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Equivalent Circuit Consideration of Frequency-Shift-Type Acceleration Sensor
周波数変化型加速度センサの等価回路考察

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1. Introduction

Recently, a highly sensitive acceleration sensor suitable for MEMS structure is required for attitude control of moving objects such as vehicles and robots. [1] As such a sensor, a frequency-shift-type acceleration sensor utilizing the resonance frequency of the bending vibrator by the axial force has been proposed.[1, 2] Although multi-axialization and combination with an angular velocity sensor are studied[3], an electrical equivalent circuit for estimating various characteristics of the frequency-shift-type sensor has not been derived.

Therefore, the equivalent circuit representation for the piezoelectrically driven sensor model is investigated here. The equation for estimating the resonance frequency of the vibrator approximately is derived. Moreover, acceleration dependence of the equivalent circuit constants is analyzed by the finite element method, and compared with the measured one.

2. Structure and Mode of Vibration

Fig. 1 shows the basic structure of the acceleration sensor with a bending vibrator. The sensor is made of stainless steel (SUS304) , and its vibrator is piezoelectrically driven. The frequency of the vibrator is shifted by the axial force due to the acceleration α applied to the mass from the x axis direction. Therefore, the acceleration can be estimated from the frequency shift. **Fig. 2** shows the out-of-plane vibration modes of the vibraor.

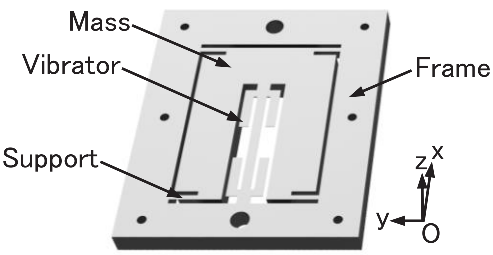
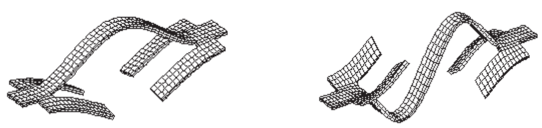


Fig. 1 Structure of acceleration sensor.



(a) 1st mode (b) 2nd mode

Fig. 2 Vibration modes of bending vibrator.

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3. Equivalent Circuit Consideration

3.1 Approximate estimation of resonance frequency

In the case of a usual bending vibrator with a uniform rectangular cross-section, the n-th mode resonance frequency f_n considering the influence of the axial force is given by the following equation.[4]

$$f_n = \frac{\alpha_n^2}{2\pi \ell_{en}^2}\sqrt{\frac{EI}{\rho A}} \tag{1}$$

Where E, ρ, A and I are Young's modulus, the density, the cross-sectional area and the moment of inertia of area, also ℓ_{en} and α_n are the length of the vibrator and the frequency constant of n-th mode, respectively. The constant α_n is given as a function of the axial force F. The constants, α_{01} and α_{02} of the 1st and 2nd mode become well-known values of 4.7300 and 7.8532, respectively when F=0. The characteristics of f_n-ℓ_{en}/ℓ_n are calculated by eq. (1) as shown in **Fig. 3**, where ℓ_n is the total length of the bending vibrator of the sensor. The resonance frequencies f_{01} and f_{02} of the vibrator are also shown in the figure. The thickness of the vibrator is 0.2mm. From the figure, the value of ℓ_{en}/ℓ_n for the 1st or 2nd mode is determined as 0.79 or 0.77, respectively. Accordingly, the effective lengths ℓ_{en} for realizing the frequencies f_{01} and f_{02} are

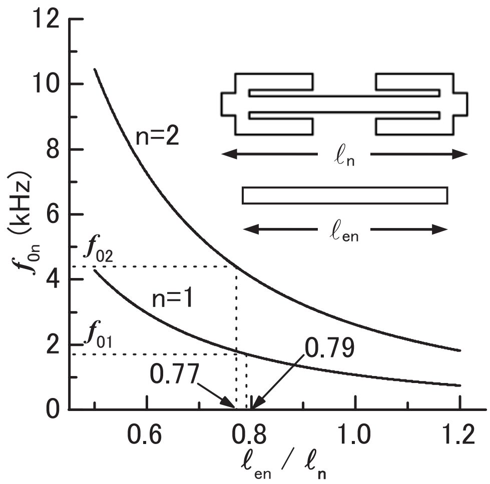

Fig. 3 Characteristics of f_{0n} - ℓ_{en}/ℓ_n.

estimated, the frequency shift by the axial force can be easily analyzed by using eq. (1).

3.2 Electrical equivalent circuit

Fig. 4 shows the electrical equivalent circuit of the bending vibrator. The values of the circuit constants analyzed by the finite element method and the measured values are listed in **Table I**. From the table, it became clear that the analyzed values agree with the measured ones.

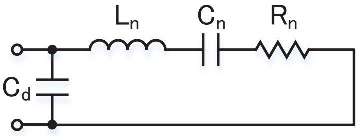

Fig. 4 Equivalent circuit of vibrator.

Table I Resonance frequency and equivalent circuit constants of sensor

	1st mode (n=1)		2nd mode (n=2)	
	Measured	Analyzed	Measured	Analyzed
f_0 (Hz)	1685.7	1695.7	4562.5	4559.0
C_d (pF)	494.7	492.0	747.8	766.0
C_n (pF)	1.262	1.254	1.684	1.689
L_n (H)	7082.8	7026.8	720.48	721.50

3.3 Acceleration dependence of circuit constants

Fig. 5 shows the relationship between the acceleration α changed within the range of ±1G and the resonance frequency shift ratio of $\Delta f_x/f_0$ analyzed by the finite element method. The measured values are also shown in the figure. The analyzed values are almost the same as the measured ones.[4] Moreover, relationship between α and C_n, and relationship between α and L_n are shown in **Figs. 6** and **7** respectively. The changes in the values of C_n and L_n were very small. It was confirmed that the analyzed values agree with the measured ones.

4. Conclusions

The resonance frequency, the equivalent circuit constants and their acceleration dependence of the piezoelectrically driven frequency-shift-type acceleration sensor were analyzed by the finite element method. As a result, it was confirmed that the analyzed values agree with the measured ones. As a future work, a simplified approach to estimate the resonance frequency and the equivalent circuit constants taking the influence of the axial force into consideration should be investigated.

Acknowledgment

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References

1) J. Takahashi, S. Sugawara and J. Terada: Jpn. J. Appl. Phys. **42** (2003) 3124.
2) J. Takahashi and S. Sugawara: Jpn. J. Appl. Phys. **43** (2004) 3035.
3) S. Sugawara, H. Suzuki and T. Saito: Jpn. J. Appl. Phys. **46** (2007) 4652.
4) S. Sugawara, K. Masuda and Y. Tomikawa: Jpn. J. Appl. Phys. **40** (2001) 3683.

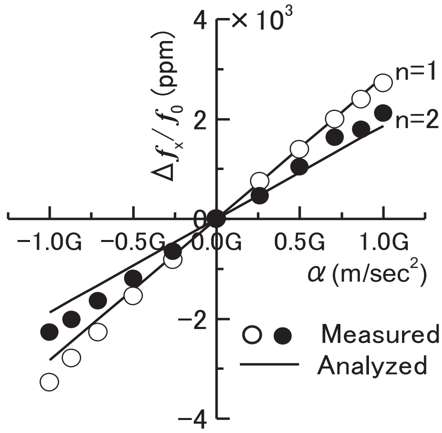

Fig. 5 Characteristics of $\Delta f_x/f_0$ - α.

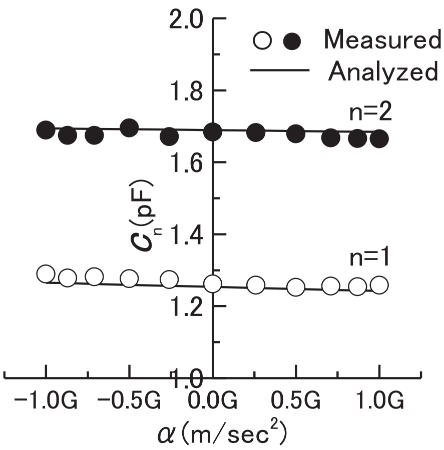

Fig. 6 Characteristics of C_n - α.

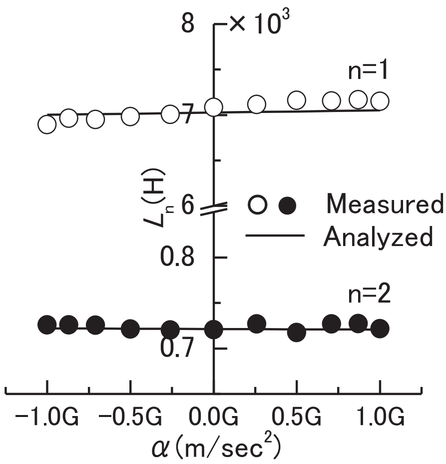

Fig. 7 Characteristics of L_n - α.