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consideration on design of the sensitivity in piezoelectric vibratory tactile sensor

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The piezoelectric vibratory tactile sensors have been used for measuring the softness and hardness of an object. They make use of changes in the resonance frequency when their vibrating sections are brought into contact with an object. In this study, the sensitivity of the frequency change on the tactile sensors is experimentally considered. The longitudinal-bar type and the fixed-free-bar type resonators are used as the tactile sensors. Then, the experimental characteristics of the manufactured tactile sensors are shown by measuring the softness and hardness of the test pieces. The differences of the characteristics on sensitivity are discussed from the viewpoint of the resonance frequency, vibration mode and the dimensions of resonators. It is clarified that the sensitivity on the tactile sensor is inversely proportional to the mass of a resonator. Moreover, the resonance frequency changes on the tactile sensor by the load force and the additional mass effect, in case of contacting with an object, are analysed using the finite element method. The results obtained will be useful for designing the piezoelectric vibratory tactile sensor.

1 Introduction

Various piezoelectric vibratory tactile sensors have been proposed for measuring the softness and hardness of an object [1-7]. These tactile sensors utilize the longitudinal-mode [1,2], flexural-mode [4] or edge-mode vibration [7] 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 [1,8], and has already been analysed using a Mason equivalent circuit [2] and a distributed constant-circuit of the resonator [9]. However, these results are yet insufficient to design the piezoelectric vibratory tactile sensor.

In this paper, the sensitivity of the tactile sensor in terms of the frequency change of the resonator is considered for designing the piezoelectric vibratory tactile sensor. The longitudinal-bar type resonator and the fixed-free-bar type resonator are adopted as tactile sensors. First, 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, different types of resonators with different vibration modes, which are fabricated of metal alloy and piezoelectric ceramics, are manufactured as tactile sensors. The characteristics of the tactile sensors are measured using standard rubber test pieces of different hardness. The experimental results of sensitivities for the tactile sensors are discussed from the viewpoints of the vibration mode and the mass of the resonator. Then, the resonance frequency change by the load force and the additional mass effect, in case of contacting with the object, are analysed using the finite element method.

2 Structure of tactile sensor and resonant frequency change

Figures 1(a) and 1(b) show the construction of tactile sensors with a longitudinal-bar resonator and a fixed-free-bar resonator, respectively. When the tactile sensors, which are driven in the longitudinal mode or in the flexural one, touch an object, the softness and hardness of the object are detected as changes in resonance frequencies.

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

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

, where m_e is an additional mass.

Then, the resonance frequency change is expressed by

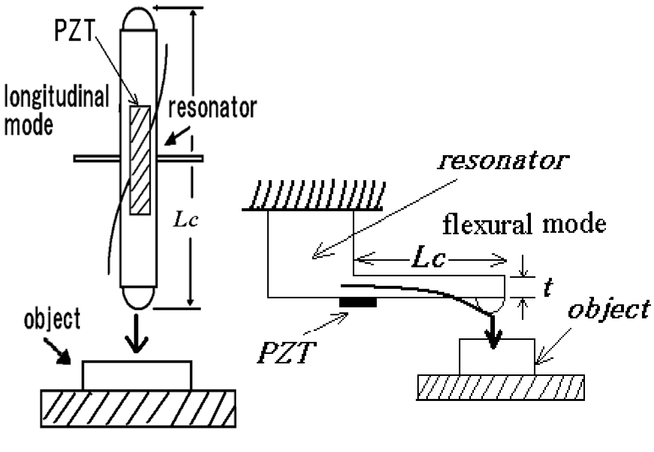
$$\frac{f}{f_0} = \left(1 + \frac{m_e}{m_0}\right)^{-\frac{1}{2}} \tag{3}$$

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

$$\frac{\Delta f}{f_0} \cong -\frac{m_e}{2m_0} \tag{4}$$

, where $\Delta f = f - f_0$.

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 mass is suitable for increasing the sensitivity.



(a) Longitudinal-bar type (b) Fixed-free-bar type

Fig.1 Construction of tactile sensors.

3 Experimental investigation

3.1 Structure of fabricated resonator for tactile sensor

To evaluate the approximate equation of resonance frequency change, two kinds of tactile sensors were fabricated. The dimensions of fabricated resonators are shown in Table 1. The tactile sensors are piezoelectrically driven on the longitudinal mode in Fig.1(a) and on the flexural mode in Fig.1(b). 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 and the bottom of the arms on the fixed-free 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 analyser. 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 (mm).

(a) longitudinal-bar type

	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

(b) fixed-free-bar type

Arm Length : Lc	Width : W	Thickness : t
11, 18, 25, 33	2.0	0.5, 1.0, 1.5, 2.0

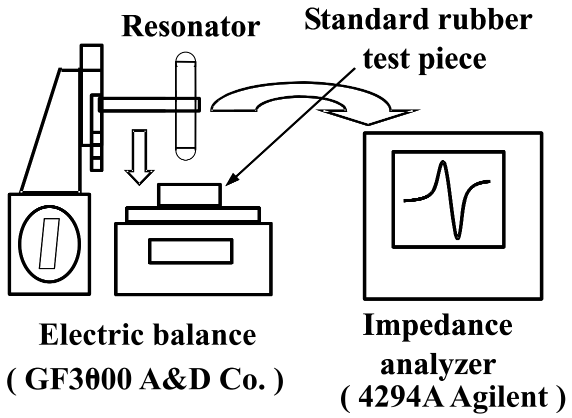


Fig.2 Experimental setup for measuring characteristics of tactile sensors.

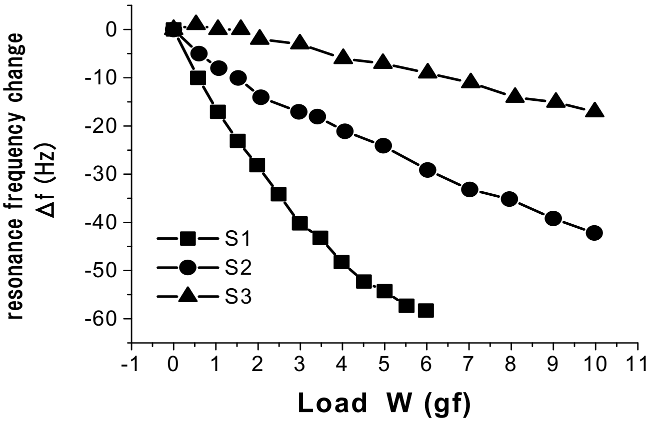
Table 2. Material constants of test pieces.

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

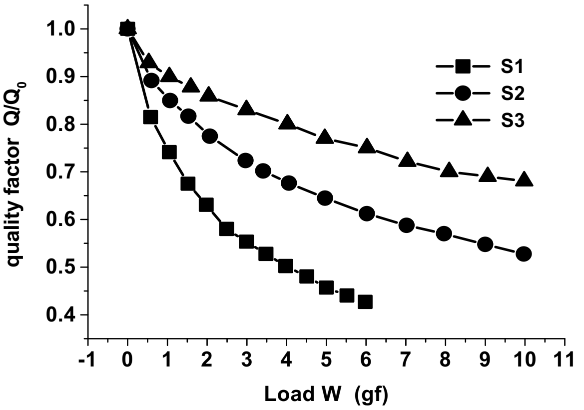
3.2 Experimental characteristics of longitudinal-bar type tactile sensor

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(a) and 3(b) show 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(a). 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 3(b) shows the relative quality factor of tactile sensor. The relative quality factor is expressed as Q/Q_0, where Q is the quality factor when a load is applied and Q_0 is the quality factor with no load. The quality factors of tactile sensor also decreased to the load force.

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 [9]. Figure 4 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.



(a) resonance frequency change



(b) quality factor change

Fig.3 Experimental characteristics of longitudinal-bar type tactile sensor. (Lc=50mm, f_0=51.55kHz, first mode)

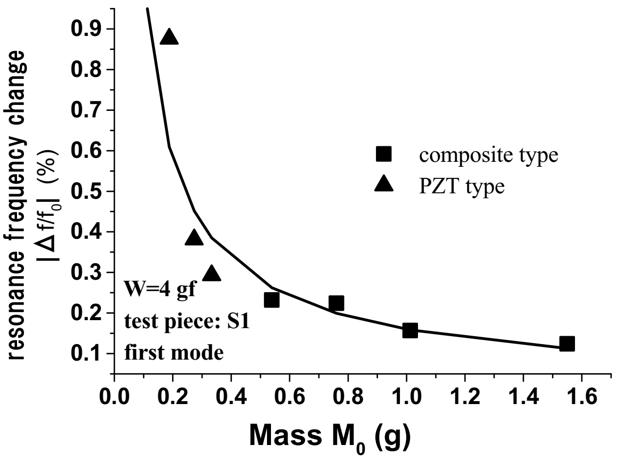


Fig.4 Relationship between sensitivity and mass of the longitudinal-bar type tactile sensor.

3.3 Experimental characteristics of fixed-free-bar type tactile sensor

Figures 5(a) and 5(b) show the experimental results for the tactile sensor with the fixed-free-bar resonator, where L_c=33mm, t=1.0mm and the resonance frequency of f_0=5.094kHz. The resonance frequency and quality factor decreased by the load force as the same way in Fig.3. Table 3 is a summary of the experimental results for the fixed-free-bar type tactile sensor of the same length in different flexural vibration modes. Frequency change Δf increases with higher vibration mode of the resonator. However, frequency change ratio $|\Delta f/f_0|$, which corresponds to the sensitivity of the tactile sensor, inversely decreases with higher vibration mode. These results are different from those of the longitudinal-bar type tactile sensors.

On the other hand, Fig.6 shows the experimental relationship between $|\Delta f/f_0|$ at load W=4gf and the mass M_0 of the resonator. It was clarified that the value of $|\Delta f/f_0|$ was also inversely proportional to the mass as in eq(4). It is estimated that $|\Delta f/f_0| \propto M_0^{-1.13}$.

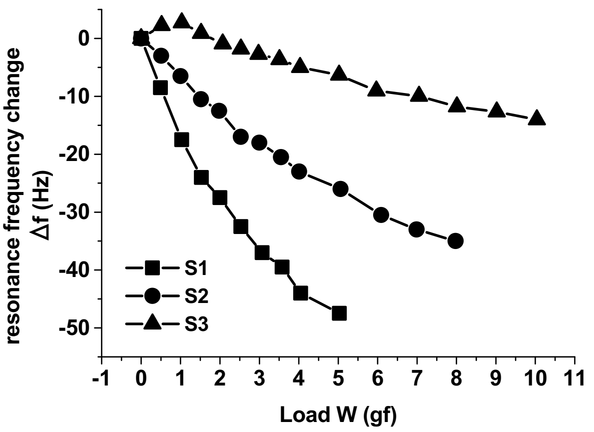
Table 3. Experimentally determined characteristics of tactile sensors using different vibration modes (Lc=18mm, t=1mm, test piece:S1, load W=4.0gf)

Vibration mode	Resonance frequency f_0 (kHz)	Frequency change Δf (Hz)	Frequency change ratio $|\Delta f / f_0|$ (%)
First	2.066	-16.2	0.78
Second	12.81	-40.7	0.32
Third	33.35	-48.1	0.14

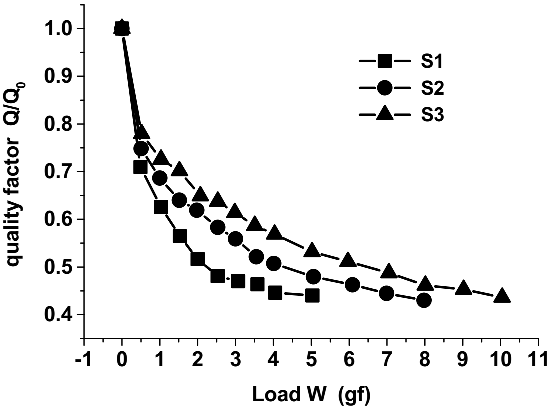
4 Results of finite element analysis

4.1 Resonance frequency change by the load force

To consider the resonance frequency change by the load force and the additional mass effect in contacting the object, the resonance frequencies of the resonator were calculated using the finite element method. Figures 7(a) and 7(b) show the calculated results of the resonance frequency change $\Delta f/f_0$ by the load force W as parameters of vibration mode and length of the longitudinal bar resonator. It is quantitatively clarified that the value of $|\Delta f/f_0|$ is far small, 0.1ppm or less, and there is a little influence by the load force. On the other hand, Fig. 8 shows the calculated results of $\Delta f/f_0$ with the fixed-free bar resonator. The value of $\Delta f/f_0$ decreases linearly to the load force W and the decreased values for the first vibration mode are larger than



(a) resonance frequency change



(b) quality factor change

Fig.5 Experimental characteristics of fixed-free-bar type tactile sensor.
(Lc=11mm, t=1mm, f_0=5.094kHz, first mode)

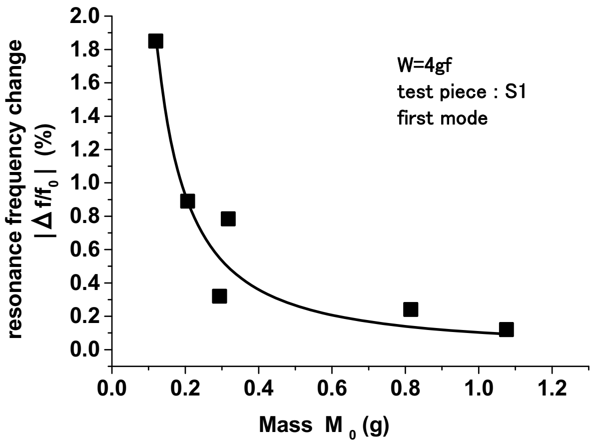
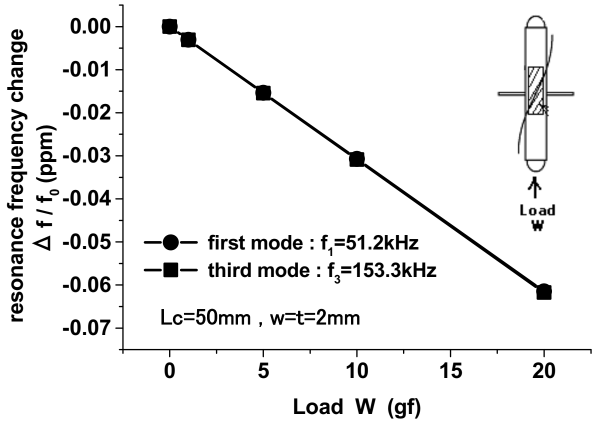
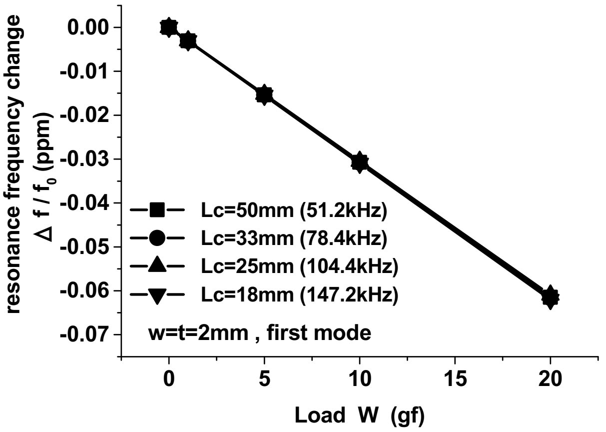


Fig.6 Relationship between sensitivity and mass of the fixed-free-bar type tactile sensor.

those for the second and third vibration modes. It is considered that the stress distribution by static load force W is similar to the dynamic stress distribution by the first mode vibration. Figure 9 shows the calculated results of $\Delta f/f_0$ as a parameter of arm length L_c . From these results and other calculations, it is clarified that the value of $|\Delta f/f_0|$ is large as L_c becomes larger and as thickness t becomes smaller. It is quantitatively clarified that the value of $|\Delta f/f_0|$ is 250ppm or less within the limit of the load force $W \leqq 20$gf .



(a) relationship between resonance frequency change and load force as a parameter of vibration mode.



(b) relationship between resonance frequency change and load as a parameter of resonator length.

Fig.7 Calculated results of resonance frequency change by load force using longitudinal-bar type tactile sensor.

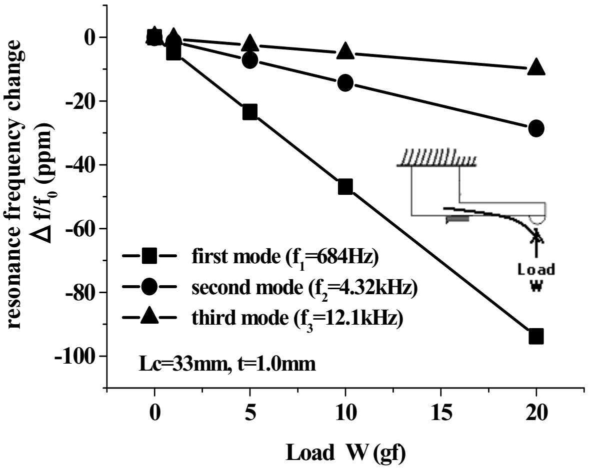


Fig.8 Calculated results of resonance frequency change by load force using fixed-free-bar resonator (I).

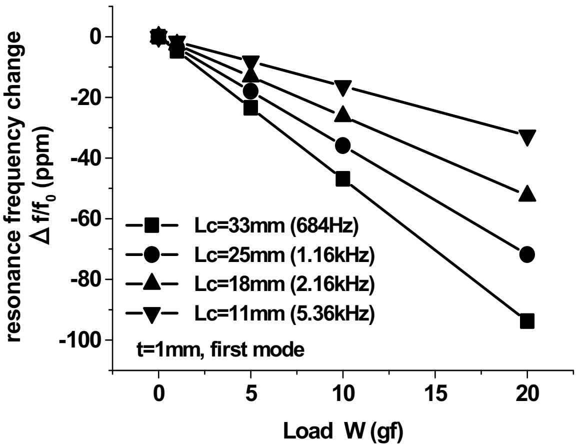


Fig.9 Calculated results of resonance frequency change by load force using fixed-free-bar resonator (II).

4.2 Resonance frequency change by the additional mass effect

The additional mass effect in contacting with an object was dealt by making the finite element model of resonator in which the minute mass was added to a resonator tip. Figure 10 shows the calculated results of the resonance frequency change $\Delta f/f_0$ by the additional mass Δm as parameters of vibration mode using the longitudinal-bar type resonator. The value of $\Delta f/f_0$ decreases gradually to the additional mass Δm. The decreased values for the third vibration mode are larger than the first vibration mode. Figure 11 shows the calculated results as a parameter of resonator length. The frequency change ratio $|\Delta f/f_0|$ of resonator with small length is larger than the other resonators. These results are corresponding to the meaning of eq.(4).

On the other hand, Fig.12 shows the calculated resonance frequency change using fixed-free-bar resonator. Frequency change ratio $|\Delta f/f_0|$ increases with lower vibration mode of the resonator. It is thought that the asymmetry of structure on fixed-free-bar resonator is larger than that of the longitudinal-bar resonator. Figure 13 shows the calculated results of resonance frequency change as a parameter of arm length. Frequency change ratio $|\Delta f/f_0|$ of resonator with small arm length is also lager than the other resonators.

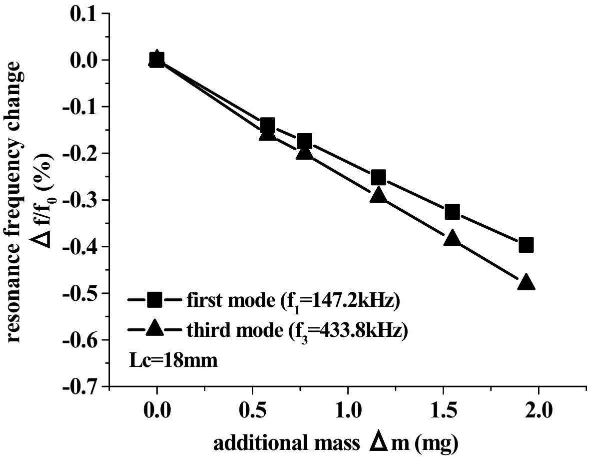


Fig.10 Calculated results of resonance frequency change by additional mass effect as a parameter of vibration mode using longitudinal-bar resonator.

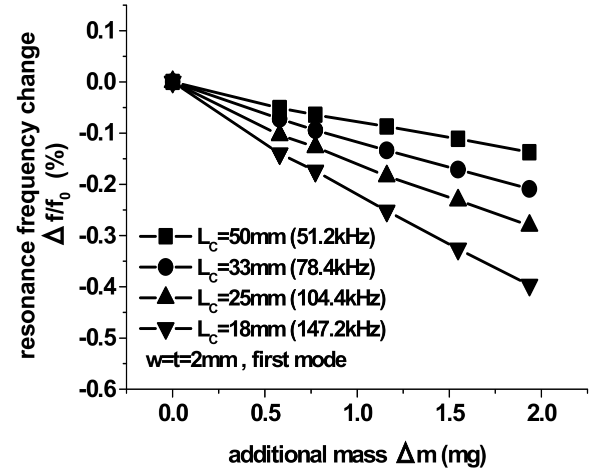


Fig.11 Calculated results of resonance frequency change by additional mass effect as a parameter of resonator length using longitudinal-bar resonator.

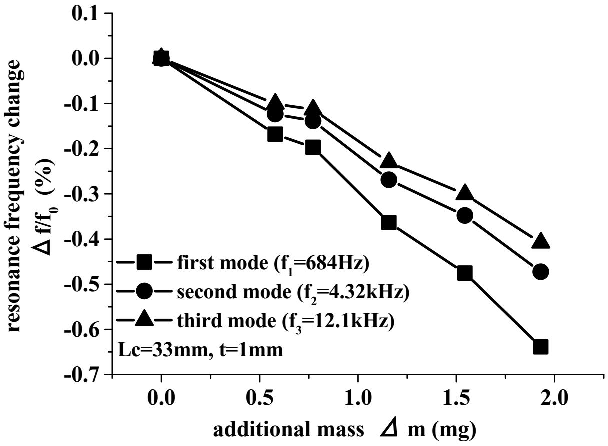


Fig.12 Calculated results of resonance frequency change by additional mass effect as a parameter of vibration mode using fixed-free-bar resonator.

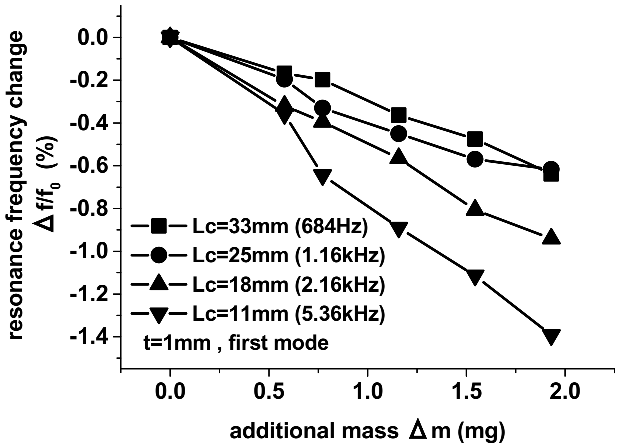


Fig.13 Calculated results of resonance frequency change by additional mass effect as a parameter of arm length using fixed-free-bar resonator.

5 Conclusion

The sensitivity of piezoelectric vibratory tactile sensor was studied in this paper. The results obtained are summarized as follows.

(1) The approximate equation of the frequency change of the tactile sensor in contacting with a softer object was shown.

(2) The characteristics of frequency change for several tactile sensors were measured using standard rubber test pieces of different hardness. It was experimentally clarified that the sensitivity of tactile sensor is inversely proportional to the mass of the resonator.

(3) The resonance frequency change by the load force and the additional mass effect were quantitatively analysed using the finite element method.

These results in this study may be useful for designing on the piezoelectric vibratory tactile sensor.

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