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Analysis of Characteristics of Coupled Bending Vibrators Used as a Force Sensor
力センサ用結合型横振動子の特性解析

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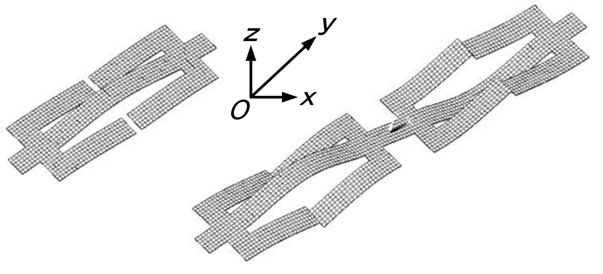
1. Introduction

Recently, a small low-cost acceleration sensor with high sensitivity has been required for application to the attitude control and navigation systems of moving objects, such as vehicles. To develop such a sensor, the authors have studied an acceleration sensor that utilizes the phenomenon that the resonance frequency of a bending vibrator changes by the axial force.[1-11] As one example of these sensors the sensor using a coupled bending vibrator was also proposed.[12] However, the characteristics of this vibrator were not clarified sufficiently.

The characteristics of the coupled bending vibrator are analyzed here by the finite-element method, and then the characteristics as a force sensor are studied. The characteristics are confirmed experimentally.

2. Structure of Vibrator

Fig. 1(a) shows the vibration mode of the bending vibrator.[2] Displacements at both ends of the vibrator are designed so as to become very small. **Fig. 1(b)** shows the coupled bending vibrator which combines the two vibrators mechanically.



(a) Bending vibrator (b) Coupled vibrator

Fig. 1 Vibration modes of vibrator.

The coupled vibrator is used as a force sensor of the acceleration sensor shown in **Fig. 2**. The vibrator is fixed to the frame at both ends, and the center portion of the vibrator is connected to the mass at both sides with short bars. The mass is fixed to the frame with four support bars. This sensor structure detects the acceleration along the x-axis.

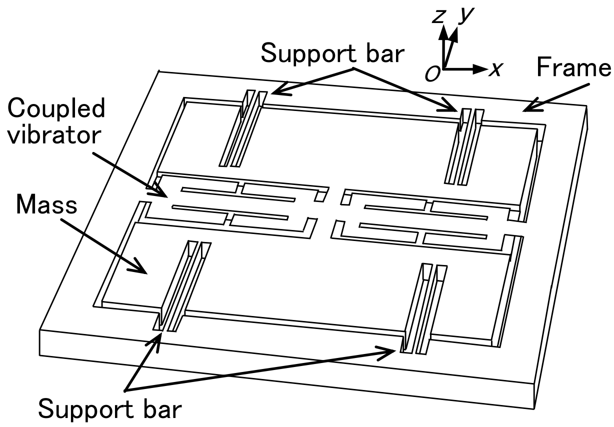


Fig. 2 Example of acceleration sensor.

3. Analysis of Coupled Bending Vibrator

The coupled vibrator is made from stainless steel (SUS304). Young's modulus and the density are E=1.99×10^{11} N/m^2 and ρ=7.9×10^3 kg/m^3, respectively. The dimensions of the vibrator are given as **Fig. 3**. As software for the finite-element analysis, Ansys 12.0 of Cybernet System was used.

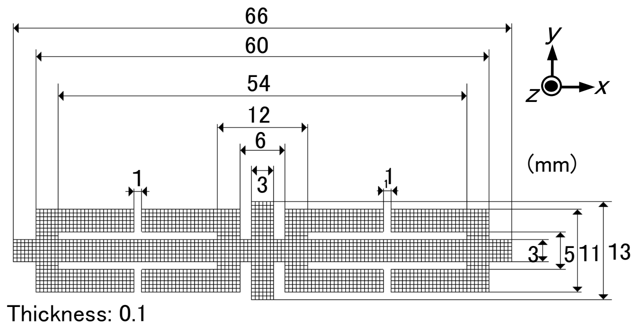


Fig. 3 Dimensions of coupled vibrator.

Fig. 4 shows the calculated resonance frequencies when both ends of the vibrator are fixed and the length of short bar at the center portion is changed. As shown in the figure, the mode of vibration in **Fig. 1(b)** dose not couple with other modes and is very stable. The length of short bar is

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5 mm in the construction of acceleration sensor. **Fig. 5** shows the modes of vibration at the resonance frequencies when the length of short bar is 6.52 mm.

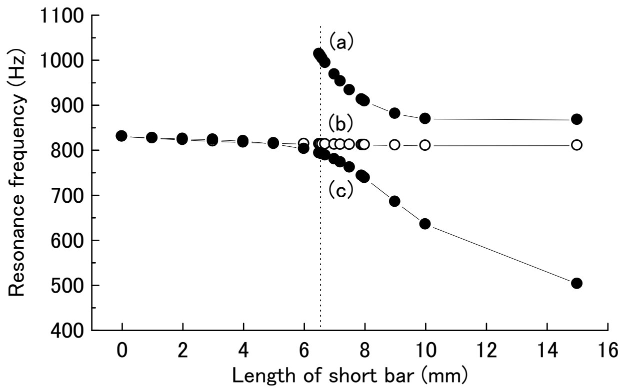
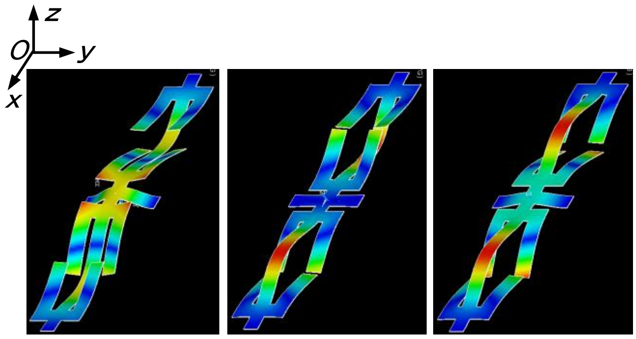


Fig. 4 Calculated characteristics of resonance frequencies－length of short bar.



(a) (b) (c)

Fig. 5 Modes of coupled vibrator with short bars.

The axial force F is applied at both ends of the short bars along the x-axis when both ends of the coupled vibrator are fixed. Changes of the vibration mode are shown in **Table I**. The amplitude of the right bending vibrator which constructs the coupled vibrator decreases by the increase of a compressive force.

Table I. Change of vibration mode by axial force.

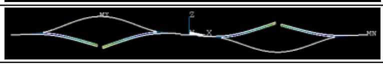
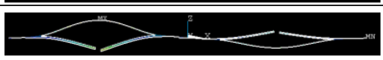
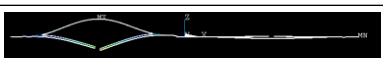
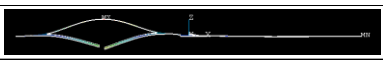
F(N)	Vibration mode	f (Hz)
0		815.269
10^{-3}		815.268
10^{-2}		815.384
10^{-1}		818.593
1.0		851.516

Fig. 6 shows the calculated output voltages when the driving frequency is changed. Four small piezoelectric ceramics ($2\times8\times0.1$ mm^3) are bonded on the long arms of the coupled vibrator. The maximum voltages, V_{pick1} and V_{pick2}, were calculated as 0.91 and 1.37V at the resonance frequencies and the values of 1.12 and 1.39V were obtained experimentally.

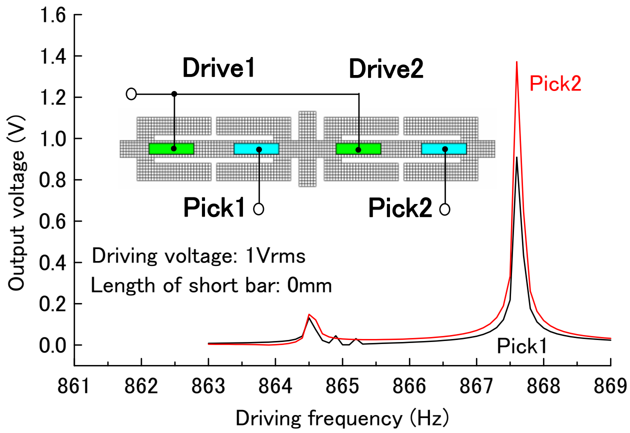


Fig. 6 Calculated characteristics of output voltage －driving frequency.

5. Conclusions

The characteristics of the coupled bending vibrator are analyzed by the finite-element method, and then the characteristics as a force sensor are also studied. The obtained results are summarized as follows.

(1) The coupled vibrator which combines two bending vibrators mechanically does not couple with other modes and is very stable.

(2) The amplitude of one bending vibrator which constructs the coupled vibrator decreases by the increase of a compressive force.

(3) The output voltages are calculated and confirmed experimentally.

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