Piezo-electret Vibration Sensors Designed for Acoustic-Electric Guitars

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ABSTRACT

A piezo-electret vibration sensor designed for acoustic-electric guitars is evaluated. A piezo-electret, which is a cellular polypropylene electret film, is laminated with a 150-μm-thick polyethylene terephthalate (PET) film to achieve sufficient durability for general use. Additionally, a 10-μm-thick silver electrode is printed on the top surface as a shield electrode. This electrode adds a mass of only 63 mg to the sensor. The sensor is attached to the soundboard of a guitar body. An impact force is applied to the top of the saddle of the guitar body. The output voltage of the sensor owing to the vibration of the soundboard is measured by a voltage follower and an FFT analyzer. Conventional sensors that use lead zirconate titanate (PZT) ceramics are also tested. The results show that only the piezo-electret sensor detects the vibration of the soundboard over a wide frequency range up to 10 kHz. The time response of the sensor also corresponds to the vibration of the soundboard. However, the output voltage of the sensor is 1/10 to 1/100 of that of the PZT sensors. The effective d_{33} value of the sensor is 1.58 pC/N at 1 kHz. The value is only 1/280 of the apparent d_{33} value of the piezo-electret, owing to an increase in the effective elastic modulus in the thickness direction caused by lamination with the PET film.

Index Terms — **piezoelectricity, piezo-electret, ferro-electret, vibration sensor, musical instruments, cellular polypropylene**

1 INTRODUCTION

VARIOUS applications using piezo-electrets or ferro-electrets have been proposed since the report of a piezoelectric d_{33} constant over 100 pC/N [1–5].

Vibration sensors and acoustic transducers are typical applications of piezo-electrets. For example, a high-sensitivity piezo-electret microphone with a simple design has been realized [6]. This microphone consisted entirely of stacked piezo-electret films with electrical shielding. The sensitivity of the microphone depended on the number of stacking films and reached 15 mV/Pa at 1 kHz with 6 stacking films. This microphone also showed a distortion of less than 1 % at a sound pressure level (SPL) of 164 dB.

In addition, piezo-electrets are useful for broadband airborne transducers. The effective frequency range of the ultrasound generator and detector was from 100 to 300 kHz [7].

Accelerometers based on piezo-electrets have also shown good performance. The frequency range of the piezo-electret accelerometer was 10 Hz to 5 kHz, and it showed good linearity of sensitivity [8].

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Piezo-electrets have been used to study the vibration modes of musical instruments. The vibration of a violin bow was measured by piezo-electret vibration sensors [9]. Two piezo-electret sensors were installed at the tip and the frog of the bow. Because of the large d_{33} constant of the piezo-electrets, the experimental results clearly showed the longitudinal bow-hair modes. The acoustic-electric guitar is a musical instrument combining piezoelectric sensors with an acoustic musical instrument. Normally, lead zirconate titanate (PZT) ceramics are used as sensors. A piezoelectric sensor is normally fixed between a saddle and a soundboard or attached to a soundboard. The sensor detects the vibration of a string transmitted through the saddle or a vibration of the soundboard.

An under-saddle guitar pickup using a piezo-electret was reported [10]. The sensitivity of the sensor was compared with that of conventional piezoelectric pickups for practical applications. The piezo-electret sensor did not show a boosted bass response or a slightly pronounced high frequency response, which are disadvantages of conventional piezoelectric pickups. Some disadvantages of the piezo-electret pickup were also reported. The sensitivity of the piezo-electret pickup increased as the string tension decreased and varied below 1 kHz depending on the excitation force. The piezo-electret pickup had slightly more distortion and a slightly higher noise floor. It was also reported that the response of the piezo-electret pickup did not correspond to the acoustic radiation of guitars. To address these disadvantages, digital signal processing and digital filters must be combined with the piezo-electret pickup to improve its response [11].

The structure optimization and poling mechanism of the piezo-electret have been studied in detail. Inflation control of voids for optimizing the electromechanical properties and a model for the piezoelectric d_{33} coefficient were proposed [12]. Maximum values of d_{33} = 2000 pC/N in the quasi-static state and d_{33} = 600 pC/N in the dynamic state were realized [13].

According to reports about the charging mechanism of cellular polymers, microdischarges occur within the voids above the threshold voltage for breakdown in the voids [14]. Paschen breakdown fields in micrometer-sized voids showed good consistency with the standard Paschen curves [15]. Direct hysteresis measurements showed that polarization was generated in cells of cellular polymers during corona poling [16]. Additionally, a large d_{33} in a fluoropolymer forming a similar cellular structure was reported, which could improve heat resistance [17, 18].

These publications suggest that the higher potential pickup of piezo-electrets can be realized. In this paper, we investigate the possibility of a piezo-electret vibration sensor detecting the vibration of a soundboard of an acoustic guitar. The purpose of this paper is to examine vibration detection behavior and the possibility of its commercialization in piezo-electret sensors. Therefore, this sensor is required to realize not only suitable sensitivity characteristics but also sufficient durability as a consumer product. The piezo-electret is protected by a film in this study. The vibration sensing performance of the piezo-electret sensor is compared with that of conventional PZT piezoelectric sensors.

2 PIEZOELECTRICITY AND ELASTICITY OF THE PIEZO-ELECTRET USED IN THE SENSOR

Figure 1 shows a scanning electron microscope (SEM) image of the cellular polypropylene (PP) film (provided by Yupo Corporation) used in this study. The thickness of the film was approximately 70 μm. The volume ratio of PP and air was 50 %. The cell was flat with a thickness of several microns. Each cell was covered with a PP film with a thickness of several microns. A negative corona discharge up to -10 kV was applied to the sample. Aluminum electrodes were deposited on both surfaces of the sample.

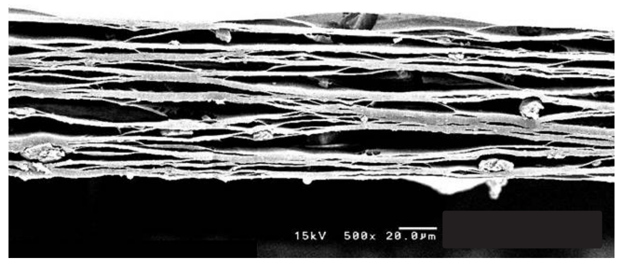

Figure 1. SEM image of the cross-section of the cellular PP film used in this study.

The thickness mode of the piezoelectric constant e_{33} and the elastic stiffness c_{33} of the sample were determined by the piezoelectric resonance method [19, 20]. Figure 2 shows the frequency dependence of the real and imaginary parts of the complex dielectric constant ($\varepsilon^* = \varepsilon' - i\,\varepsilon''$) measured by an impedance analyzer (4194A, Hewlett-Packard). The sample showed the TE mode of piezoelectric resonance in the frequency range from 150 kHz to 400 kHz. The experimental data were fitted using an equation of the dielectric constant including the TE mode of piezoelectric resonance. The equation is expressed as:

$$\varepsilon = \varepsilon^S \frac{1}{1 - k_t^2 \dfrac{\tan a(\omega)}{a(\omega)}}, \qquad (1)$$

where ε^S is the dielectric constant under a constant elastic strain S, k_t is the electromechanical coupling factor, and ω is the angular frequency.

The parameter a is expressed as:

$$a(\omega) = \frac{\omega t}{2v}, \qquad (2)$$

where t is the thickness, and v is the acoustic velocity defined by:

$$v = \sqrt{\frac{c_{33}^D}{\rho}}, \qquad (3)$$

where c_{33}^D is the elastic stiffness in the thickness direction under a constant electric displacement D and ρ is the density.

The density of the sample is ρ = 500 kg/m^3. k_t is given by the equation

$$k_t^2 = \frac{e_{33}^{\ 2}}{c_{33}^D \varepsilon^S}. \tag{4}$$

The solid lines in Figure 2 show the fitting results. The results indicated k_t = 0.094, c_{33}^D = 0.54 MPa, e_{33} = 0.24 mC/m^2, and v = 33 m/s.

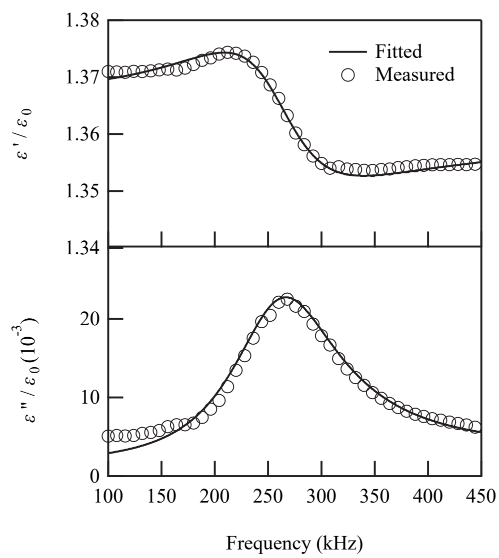

Figure 2. Piezoelectric resonance of the TE mode of the piezo-electret film.

3 FREQUENCY AND TIME RESPONSE OF THE SENSOR FOR APPLICATION IN GUITARS

3.1 METHOD OF VIBRATION DETECTION IN ACOUSTIC-ELECTRIC GUITARS

Figures 3a and 3b show schematic diagrams of a top view and a cross-section of the piezo-electret sensor designed in this study. The dimensions of the piezo-electret were 25 mm × 25 mm. Aluminum electrodes were deposited on both surfaces of the piezo-electret. The piezo-electret was laminated with a protective 30 mm × 30 mm PET film with a thickness of 150 µm. Piezo-electret and PET films were bonded by double-sided tape (NW series, Nichiban). PET films of various thicknesses may be used to find the optimum structure of the piezo-electret sensor. The purpose of this work was to evaluate the performance of the guitar sensor for commercial use. Therefore, we used standard commercialized PET film, which is the most easily available and low cost.

A 10-µm-thick silver paste electrode was printed on the top surface of the sensor as a shield electrode and a mass of 63 mg. A lead wire was connected to the aluminum electrode of the piezo-electret by silver paste. The aluminum electrode adjacent to the silver electrode was used for signal output. The other aluminum electrode was connected to the silver electrode and grounded.

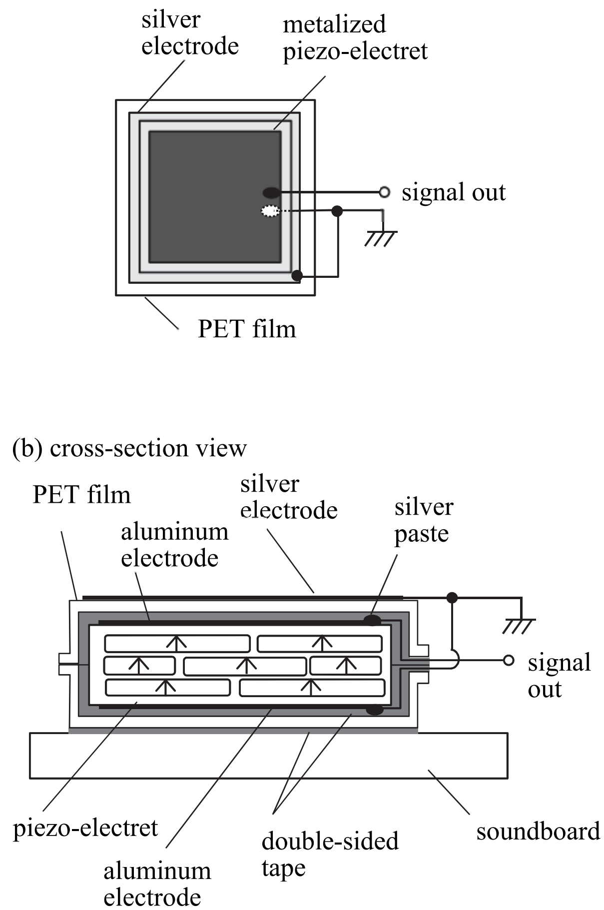

Figure 3. Schematic diagram of (a) the top view and (b) the cross-section view of the piezo-electret sensor on the soundboard of a guitar.

The piezo-electret sensor was attached to the surface of a soundboard of a guitar by using the same double-sided tape. The thickness of the soundboard was approximately 2.8 mm. A board of spruce (Picea) was used as the soundboard.

Figures 4a, 4b and 4c show typical mounting methods for piezoelectric sensors in acoustic guitars. Piezoelectric sensors are equipped under-saddle or attached to a soundboard. In this paper, the former is called the under-saddle type, and the latter is called the soundboard type. In the figures, (a) top view of both types, cross-section views of (b) the under-saddle type and (c) the soundboard type are shown. In commercial acoustic-electric guitars, a preamplifier with a digital signal processor or digital filter is connected to piezoelectric sensors.

Figures 5a and 5b show the methods of impact force testing for sensors equipped with acoustic-electric guitars. As shown in Figure 5a, the piezo-electret sensor was attached to the soundboard. A PZT sensor consisting of a PZT disk with a diameter of 25 mm and a thickness of 0.2 mm and a brass plate with a thickness of 0.3 mm was tested in the same way. When a PZT sensor was attached to the soundboard, felt fabric was inserted between the soundboard and the PZT sensor in the same way as in an actual guitar to prevent attenuation of vibration of the soundboard. The piezo-electret sensor was

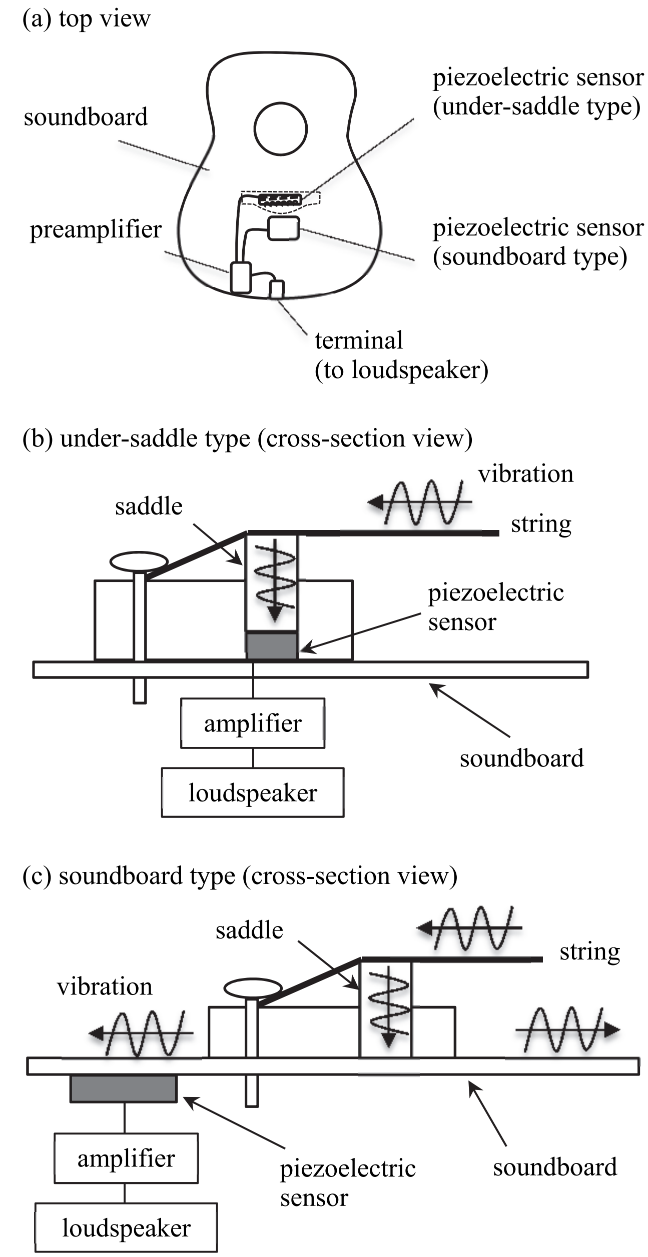

Figure 4. Schematic views of the vibration detection method in acoustic-electric guitars; (a) top view, (b) cross-section view of under-saddle type, and (c) cross-section view of soundboard type.

attached to the soundboard without felt fabric. Furthermore, as shown in Figure 5b, the under-saddle type of a PZT sensor was also tested for comparison.

The vibration of the soundboard was excited by tapping the top of the saddle with an impact hammer (Type 8203, B&K) instead of by vibration of the strings. The vibration of the soundboard was measured by a micro accelerometer (NP-3211, Ono Sokki). The piezo-electret sensor and PZT sensors were connected to a voltage follower with an input impedance of 11 MΩ. The time and frequency spectra of the output signals of the test sensors were measured through the voltage follower. The output signals of the impact hammer and the voltage follower were analyzed by the FFT analyzer (DS3000, Ono sokki).

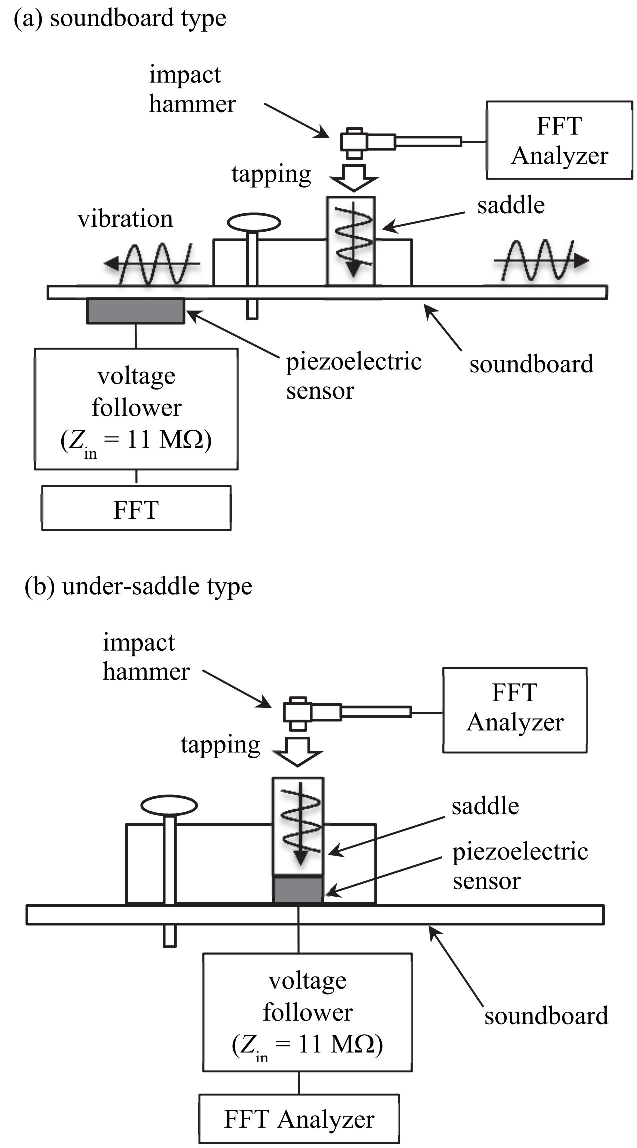

Figure 5. Impact response test for sensors equipped to acoustic-electric guitars; (a) soundboard type, and (b) under-saddle type.

3.2 TIME RESPONSE AND FREQUENCY SPECTRUM OF THE PIEZO-ELECTRET SENSOR

Figure 6a shows the time spectrum of the impact force F_I. The maximum impact force F_{IMax} was 15 N. The time spectrum showed that the half width was 80 μs. Figure 6b shows the time response of the vibration of the soundboard generated by F_I. The ratio of the acceleration of the soundboard a_B and the maximum impact force F_{IMax} is plotted. The result shows that the vibration of the soundboard attenuated until 10 ms. Figure 6c shows the frequency spectrum of a_B/F_{IMax} shown in Figure 6b from 80 Hz to 10 kHz on the dB scale (0 dB = 1 m/s^2/N). The results show that various frequency components of a_B/F_{IMax} appeared up to 10 kHz with magnitudes of 25 dB to 35 dB. Furthermore, a_B showed minimum values at 150 Hz and from 400 Hz to 600 Hz.

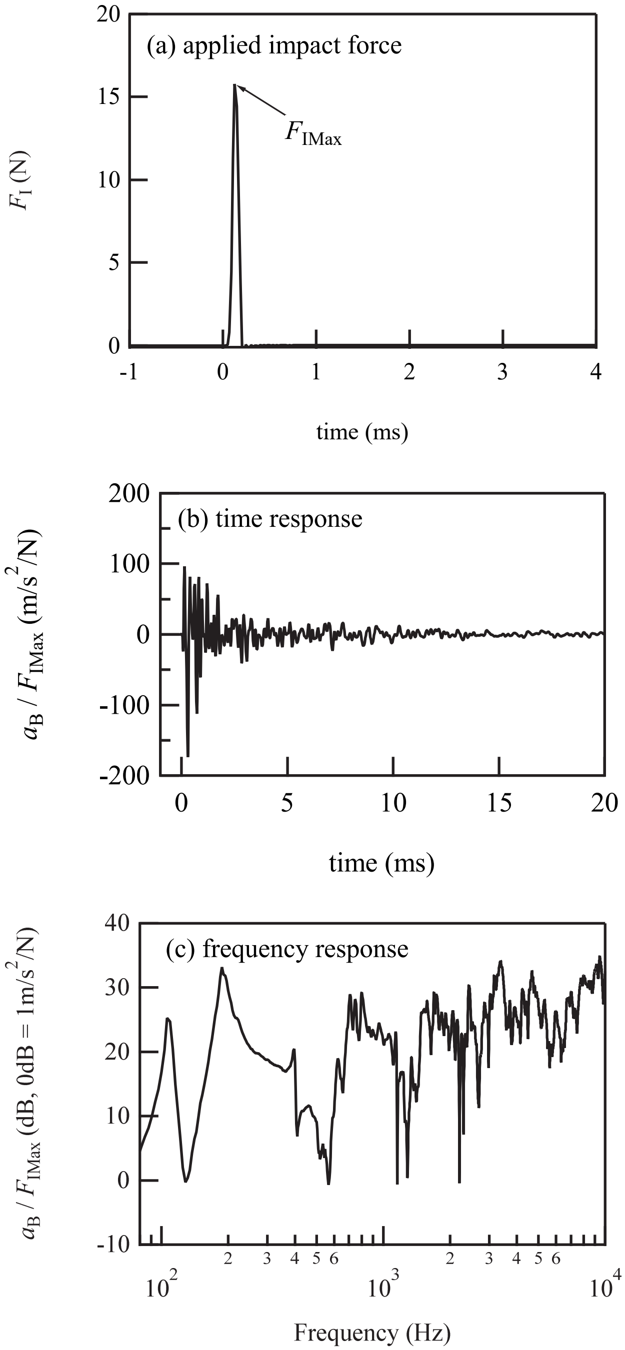

Figure 6. Vibration characteristics of the soundboard (a) impact force F_I,; (b) time response of the acceleration a_B/F_{IMax}, and (c) frequency response of a_B/F_{IMax} in dB scale.

Figure 7 shows the time responses of the output voltage V_{out} generated by F_I in (a) the piezo-electret sensor, (b) the PZT sensor attached to the soundboard, and (c) the PZT sensor equipped under-saddle. The ratio V_{out}/F_{IMax} was plotted. In the piezo-electret sensor, V_{out}/F_{IMax} exceeded 40 μV/N owing to the impact force and was almost completely attenuated after 10 ms. The time response corresponded to the vibration attenuation of the soundboard shown in Figure 6b. As shown in Figure 7b, the output signal of the PZT sensor attached to the soundboard was 10 times larger than that in the piezo-electret sensor. However, the output signal remained over 20 ms, which was twice as long as the decay time of the soundboard.

When the PZT sensor was equipped under-saddle, as shown in Figure 7c, the maximum output voltage was 100 times larger than that of the piezo-electret sensor. However, the output voltage decayed quickly. This result indicates that this PZT sensor detected the impact force directly.

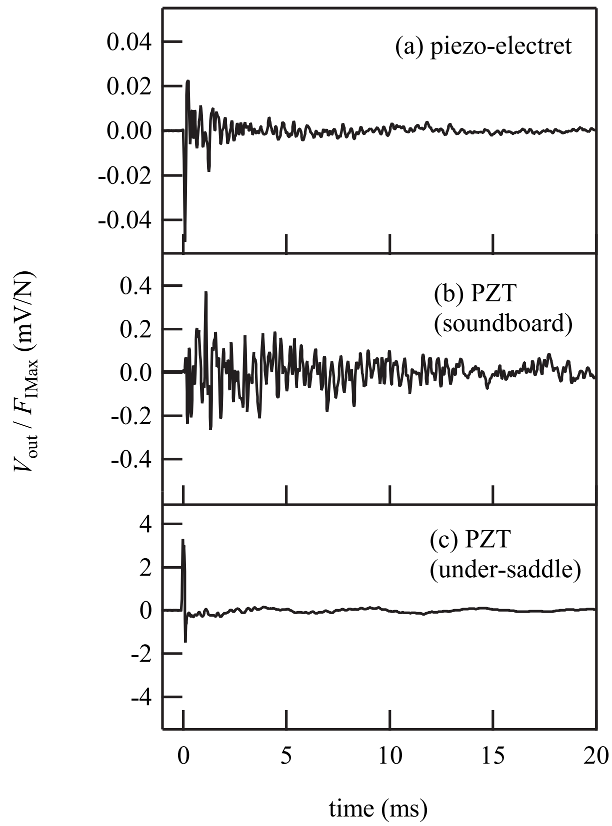

Figure 7. Time response of the output voltage V_{out}/F_{IMax} of (a) the piezo-electret sensor, (b) the PZT sensor attached to the soundboard, and (c) the PZT sensor equipped under-saddle.

Figures 8a, 8b, and 8c show the frequency spectra of V_{out}/F_{IMax} in the piezo-electret sensor, the PZT sensor attached to the soundboard, and the PZT sensor equipped under-saddle in dB scale (0 dB = 1 mV/N), respectively. Compared with the frequency spectrum of the soundboard vibration shown in Figure 6c, the results show that the piezo-electret sensor did not correctly detect the vibration below 300 Hz. However, the sensor detected vibrations over a broad frequency range from 300 Hz to 10 kHz. On the other hand, the PZT sensors of both the soundboard type and the under-saddle type detected vibrations only at 100 Hz and 200 Hz.

The results shown in Figures 6, 7, and 8 reveal that the output signal of the piezo-electret sensor was only 1/10 to 1/100 of that in the PZT sensors. However, the time response and the frequency spectrum of the output signal above 300 Hz corresponded to vibration characteristics of the soundboard.

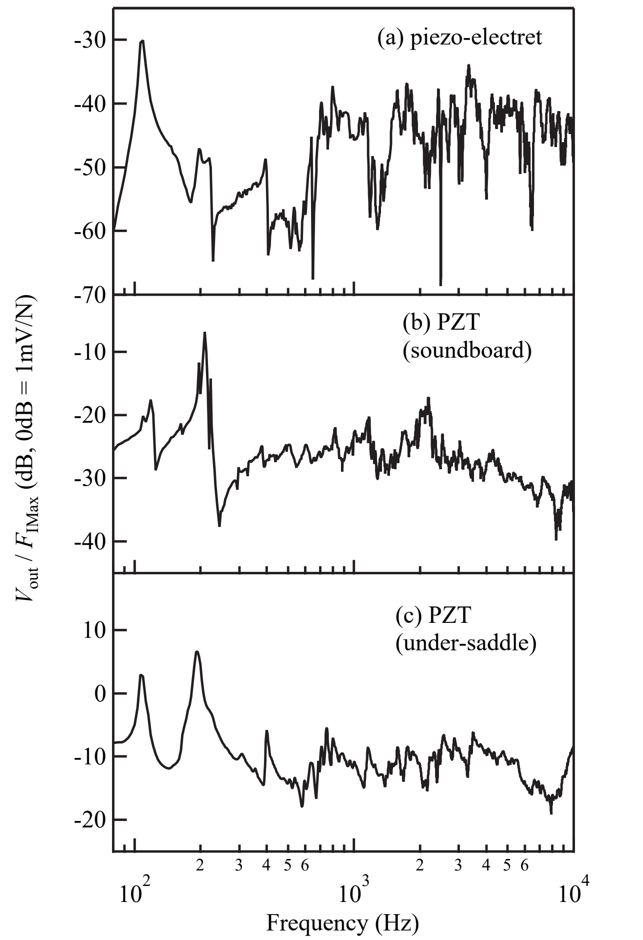

Figure 8. Frequency spectra of the output voltage V_{out}/F_{IMax} of (a) the piezo-electret sensor, (b) the PZT sensor attached to the soundboard, and (c) the PZT sensor equipped under-saddle.

3.3 VIBRATION DETECTION MECHANISM OF THE PIEZO-ELECTRET SENSOR

A piezoelectric vibration sensor consists of a piezoelectric element and a metal mass fixed to the piezoelectric element [21]. The piezoelectric element generates electric charge in proportion to the stress caused by the acceleration of the metal mass. The piezo-electret sensor tested in this study consists of only a piezo-electret laminated with a PET film and silver electrode printed on the sensor. The silver electrode also acts as a mass in the sensor.

The electromechanical properties of the piezo-electret are illustrated by *e*-form equations of piezoelectricity owing to strain in the thickness direction. The basic equations are given by:

$$D_3 = \varepsilon_{33}^S E_3 + e_{33} S_3 , \tag{5}$$

$$T_3 = c_{33}^E S_3 - e_{33} E_3 , \tag{6}$$

where D_3, E_3, S_3, and T_3 are the thickness-direction components of the electric displacement, the electric field, the mechanical strain, and the mechanical stress, respectively [22]. c_{33}^E is the elastic stiffness under a constant electric field E. Equations (5) and (6) yield

$$D_3 = \frac{e_{33}}{c_{33}^E} T_3 + \varepsilon_{33}^T E_3 , \tag{7}$$

where ε_{33}^T is the permittivity under a constant strain T. The relationship between ε_{33}^S and ε_{33}^T is given by:

$$\varepsilon_{33}^T = \frac{\varepsilon_{33}^S}{1 - k_t^{\ 2}} . \tag{8}$$

The coefficient of T_3 provides the apparent piezoelectric d constant d_{33}^a under $S_1 = 0$ and $S_2 = 0$ as:

$$d_{33}^a = \frac{e_{33}}{c_{33}^E} . \tag{9}$$

Using the aforementioned experimental results for the piezoelectric resonance, $d_{33}^a = 448$ pC/N was obtained.

As described above, the elastic stiffness in the thickness direction c_{33}^D was only 0.54 MPa in the piezo-electret. This indicates that the strain in the thickness direction is due to the change in volume of the air surrounded by the PP film.

Below the resonance frequency in the thickness direction, an equivalent model of the piezo-electret sensor attached to the soundboard becomes the one-dimensional mechanical model shown in Figure 9. Damping can be neglected below the resonance frequency. The weights of the piezo-electret and the PET film on the piezo-electret were 0.02 mg and 0.1 mg, respectively. These are neglected because they are smaller than the weight of a silver electrode m_{SE} = 63 mg. As the piezo-electret was laminated with a PET film by double-sided tape, the effective spring constant was the spring constant of the piezo-electret k_{PE} and that of the laminate film k_{LF} connected in parallel.

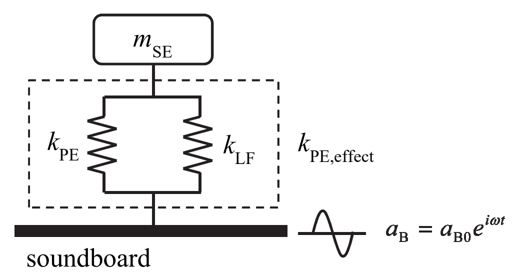

Figure 9. One-dimensional mechanical equivalent model of the piezo- electret sensor attached to the soundboard

The density, Young's modulus, and acoustic velocity of the spruce board were 420 kg/m^3, 11.5 GPa, and 5230 m/s^2 [23]. These values indicate that the resonance frequency of the soundboard became 934 kHz in the thickness direction. Therefore, no sound waves were generated in the thickness direction of the soundboard below 10 kHz.

The acceleration of the soundboard a_B is expressed as:

$$a_B = a_{B0} e^{i\omega t} . \tag{10}$$

Below the resonance frequency in the thickness direction in the sensor, the mechanical force in the thickness direction F_3 owing to the vibration is:

$$F_3 = m_{SE} a_B \, . \quad (11)$$

The output charge of sensor $Q_{out} = d_{33}^{a} F_3$ is:

$$Q_{out} = d_{33,effect}^{a} m_{SE} a_B \, . \quad (12)$$

where $d_{33,effect}^{a}$ is the effective piezoelectric d_{33}^{a} constant of the piezo-electret in the sensor.

Because the PET film was placed between the silver electrode and the upper electrode of the piezo-electret, the capacitance of the sensor became the sum of the capacitance of the piezo-electret C_{PE} and the PET film C_{PET}. The output voltage of the sensor becomes:

$$V_{out} = \frac{Q_{out}}{C_{PE} + C_{PET}} \, , \quad (13)$$

In this work, the capacitance values were C_{PE} = 110 pF and C_{PET} = 110 pF.

The experimental results showed that the piezo-electret sensor detected vibration of the soundboard from 300 Hz to 10 kHz. The sensitivity in the piezo-electret sensor S_{PE} in the frequency range was estimated by the ratio V_{out}/a_B shown in Figures 6c and 8a. Figure 10 shows the frequency dependence of S_{PE} from 300 Hz to 10 kHz. The result shows that the sensitivity of the sensor S_{PE} was approximately -70 dB when 0 dB = 1 mV/m/s^2. According to Figure 6c, the acceleration of soundboard a_B was approximately 300 m/s^2. The output signal of the piezo-electret sensor was only 0.14 mV. The data error is caused by the small output signal of the piezo-electret sensor. The error of S_{PE} is expected to be decreased by applying the optimum structure of the piezo-electret reported so far [12–18].

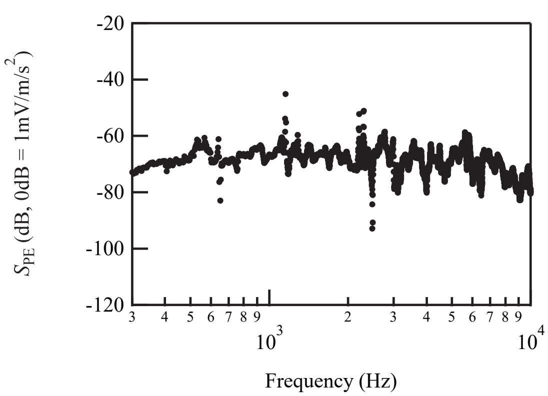

Figure 10. Frequency dependence of the sensitivity of piezo-electret sensor S_{PE}.

Equations (12) and (13) also yield the effective d_{33} constant $d_{33,effect}^{a}$ as

$$d_{33,effect}^{a} = \frac{S_{PE}(C_{PE} + C_{PET})}{m_{SE}} \, . \quad (14)$$

At 1 kHz, the S_{PE} was 0.45 μV/m/s^2. As mentioned above, the mass acting as a force on the piezo-electret was m_{SE} = 63 mg. The effective d_{33} constant becomes $d_{33,effect}^{a}$ = 1.58 pC/N by Equation (14), which is only 1/280 of d_{33}^{a}. These result and Equation (9) suggest that the effective value of elasticity in the thickness direction increases to approximately 0.15 GPa, which is approximately 280 times the value in the piezo-electret owing to the lamination with the PET film and the double-sided tape.

The resonance frequency depends on the effective mass and effective elasticity of the sensor. Increases in the mass and elasticity were 3,200 times and 280 times the values of the piezo-electret, respectively. The change in the resonance frequency, which is given by the square root of the ratio of changes in elasticity and mass, was 0.3. These results suggest that the resonance frequency of the sensor is 78 kHz.

4 CONCLUSIONS

The vibration sensitivity of a piezo-electret sensor designed for an acoustic-electric guitar was evaluated. The piezo-electret was laminated with a 150-μm-thick PET film using double-sided tape to improve durability. A 10-μm-thick silver electrode was printed on the top surface as a shield electrode. This electrode acted as a mass of only 63 mg, which is 3,600 times the weight of the piezo-electret. The output voltage of the piezo-electret sensor was only 1/10 to 1/100 of that in conventional sensors consisting of PZT ceramics. However, the piezo-electret sensor succeeded in detecting the vibration of the soundboard of the guitar from 300 kHz to 10 kHz. Its time response also corresponded to the vibration of the soundboard. The sensitivity of the piezo-electret sensor was approximately -70 dB (0 dB =1 mV/m/s^2) in the frequency range.

The effective d_{33} value of the sensor at 1 kHz was 1.58 pC/N, which was only 1/280 of the piezo-electret. The results suggested that the effective value of the elastic modulus in the thickness direction is increased to approximately 0.15 GPa, which is 280 times the value in the piezo-electret, by laminating with a PET film. The resonance frequency of the piezo-electret sensor was estimated by the effective mass and the effective elastic constant. The resonance frequency became 78 kHz.

A previous paper showed that the sensitivity of a piezo-electret sensor equipped under-saddle depended on the static force and magnitude of vibration [10]. Additionally, DSP and digital filters were required to improve the output signal of the sensor [11]. The piezoelectric sensor studied in this paper detects the vibration of the soundboard from 300 Hz to 10 kHz by attaching to the board without using DSP and digital filters. The sound quality evaluation of this sensor will be studied.

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