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The study of sensitivity on piezoelectric vibratory tactile sensor using a longitudinal bar resonator

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ABSTRACT

Piezoelectric vibratory tactile sensors are used for measuring the softness and hardness of an object. In this research, the sensitivity of the longitudinal bar type tactile sensor was considered to establish the design guideline of the vibratory tactile sensor. First, the sensitivity on the frequency change of the longitudinal bar resonator in contact with an object was approximately derived for designing the vibratory tactile sensor. It was experimentally clarified that the sensitivity was inversely proportional to the equivalent mass of the bar resonator. Next, the shape of a longitudinal bar resonator was calculated using the finite element method for improving the sensitivity on the vibratory tactile sensor. It was shown that the sensitivity was increased using the horn type tactile sensor. The obtained results will be useful for designing the piezoelectric vibratory tactile sensor.

1. INTRODUCTION

Various kinds of tactile sensors have been used for measuring the physical characteristics of an object [1-5]. Recently, the piezoelectric vibratory tactile sensors have been proposed for measuring the softness and hardness of an object [6-14]. These tactile sensors utilize the longitudinal mode [6,7], flexural mode [9] or edge mode vibration [12,13] of the resonators. They make use of changes in the resonance frequencies of the resonators, which are induced when their vibrating tips are brought into contact with an object. In these tactile sensors, the longitudinal bar type sensor has been the most studied [6,15], and has already been analyzed using a Mason equivalent circuit [7] and a distributed constant circuit of the resonator [16]. However, these results are yet insufficient to design the piezoelectric vibratory tactile sensor.

In this paper, the design guideline of sensitivity on the tactile sensors with longitudinal bar resonators is considered from the viewpoint of developing a systematicdesign method of vibratory tactile sensor. First, the sensitivity of the tactile sensor in terms of the frequency change of the resonator is considered for designing the longitudinal bar type tactile sensor. The approximate equation of the frequency change of the tactile sensor in case of contacting with a softer object is derived. A method for improving the sensitivity of the tactile sensor is considered. Next, the shape of the longitudinal bar resonator is studied for improving the sensitivity on the tactile sensor. The equivalent masses and equivalent mass coefficient of the horn type resonators are calculated using the finite element method. Then, the vibration displacement of the horn type tactile sensor are analyzed for determine the structure which are not influenced by supporting conditions. The characteristics of the tactile sensors are measured using standard rubber testpieces of different hardness. The experimental results of sensitivity for the tactile sensors are discussed from the viewpoint of the equivalent mass of the resonator.

2. SITIVITY OF TACTILE SENSOR

2.1 Sensitivity of resonance frequency change

Figure 1 shows the construction of conventional tactile sensor with a longitudinal bar resonator. When the tactile sensor, which is driven in the longitudinal mode, touches an object, the softness and hardness of the object are detected as changes in resonance frequencies.

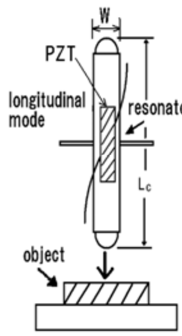


Figure 1: Construction of conventional tactile sensor with longitudinal bar resonator.

In general, the resonance angular frequency ω_0 of a resonator is shown by

$$\omega_0{}^2 = \frac{s}{m_0} \quad . \tag{1}$$

Here, m_0 and s are the equivalent mass and stiffness of the resonator, respectively.

When the resonator is contacted with a softer object, the resonant frequency changes by an additional mass effect. In this case, the resonance angular frequency ω is approximately given by

$$\omega^2 = \frac{s}{m_0 + m_e} \quad . \tag{2}$$

, where m_e is an additional mass.

Then, the resonance frequency change is expressed by

$$\frac{f}{f_0} = \left(1 + \frac{m_e}{m_0}\right)^{-\frac{1}{2}} \quad . \tag{3}$$

Moreover, in the case of assuming that $1 \gg m_e/m_0$, the sensitivity of the frequency change ratio is expressed as

$$\frac{\Delta f}{f_0} \cong -\frac{m_e}{2m_0} = -\frac{m_e}{2\delta M_0} \quad . \tag{4}$$

, where $\Delta f = f - f_0$ and δ ($= m_0/M_0$; M_0:total mass) is the equivalent mass coefficient.

This approximate equation means that the sensitivity of tactile sensor is inversely proportional to the equivalent mass of the resonator. Then, the resonator with small δ is suitable for increasing the sensitivity.

2.2 Structure of fabricated resonator for tactile sensor

To evaluate the approximate equation of sensitivity, the tactile sensors with longitudinal bar type resonators were fabricated. The dimensions of fabricated resonators are shown in Table 1. The tactile sensors were piezoelectrically driven on the longitudinal mode in Fig.1. The tactile sensors for experiment were manufactured from SUS304 stainless steel using an electric discharge machine. The sensor tips of these resonators were hemispheres with a radius R=1.0mm and made of SUJ-2. Piezoelectric plates were attached to the center of the longitudinal bars to drive these resonators. Figure 2 shows the experimental setup for measuring the characteristics of the tactile sensors. To obtain the characteristics on tactile sensors, the resonators were placed in contact with standard rubber test pieces. The resonance frequencies were measured with an impedance analyzer. The impressed load force was measured with an electric balance. The size of the test pieces of S1-S3 (AXIOM Co.) was 44mm in diameter and 10mm in thickness, and material constants are shown in Table 2.

Table 1. Dimensions of resonators (unit:mm)

Length:Lc		Width:W	Thickness:t
Composite type	18, 25, 33,50	2.0	2.0
PZT type	11.3, 16.5, 21	2.0	0.9

Table 2. Material constants of test pieces

Type	S1	S2	S3
Young's modulus (MPa)	0.04	0.06	0.15
Density (kg/m^3)	1045	1080	1100

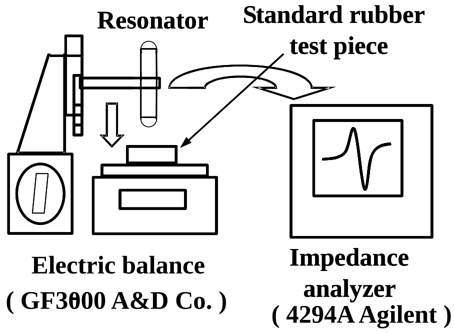


Figure 2: Experimental setup for measuring characteristics of tactile sensors.

2.3 Experimental characteristics of conventional bar type tactile sensor

When the tactile sensor is brought into contact with a softer object, the resonance frequency of the resonator decreases as a result of an additional mass effect. Figures 3 shows the experimental results for the tactile sensor with the longitudinal bar resonator, where Lc=50mm and resonance frequency f_0=51.55kHz. When the load added to test pieces increased, the resonance frequencies of the resonator gradually decreased as in Fig.3. The amount of decrease of resonance frequency is expressed as Δf ($= f_L - f_0$), where f_L is the resonance frequency when a load is applied and f_0 is the resonance frequency with no load. The characteristics between the load and Δf show the tendency that the amount of decrease for the soft test piece S1 is larger than the hard test pieces S2 and S3. Figure 4 shows the experimental results for another tactile sensor, where Lc=18mm and f_0=148.88kHz. It was clarified that Δf and frequency change ratio $|\Delta f/f_0|$ are larger than these in the case where the longitudinal bar resonator is used with smaller total mass.

On the other hand, from the experimental results with the longitudinal bar type tactile sensor of the same length in different vibration mode, it was clarified that the frequency change ratio $|\Delta f/f_0|$ was almost the same value [16]. Figure 5 shows the relationship between the frequency change ratio $|\Delta f/f_0|$ at load W=4gf and the mass M_0 of the resonator. It is clear that the sensitivity of $|\Delta f/f_0|$ is inversely proportional to the mass of the resonator as shown by eq.(4). The relationship between $|\Delta f/f_0|$ and M_0 is estimated to be $|\Delta f/f_0| \propto M_0^{-0.799}$ by curve fitting.

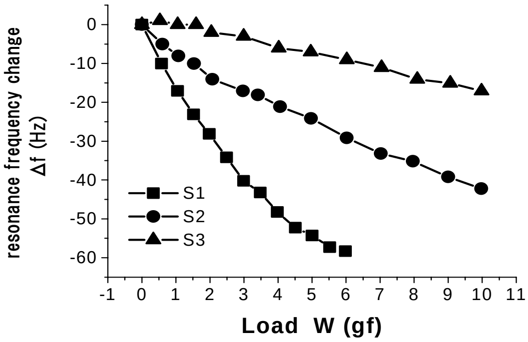


Figure 3: Experimental characteristics of composite type tactile sensor (I).(Lc=50mm, f_0=51.55kHz)

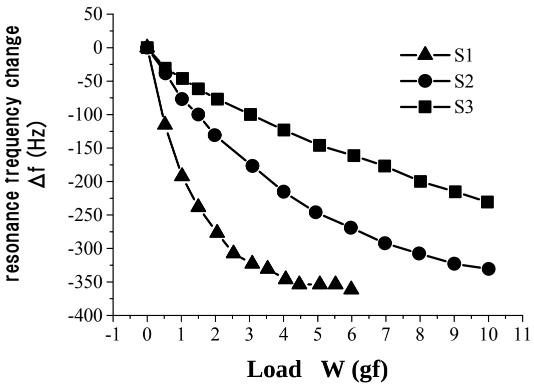


Figure 4: Experimental characteristics of composite type tactile sensor (II).(Lc=18mm, f_0=148.88kHz)

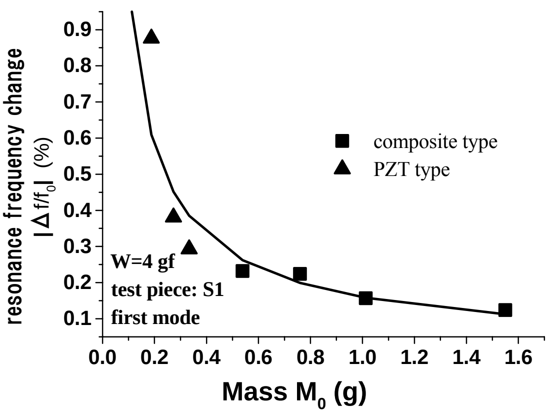
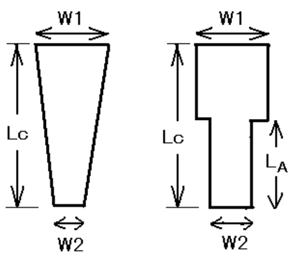


Figure 5: Relationship between sensitivity and mass of the conventional bar type tactile sensor.

3. ANALYSIS OF THE HORN TYPE TACTILE SENSOR

3.1 Calculated results of the equivalent mass

The sensitivity of tactile sensor can be improved by modifying the shape of bar resonator with small equivalent mass coefficient δ. To consider the effect on a shape of the bar resonator, the horn type resonators shown in Fig.6 were adopted as tactile sensors. The equivalent masses and equivalent mass coefficients of the horn type resonators were calculated using the finite element method. The analysis was performed using the finite element analysis program ANSYS ver.11. Young's modulus, Poisson's ratio and the density of the horn type resonators fabricated from SUS304 stainless steel were $E=1.99\times10^{11}(N/m^2)$, σ =0.34 and ρ =7900(kg/m^3), respectively.



(a) Conical horn type. (b) Stepped horn type.
Figure 6: Horn type bar resonators.

Table 3 shows the calculated results of the equivalent mass of the resonator in Fig.6(a). It is clarified that the equivalent mass m_0 and the equivalent mass coefficient δ are small as the width W_2 of the sensor tip becomes smaller. On the other hand, Figs. 7 and 8 show the calculated results of the equivalent mass and the equivalent mass coefficient in Fig.6(b). The values of m_0 and δ become small when $L_A \fallingdotseq$ 6mm. From these calculated results, it became clear that there is a possibility to improve sensitivity by designing the shape of the longitudinal bar resonator.

Table 3. Calculated results of equivalent mass.(Lc=16mm, W1=4mm, t=2mm)

W2 (mm)	4.0	2.0	1.0
Equivalent mass m_0 (g)	0.494	0.262	0.158
Total mass M_0 (g)	1.011	0.758	0.632
Equivalent mass coefficient δ	0.49	0.35	0.25
Resonance frequency (kHz)	156.2	159.0	165.7

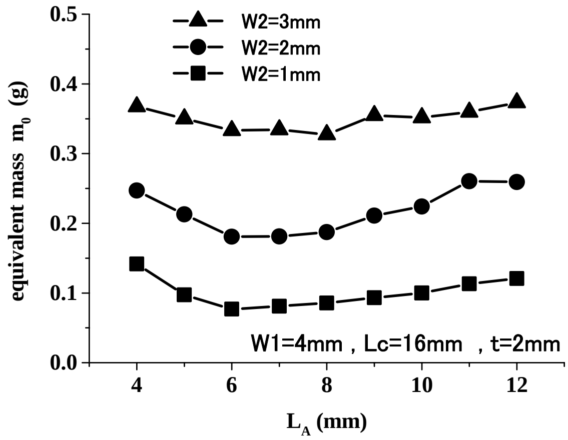


Figure 7 : Calculated relationship between L_A and m_0.

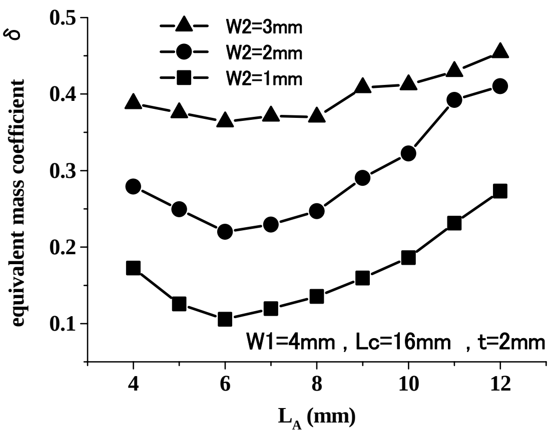


Figure 8 : Calculated relationship between L_A and δ.

3.2 Vibration displacement analysis

Figure 9 shows the elevation and plane views of the conical horn type tactile sensor with a supporting structure. The sensor tip of the resonator was hemispheric with a radius R=1.0 mm. The dimensions of the tactile sensor are shown in Table 4. To reduce the vibration displacement at the supporting point Ps in Fig. 9, vibration displacement analysis is performed at various values of the arm width Wa and base length L_b. Figure 10 shows the calculated resonance frequency change $|\Delta f/f_0|$ at various conditions of the supporting points. In these figures, $\Delta f/f_0$ is expressed as $\Delta f=f_{clamp}-f_{free}$, $f_0= f_{free}$, where f_{clamp} is the resonance frequency under the clamping condition in the supporting area, and f_{free} is that under the free condition. The characteristics of resonance frequency change in the case of using the conventional longitudinal resonator with W2=4 mm and L_A=0 mm are also shown for comparison with those in the case of using the conical horn type and stepped horn type of L_A=6 mm and W2=2 mm resonators. From these results, it is clarified that $|\Delta f/f_0|$ is very small, 20 ppm or less, when Wa=0.8 mm and $L_b \geqq 4.0$ mm, and there is only a small effect of the supporting condition.

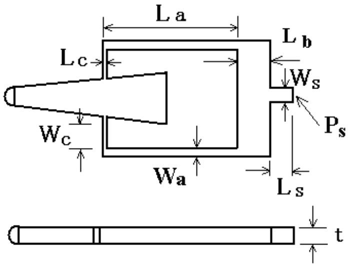
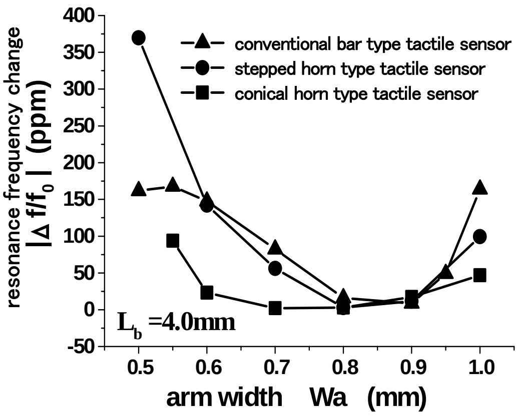


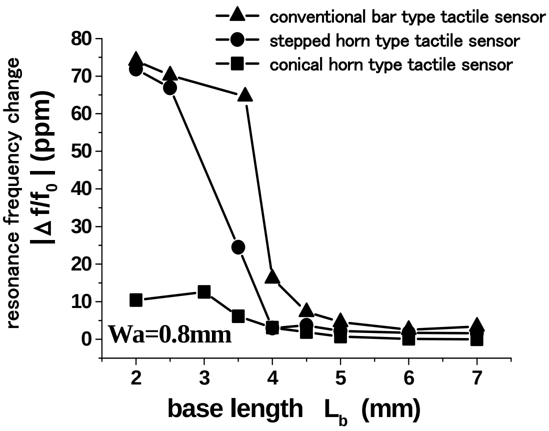
Figure 9: Horn type tactile sensor with a supporting structure.

Table 4. Dimensions of horn type tactile sensor(unit:mm)

La	L_b	Lc	Wa	Wc	Ws	Ls	t
12	variable	0.5	variable	0.5	1.0	2.0	2.0



(a) Calculated relationship between $|\Delta f/f_0|$ and Wa.



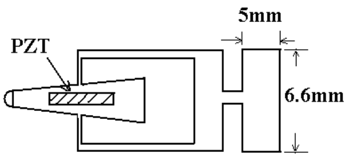
(b) Calculated relationship between $|\Delta f/f_0|$ and L_b.

Figure 10: Calculated resonance frequency change caused by supporting condition.

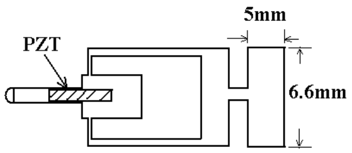
4. EXPERIMENTAL INVESTIGATION

4.1 Experimental results of horn type resonator

To evaluate the results of FEM analysis described in§3, the two kinds of tactile sensors with Wa=0.8 mm and Lb=5.0 mm were fabricated. The schematics of the fabricated horn type resonators are shown in Figs. 11(a) and 11(b). The resonators were fabricated from SUS304 stainless steel using an electric discharge machine. Piezoelectric ceramic plates ($5.0\times2.0\times0.16$ mm^3) were attached to the center of the longitudinal bar to drive these resonators. Table 5 shows the analytical and experimental results for the resonators shown in Fig. 11 and convebtional bar type resonator. The measured resonant frequencies coincide with the calculated values with a difference of 3.4 % or less. These are considered to be due to the difference in material constant and the effect of piezoelectric ceramics attached to the resonator. Then, the quality factor Q_{clamp} for a clamp support is 1 % less than Q_{free} on a soft support. These results indirectly show that the vibration displacement analysis by the finite element method is reasonable. However, as the horn type resonators have asymmetric structures, these quality factors Q are lower than that of the conventional longitudinal bar resonator. Table 6 shows the experimental equivalent masses of the resonators. As the measured equivalent masses are smaller than the calculated values, the characteristics show a corresponding tendency.



(a) Conical horn type tactile sensor.



(b) Stepped horn type tactile sensor.

Figure 11: Fabricated tactile sensor for experiment.

Table 5. Experimental results of resonators.

(a) Conventional bar type resonator.

	f_{free} (kHz)	f_{clamp} (kHz)	Q_{free}	Q_{clamp}
Calculated value	153.72	153.72		
Experimental value	158.91	158.90	3186	3186
Difference(%)	3.4	3.4		

(b) Conical horn type resonator.

	f_{free} (kHz)	f_{clamp} (kHz)	Q_{free}	Q_{clamp}
Calculated value	154.22	154.22		
Experimental value	156.28	156.29	864	864
Difference(%)	1.3	1.3		

(c) Stepped horn type resonator.

	f_{free} (kHz)	f_{clamp} (kHz)	Q_{free}	Q_{clamp}
Calculated value	156.18	156.18		
Experimental value	159.15	159.13	1329	1316
Difference(%)	1.9	1.9		

Table 5. Experimental results ofequivalent masses.

(a) Conventional bar type resonator.

	equivalent mass m_0(g)	equivalent mass coefficient δ
Calculated value	0.49	0.49
Experimental value	0.40	0.40

(b) Conical horn type resonator.

	equivalent mass m_0(g)	equivalent mass coefficient δ
Calculated value	0.26	0.35
Experimental value	0.23	0.30

(c) Stepped horn type resonator.

	equivalent mass m_0(g)	equivalent mass coefficient δ
Calculated value	0.18	0.22
Experimental value	0.15	0.18

4.2 Experimental characteristics of horn type tactile sensor

Figure 11 shows the experimental results for the tactile sensor with the conventional longitudinal bar resonator of Lc=16 mm and W1=W2=4 mm. As the load added to the test rubber pieces increased, the resonance frequency of the resonator decreased gradually. The frequency change ratio $|\Delta f/f_0|$, which corresponds to the sensitivity of the tactile sensor in eq.(4), is given by 0.096 % with load W=1 gf on test piece S1.

On the other hand, Figs. 12 and 13 show the experimental results for the horn type tactile sensors in Figs. 11(a) and 11(b), respectivity. The frequency changes Δf are larger than those shown in Fig. 11 for the same load. The frequency change ratio $|\Delta f/f_0|$ is given by 0.15% and 0.24 % with load W=1 gf on S1, respectivity. Since the equivalent masses of the horn type resonators are 0.575 times and 0.375 times smaller than that of the conventional longitudinal bar resonator, as shown in Table 5, the frequency change ratio $|\Delta f/f_0|$ would be 1.6-fold and 2.5-fold larger, respectivity. It is experimentally clarified that sensitivity is inversely proportional to the equivalent mass of the resonator and is improved by modifying the shape of the resonator with small equivalent mass coefficient.

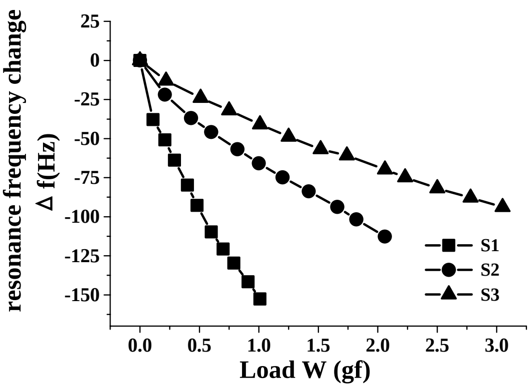


Figure 11: Experimental characteristics of conventional bar type tactile sensor. (f_0=158.9kHz)

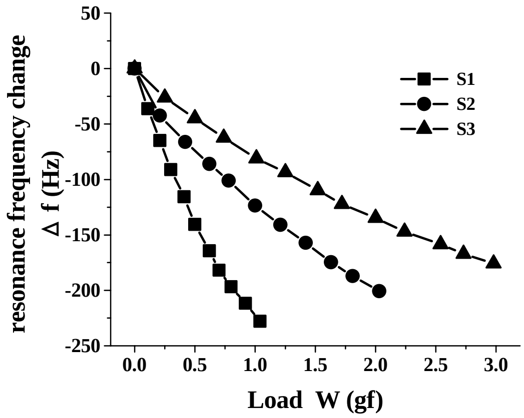


Figure 12: Experimental characteristics of conical horn type tactile sensor. (f_0=156.29kHz)

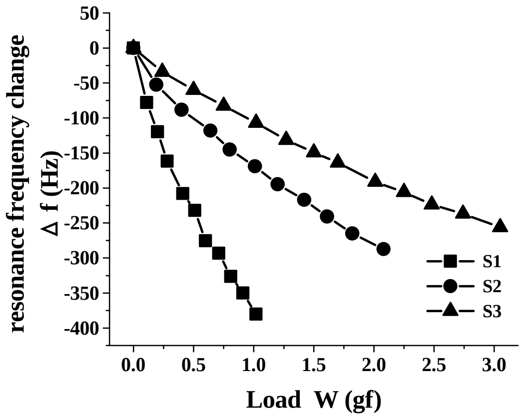


Figure 13: Experimental characteristics of stepped horn type tactile sensor. (f_0=159.13kHz)

5. CONCLUSIONS

In this resarch, the tactile sensor with a longitudinal bar resonator was examined for developing a systematic design method of vibratory tactile sensor, and the results were experimentally confirmed. The results obtained are summarized as follows.

(1)The approximate equation of resonance frequency change of the tactile sensor was derived. The approximate sensitivity in terms of the equivalent mass of the resonator was shown.

(2)The equivalent masses of the horn type resonators were calculated using the finite element method. The dimensions of the horn type tactile sensors, which had small equivalent mass and was not affected by supporting conditions, were determined.

(3)The characteristics of the horn type tactile sensor were measured using standard test rubber pieces of different hardness values. It was experimentally clarified that the sensitivity of the longitudinal bar type tactile sensor was inversely proportional to the equivalent mass of the resonator.

The horn type tactile sensor showed an increased sensitivity, and is expected to be a novel tactile sensor with high performance. The results in this study may be useful for developing a piezoelectric vibratory tactile sensor.

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