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Consideration of Design Guidelines for Piezoelectric Vibratory Tactile Sensors

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1. Introduction

Various kinds of piezoelectric vibratory tactile sensors have been proposed for the physical characteristics such as 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 are experimentally examined for developing a design guidelines for piezoelectric vibratory tactile sensors.

2. Sensitivity of tactile sensor

Figure 1 shows the construction of piezoelectric vibratory 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.

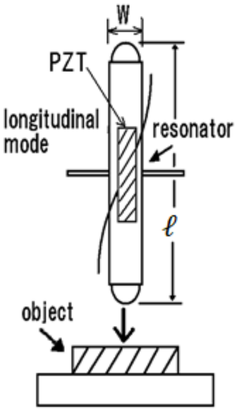

Fig.1 Construction of tactile sensor with longitudinal bar resonator.

Figure 2 shows the distributed constant-circuit model of this tactile sensor. In Fig. 2, Z_0, γ, and ℓ are the characteristic impedance, propagation constant and total length of the bar resonator, respectively. Moreover, Zx expresses the contact impedance when the vibrating sensor tip is in contact with an object. This contact impedance changes with the shape of the sensor tip and the contact load force. This equivalent circuit model is used for the calculation of the characteristics of sensitivity on tactile sensor.

The input impedance Zin in Fig. 2 is generally obtained by

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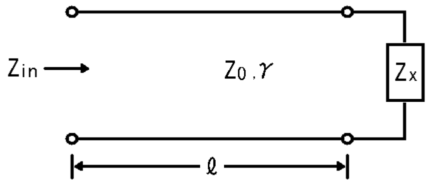

Fig.2 Distributed constant-circuit model of longitudinal bar-type tactile sensor.

$$Z_{in} = Z_0 \frac{(Z_0 + Z_x)e^{\gamma\ell} - (Z_0 - Z_x)e^{-\gamma\ell}}{(Z_0 + Z_x)e^{\gamma\ell} + (Z_0 - Z_x)e^{-\gamma\ell}} \tag{1}$$

The attenuations of the longitudinal-bar resonator and the object are ignored for simplification and it is assumed that $\gamma = j\beta = j\omega_0 / v_0 ,\ v_0 = \sqrt{E/\rho}$, and Zx=jX, where E and ρ are Young's modulus and the density of the resonator.

By setting Zin=0, the following equation is obtained.

$$\beta\ell = \tan^{-1}\left(-\frac{X}{Z_0} \right) \tag{2}$$

Then, the resonance frequency of the longitudinal-bar resonator in contact with an object is given by

$$f \cong \frac{v_0}{2\pi\ell}\left[n\pi + \tan^{-1}\left(-\frac{X}{Z_0} \right) \right] \tag{3}$$

In particular, assuming that $|X / Z_0| \ll 1$, the approximate value of frequency change is given by

$$\Delta f \cong -\frac{f_0}{n\pi}\cdot\frac{X}{Z_0} = -\frac{1}{2\pi\ell}\sqrt{\frac{E}{\rho}}\cdot\frac{X}{Z_0} \quad ,\ f_0 = \frac{n}{2\ell}\sqrt{\frac{E}{\rho}} \tag{4}$$

When the contact with an object acts as an additional mass effect such that X>0, the resonance frequency of the resonator decreases. On the other hand, when the contact acts as a stiffness effect such that X<0, the resonance frequency increases.

(1) In the case of assuming $X=\omega_0 m_e$, where m_e is an additional mass for a soft object, the sensitivity of the frequency change ratio is approximately expressed as

$$\frac{\Delta f}{f_0} \cong -\frac{m_e}{M} = -\frac{m_e}{2m_0} \tag{5}$$

Here, M and m_0(=M/2) are the tatal mass and equivalent mass of the longitudinal bar resonator, respectively.

(2) In the case of assuming $X=-s_L/\omega_0$, where s_L is an additional stiffness for a hard object, the

frequency change ratio is approximately expressed as

$$\frac{\Delta f}{f_0} \cong \frac{s_L}{2\omega_0^2 m_0} = \frac{s_L}{2s_0} \qquad (6)$$

Here, s_0 is the equivalent stiffness of the resonator.

3. Experimental investigation

3.1 Experimental results using the soft objects

Figure 3 shows the experimental results for the longitudinal bar type tactile sensor 10). When the load added to test pieces increased, the resonance frequencies of the resonator gradually decreased shown in eq.(5). 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 relationship between the frequency change ratio $|\Delta f/f_0|$ at load W=5gf and the mass M of the resonator. It is clear that $|\Delta f/f_0|$ is inversely proportional to the mass of the resonator. The relationship between $|\Delta f/f_0|$ and M is estimated to be $|\Delta f/f_0| \propto M^{-0.799}$ by curve fitting 10).

3.2 Experimental results using the hard objects

Figure 5 shows the experimental results using the hard objects. When the load added to test pieces increased, the resonance frequencies of the resonator gradually increase shown in eq.(6). The characteristics between the load W and Δf show the tendency that the amount of increase for the harder test piece SPCC(E=206GPa) is larger than the test pieces of C2801(E=103GPa) and A5052(E=71GPa). Figure 6 shows the relationship between the frequency change ratio $|\Delta f/f_0|$ at load W=30gf and the equivalent stiffness s_0 of the resonator. It is clear that $|\Delta f/f_0|$ is inversely proportional to the stiffness of the resonator. The relationship between $|\Delta f/f_0|$ and s_0 is estimated to be $|\Delta f/f_0| \propto s_0^{-1.37}$ by curve fitting.

4. Conclusion

The characteristics of resonance frequency change on tactile sensor for measuring the soft and hard objects were experimentally examined. The design guidelines for piezoelectric vibratory tactile sensors were experimentally clarified.

References

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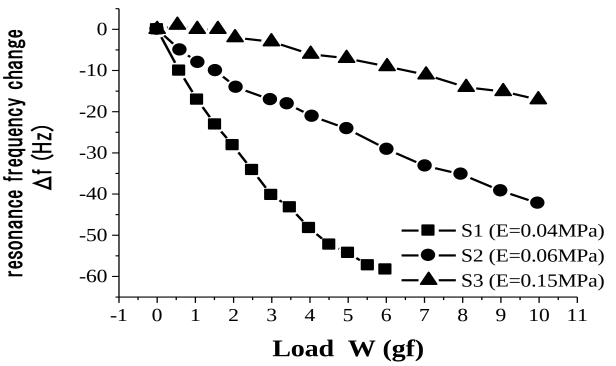

Fig.3. Experimental characteristics of longitudinal bar type tactile sensor I.(ℓ =50mm,f_0=51.55kHz)

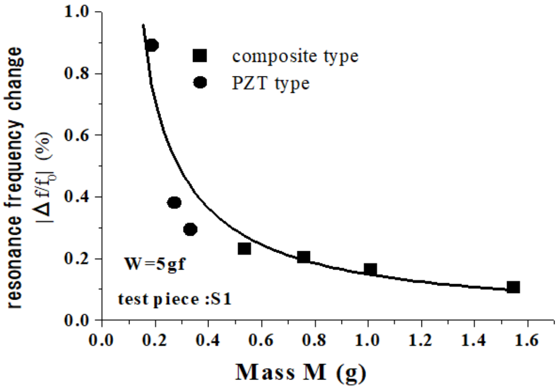

Fig.4. Experimental relationships between $|\Delta f/f_0|$ and mass M.

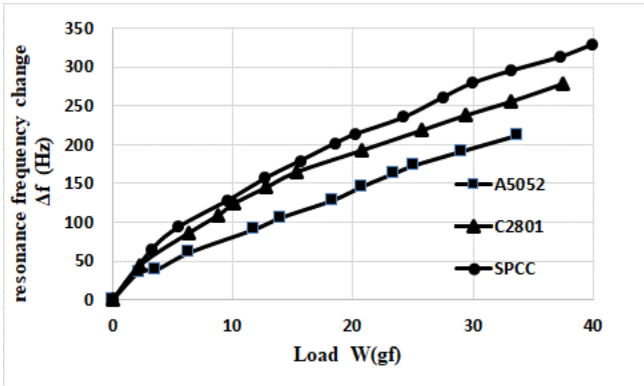

Fig.5. Experimental characteristics of longitudinal bar type tactile sensor II.(ℓ =17mm,f_0=158.8kHz)

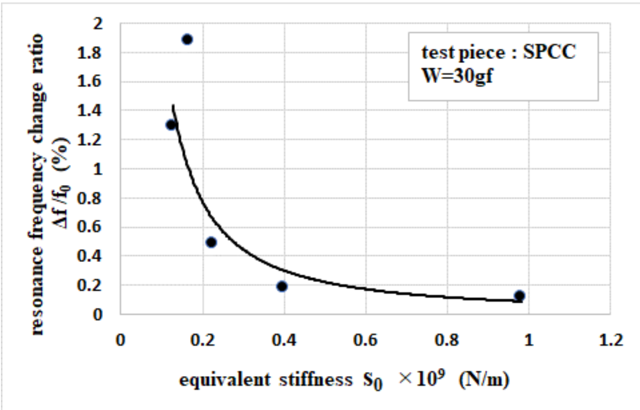

Fig.6. Experimental relationships between $|\Delta f/f_0|$ and equivalent stiffness s_0.