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Triaxial Piezoelectric Sensor Serving as Bridge of String Instruments
駒の機能を有する弦楽器用３軸圧電センサ

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1. Introduction

Sound generation mechanism of musical instruments has been attracted many researchers. One of their researches is to make physical models of string instruments which depend on experimentally observed data; such as vibrations of string and body. To observe vibration from the string to the body via a bridge, which is necessary to investigate a coupled vibration mechanism in string instruments, a piezoelectric sensor has been proposed and investigated [1]. The previously proposed sensor, which is shown in Fig. 1, is made up of some components; a saddle, a bridge, and a piezoelectric plate. This sensor has a characteristic that it works not only as a sensor but also as a bridge. Triaxial forces applied to the bridge by string vibration are measured as charge value owing to a longitudinal deformation of the plate. We have confirmed that the previous sensor could measure the applied triaxial forces independently. However, it has also been confirmed that the previously proposed sensor has a need to be improved; low-charge sensitivity due to smallness of electrodes on the piezoelectric ceramic.

To improve the confirmed need, we propose a new piezoelectric sensor which consists of a single-piece piezoelectric ceramic, as shown in **Fig. 2 (a)**. This sensor has large electrodes and expected to achieve high-charge sensitivity compared to the previously proposed one. Moreover, the single-piece structure achieves simplicity both in structure and manufacturing process.

In this paper, sensitivity of the newly proposed sensor is analyzed and compared to the previously proposed one, using finite element method (FEM).

2. Structure of Proposed Sensor

The newly proposed sensor, as shown in Fig. 2 (a), has five electrodes, I through IV and GND. We define that the piezoelectric ceramic is polarized in direction of z, and the string is stretched across the top of the sensor in direction of x. In this case, a relationship above charges, Q_{I} through Q_{IV}, applied triaxial forces, F_x, F_y, and F_z, and sensitivity matrix, is shown as;

$$\begin{pmatrix} Q_{\mathrm{I}} \\ Q_{\mathrm{II}} \\ Q_{\mathrm{III}} \\ Q_{\mathrm{IV}} \end{pmatrix} = \begin{pmatrix} -s_{\mathrm{I}x} & 0 & s_{\mathrm{I}z} \\ s_{\mathrm{I}x} & 0 & s_{\mathrm{I}z} \\ 0 & -s_{\mathrm{III}y} & s_{\mathrm{III}z} \\ 0 & s_{\mathrm{III}y} & s_{\mathrm{III}z} \end{pmatrix} \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix}. \quad (1)$$

Based on eq. (1), F_x, F_y, and F_z can be measured from following equations;

$$F_x = \frac{Q_{\mathrm{II}} - Q_{\mathrm{I}}}{2s_{\mathrm{I}x}}, \quad (2)$$

$$F_y = \frac{Q_{\mathrm{IV}} - Q_{\mathrm{III}}}{2s_{\mathrm{III}y}}, \quad (3)$$

$$F_z = \frac{Q_{\mathrm{I}} + Q_{\mathrm{II}}}{2s_{\mathrm{I}z}} \text{ or } \frac{Q_{\mathrm{III}} + Q_{\mathrm{IV}}}{2s_{\mathrm{III}z}}. \quad (4)$$

Eqs. (2) through (4) means that the sensitivity of measured forces depend on that of charges. To improve large charge sensitivities, the newly proposed sensor is designed to have large-size electrodes considering its size as the bridge.

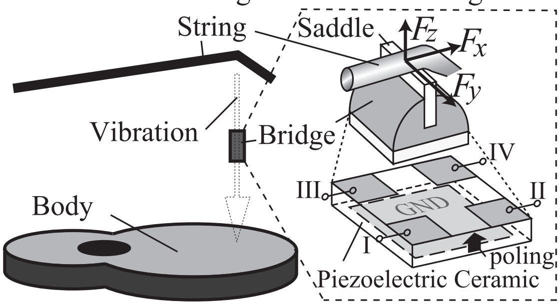

Fig. 1 Previously proposed sensor for measurement of force received by triaxial vibration.

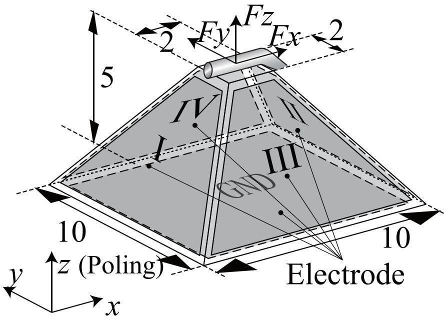

Fig. 2 Newly proposed sensor to measure triaxial forces applied by string vibration.

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3. Evaluation of Sensitivity using FEM

We evaluate charge sensitivities using the FEM, and compare the sensitivities between the proposed and the previous sensor to confirm the advantage of the proposed sensor. The sensor model is shown in Fig. 2 (a). The material is piezoelectric ceramic. The bottom surface is fixed mechanically. The model is discretized with 6696 2nd order tetrahedral elements. To derive the charge sensitivities, we calculate the electrostatic capacities and the open voltages of electrode I through IV in static analysis. Firstly, to calculate the capacities, a surface charge density of the sensor is analyzed. A result is shown in **Fig. 3** when a voltage of 1 V is applied to the electrode I, and rest electrodes II through IV, are opened. The analyzed density is integrated by an area of electrode I, and its capacity is calculated. The charge densities of electrode II through IV are analyzed in a similar manner, and the capacities are calculated. These capacities are shown in first column of **Table I**. Next, open voltages are analyzed under the forces applied to the sensor. Force of 1 N toward the *x* direction is applied to a dip for putting the string. The voltage of sensor surface is shown in **Fig. 4 (a)**. In a similar manner, results forced toward the *y* and *z* directions are shown in **Fig. 4 (b)** and **4 (c)**, respectively. The voltages of electrode I through IV when force is applied toward *x*, *y* and *z* directions are shown in second, third, and fourth columns of Table I, respectively. Finally, each generated charges of electrode I through IV, Q_{I} through Q_{IV} are obtained by production of the capacities and the voltages. Forces F_x, F_y, and F_z is derived by eqs. (2), (3), and (4). The derived sensitivities toward *x*, *y* and *z* directions are shown in first row of **Table II**. The previous sensor is similarly analyzed, and the charge sensitivities are derived. The results are shown in second row in Table II. The sensitivities of proposed sensor become about three times higher than those of the previous sensor. The reason for this increase is considered to be that we get larger electrode areas of the proposed sensor than that of previous sensor.

In the future, we will try to evaluate a variation of the sensitivities in the experiment to demonstrate decrease of the variation of the proposed sensor because the structure of the sensor becomes simplified.

4. Conclusions

We propose a triaxial piezoelectric sensor measuring triaxial forces applied by string vibration. To improve charge sensitivities, the newly proposed sensor is designed to have large-size electrodes considering its size as the bridge. The sensitivities of proposed sensor are compared with that of previous sensor using FEM. The sensitivities of proposed sensor become about three times higher than those of previous sensor.

Acknowledgment
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References
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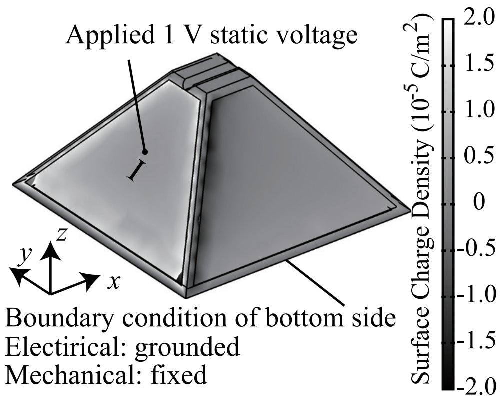

Fig. 3 Surface charge density of the sensor under applying 1 V static voltage to electrode I.

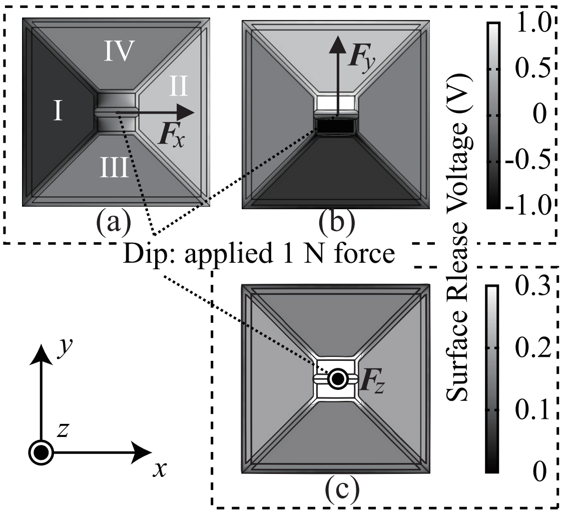

Fig. 4 Surface release voltages under applying force of 1 N to dip: (a) *x* force (b) *y* force (c) *z* force.

Table I Capacities and release voltages of electrode I though IV.

Electrode	Capacity (pF)	Voltage (mV) *x*	*y*	*z*
I	262	-595	-1	201
II	267	594	0	200
III	265	0	-603	155
IV	266	0	603	155

Table II Sensitivities of previous and proposed sensor.

		x	*y*	*z*
Chage Sensitivity (pC/N)	Proposed	315	320	106
	Previous	131	118	31