Direct experimental verification of the sound-induced tunable resonance on a flexible electrorheological layer

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The tunable behaviors of low-frequency sound waves transmitted through a flexible electrorheological (ER) layer with plastic-aluminum electrodes are investigated. It shows that, within 80–210 Hz, the sound-pressure level (SPL) decreases with the electric field \( E \), while within 210–300 Hz, the SPL increases with \( E \). The vibration displacement of the ER layer surface is directly measured via a laser Doppler vibrometer. It reveals that two resonance modes exist on the ER layer and all the modes are tunable via the electric field. Around the first resonant frequency of 100 Hz, the vibration displacement decreases with the increase of \( E \), while around the second resonant frequency of about 180 Hz, the vibration displacement increases with \( E \). The consistently varying characteristics with respect to the electric field imply an intrinsic relation between the vibration of the ER layer and the sound transmission. The relation is further qualitatively explained by the vibration-radiation model. The tunable resonance effect in the ER layer would be useful in constructing tunable phononic crystals and other acoustic devices. © 2007 American Institute of Physics. [DOI: 10.1063/1.2719277]

I. INTRODUCTION

Electrorheological (ER) fluids, as an active member of smart or intelligent materials, are receiving great research interest nowadays, largely due to their versatile application potential. 1–17 ER fluids usually consist of micrometer- (or nanometer-)scale particles with high dielectric permittivity dispersed uniformly in carrier oils with low permittivity and low conductivity (e.g., silicon oil). 1–5 Under an external electric field, the fine particles in ER fluids rapidly form chains or columns along the direction of the electric field due to the electric field-induced electrostatic interaction among particles, thus resulting in striking changes in many physical properties. Conventional applications of ER fluids in the electromechanical field are based on the working modes of shear, flow, squeeze, and mixed types. 6 The fundamental mechanical components in smart ER devices include all kinds of valves, clutches, and dampers. These can make ER fluids versatilely usable as micropumps 7 and micromixers 8 in microfluidics, shock absorbers, anti-lock brake systems 9 in automobile, flywheels 10 in exercise bicycles, haptic devices in robots and virtual realities, 11,12 positioning controllers 13 and surfaces polishers in precision mechanism, and so on. Furthermore, Bohon et al. 14 and Shaw et al. 15 have proposed the exciting application of ER materials for artificial muscles and smart skins. Beside these, recent research on passive and static optic display with ER fluids 16 and a possible application on ER effect in blood diagnosis 17 has also been reported.

On the other hand, recently there has also been a research hot spot about wave functional materials, which includes photonic crystals, 18 left-handed metamaterials, 19,20 and phononic crystals. 21–23 In these materials, the wave propagation has unusual features, such as negative refraction, subwavelength focusing and plate slab lens, 24 etc., and hence may have many novel applications in optic imaging, communication, and radar or sonar technologies. Generally, the Bragg scattering is very important in the formation of band gaps in the photonic and phononic crystals. The Bragg mechanism requires strict periodicity and order; hence, it poses a challenge to manufacture the photonic crystals in visible-light range. Subsequently, Sheng et al. 22 proposed a local resonance mechanism that utilizes the local resonance of the structural element to realize the band gap, featuring the small size of structural element to control large wavelength waves. Hence, the local resonance mechanism is very useful to construct sonic-band-gap devices with compact structures to work in low-frequency region.

The microstructure evolution or the viscoelastic variation induced by electric field in ER materials also strongly modulates the propagation of sound waves. 25–28 In our previous studies, we have devised a sandwiched flexible ER layer and investigated the transmitted sound behaviors. 29,30 The tunability of the transmitted sound-pressure level (SPL) and the transmitted sound phase with respect to the external electric field are found. The corresponding wavelengths (2–4 m) of the frequency range with tunable behaviors are far larger than the size of the ER layer (<90 mm×90 mm×2 mm), so the proposed design may be useful in constructing tunable sonic devices (e.g., attenuators, phase tuners, amplifiers, etc.) working in low-frequency (long-wavelength) range with compact structures. It is thought that the electric field-dependent viscoelasticity in ER fluids and the vibration variations on the ER layer may be responsible for the experimental results. However, the vibration information on the surface of the ER layer is not directly measured.

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In this study, the vibration on the ER layer is directly determined by using the LDV (laser Doppler vibrometer). The experimental results verify that there is a strong resonance effect existing on the ER layer surface. A theoretical analysis based on the vibration-radiation model shows a good agreement with the experiments. The observed resonance effect very much resembles the local resonance effect that is proposed by Sheng et al.22 The flexible ER layer can be used in constructing resonance-type phononic crystals and other tunable acoustic devices.

II. EXPERIMENTS

A. Experimental processes

The configuration of the proposed flexible, thin ER layer is shown in Fig. 1(a). It includes two sheets of plastic film (0.05 mm thickness), whose inner surfaces are adhered with a thin layer (~0.05 mm thickness) of aluminum film tape (AF075, Shurtape) to serve as electrodes, ER fluid, polymethylmethacrylate (PMMA) spacer, and fixtures. The supple plastic sheets are adhered to fixtures on the sides, keeping a slight tension in the sheet surface. The ER fluid is sandwiched between the two plastic sheets. The size of the ER layer is 90 × 90 mm with a total thickness of 1.2 mm.

The experimental setup for vibration and sound measurement is shown in Fig. 1(b). A computer (Satellite A60, Toshiba) combined Siglab (model 2042, DSP Technology Inc.) is used as sound signal generator and analyzer. The Siglab device is connected with the computer on the SCSI interface. The output of the Siglab is amplified by a signal amplifier (HSA4014, NF Corp.) and then connected to a speaker (7 cm diameter). A laser Doppler vibrometer system (OFV-552 and OFV-2200, Polytec) is used to detect the vibration of the ER layer surface. The measured signal from the laser vibrometer is conveyed to the input channel 2 (C2) of the Siglab. The output of the Siglab is also connected to the input channel 1 (C1) of the Siglab as a reference.

The ER fluid used in the experiment is a suspension of cornstarch powder in silicone oil (KF-96–1, 1000CS, Shin-Etsu, Korea). The volume fraction of starch powder in ER fluid is set as 30%. The cornstarch powder is dehydrated at 60 °C for 3 h in order to reduce the leak current in the ER fluid.

In experiments, we use the swept sine method to measure the transfer function between C2 and C1 in the input port of the Siglab device. The signal from the output of the Siglab device is set as linearly scanning from 50 to 250 Hz with a constant peak-peak amplitude of ±0.4 V. If the amplitude of the transfer function of C2 over C1 is denoted as \( A_{dt} \), then the amplitude of C2 is equal to \( 0.4 \times A_{dt} \) volts. The sensitivity of the laser Doppler vibrometer is set as 80 μm/V in experiments. So, the measured displacement amplitude of the ER layer can be calculated as 0.4 × 80 × \( A_{dt} \) μm.

In the sound measurement, a capacitance microphone (Lave305A, Korea) is closely positioned above the center point of the ER layer surface and the detected sound signal is conveyed to channel 2 of the Siglab device. The sound-pressure amplitude is expressed as \( P = V/S \), where \( V \) is the converted voltage amplitude of C2 from the transfer function of C2/C1, and \( S \) represents the microphone sensitivity (\( S = 1 \text{ mV}/\text{Pa} \)). Sound-pressure level (SPL) is given by

\[
\text{SPL} = 20 \log \left( \frac{P}{P_0} \right) \text{ dB}, \quad P_0 = 20 \mu\text{Pa}.
\]

B. Experimental results

Figure 2(a) shows the vibration displacement amplitude (VDA) of the ER layer surface as a function of sound frequency. It can be seen that the displacement spectrum shows an apparent resonance characteristic. When the external electric field (with strength of \( E \)) is applied on the ER layer, two resonance peaks appear at about 100 Hz and about 200 Hz, respectively. At the peak around 100 Hz, when \( E \) increases, the peak height is reduced and, at the same time, the peak slightly moves toward the high-frequency direction. At the frequency range of 150–225 Hz, a resonance peak occurs when the electric field is applied. The peak moves also from about 150 to 225 Hz or so, and the peak height augments from about 3–5 μm as \( E \) increases from 0.39 to 3.31 kV/mm.

Correspondingly, the phase angle of the vibration displacement is also changed with the electric field strength. Figure 2(b) shows the phase angle difference for various electric fields as a function of frequency. As can be seen, the phase difference increases with \( E \) both around the peak of 100 Hz and at the range of 150–250 Hz. The frequency range of 110–150 Hz can be treated as a transition range. Within this transition range, both the VDA and the phase difference show a decrease-then-increase characteristic with the electric field strength. This characteristic may be related to the complex vibration on the ER layer. Figure 2(c) shows the displacement amplitude spectrum with frequency as high as 650

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Hz. As can be seen, within 350–600 Hz the displacement amplitude still exhibits somewhat increasing ability with the electric field.

Figure 3(a) shows the transmitted SPL through the ER layer as a function of frequency. Within 80–210 Hz, SPL decreases generally with the increase of $E$, while after frequency of about 220 Hz it shows increasing behavior with $E$. The peak around 100 Hz does not show a manifest peak frequency shift, but it has only a little tunability with respect to the electric field. A peak also exists in the frequency range of 220–250 Hz. The peak shows the behaviors of high-frequency shift tendency and amplitude increment with the electric field. These frequency-dependent characteristics are accordant with that of the vibration displacement in Fig. 2(a).

FIG. 2. The experimental results of the vibration on the ER layer surface under different electric field strength $E$. (a) Plots the vibration displacement amplitude as a function of sound frequency, while (b) shows the curves of the displacement phase angle difference vs frequency. (c) shows the displacement amplitude spectrum with frequency as high as 650 Hz.

FIG. 3. Sound transmission experimental results for the ER layer under different electric field strengths. (a) Plots the transmitted SPL as a function of sound frequency, while (b) shows the curves of transmitted sound phase vs frequency. Data for the same electric field are linked by means of cubic B-splines, as a guide for the eyes.

III. THEORETICAL MODEL AND DISCUSSION

It implies that the transmitted sound-pressure level should be closely related to the vibration of the ER layer. This point will be discussed in detail in the following paragraphs. Figure 3(b) represents the transmitted sound phase as a function of frequency. The ordinate is the phase angle difference of the electric-field-on status minus that of zero electric field. It shows that the change characteristics of the phase difference are approximately accordant with the variation characteristics of vibration displacement phase in Fig. 2(b).

The vibration and sound transmission characteristics reflected in the experiment can be qualitatively interpreted by a so-called vibration-radiation model. The ER layer can be treated as an object that has been forced to vibrate under the excitation of the vibrating air induced by the speaker. The vibrating layer can be approximately modeled as a piston sound-radiator with diameter $2a$ that is smaller than the side length of the square panel, as shown in Fig. 4(a). The sound pressure at the point $P$, which is at the central vertical axis and with a distance of $z$ from the piston center, can be expressed as:
where the sound-pressure amplitude \( p_m = \rho_0 c_0 u_k R (R-z) \). \( u_k \) can be evaluated via a reduced vibration model as depicted in Fig. 4(b).

In Fig. 4(b), the upper rubber sheet and the lower one can be modeled as two mass elements \( m_0 \) connected to the ground via elastic elements \( k_1 \) and \( k_2 \), and viscous elements \( c_1 \) and \( c_2 \), respectively. The sandwiched ER fluid is treated as an elastic element \( k_e \) and a viscous one \( c_e \) in the so-called Voigt model for viscoelastic materials.\(^{33}\) Note that when the electric field strength \( E \) increases from zero to 3.31 kV/mm in experiments, the ER fluid gradually changes from a viscosity-dominated state to an elasticity-dominated state. The total mass of the ER fluid is \( m_e \) and it is fixed on the lower rubber sheet. A force \( F \) excites the lower rubber sheet due to the vibrating air beneath. \( F \) is set as \( F_0 e^{i \omega t} \), where \( F_0 \) is the amplitude of \( F \) and \( \omega \) the sound frequency. Moreover, we set the displacements of the lower and the upper rubber sheets as \( x_1 = A_1 e^{i \omega t} \) and \( x_2 = A_2 e^{i \omega t} \), respectively. Here, \( A_1 \) and \( A_2 \) represent the displacement amplitudes and can be complex numbers. The equations of motion for the two rubber sheets can be written as

\[
\begin{align*}
(m_0 + m_e) \ddot{x}_1 + k_1 x_1 + k_e (x_1 - x_2) + c_1 \dot{x}_1 + c_e (\dot{x}_1 - \dot{x}_2) &= F_0 e^{i \omega t}, \\
(m_0 + m_e) \ddot{x}_2 + k_2 x_2 + k_e (x_2 - x_1) + c_2 \dot{x}_2 + c_e (\dot{x}_2 - \dot{x}_1) &= 0.
\end{align*}
\]

So, \( A_2 \) can be derived as

\[
A_2 = \frac{k_1}{\omega^2} \frac{F_0}{m_0} e^{i \omega t} \left[ A_1 \right] = \frac{k_1}{\omega^2} \frac{F_0}{m_0} e^{i \omega t} \left[ A_1 \right],
\]

The sound is directly radiated from the surface of the upper rubber sheet, so the velocity of the upper rubber sheet is of primary importance. It can be calculated as \( u_2 = \frac{x_2}{\omega} = \frac{x_2}{\omega} \) with the modulus of \( \omega \). By substituting this into the expression of \( p_m \), we get

\[
p_m = \rho_0 c_0 [A_2] (R-z).
\]

The effective elastic constant \( k_e \) and viscous constant \( c_e \) can be simply expressed with the complex modulus \((E' + iE'')\), where \( E' \) is storage modulus and \( E'' \) is loss modulus) as \( k_e = E'S/d \) and \( c_e = E'S/d \), where \( S \) is the electrode area and \( d \) is the thickness of ER fluid layer. In ER fluids, E’ includes two parts. One part, denoted as \( B_0 \), is related to the bulk modulus of the ER suspension without an external electric field. So, \( B_0 \) is usually independent of the electric field. The other part, denoted as \( B_1 \), is related to the electrorheological effect and determined by the external electric field. So, \( k_e \) can also be written as \( k_e = k_0 + k_1 \). Here, \( k_0 \) represents the effective elastic constant without the electric field, and \( k_1 \) represents the effective elastic constant that originates from the electrorheological effect. Then, the formula for \( k_e \) can be rewritten as \( k_e = k_0 + B_1 S/d \).

According to some experimental research on the compressive modulus of ER fluids, \( B_1 \) has a magnitude of 10\(^3\) Pa and \( E'' = k_0 = 10^5 \) Pa.\(^{34-36}\) We assume that there are three electric field strengths: \( E_0, E_1 \), and \( E_2 \), and \( E_0 = 0 \) kV/mm, \( E_0 < E_1 < E_2 \). B1 and \( E'' \) corresponding to the three electric field strengths are, respectively, set as 0, 2800, 5500 Pa and 600, 650, 720 Pa. The other constant parameters are set as \( k_1 = 5500 \) N/m, \( k_2 = 10000 \) N/m, \( k_0 = 5700 \) N/m, \( c_1 = c_2 = 2.4 \) Pa s, \( a = 12 \) mm, \( d = 3.2 \) mm, \( m_0 = 12 \times 10^{-3} \) kg, and \( m_e = 18 \times 10^{-3} \) kg.

Figure 4(a) plots the simulation results for \( |A_2|/F_0 \) which can represent the VDA as a function of sound frequency for different electric field strengths \( E \). It shows that two maximum humps appear at about 100 Hz and about 200 Hz. This result is in accordance with the features of two degree-of-freedom vibration, in which two resonance frequencies are usually expected. At the hump at around 100 Hz, two maximum humps appear at about 100 Hz and about 200 Hz.
the high-frequency direction when $E$ increases. These tunable characteristics are all verified in experiments. Figure 5(b) shows the simulated phase difference (equal to the phase of electric field status minus that of zero electric field status) as a function of frequency for the vibration displacement. It can be seen that the frequency-dependent characteristics of the theoretical results qualitatively agree with the experimental results in Fig. 2(b), both showing an increment with $E$ around the two resonance peaks. Figure 5(c) shows the calculated $\omega^2[A_z/F_0]$, which can represent the transmitted SPL as a function of frequency. Within frequency range of 150–190 Hz, the SPL decreases with $E$, while within 190–250 Hz it increases with $E$. Besides this, the peak frequency makes a shift to high-frequency direction with increase in $E$. These features also agree with the experimental results in Fig. 3(a).

The simple vibration-radiation model, which is somewhat crude, has still given a qualitative agreement between the theoretical model and experiment. It provides a clear physical picture that is helpful to understand the physical process on the ER layer. It reveals that the changes of the two resonance modes occurring on the ER layer surface under the electric field are very important. It directly causes the variations both in the transmitted sound pressure level and the sound phase. In the typical two-degree-of-freedom vibration system, the first mode can be interpreted as the in-phase resonant movement of the upper and lower plastic films, while the second mode represents the out-of-phase resonant movement of the two plastic film sheets. It is noted that the two resonance modes can be tuned via an externally applied electric field. It is expected that if the resonance modes can be tuned sufficiently strong, a negative effective elastic modulus on the ER layer may be realized. That is to say, the method proposed here may reach a negative modulus with electric-field tunable features and can be used in constructing sonic metamaterials. Besides this, the flexible composite ER layer could be used in sound-sensitive artificial skins or sound-tunable actuators, and has potential for use in robots and intelligent structures and systems.

**IV. CONCLUSIONS**

The vibration displacement on the surface of a flexible ER layer is directly measured via the laser Doppler vibrometer, and the results have also been compared with the experimental results of the transmitted sound pressure level through the same layer. The main results are summarized as follows:

(i) The variation of the displacement of the ER layer surface is closely related with the tunable characteristics of the transmitted SPL through the ER layer. Within 50–150 Hz, the displacement amplitude decreases with the electric field. Accordingly, below frequency of 200 Hz, the SPL also decreases with the electric field. As the frequency higher than 200 Hz, both the displacement amplitude and the SPL increase with the electric field.

(ii) Also, both the vibration phase on the ER layer and the transmitted sound phase vary with the electric field,
sharing nearly identical changing characteristics.

(iii) Simulation results based on the vibration-radiation model qualitatively agree with the experimental results of the VDA and the SPL, verifying the close relation of the vibration and the sound transmission.

The flexible composite ER layer could be used in constructing tunable sonic devices, such as sound-sensitive artificial skins or sound-tunable actuators, and has potential for use in robots and intelligent structures and systems.

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