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The Study of Sensitivity on Piezoelectric Vibratory Tactile Sensor for Hardness Measurement

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1. Introduction

Various piezoelectric vibratory tactile sensors have been proposed for measuring the softness and hardness of an object 1-10). They make use of the resonance frequency changes on resonators, which are induced when their vibrating indenters are brought into contact with an object. The rate of resonance frequency change depends on the acoustic impedance of an object that corresponds to the contact area of the indenter. We have previously proposed the sensitivity of the tactile sensor in terms of the frequency change in case of measureing a softer object 10). In this paper, the characteristics of tactile sensor for measuring hard object are experimentally examined for developing a systematic method of designing vibratory tactile sensors.

2. Sensitivity of tactile sensor

In general, the resonance angular frequency ω_0 of a resonator is shown by $\omega^2_0=s_0/m_0$. Here, m_0 and s_0 are the equivalent mass and stiffness of the resonator, respectively. When the resonator is contacted with a harder object, the resonant frequency changes by an additional stiffness effect. In this case, the resonance angular frequency ω is approximately given by $\omega^2=(s_0+s_L)/m_0$, where s_L is an additional stiffness. Then, the resonance frequency change is expressed by

$$\frac{f}{f_0}=\left(1+\frac{s_L}{s_0}\right)^{1/2} \tag{1}$$

Moreover, in the case of assuming that $1 \gg s_L/s_0$, the sensitivity of the frequency change ratio is expressed as

$$\frac{\Delta f}{f_0}\cong\frac{s_L}{2m_0\omega_0^2} \tag{2}$$

, where $\Delta f=f-f_0$ is the frequency change.

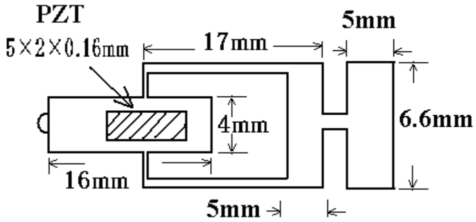
This approximate equation means that the sensitivity of tactile sensor is inversely proportional to the equivalent mass of the resonator when the resonance frequency of resonators are similar. Then, the equivqlent additional stiffness s_L is given by 11)

$$s_L=\frac{2aE_L}{1-\sigma^2} \tag{3}$$

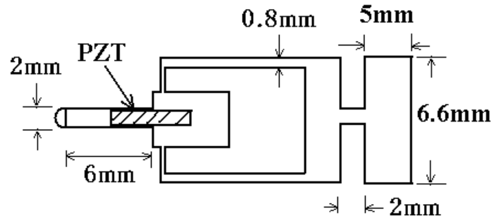
, here a is the contact radius when the indenter contacts with the object. E_L and σ are the Young's modulus and Poission's ratio, respectively.

3. Structure of tactile sensor

In this study, the longitudinal bar type resonators shown in Fig.1 were adopted as tactile sensors. The piezoelectric vibratory tactile sensors were fabricated from SUS304 stainless steel using an electric discharge machine. The sensor tip (SUJ-2) of the resonator was hemisheric with a radius R=1.0mm. Piezoelectric ceramic plates (Nepec6) were attached to the center of the longitudinal bar to drive the resonators.



(a) general longitudinal bar type resonator



(b) horn type resonator

Fig.1. Construction of vibratory tactile sensor using piezoelectric longitudinal bar resonator (thickness:2mm).

To obtain the characteristics on tactile sensors, the resonators were placed in contact with test pieces, and its resonance frequency was measured using impeadance analyzer (Agilent 4294A). The impressed load force was measured with an electric balance (A&D GF-3000). The size of the test pieces were $10\times10\times2mm^3$, and the material constants are shown in Table 1.

Table 1. Material constants of test pieces.

Type	Young's modulus E (GPa)	Density ρ (g/cm^3)
Aluminum(A5052)	71	2.68
Brass (C2801)	103	8.39
Steel (SPCC)	206	7.86

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4. Experimental investigation

4.1 Experimental results of resonators

Table 2 shows the experimental characteristics for resonators. The resonance frequencies and Q values of the resonators were almost the same. The equivalent masses of the resonators were measured by the additonal mass method. The additional mass method is the mathod to obtain the equivalent mass of the resonator from the frequency change of the resonator when a minute mass is added to the tip of the resonator. The equivalent mass of the horn type resonator was about 37.5% of the one of the general bar type resonator.

Table 2. Experimental results of resonator.

Type	Resonance frequency f_0 (kHz)	Quality factor	Equivalent mass m_0(g)
General bar type resonator	158.8	3400	0.40
Horn type resonator	159.8	3800	0.15

4.2 Experimental results of tactile sensors

When the tactile sensors were brought into contact with a harder object, the resonance frequency of the resonator increased as a result of an additional stiffness effect. Figure 2 and 3 show the experimental results for the tactile sensor with a longitudinal resonator. When the load added to test pieces increased, the resonance frequencies of the resonator gradually increase as in Fig.2. The amount of increased 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 W and Δf show the tendency that the amount of increase for the harder test piece SPCC is larger than the test pieces of C2801 and A5052.

Figure 3 shows the experimental characteristics of resonance frequency change using the horn type resonator. When the same load W is applied to the test pieces, the amount of increased resonance frequency using a horn type resonator is greater than as using a general bar type resonator in Fig.2. Table 3 shows a summary of the experimental results of the frequency change rate when load of W=90gf. It was found that the larger the Young's modulus of the test piece, the larger the frequency change late. In the same test piece, the resonance frequency change rate was 2.75 to 3.17 times larger as using a horn type resonator with a smaller equivalent mass as shown by eq.(2).

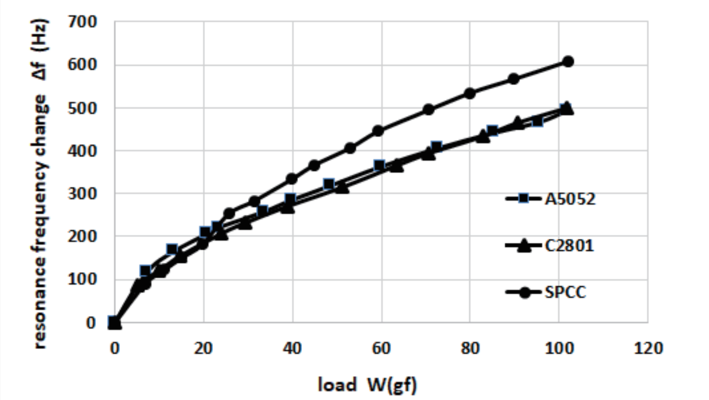

Fig.2. Experimental characteristics of ganeral longitudinal bar type tactile sensor.

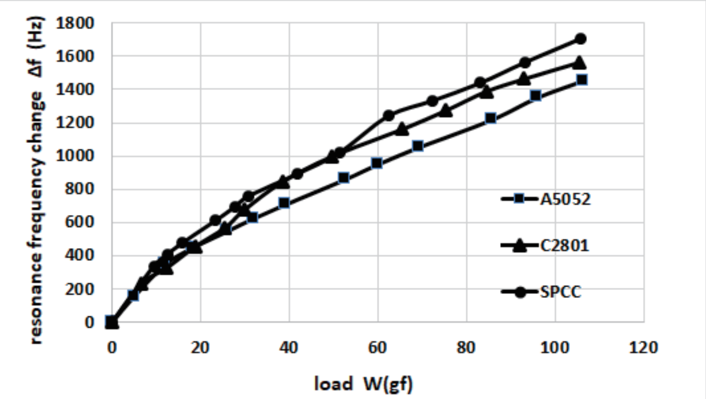

Fig.3. Experimental characteristics of horn type tactile sensor.

Table 3. Experimental results of frequency change rate(W=90gf).

Test piece	General bar type resonator(f_0=158.8kHz)	Horn type resonator (f_0=159.8kHz)
A5052	$\Delta f/f_0 ≒ 0.29\%$	$\Delta f/f_0 ≒ 0.80\%$
C2801	$\Delta f/f_0 ≒ 0.29\%$	$\Delta f/f_0 ≒ 0.92\%$
SPCC	$\Delta f/f_0 ≒ 0.356\%$	$\Delta f/f_0 ≒ 0.98\%$

5. Conclusion

The characteristics of resonance frequency change on tactile sensor for measuring the hard object were experimentally examined. It was clarified that the sensitivity of tactile sensor in terms of the frequency change ratio was inversely proportional to the equivalent mass of the resonator.

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