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각속도계 적용을 위한 이중 질량 시스템의 주파수 응답에 관한 연구

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A study on frequency response of two-mass system for gyroscope applications

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Abstract - This paper describes frequency response of two-mass system for gyroscope applications. The two-mass system of the proposed device is adapted to the sensing part of the gyroscope in this research. Two-mass system has two resonant peaks and wide flat region between two resonant peaks. The resonant frequency of driving part is in this flat region. Therefore, frequency tuning is not necessary for mode matching.

In the proposed device, resonant frequency is designed as 7183 Hz in driving part. Mass ratio of two masses in sensing part is 0.1 and device size is 6 mm × 6 mm. The device is fabricated by SiOG process. The fabricated spring width is increased from 4 μm to 4.5~4.7 μm, and the measured resonant frequency is 8392 Hz in driving mode. We operated the sensing part using parallel plate of proof mass to verify the sensing part. It is confirmed the device has a wide flat region in frequency response curve and the resonant frequency of the driving part is in the wide flat region of sensing mode.

1. Introduction

Gyroscopes are used in automotive, aviation and military application with the inertial measurement devices. Gyroscopes and accelerometers are cheaply produced due to the development of MEMS process [1-3]. Recently, the single crystalline silicon gyroscope have been researched for high sensitivity, high resolution and simple process (Silicon on Glass process) [4]. Conventionally, the single mass is used as a proof mass in vibratory MEMS gyroscope and it is necessary for frequency tuning between driving and sensing part in order to achieve high sensitivity [5]. Since it is difficult to reduce the fabrication error and environmental effect, the unwanted change of characteristics of fabricated single mass gyroscope can only be overcome by the closed loop circuit with a complex algorithms.

Cenk Acar proposed four DOF (Degree of freedom) micro-machined gyroscopes for reduction of the fabrication error and environmental effect using surface micro-machining process [6]. This group is applies this system to the sensing mode of MEMS vibratory gyroscope operated at atmospheric pressure [7]. However, the resonant frequency, 1000Hz, is very low. Therefore, this gyroscope is not available to the practical application.

This paper presents the theory and the experimental results of the two-mass system with a practically applicable resonant frequency for gyroscope applications

2. Theory

Figure 1 is the mechanical modeling of two-mass system. The absorber system is an application of two-mass system, and the proposed gyroscope is also an application of two-mass system. There is a different purpose between the absorber system and the gyroscope. The purpose of absorber system is reduction of the vibration of m_1. In contrast, the purpose of two-mass system gyroscope is to obtain the wide bandwidth using m_2.

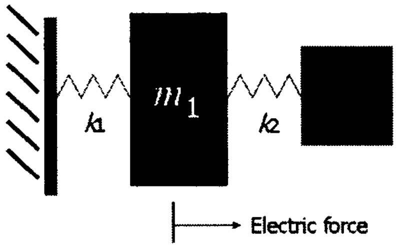


Fig. 1 Mechanical modeling of two-mass system

The basic motion equation of two-mass system is given by

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix}+\begin{bmatrix} c_1+c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix}\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix}+\begin{bmatrix} k_1+k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}=\begin{bmatrix} F_0\cos\omega t \\ 0 \end{bmatrix} \qquad (1)$$

$F=\mathrm{Re}(F_0 e^{j\omega t})$, where F_0 is real. $x=x(t)$ is displacement. The sinusoidal steady state variables are

$$x_1(t)=\mathrm{Re}(\hat{X}_1 e^{j\omega t})$$
$$x_2(t)=\mathrm{Re}(\hat{X}_2 e^{j\omega t}) \qquad (2)$$

, where $\hat{X}_1$ and $\hat{X}_2$ are complex number. From equation (1) and (2), the displacement of m_1 and m_2 can be written

$$\hat{X}_1=\frac{(k_2-m_2\omega^2+j\omega c_2)F_0}{(k_1+k_2-m_1\omega^2+j\omega c_1)(k_2-m_2\omega^2+j\omega c_2)-(k_2^2+j\omega k_2 c_2)} \qquad (3)$$

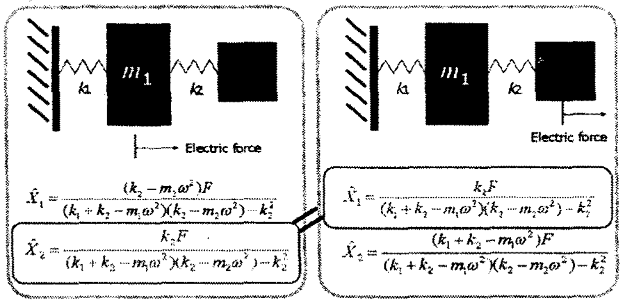
$$\hat{X}_2=\frac{k_2 F_0}{(k_1+k_2-m_1\omega^2+j\omega c_1)(k_2-m_2\omega^2+j\omega c_2)-(k_2^2+j\omega k_2 c_2)} \qquad (4)$$

When the displacement of m_1 is zero, all energy is transported to m_2. When the damping is neglected, the resonant frequency of m_1 and m_2 have to satisfy the following condition. The condition is

$$\omega^2=\frac{k_2}{m_2}=\omega_2^2 \qquad (5)$$

Therefore, when the resonant frequency of m_1 and m_2 are equal, this two-mass system is optimized.

In the conventional two-mass system, m_1 is operated by electrode of m_1, and m_2 is moving by transferred force of m_1. Since the electrode can not be implemented to the m_1 for applying this device to the gyroscope, it is difficult to obtain the frequency response of two-mass system in sensing mode. We studied out the method to obtain the frequency response of two-mass system for gyroscope applications. The method is explained in figure 2. When we assumed that damping is zero, we found out that m_2 excited by m_1 and m_1 excited by m_2 have the same displacement. Using this method, we can obtain the frequency response of this two-mass system.



(a) conventional two-mass system **(b) two-mass system for gyroscope application**

Fig. 2 How to obtain the frequency response of sensing part

3. Design

The proposed two-mass system is composed of driving mass, frame mass and proof mass. The driving part is operated by comb type electrode and sensing part is operated by parallel plate electrode. Figure 3 is schematics of proposed device. Device size is 6 mm × 6 mm and mass ratio (m_2/m_1) is 0.1. The resonant frequency of the frame and proof mass is 7010 Hz and the driving frequency is 7183 Hz.

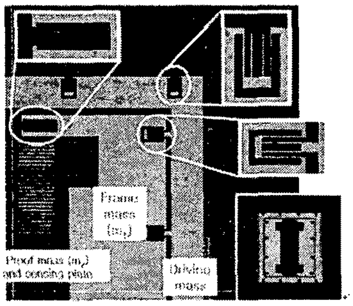
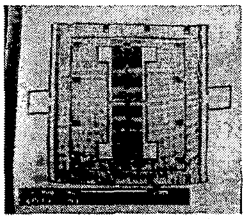


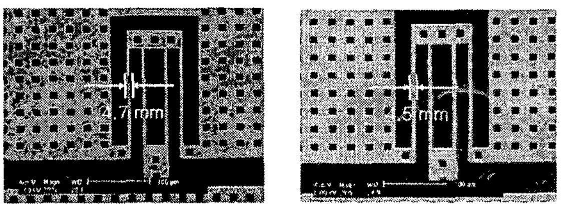
Fig. 3 Schematics of two-mass system gyroscope

4. Fabrication results

This gyroscope is fabricated by SiOG process. The thickness of the device layer(silicon) is 50 μm. Figure 4 shows the SEM images of the fabricated device. The fabricated spring width is increased from 4 μm to 4.5~4.7 μm and the etch hole size is decreased from 12 × 12 μm^2 to 11.5 × 11.5 μm^2.



(a) fabricated device on the PCB



(b) Top side of spring **(c) Bottom side of spring**

Fig. 4 Fabricated results

5. Measurement results

Figure 5 is the frequency response of driving and sensing part. The resonant frequency of the driving part was increased from 7183 Hz to 8392 Hz, since the width of spring is changed by fabrication error. There was a wide flat region in the sensing part which is used as a bandwidth. The measured bandwidth was 2000 Hz.

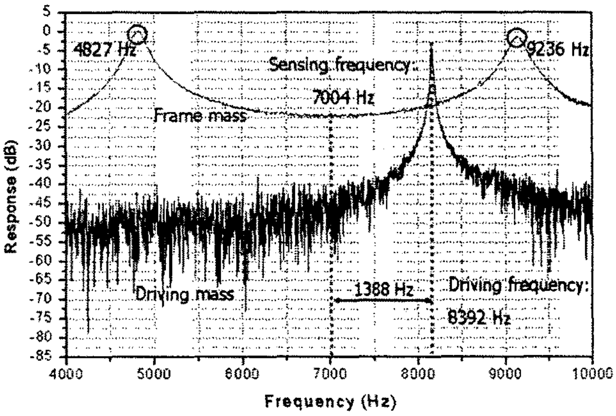


Fig. 5 Measured frequency response in the driving mass and sensing part (frame mass) using DMS

In this result, we confirmed that the resonant frequency of driving mode was measured in the bandwidth of sensing part, in spite of frequency difference, 1338 Hz, resulted from fabrication error.

6. Conclusion

This paper proposed the two-mass system for gyroscope application. This two-mass system with a wide flat region was designed in order to reduce the degradation of the performance by variation of resonant frequency. The fabricated spring width is increased from 4 μm to 4.5~4.7 μm and measured resonant frequency is increased from 7010 Hz to 8392 Hz in the driving mode since the width of spring is changed by fabrication error. We inspected the m_1 to verity the frequency response of sensing part. In the result, we confirmed that the resonant frequency of driving mode was measured in the bandwidth of sensing part, in spite of frequency difference, 1338 Hz, resulted from fabrication error. Therefore, frequency tuning is not necessary for mode matching in this system.

Acknowledgement

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