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ANALYSIS OF SOUND ABSORPTION CHARACTERISTICS OF PIEZOELECTRIC FILM SHUNTED WITH ELECTRIC CIRCUITS USING EQUIVALENT MECHANICAL MODEL

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Piezoelectric material can be converted between mechanical and electrical energy each other. In general, viscoelastic material, such as polymeric material, dissipates a part of the applied mechanical energy by the viscosity. On the other hand, piezoelectric material dissipates a part of the converted electric energy by an electric resistance component of the material in addition to the energy loss by viscosity. The electric energy loss is improved by the optimization of the electric impedance. In a previous study, for polyvinylidene fluoride (PVDF), which is one of the typical piezoelectric polymer, shunted with an inductance as an electric circuit, damping performance improved significantly at an electric resonance frequency which is decided from the capacitance of the sample and the inductance. In this study, we applied this system to the panel-type sound absorber. It showed the sound absorption peaks at the electric resonance frequency as well as the natural frequency. This system can be controlled the sound absorption frequency by the inductance. In addition, we derived the equation representing the vibration behavior and sound absorption characteristics using equivalent mechanical model. Calculated results from the material and electric parameters gave good agreement with the measured ones.

Keywords: sound absorption, piezoelectric materials, electric circuits, equivalent mechanical model

1. Introduction

Piezoelectric material can be converted between mechanical and electrical energy each other. In general, viscoelastic material, such as polymeric material, dissipates a part of the applied mechanical energy by the viscosity. On the other hand, piezoelectric material dissipates a part of the converted electric energy by an electric resistance component of the material in addition to the energy loss by viscosity. In the equivalent electric circuit model, piezoelectric material is represented by the power source, capacitance (C_s) and resistance (R_s) (Figure 1(a)). Those three components correspond to the piezoelectricity and the real and imaginary part of the permittivity respectively. An electric energy is dissipates by the resistance component, but the phase difference generating by the capacitance component decreases in the energy dissipation. In order to improve the energy dissipation by the resistance component, it needs to decrease in the capacitance of the sample. Hagood et al. derived the equation representing the viscoelasticity of piezoelectric material shunted with the external electric circuits, and confirmed the variation in the viscoelasticity of piezoelectric ceramic by the shunting with the inductance as the external electric circuits [1]. The damping performance improved significantly at an electric resonance frequency which is decided from the capacitance of the sample and the inductance. Date et al. studied the viscoelasticity of piezoelectric polymer shunted with the inductance or the negative capacitance [2]. Also, we investigated theoretically and experimentally the influence of material and circuit parameters on the viscoelasticity for polyvinylidene fluoride (PVDF), which is one of the typical piezoelectric polymer, shunted with an inductance (Figure 1(b)) [3].

We applied this system which is comprised of piezoelectric film and the inductance as the external circuit to the panel-type sound absorber. As mentioned above, this system shows high damping performance at the electric resonance frequency decided from the capacitance of sample and the inductance. This system, therefore, can absorb the sound at only specific frequency and its frequency is controllable by the inductance. In this study, the sound absorption characteristics of piezoelectric polymer film shunted with the inductance as external electric circuits were investigated. We also derived the equation representing the vibration behavior and sound absorption coefficient using equivalent mechanical model.

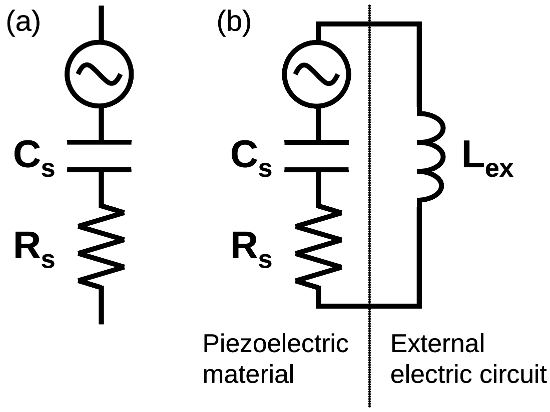


Figure 1 Equivalent electrical circuit models of (a) piezoelectric materials and (b) piezoelectric materials with shunt external electrical circuit.

2. Theoretical analysis

Sound absorption coefficient, α, is described by the equation

$$\alpha = 1 - \frac{\left| z - \rho_a c_a \right|^2}{\left| z + \rho_a c_a \right|^2} \tag{1}$$

, where ρ_a is the density of the air and c_a is the sound velocity in the air. z is acoustic impedance and is represented by the equation as below using the sound pressure p_1 and the particle velocity u on the sample surface.

$$z = \frac{p_1}{u} \tag{2}$$

Substituting velocity of the panel vibration v for u, sound absorption coefficient of panel type sound absorber is calculated by equ. 1.

The vibration of continuous body such as a panel is considered as the multi-degree-of freedom vibration system and shows the response superposed each order of natural vibration mode. We used modal method for the vibration analysis, because the multi-degree-of freedom vibration system needs many parameters and the calculation using that is complicated. By the modal method, we can be treated the vibration in each mode as single-degree-of freedom vibration system independently.

Yamada et al. studied on the sound absorption characteristics for metal plates equipped with piezoelectric elements shunted with electric circuits (inductance and resistance) using equivalent mechanical model [4, 5]. Piezoelectric elements was applied voltage which was related to displacement of plate and worked as dynamic absorber. The equivalent mechanical model represents the combination of typical mechanical components and mechanical components converted from electric components. Resistance, inductance and capacitance are converted to dashpot, mass and spring respectively. In this study, we substituted spring for complex spring in the equivalent model by Yamada et al., because we focused on the vibration behavior of piezoelectric viscoelastic body shunted directly with electric circuits.

Figure 2 shows the equivalent mechanical model of *i*th vibration of piezoelectric material shunted with electric circuits. In this figure, Q_i, M_i, K^*_i, γ_i and Θ_i are modal external force coefficient, modal mass, modal complex spring constant, modal displacement and modal electromechanical coupling factor of *i*th vibration respectively. ω is angular frequency. C^s_p, L, R and q are capacitance of a sample, inductance in external electric circuits, total resistance in this system and electric charge. p_1 and p_2 are a sound pressure on the speaker-side and the back-side of a sample.

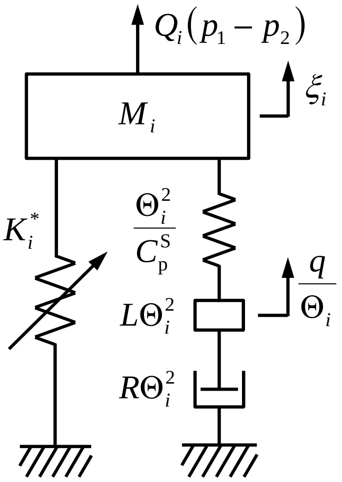


Figure 2 Equivalent mechanical model of *i*th vibration of piezoelectric material shunted with the inductance and the negative resistance as electric circuits.

The motion equation of this model is represented as follows.

$$\left\{-M_i\omega^2 + K_i^* + \frac{\Theta_i^2}{C_p^S}\left[1 - \frac{1}{C_p^S}\left(\frac{1}{-L\omega^2 + 1/C_p^S + j\omega R}\right)\right]\right\}\xi_i = Q_i(p_1 - p_2) \quad (3)$$

$$\frac{\Theta_i^2}{C_p^S} = \frac{k^2}{1-k^2}K_i^* \quad (4)$$

, where k is electromechanical coupling factor. We can derive the equations corresponding to the displacement amplitude and velocity from equ. 3 and 4, and obtain sound absorption coefficient from equ. 1 and 2.

3. Experiment

Polycarbonate (PC; Takiron Co. Ltd.) spray-coated with PVDF, denoted by PC+P(VDF-TrFE), was used as a panel sample of piezoelectric materials in this study. PC is a base panel to optimize the elasticity of panel. Thickness of PVDF and PC is 40 μm and 0.8 mm respectively. Electrodes were deposited on both sides of PVDF film and connected to the external electric circuits. The external electric circuits are comprised of the inductance and the negative resistance.

Normal incident sound absorption coefficient and vibration displacement amplitude was measured simultaneously using the impedance tube we made. The inner diameter of impedance tube was 80 mm. Normal incident sound absorption coefficient was obtained using transfer-function method (ISO 10534-2). Displacement amplitude at the center of a sample was measured by laser Doppler vibrometer (Polytec Co. Ltd., CLV700+OFV2500). Obtained displacement amplitude was normalized by the incident sound pressure. The distance between sample and rigid wall (glass plate) is 10 mm. Dynamic modulus, permittivity and piezoelectric coefficient were measured using Rheolograph-Solid (Toyo seiki Co. Ltd.).

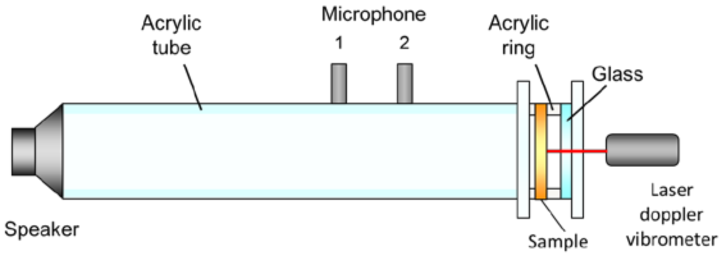
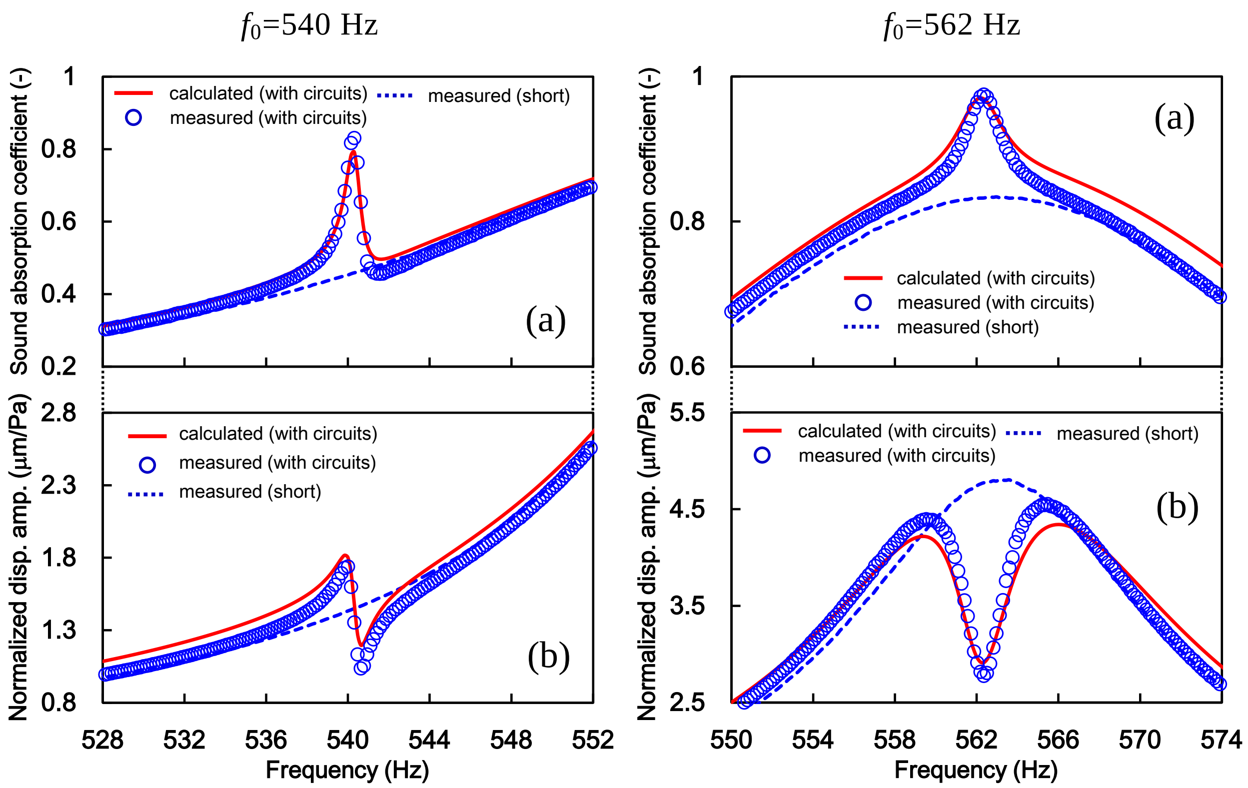


Figure 3 Schematic diagram of the simultaneous measuring system of normal incident sound absorption coefficient and sample vibration.

4. Results and Discussion

Panel-type sound absorber shows sound absorption peaks at natural frequencies of the panel. One sound absorption peak was observed at 562 Hz in the measuring frequency range. The electric resonance frequency (f_0) was adjusted to 540, 562 and 580 Hz by controlling the inductance. Figure 4 shows a normal incident sound absorption coefficient and a normalized displacement amplitude around f_0 for PC+P(VDF-TrFE) shunted with electric circuits. For comparison, those for PC+P(VDF-TrFE) without electric circuits (short) also displayed in the graph.

In all cases, a new sound absorption peak appeared at electric resonance frequency. This means that the sound absorber whose sound absorbing frequency is controllable was obtained. Calculation results of sound absorption coefficient and normalized displacement amplitude are also shown in figure 4. Electric parameters such as *C*sp and R were obtained from angular frequency dependence of generating voltage of sample. Modal mechanical parameter such as *M*i, *K**i were obtained from the results for sample without electric circuit. For both sound absorption coefficient and displacement amplitude, calculation results were in good agreement with measured results. As a result, the validity of the theoretical equation shown above was confirmed.



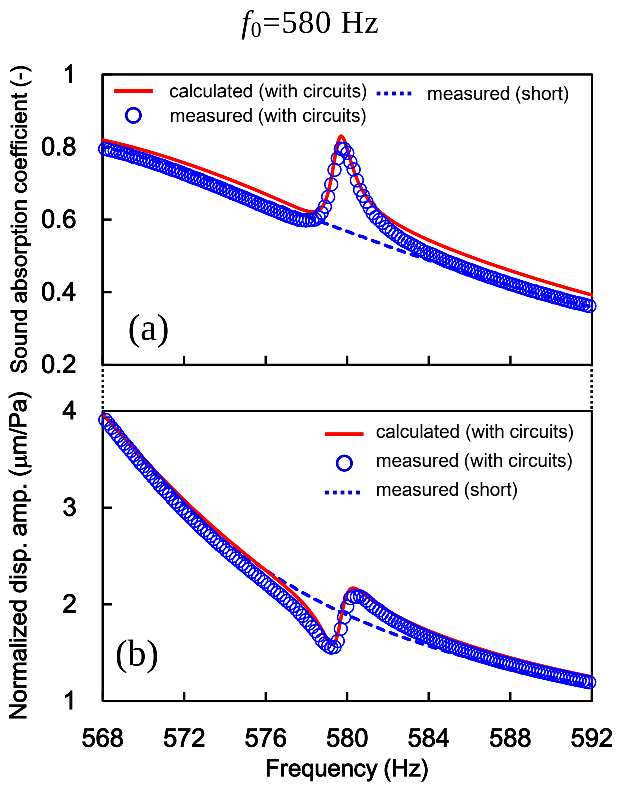


Figure 4 Frequency dependence of (a) normal incident sound absorption coefficient and (b) displacement amplitude normalized by sound pressure of interface of PC+P(VDF-TrFE) with and without electric circuits. Electric resonance frequency (f_0) is 540, 562 and 580 Hz.

5. Conculusion

In this study, the sound absorption characteristics of PC spray-coated with P(VDF-TrFE), which is piezoelectric polymer, shunted with an electric circuits were investigated. At the electric resonance frequency decided from capacitance of the sample and inductance in an electric circuit, a new sound absorption peak was appeared. This sound absorber can be controlled the sound absorption frequency by inductance and can absorb only the sound of specific frequency. Moreover sound absorption coefficient and displacement amplitude calculated using equivalent mechanical model was in good agreement with measured ones. Those theoretical equations were reasonable and can be used to optimize the sound absorption characteristics.

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