hollow ball ‘super atom’ [25], our team achieved the negative values of effective mass density and effective elastic modulus at the same time [26]. The negative values of both acoustic parameters are obtained by the ‘flute’ model (punch hole on the hollow steel tube), which is also established by our team [27, 28].

Based on the principle of metamaterials, a metamaterial structure of foamed metal copper saturated with ER fluid was designed in this study. The acoustic transmission behaviour of the metamaterial structure under different electric fields was evaluated using the underwater ultrasonic transmission platform. Experimental results showed that the metamaterial structure has regulatory effect in the ultra-wideband transmission of sound waves. This study lays the foundation for the design of intelligent tuneable acoustic materials for ultrasound propagation underwater.

### Theoretical analysis

Biot theory is important for the study of elastic wave propagation in viscous compressible fluid-saturated porous elastomers [29, 30]. Since the 1950s, Biot theory has played an important role in the fields of seismic wave, geological analysis, and porous materials, and its basic equation has been widely developed and applied [31, 32]. Based on a series of hypotheses, the Lagrangian equation is used to establish the dynamic equation considering the mutual coupling of viscosity and inertia using the thermodynamic principle to obtain the function expression of the dissipation of the medium and the kinetic energy of the system [33]. Stress–strain equation and displacement wave equation in Biot theory contain several important physical quantities, especially the Biot elastic coefficient. However, due to the complexity of the Biot elastic coefficient, many scholars have derived a variety of modified Biot theories. Biot and Willis et al [34] obtained the relationship between Biot elastic modulus and bulk modulus, fluid bulk modulus and bulk modulus by the jacketed test and the unjacketed test. Claude Depollier et al [35] analyzed Biot elastic coefficients of homogeneous and non-homogeneous materials. Stoll et al [36] applied Biot theory to study sound propagation in sediment media, and established the Biot–Stoll theory. When acoustic wave propagates in a porous skeleton composed of solid particles, the wave equation can be expressed as:

\[
\nabla^2(p_e - \zeta) = \frac{\partial^2}{\partial t^2}(\rho e - \rho_1 \zeta),
\]

\[
\nabla^2(\zeta e - \bar{M} \zeta) = \frac{\partial^2}{\partial t^2}(\rho_1 e - m \zeta) - \frac{F_0 \partial \zeta}{k \partial t},
\]

where \(e\) is the expansion coefficient when the porous skeleton is regarded as a continuous medium, and \(\zeta\) is the relative expansion coefficient between the skeleton and the saturated fluid, both as a function of the skeletal displacement vector \(u\), pore fluid displacement vector \(U\) and porosity \(\theta\), \(e = \nabla \cdot u\), \(\zeta = \theta \nabla \cdot (u - U)\); \(\rho, \rho_1\) and \(m\) are the total mass density, fluid mass density and additional mass, respectively; \(m = \alpha \rho \theta / \theta\), where \(\alpha\) is the pore bending factor; \(F, \eta\), and \(k\) are the viscosity coefficient correction factor, viscosity coefficient and permeability, respectively; and \(\Pi, \bar{C}, \text{ and } \bar{M}\) are Biot elastic moduli, which can be expressed by the elastic modulus of the skeletal body \(K_b\), elastic modulus of the pore fluid \(K_i\) and modulus of elasticity of the granular body \(K_c\).

\[
\Pi = \frac{(K_r - K_b)^2}{D - K_b} + K_b + \frac{4}{3} \bar{p},
\]

\[
\bar{C} = \frac{K_r (K_r - K_b)}{D - K_b},
\]

\[
\bar{M} = \frac{K_i^2}{D - K_b},
\]

\[
D = K_c \left[1 + \theta \left(\frac{K_r}{K_i} - 1\right) \left(\frac{K_r - K_b}{D - K_b}\right)\right].
\]

where \(\bar{p}\) is the shear elastic modulus of the frame. Equations (3)–(6) show that the elastic moduli of porous media and saturated fluid affect the Biot elastic modulus, and then determine the wave equation.

When ER fluid is under the high-voltage electric field, the dispersed particles in the base fluid will quickly form a chain or columnar structure along the direction of the electric field. These chain structures can also be regarded as a skeletal structure. In addition, this structural change causes variations in many physical properties such as shear stress, elastic modulus and viscosity. Researchers have studied the mechanical properties of the ER fluid under an electric field. Both theoretical and experimental results show that the shear modulus and tensile modulus of ER fluids increase with the increase of DC voltage. The elastic modulus \(K\) and the mass density of the medium \(\rho\) are the basic parameters that play a decisive role in the propagation of sound waves. The acoustic impedance and the acoustic velocity in the medium can be expressed as \(Z = \sqrt{K \rho}, c = \sqrt{\frac{K}{\rho_0}}\).

### Sample preparation and experimental setup

Figure 1(a) shows the structure of the foamed metal composite with ER fluid. The structure includes two layers of the foamed metal copper with a thickness of 2.5 mm, 1 mm thick epoxy-plate rectangular ring and a starch-silicone ER fluid.
This ‘sandwich’ structure is encapsulated in a polyethylene film to accommodate experimental measurements in water. The size of the sample is 50 mm × 90 mm, where the foamed metal copper is a commercially available porous material having a pore size of 0.1–1 mm and a porosity of 60%–98%. The foamed metal copper plate is cut into a semi-concave, and the main size is 50 mm × 65 mm, which is used to load the electric field and for the absorption and control of sound. The inner diameter of the epoxy-plate rectangular ring is 40 mm × 55 mm, and the outer ring size is 50 mm × 70 mm, which is used to support the two foams, and the internal space is filled with ER fluid. The ER fluid is a suspension prepared by grinding corn starch in dimethyl silicone oil. Before the experiment, the rheological properties of the ER fluid are evaluated by rheometry. To obtain the best rheological properties of ER fluid under such environment, corn starch was first dried in a vacuum oven at 40 °C for 2 h and then vacuum-dried for 5 min by adding isothermal silicone oil. Finally, the ER fluid was homogeneously ground in a mortar. Figure 1(b) shows the rheological curves of the ER fluids with a volume fraction of 35% under this condition.

The ultrasonic transmission measurement device is shown in figure 2. The measurement environment is a pool with a size of 1300 mm × 400 mm × 600 mm. Ultrasonic emission and transmission of signal were acquired using a PCI-2 ultrasonic emission system (US Acoustics Corporation). The ultrasonic emission system outputs low-voltage and high-voltage two-column synchronization signal through the standard signal sound card; a low-voltage signal is directly inputted to the sound acquisition card, which can record the transmission signal; high-pressure signal transmits ultrasonic wave by the transducer, ultrasonic wave is collected by the receiving probe after transmission through the media; and the collected signal is converted into a low-voltage signal by a power amplifier and inputted to the sound acquisition card. Both transducers are R6UC underwater probes manufactured by the American Physical Acoustics Corporation operating at 35–100 kHz. The sound emission card and acquisition card are controlled respectively by WaveGen and AEwin software installed in the computer system. Voltage on both sides of the sample was applied using a DC high voltage power supply (Shenyang Teaching Instrument Factory) through the wire to load and control.

**Experimental test**

In the transmission measurement, the distance between the two probes was fixed at 4 cm. Ultrasonic wave with the same amplitude was generated by PCI-2 acoustic emission system controlled by the ultrasonic emission software WaveGen. Then, AEwin software was used to record the transmission
The amplitude of the transmitted signal waveform $U_1$ was read using the data cursor by replaying the waveform data collected by AEwin software. Finally, the data were collated shown in figure 3.

The measurement results in figure 3 show that the ultra-wide band of 35–75 kHz in the measurement frequency band has obvious regulation of the ultrasonic transmission amplitude. When there is no sample, that is, when the space between the two probes was filled only with water, the transmission amplitude is the highest. When the sample is placed in the middle of two probes and the loading voltage is 0, the transmission amplitude of sound wave is the lowest. The amplitude increases with the increase in electric field, and it is lower than the transmission amplitude when the sample is not present. Moreover, the most obvious amplitude regulation of ultrasonic transmission is observed in the ultra-wide band of 35–55 kHz when the volume fraction is 35%. For example, at 40 kHz, when the electric field intensity is 1, 2 and 3 kV mm$^{-1}$, the amplitude increased by 30.54%, 45.24% and 50.07%, respectively, compared to that without electric field. At 50 kHz, the relative increases are 19.15%, 36.5% and 41.45%, respectively. The difference between the different cases of transmission amplitude in amplitude is averaged to analyze quantitatively the changes of the amplitude of ultrasonic transmission; the results are shown in table 1.

Table 1 shows that the ability to adjust the amplitude of the transmission of sound waves becomes smaller when the electric field intensity increases at the same additional voltage. In addition, the volume fraction of ER fluid affects the attenuation of sound waves in the metamaterial structure and the ability of the electric field to regulate the transmission of sound waves. When the volume fraction of ER fluid is increased from 25% to 35%, the ultrasonic amplitude decreases from 43.9 to 117.54 mV, and the amplitude of transmission acoustic wave increases at the same voltage. The amplitude of transmission acoustic wave decreases and the control ability of electric field decreases when the volume fraction of ER fluid changes. The amplitude of the transmission controlled by the metamaterial structure and electric field increase at first, and then decrease with the increase in volume fraction of ER fluid.

The Biot theoretical analysis shows that the change in elastic modulus of the skeleton, fluid, or particle in the fluid-saturated porous media affects the propagation of acoustic wave in the medium. However, the Biot theory takes into account many parameters. The structural parameters of the porous metal foam and ER fluid metamaterial are very complex. Therefore, the metamaterial structure is regarded as uniform. Based on impedance theory and wave theory of layered media, the acoustic transmission characteristics can be analyzed using the macroscopic properties of the metamaterial structure.

As shown in figure 4(a), in the experimental environment, the ultrasonic waves emitted by the transmitting probe pass through water, the metamaterial structure of metal foam and ER fluid, and then the water before arriving at the receiving probe. According to wave theory of layered media, the acoustic transmission coefficient of three-layer media can be obtained using [37]:

$$T = \frac{4z_1z_3}{(z_1 + z_3)^2\cos^2 k_2d + \left(z_2 + \frac{z_1 + z_3}{z_2}\right)\sin^2 k_2d},$$  \hspace{1cm} (7)

where $z_1$, $z_2$ and $z_3$ are the characteristic impedances of the three-layer dielectric, $k_2$ is the wavenumber of the middle layer and $d$ is the thickness of the intermediate layer. Given that both media 1 and 3 are aqueous media, equation (1) can be simplified.

$$T = \frac{4}{4\cos^2 k_2d + \left(\frac{z_1}{z_3}\right)\sin^2 k_2d}.$$  \hspace{1cm} (8)

Figure 4(b) shows the diagram of sound intensity transmission coefficient when two sides of the medium are the same. The abscissa of the figure is the normalized thickness of the wavelength of the middle layer. The number marked next to the curve is $z_2$, the water acoustic impedance is $z_1 = 1.48 \times 10^6$ N s m$^{-3}$, $d = 6$ mm, and the normalized thickness is between 0.2 and 0.5 when the velocity of the middle layer under the same conditions. The figure shows that the transmission intensity of sound waves varies at different frequencies and the transmission intensity changes because the applied electric field alters the acoustic impedance of the sample at the same frequency. Acoustic impedance is related to the mass density and elastic modulus of the medium, that is, electric field changes the microstructure of the sample and alters its mass density and elastic modulus.

The experimental results show that the regular pattern is caused by the interaction between the rheological behaviour of the ER fluid and the foamed metal structure in the metamaterial structure. Foam metal is a porous medium and ER fluid is a suspension of starch granules and silicone oil. Sound waves are scattered and absorbed by the foam metal and...
starch particles when they are transmitted from the metamaterial structure, and the transmission wave amplitude decreases. When the electric field is loaded, the starch particles are polarized and form microstructures, such as chains or columns, under the electrostatic forces. On one hand, the foam metal pores are filled with this microstructure, thus changing the foam metal pore size, porosity and other structural parameters. On the other hand, the ER fluid between the two copper metal foams forms a chain-like structure along the direction of the electric field, that is, in the propagation direction of the sound waves. These changes alter the elastic modulus of the structure, thus changing the acoustic impedance, which enhances the transmission of the ultrasound. As the electric field strength increases, these changes tend to stabilise. Therefore, with the increase in electric field, the regulation of amplitude of the acoustic wave is reduced at the potential gradient of the same gradient. The difference in volume fraction of ER fluid will affect the filling rate of starch particles and the size and distribution of chain-like microstructures. The experimental results show that acoustic wave

\[ \text{Table 1. Mean change of ultrasonic transmission amplitude.} \]

<table>
<thead>
<tr>
<th>Volume fraction</th>
<th>No sample subtract</th>
<th>Have sample subtract</th>
<th>( E = 1 \text{ kV mm}^{-1} ) subtract</th>
<th>( E = 2 \text{ kV mm}^{-1} ) subtract</th>
<th>( E = 3 \text{ kV mm}^{-1} ) subtract</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>43.9</td>
<td>13.85</td>
<td>0.53</td>
<td>0.3</td>
<td>5.87</td>
</tr>
<tr>
<td>30%</td>
<td>63.63</td>
<td>44.12</td>
<td>7.23</td>
<td>2.98</td>
<td></td>
</tr>
<tr>
<td>35%</td>
<td>117.54</td>
<td>56.58</td>
<td>22.18</td>
<td>9.06</td>
<td></td>
</tr>
<tr>
<td>40%</td>
<td>66.49</td>
<td>19.2</td>
<td>6.06</td>
<td></td>
<td>5.87</td>
</tr>
</tbody>
</table>

\[ \text{Figure 3. Relation between amplitude and frequency of transmission sound wave under different volume fractions and electric fields.} \]
can obviously controlled only when the volume fraction of ER fluid is moderate.

**Transmission phase**

Analysis of amplitude modulation of transmitted acoustic wave by a compound structure suggests that application of an electric field changes the elastic modulus and other parameters of the metamaterial structure, thereby affecting the propagation velocity of the acoustic wave in the medium. Hence, the phase of transmitted sound waves was studied. The metamaterial structure of the foamed metal with 35% volume fraction of the ER fluid was tested and the experimental conditions were kept constant. The waveform data acquired by the AEwin software was replaced, and \( t_0 \) and \( t_1 \) correspond to the peaks of the two adjacent waveforms when the incident signal and the transmitted signal are read by the data cursor. The phase difference between the transmitted signal and the incident signal is taken as the phase of the transmitted signal, that is, \( \phi = 2\pi f (t_1 - t_0) \), where \( f \) is the frequency of the incident acoustic wave. Finally, the phase data are collated and shown in figure 5.

Figure 5(a) shows that the transmission phase has increased after the sample was placed between the two probes. The transmission phase also increases with the increase in electric field strength. To observe the change of phase under different applied electric fields, the phase of the sample without electric field is taken as the reference phase and compared with the phase when the electric field is applied. The results shown in figure 5(b) indicate that the ultra-wide band of 35–75 kHz demonstrates obvious phase regulation of ultrasonic transmission. The most obvious wave band is found at 45–55 kHz. For example, when the electric field intensity is 1, 2 and 3 kV mm\(^{-1}\), the transmission phase increased by 54.48%, 65.5% and 75.17%, respectively, compared with that without electric field when the frequency is 50 kHz. The phase information is determined by \( t_0 \) and \( t_1 \). The phase difference increases with the increase in electric field intensity, that is, the time it takes for sound waves to emerge from the transmitting probe to the receiving probe is prolonged. The experimental results show that the velocity of

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**Figure 4.** Schematic diagram of the three-layer medium (a); the acoustic transmission of coefficient three-layer structure (b).

**Figure 5.** Transmission phase results of metamaterial structure of the foamed metal with 35% volume fraction of the ER fluid.
the ultrasonic wave in the sample decreases with the increase in electric field intensity when the other parameters and the experimental environment are changed except for the applied electric field. Similar to the previous analysis on amplitude control, the phase modulation is attributed to the changes in elastic modulus of the metamaterial structure caused by the interaction between the foamed metal structure and the rheological behaviour of the ER fluid under an applied electric field.

Conclusion

A metamaterial structure formed by a foamed metal and an ER fluid was designed based on the principle of metamaterials. The amplitude and phase control of the structure (metal foam and ER fluid based on starch and oil) for ultrasonic transmission were investigated. The experimental results show that the metamaterial structure can control the transmission of ultra-wideband acoustic wave from 35 to 80 kHz. The transmission amplitude of ultrasonic wave increases with the increase in applied electric field. However, the transmission amplitude decreases under the same electric field gradient with increase in electric field. The amplitude of the transmission controlled by the metamaterial structure and electric field increase at first and then decrease with the increase in volume fraction of ER fluid. Moreover, the transmission phase and velocity of the ultrasonic wave increase with the increase in electric field. These changes are caused by the interaction between the ER fluid with a chain-like microstructure and the porous metal foam. This interaction changes the microscopic structural parameters and the Biot elastic modulus of the sample, thereby changing the acoustic impedance and sound velocity. Therefore, the transmission amplitude and phase of the ultrasonic wave can be controlled by adjusting the electric field intensity.

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