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Non-contact detection of external force using quartz crystal resonator

水晶振動子を用いた非接触検出型力センサ

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1. Introduction

For realizing a sustainable society, detecting a]bnormalities or deterioration of structures, such as bridges, tunnels and buildings, is strongly required. For this purpose, we propose a non-contact detectible force sensor based on nonlinear elastic modulus. This sensor would be useful not only for the civil engineering but also for the medical devices. For example, a bone extension device[1] becomes high-functional because the bone extension process can be operated with force feedback.

In this study, the non-contact detectable force sensor is proposed, which utilizes an AT-cut quartz crystal resonator with a pair of spiral coils (Fig. **1**). This structure is simple and easy for miniaturization. Quartz crystal is one of the most stable materials with high Q (quality factor) value. In addition, the deviation is narrow over wide temperature range. The resonant frequency is a function of the applied external force due to the nonlinear elastic modulus; then from the resonant frequency change of the quartz crystal, the applied force can be measured from force-frequency characteristics[2-3].

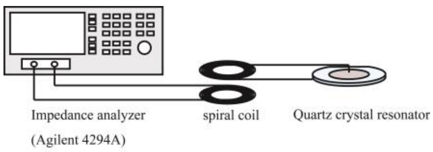

Fig. 1 Experimental setup

2. The principle of force sensor and non-contact detection

Thickness-shear mode was excited with a disk shaped quartz crystal using an energy trapping (Fig. **2**). The energy trapping enables to clamp the quartz crystal resonator without affecting the resonant vibration. Our proposal is to detect the resonant frequency change with an electromagnetic induction coupling for the non-contact detection. The relationship between the applied force F and resonant frequency change Δf is expressed as

$$F = \frac{nD}{K_f f^2 \eta} \Delta f \qquad (1)$$

where f is the resonant frequency, n is the order of overtone, K_f is the normalized coefficient, D is the diameter of the crystal plate and η is the effect of holders[4].

For the non-contact detection, the quartz crystal was connected to a spiral coil. The other coil was faced to this coil to detect the electrical properties of the quartz resonator. This non-contact detection method has advantage for miniaturization such as RFID (Radio Frequency IDentification). A pair of spiral coils was consisted of Litz wires to prevent the skin effect that results in high resistance.

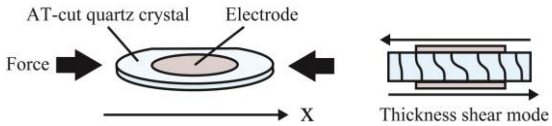

Fig. 2 Quartz crystal resonator using an energy trapping

3. Experimental

The dimensions of quartz crystal were φ8.7[mm] in diameter, 0.3 [mm] thickness and the gold electrode diameter was φ5.0[mm]. The resonant frequency of the fundamental thickness-shear mode was about 5[MHz]. The external force was applied to the quartz resonator in the x-axis direction because this direction has an excellent force sensitivity[4] to the resonant frequency shift. The quartz resonator was clamped from the 1.3[mm] apart from the edge of the x-axis direction as shown Fig. 3. The external force value was estimated from the spring length. The turns of spiral coils was 20, the inner diameter was 10[mm] and the outer diameter was 25[mm]. The pair of spiral coils was faced each other to match their center positions.

Figure 4 denotes an equivalent circuit of the sensor. The spiral coils were transformed to a T-type equivalent circuit based on electromagnetic induction coupling. The mutual inductance M is expressed as

$$M = k\sqrt{\mathrm{L}_1 \mathrm{L}_2} \qquad (2)$$

where k is coupling coefficient.

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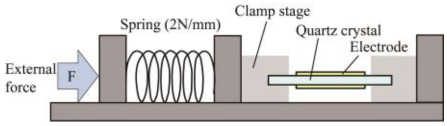

Fig. 3 Experimental for applying the external force

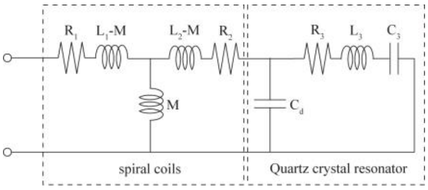

Fig. 4 Equivalent circuit

4. Results

With the clamping effect, the Q value was reduced to 67,600 from 182,000. However, this value was enough high to detect the resonant frequency change. Through the non-contact detection with spiral coils, the electrical property of the quartz resonator was detected with the coil gap, 0, 5 and 10[mm] as shown in Fig. 5. The series and the parallel resonant frequencies were appeared. These frequencies depend on the coil gap because this gap modifies the coupling coefficient.

Figure 6 shows the relationship between the applied force and the parallel resonant frequency with the coil gap, 0, 5 and 10[mm]. The parallel resonant frequency was decreased by applying compressive force. This relationship was linearly property, and the sensitivity was -17[Hz/N] with all gaps. Figure 7 denotes the relationship between the coil gap and the resonant frequencies without the applied force. From these results, we found that the coil gap also affects the resonant frequency shift same to the external force. In order to eliminate the coil gap effect to the resonant frequency shift, we calculated the frequency difference between the series and the parallel resonant frequencies. As shown in Fig. 8, difference between the series and the parallel resonant frequencies indicates the coil gap regardless to the applied force 0, 10 and 20[N].

Figure 9 denotes the applied force could be detected even if coil gap, 0, 5 or 10[mm]. By calculating the difference between the series and parallel resonant frequencies, the force sensing error was 5.3[%] with the coil gap of 10[mm]

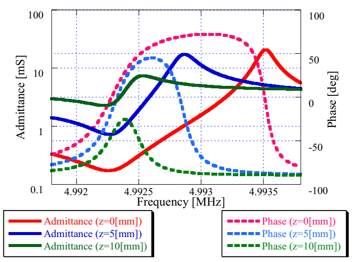

Fig. 5 Admittance characteristics

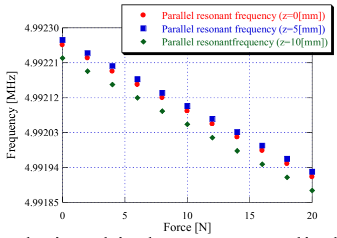

Fig. 6 Relationship between applied force and parallel resonant frequency

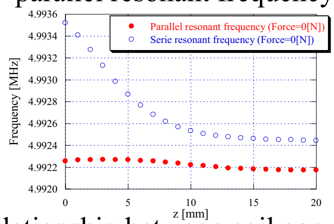

Fig. 7 Relationship between coil gap and resonant frequencies

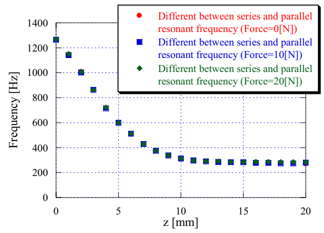

Fig. 8 Difference between series and parallel resonant frequencies

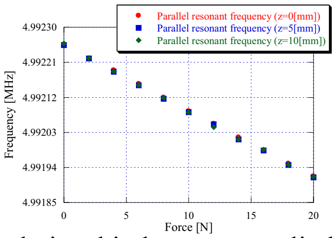

Fig. 9 Relationship between applied force and compensated parallel resonant frequency

5 Conclusion

We proposed a non-contact detection of the external force using a quartz crystal resonator. The external force was detected with the sensitivity -17[Hz/N]. In addition, the spiral coil gap effect could be compensated by calculating the difference of the series and the parallel resonant frequencies.

References

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