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Vibratory Gyroscope Using Coaxial Resonator
同軸音叉型振動子を用いるジャイロセンサ

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1. Introduction

Vibratory gyroscopes are used in electronic devices because of their cost-effectiveness and compactness. Recently, the use of vibratory gyroscopes spreads in wide fields such as robot motion control and portable navigation systems. To use in these new fields, gyroscopes are required to sensing more complicated motion, especially wide-range sensing. Though resonators used in gyroscopes were studied and many shapes were proposed[1,2], these vibratory gyroscopes use a single pair of degenerate modes for driving and detecting modes. For sensing low speed rotation, high *Q* value is required for resonators, however the resonators with high *Q* cannot respond to high speed rotation.[3] Therefore, using a single pair of degenerate modes has difficulty with wide-range sensing. To attain wide-range sensing, we propose the gyroscope using two pair of degenerate modes, by applying a coaxial resonator with several pairs of degeranate modes[4]. In this paper, we examined the characteristics of this new-type gyroscope.

2. Structure of Resonator

Figure 1 (a) shows the structure of a coaxial resonator, which is composed of a cylinder and a column made of free-cutting brass. The image of vibration modes we applied for the gyroscope is shown in Fig. 1(b), calculated by FEM eigenvalue analysis. Resonance frequencies and *Q* values of each mode are shown in **Table I,** derived experimentally from the frequency spectrum. In Fig. 1(b), Mode 1 and Mode 2 are caused by the columnar and the cylindrical structure, respectively. Both of them have a degenerate mode (Mode 1', Mode 2'), as shown in **Fig. 2**. The direction of arrows shows movement of material particles in each point. When a sinusoidal driving velocity, $\boldsymbol{v}_x$, is applied at resonance frequencies to P_1 and P_2 in x-direction respectively, driving modes are generated. In that case, P_1' and P_2' are nodes of driving modes, therefore detecting modes are not observed. When the angular velocity, $\boldsymbol{\Omega}$, around z-direction is applied to the resonator, the Coriolis force, $\boldsymbol{F}_c$, appeared in the direction perpendicular to the motion of the resonator. $\boldsymbol{F}_c$ is given by

$$\boldsymbol{F}_c = -2m_e\boldsymbol{\Omega} \times \boldsymbol{v}_x , \quad (1)$$

where m_e is a mass of equivalent movement, and a cross '×' means the cross–product operation. When Mode 1 is generated, Mode 1' vibrating in y direction are caused by $\boldsymbol{F}_c$. In Mode 2', material particles move in perpendicular direction to Mode 2. Therefore, Mode 2 and Mode 2' are orthogonal modes and Mode 2' is caused by $\boldsymbol{F}_c$. Measurement of $\boldsymbol{F}_c$ from detecting modes' amplitude provide estimates of the angular velocity $\boldsymbol{\Omega}$.

3. Characteristics of Gyroscope

To evaluate the resonator as a gyroscope, we used a giant magnetostrictive material (GMM) based actuator for exciting driving modes and

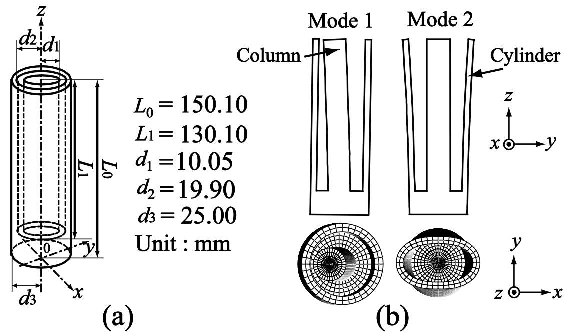
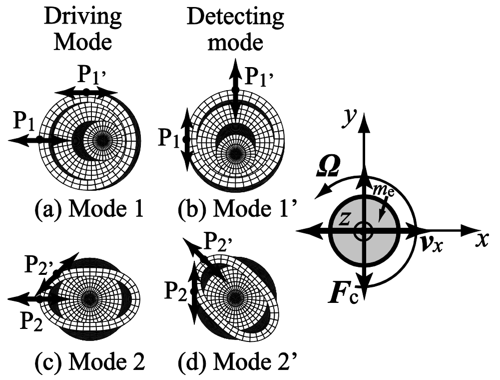


Fig. 1 Structure of the coaxial resonator.

Table I Resonance frequency and *Q* value.

Mode	Frequency (Hz)	*Q* value
Mode 1	600	19,890
Mode 1'	601	18,370
Mode 2	4,367	3,270
Mode 2'	4,369	3,260



(a) Mode 1 (b) Mode 1'
(c) Mode 2 (d) Mode 2'

Fig. 2 Driving – Detecting modes.

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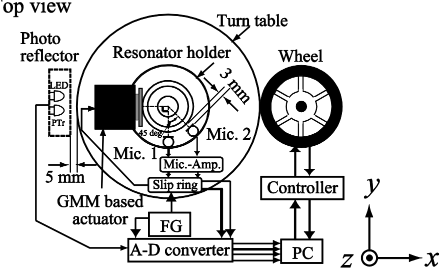
microphones for measurement of detecting modes' vibration. **Figure 3** shows the experimental set up. The function generator applied sinusoidal voltage to the actuator. The frequencies of applied voltage were 601 and 4,371 Hz for Mode 1 and Mode 2, respectively. The differences between their resonance frequencies and applied ones may be caused by mass loading effects of the actuator. Mic. 1 was used for detecting Mode 1', and Mic. 2 for Mode 2'. The rotation of the motor was reversible and its speed was variable by proportional control. In one trial, we changed the motor speed in 25 steps. In each step of the rotation speed, the sound pressure signals were measured five times. The experiments of 10 trials were carried out. A stripe pattern was wound around the turn table for measurement of the gyroscopes rotation by the photo reflector.

Figure 4 shows the relationship between averaged voltage gains of real and imaginary part of each mode and the rotation speed. The voltage gain is defined as the ratio of the output voltage to the input voltage applied by the function generator. The measured values are all biased with the leaking signal which is a constant voltage observed in no rotation. Thus we subtracted this bias from the voltage gain. Figure 4 shows that there are differences of the linear regions and sensitivities between Mode 1' and Mode 2'. The linear region of Mode 1' is ±200 deg/s. That of Mode 2' is expected more than ±600 deg/s. **Table II** shows slopes of each mode as sensitivities in the linear regions, obtained by linearization. The sensitivity of Mode 1' is higher than that of Mode 2'. It is considered that this result caused by the difference of *Q* values. Mode 1' has higher *Q* value than Mode 2', therefore Mode 1' has the higher sensitivity and narrower linear region than Mode 2'.

(a)
Top view



(b)
Side view

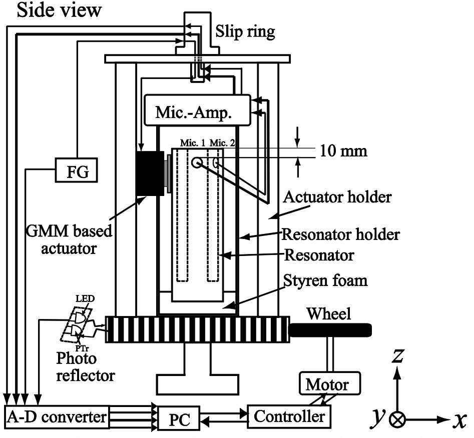


Fig. 3 Schematic view of experimental setup.

4. Conclusions

We propose a vibratory gyroscope using a coaxial resonator, which utilizes two pairs of degenerate modes. From the experimental results, we found that two detecting modes had different characteristics because of their *Q* values. It can be seen that using several pairs of driving-detecting modes enables gyroscopes to sense in wide range. As future works, investigation using two vibration modes simultaneously is planned.

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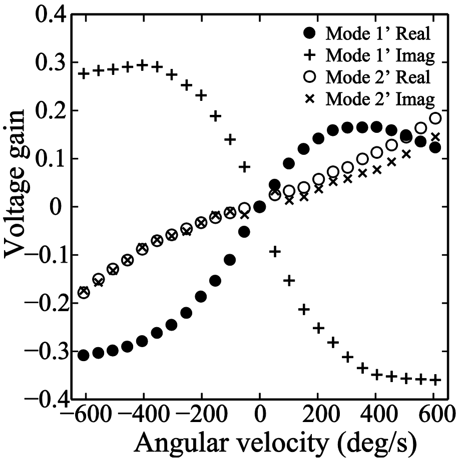

Fig. 4 Experimental result.

Table II Sensitivity and linear region.

Mode	Sensitivity(s/deg)	Linear region(deg/s)
Mode 1' (Real)	8.6×10^{-4}	±200
Mode 1' (Imag)	-1.3×10^{-3}	±200
Mode 2' (Real)	2.7×10^{-4}	±600
Mode 2' (Imag)	2.3×10^{-4}	±600