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Design and development of a 3-axis micro gyroscope with vibratory ring springs

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Abstract

This work presents the design, simulation and experiment of a miniaturized 3-axis gyroscope with vibratory ring springs. Its total size is 2mmx2mm. The designed gyroscope has the vibrating ring spring to accomplish all sensing schemes necessary for 3-axis angular rate. The gyroscope is composed of the inner and outer ring springs, the x-direction and y-direction driving parts, the rolling sensing, and the pitch sensing and the yaw sensing parts. FEA analysis was performed to get the driving mode and the sensing mode using ANSYS program. The gyroscope was fabricated by using SOI process. The resonance frequencies of the fabricated gyroscope are respectively 16.9kHz for the driving mode, 17.04kHz for the yaw sensing mode, and 16.47kHz for the pitch and rolling sensing modes. The frequency difference for the mode matching sensing is within 0.1% and it is in the controllable range. The resonance Q factors are 720 for the driving mode, 4370 for the pitch and roll sensing mode and 3922 for the yaw sensing mode, respectively.

1. Introduction

Recently, MEMS technology is in use on to miniaturize a number of various electronic devices and systems. Among them, MEMS gyroscope is variously used to detect the angular rate for the posture control or the rotational speed detection in the field in an automobile, a mobile phone, appliances, gaming devices, IMU and etc. Micro machined gyroscopes have been implemented by using the Coriolis’ effect of the moving mass. They are classified by vibratory rate and vibrating ring gyroscopes [1-4]. Especially, the vibrating ring gyroscope has a circular ring-shaped structure and when Coriolis acceleration is applied according to the angular velocity, the sense mode occurs to vibrate toward 45° after drive. The vibrating ring gyroscope is immune to the spurious vibration and temperature change, and has the symmetric structure which also shows outstanding rotational detection [5]. The ring gyroscope
have been studied for a single axis device at [6] and a 3 axis silicon ring gyroscope using in-plane & out-of-plane operation at [7], etc. 3 axis angular velocity is measured using the in-plane and out of plane structure to contain into same die. Gyroscopes of a gimbal structure actuator and other 2 axis sensing structure are reported at [8]. Rotational driving gyroscopes have been developed.

In this paper, a miniaturized gyroscope with vibratory ring springs is proposed for the detection of 3 axis angular rate. Its size is 2mmx2mm and it operates as in-plane and out-of-plane mode using same driving motion.

2. Design concept

2.1. The structure of the 3 axis gyroscope

The gyroscope is composed of the inner and outer ring springs, the x-direction and y-direction driving parts, the x-axis rate sensing, and y-axis rate sensing parts, and the z-axis rate sensing parts, as shown in fig.1. Comb drive actuators are connected to outer ring spring for stable sinusoidal driving. The z axis sensing is designed as in-plane mode which measures the horizontal capacitance variation and the x-y sensing are designed as out-of plane mode which takes a measurement of vertical capacitance variation by the Coriolis force due to the angular velocity.

![Fig.1. Schematic diagram of the 3-axis gyroscope](image)

2.2. Working principle

The working principle of the gyroscope is shown in Fig.2 (a). The ring springs operates according to the comb drive moving vertically and horizontally and has the low mechanical energy. The spring is released from the surface and is supported by the additional spring, which doesn’t work in vibration mode. In-plane mode and out-of plane mode sensing are implemented by the gimbal structure shown in Fig. 2 (b) and (c). When the ring spring moves in x-axis, due to yaw angular rate the structure in a gimbal is applied to y-axis force to work in in-plane mode, and also due to pitch or rolling angular rate the structure in another gimbal is applied to z-axis force to work in out-of plane mode.

![Fig.2. The working principle](image)
3. Modeling and analysis

The gyroscope is designed to be composed of ring springs that have inner ring and outer ring (double ring), and the gimbal structure for the capacitive sensing of rolling and pitch angular rate (out-of-plane), and for the capacitive sensing of yaw angular rate (in-plane), and anchors for the released support of the gyroscope. The total size of the designed gyroscope is $2 \text{ mm} \times 2 \text{ mm}$, and the radius of inner ring and outer ring is $600 \ \mu\text{m}$, $920 \ \mu\text{m}$ respectively, and thickness and width is $30 \ \mu\text{m}$, and width of beam is $2 \ \mu\text{m}$. (more parameters are shown in table 1).

3.1. ANSYS simulation

The exact mode matching is essential to achieve the high performance gyroscope. To determine the resonant frequency characteristic the designed gyroscope was simulated using ANSYS program. First, the design parameters of the gyroscope are summarized in Table 1.

<table>
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<tr>
<th>Table 1. Design parameters of the miniaturized 3-axis gyroscope</th>
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<td>Mass</td>
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<td>Resonant frequency</td>
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<td>Spring constant</td>
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The operating drive mode, yaw sensing, pitch/roll sensing mode is shown in the fig.5, and the resonant frequency is (a) 21.73kHz, (b) 21.18kHz, (c) 21.91kHz, respectively.

![Fig. 3. ANSYS simulation: (a) drive mode (b) yaw rate sensing mode (c) pitch & rolling rate sensing mode](image)

4. Fabrication results

The 3-axis micro gyroscope is fabricated using the SOI process. The SEM image of the fabricated 3-axis micro gyroscope is shown in fig.4. The fabricated gyroscope has the undercut of 0.165um so that the resulting tested resonance frequencies have shifted from the design value. The measured resonance frequencies are respectively 16925Hz for the drive mode, 17044Hz for the in-plane mode and 16925Hz for the out-of-plane. The frequency difference for the mode matching sensing is within 0.1% and it is in the controllable range. The resonance Q factors are measured to be 720 for the driving mode, 4370 for the out-of-plane mode and 3922 for the in-plane mode, respectively. The Q factor of the sensing resonant frequency versus the pressure is unchanged under 0.7 torr and is about 4000.
5. Conclusion

In this paper, the 2 mm x 2 mm sized 3-axis gyroscope with a vibratory ring spring was designed and fabricated. The gyroscope is composed of the inner and outer ring springs, the x-direction and y-direction driving parts, the x-axis rate sensing, and y-axis rate sensing parts, and the z-axis rate sensing parts. When the ring spring moves in one-axis direction, the structures in a gimbal are applied on Coriolis force to work in in-plane mode or in out-of plane mode. ANSYS simulation was performed for the mode matching. The resonant frequencies of the fabricated gyroscope are respectively 16925Hz for the drive mode, 17044Hz for the in-plane mode and 16925Hz for the out-of plane. The frequency difference for the mode matching sensing is within 0.1% and it is in the controllable range. The Q factor of the sensing resonant frequency versus the pressure is unchanged under 0.7 torr and is about 4000. For the further study, vacuum packaging is needed.

References