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A Study of Density Measurement using Piezoelectric Vibratory Tactile Sensor

圧電振動型触覚センサを用いた対象物の密度測定

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1. Introduction

The piezoelectric vibratory tactile sensors have been proposed for measuring the softness and hardness of an object [1-3]. They make use of changes in the resonance frequencies of resonators, which are induced when their vibrating sections are brought into contact with an object. We have previously proposed the sensitivity of the tactile sensor in terms of the frequency change for developing a systematic method of designing vibratory tactile sensors. In this paper, the method on measureing the density of an object is newly examined using the vibratory tactile sensor.

2. Analysis method

In general, the resonance angular frequency ω_0 of a resonator is shown by $\omega^2_0=s/m_0$. Here, m_0 and s are the equivalent mass and stiffness of the resonator, respectively. When the tip of resonator is contacted with a softer object, resonance frequency decreases owing to an additional mass effect. In this case, the resonance angular frequency ω is approximately given by $\omega^2=s/(m_0+m_e)$, where m_e is an additional mass for a softer object.

Then, an additional mass m_e is expressed by [4),5)]

$$m_e = m_0\left(\frac{f^2{}_0}{f^2}-1\right). \tag{1}$$

On the other hand, in case that the vibrating tip of resonator was brought into contact with a softer object, an additional mass m_e was given by eq.(2) [6)].

$$m_e = \frac{0.1}{1-\sigma}\cdot\rho S_C^{\frac{3}{2}} \tag{2}$$

Here, ρ and σ are the density and the Poisson's ratio, respectively. Sc is the contacted area given by eqs.(3)-(5).

$$S_C = \pi a^2 \tag{3}$$

$$a = \sqrt{t(2R-t)} \tag{4}$$

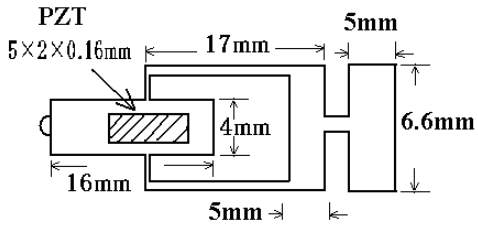
$$t = F_N^{\frac{2}{3}}\left[\frac{3}{4}\cdot\frac{1-\sigma^2}{E_S}\right]^{\frac{2}{3}} R^{-\frac{1}{3}} \tag{5}$$

Where, R is the radius of sensor tip and Es is Young's modulus of an object. F_N is the static load force applied to the resonator. Then, when the Young's modulus and the Poisson's ratio of an object were already obtained, the density is able to be calculated using the frequency changes Δf ($=f-f_0$) on the tactile sensor by eqs.(1) and (2).

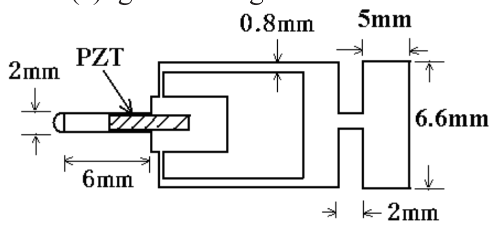
3. Experimental investigation

3.1 Experimental method

Figures 1(a) and 1(b) show the piezoelectric vibratory tactile sensors for experiment. The 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 resonator



(b) horn type resonator

Fig.1.Construction of vibratory tactile sensor (thickness:2mm).

To obtain the characteristics on tactile sensors, the resonators were placed in contact with test rubber 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 rebber pieces of S1-S6 (AXIOM Co.) was 44mm in diameter and 10mm in thickness, and the material constants are shown in Table 1.

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Table 1. Material constants of test rubber pieces.

Type	S1	S2	S3	S4	S5	S6
Young's modulus (kPa)	23	47	92	168	292	512
Density ρ (kg/m^3)	1096	1116	1141	1175	1207	1246

3.2 Experimental results

Table 2 shows the experimental results for the resonators shown in Figs. 1(a) and 1(b). Equivalent masses in Table 2 were calculated by finite element method. When the tactile sensors were brought into contact with a soft object, the resonance frequency of the resonator decreased as a result of an additional mass effect. As the load added to the test rubber pieces increased, the additional mass effect increased and the resonance frequency of the resonator decreased gradually. Figure 2 shows the characteristics of additional mass using the general bar resonator in Fig.1(a). The measured additional masses were calculated by eq.(1) using the resonance frequency change and the equivalent mass m_0 in Table 2. On the other hand, the calculated additional masses were given by eq.(2) with minimum mean-square error estimation on fitting the value of density. Figure 3 shows the characteristics of additional mass using the horn type resonator in Fig.1(b). It is clarified that the similar characteristics of additional masses were obtained using the resonators with the different equivalent masses. The calculated optimum values on density of each test pieces were shown in Fig.4. It is also indicated that the values of density in Table 1, which were measured by the mass and volume of test pieces. The similar characteristics between the experimental results and the calculated ones are obtained. However, the simulated values of density are lower than the experimental values. This seems to be due to the influence on the estimated equivalent mass of resonator and Young's modulus of viscoelastic test piece [7]. It is planned to examine these influences in detail.

Table 2. Characteristics of tactile sensor.

	Resonance frequency f_0 (kHz)	Quality factor	Equivalent mass m_0 (g)
Type (a)	159.02	2847	0.49
Type (b)	159.46	1583	0.18

4. Conclusion

The density measurement of an object was studied using a vibratory tactile sensor in this paper. It was examined that the possibility for detecting the density of test pieces using the tactile sensor.
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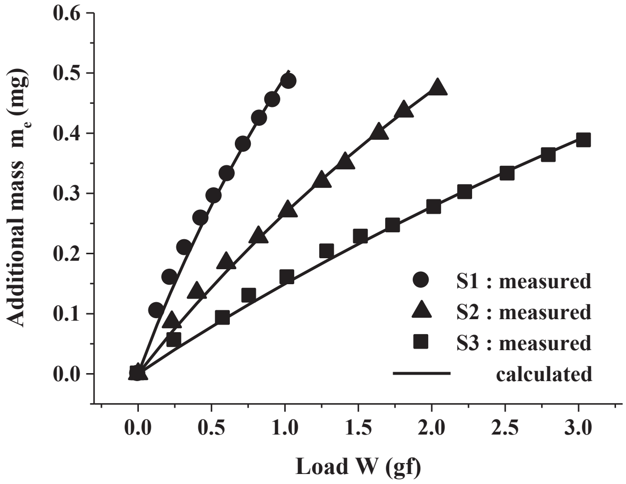

Fig.2. Characteristics of additional mass (1).

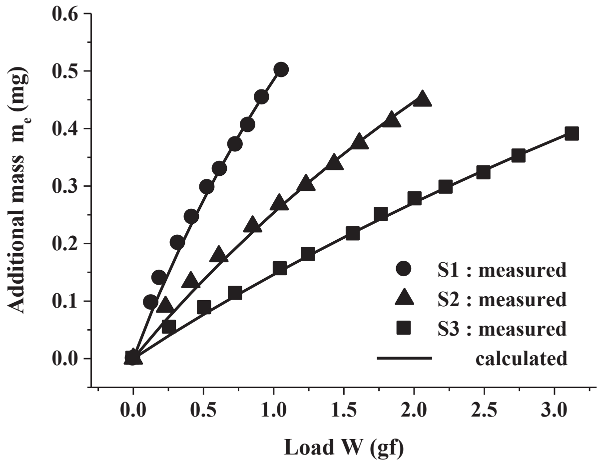

Fig.3. Characteristics of additional mass (2).

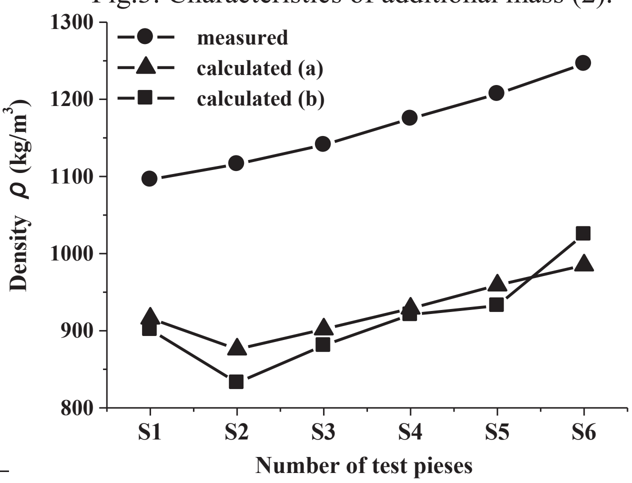

Fig.4. Characteristics of density.

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