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Tactical grade MEMS vibrating ring gyroscope with high shock reliability

Sungjin Yoon [a,b,1], Usung Park [a,1], Jaewook Rhim [a], Sang Sik Yang [b,*]

[a] Agency for Defense Development, Daejeon 305-152, Republic of Korea
[b] School of Electronics & Computer Engineering, College of Information Technology, Ajou University, Suwon 443-749, Republic of Korea

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ABSTRACT

This study presents a microelectromechanical systems (MEMS) vibrating ring gyroscope (VRG), which can survive high shocks and then maintains the level of performance required for tactical navigation. The mechanical structure was designed using a combination of mathematical analysis and the finite element method. The high-aspect-ratio structures were then manufactured through an efficient fabrication process using a silicon-on-aluminum patterned glass (SOPG) wafer. To demonstrate the high shock resistance of the fabricated VRG, a shock of 15,000 *g* was applied by a gas-gun, and its performance parameters were measured. The VRG, which has an operating frequency of 17 kHz, demonstrated performance satisfying the tactical grade requirements, i.e., bias instability, scale factor accuracy, and angular random walk less than 1°/h, 50 ppm, and $0.1°/h^{1/2}$, respectively. The test results show that the proposed VRG can be used effectively in tactical navigation systems, especially when both performance and high shock reliability are crucial, such as in guided munitions.

1. Introduction

Recently, microelectromechanical systems (MEMS) technology has enabled the miniaturization and mass-production of low-cost gyroscopes, which have replaced the conventional ones. They are now widely used in various fields, such as in anti-shaking systems for video cameras, navigation and driving stabilization systems for automotive applications, and aerospace and military systems that operate in harsh environments [1,2]. The military application is considered the most stringent field requiring the highest standards of reliability and precision. For this reason, MEMS gyroscopes for use in tactical short-range missiles and smart projectiles have been extensively studied [3].

Most MEMS gyroscopes are classified as vibratory gyroscopes, and their basic operating principle is based on energy transfer caused by the Coriolis force between two vibration modes of a vibrating element [4]. Typically, the micromachined vibratory gyroscopes can be further categorized according to the structure of the vibrating element into the tuning fork type and the vibrating ring type [4–6].

The vibrating ring type gyroscope has the following advantages over the tuning fork type: (1) It is robust against external shock because its mass is evenly distributed over its axisymmetric structure [4,7]. (2) It is possible to increase its sensitivity proportional to the quality factor (Q-factor) because the sensing and driving modes have approximately the same frequency [4,7,8]. (3) It is less sensitive to temperature because the structure is uniformly affected by the thermal environment [9]. (4) The frequency mismatch caused by the asymmetric distribution of mass and stiffness can be electrically compensated using balancing electrodes [10].

These advantages of the vibrating ring type gyroscopes indicate their potential to simultaneously satisfy the high shock resistance and precision requirements. Therefore, several researchers have investigated their use. However, a detailed verification of the high shock resistance and evaluation of the post-shock performance of vibrating ring type gyroscopes have not been conducted yet [11–13].

In this paper, a micromachined vibrating ring gyroscope (VRG) is proposed and standardized test results are presented to demonstrate its high shock resistance and ability to maintain a high level of performance after the shock. The structure was designed to achieve the performance objectives through the combination of mathematical analysis and finite element analysis (FEA). Its shock resistance was then evaluated by an impact simulation in commercial FEA software. Furthermore, the proposed VRG was manufactured by a specialized fabrication process developed to realize the high-aspect-ratio structures efficiently. A shock experiment was conducted using a gas-gun test system. The dynamic and performance characteristics of the fabricated VRG were measured before and after a shock of 15,000 *g* and analyzed to verify its shock resistance.

2. Design description

The proposed gyroscope is composed of a ring resonator and attached flexures which support the ring (Fig. 1). The ring resonator is driven electrostatically to vibrate along the driving axis at a resonant frequency. The mass elements of the ring undergoing vibration act like

* Corresponding author at: School of Electronics & Computer Engineering, College of Information Technology, Ajou University, Woncheon-dong, Yeongtong-gu, Suwon-si, Gyeonggi-do, Republic of Korea.
E-mail address: ssyang.ajou@gmail.com (S.S. Yang).
[1] S. Yoon and U. Park contributed equally to this work.

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a Foucault pendulum, attempting to keep the direction of its linear momentum fixed in the inertial space while the ring rotates about its axis. When an angular rate is applied perpendicular to the plane of the ring, the resulting Coriolis force acts on the vibrating ring such that another vibration mode along the sensing axis is excited, and is detected electrostatically by the sensing electrodes.

The gyroscope is designed to maintain a tactical grade performance level even after the shock of 15,000 *g*. The size of the device is about 5×5 mm^2, and the additional objectives for stable operation are as follows: operating frequency of the driving and sensing modes greater than 10 kHz; frequency difference between the driving mode and other modes greater than 1.5 kHz; lowest resonant frequency greater than 2 kHz.

2.1. Mathematical formulation

To determine the resonant frequencies in the driving and sensing modes of the VRG, the equations of motion for a circular ring, derived from the arch (i.e., curved beam) model [14], is used.

$$\frac{EI}{R^4}\left(\frac{\partial^2 u_\theta}{\partial\theta^2} - \frac{\partial^3 u}{\partial\theta^3}\right) + \frac{EA}{R^2}\left(\frac{\partial^2 u_\theta}{\partial\theta^2} - \frac{\partial^3 u_r}{\partial\theta}\right) + q_\theta = \rho A\frac{\partial^2 w}{\partial t^2} \tag{1}$$

$$\frac{EI}{R^4}\left(\frac{\partial^3 u_\theta}{\partial\theta^3} - \frac{\partial^4 u_r}{\partial\theta^4}\right) - \frac{EA}{R^2}\left(\frac{\partial u_\theta}{\partial\theta} + u_r\right) + q_r = \rho A\frac{\partial^2 u_\theta}{\partial t^2} \tag{2}$$

where R is the radius of the ring, u_r is the transverse displacement in the radial direction, $u\theta$ is the circumferential displacement, q_r and $q\theta$ are the corresponding external forces per unit length, E is the Young's modulus, A is the cross-sectional area, I is the second moment of area, and ρ is the density.

Assuming that damping is negligible because the ring is closed, the mode shape of the nth mode can be expressed in the following form:

$$w(\theta, t) = W_n(t)\cos n\theta \tag{3}$$

$$u(\theta, t) = U_n(t)\sin n\theta \tag{4}$$

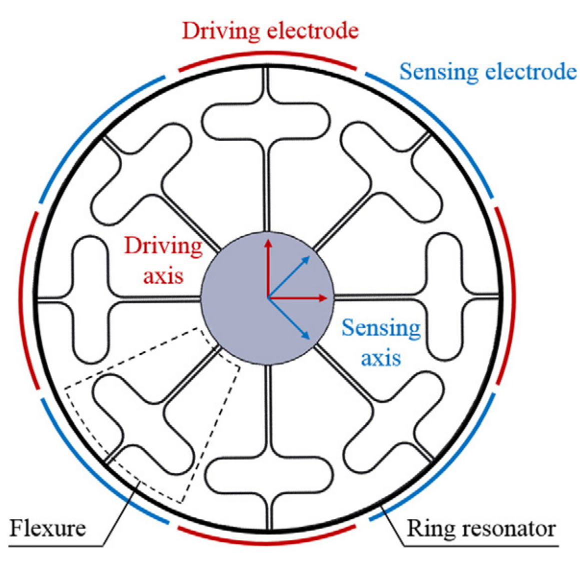

Fig. 1. Schematic of vibrating ring gyroscope.

For in-plane flexural motion, the extension of the mid-surface can be neglected [14]:

$$w = -\frac{\partial u}{\partial\theta} \text{ and } nU_n + W_n = 0. \tag{5}$$

Using the Eqs. (1)–(5), the strain energy S_n and kinetic energy T_n of the ring and the flexures can be derived. Then, from the conservation of energy, the resonant frequency in the nth mode, ω_n, can be expressed as

$$\omega_n^2 = \frac{(S_n)_{max}}{\frac{(T_n)_{max}}{\omega_n^2}} = \frac{\frac{EI_z n^2(n^2-1)^2\pi}{2R^3} + \frac{K_D}{2}}{(n^2-1)\left(\frac{\pi}{2}\rho AR + \frac{m_f}{3}\right)} \tag{6}$$

where m_f and K_D are the mass and stiffness of a single flexure.

1) $n = 1$ mode
   In this vibration mode, the ring itself does not deform but behaves like a lumped mass as a whole. Deflections occur only in the supporting flexures. Although this mode is not utilized in the operation of the gyroscope, its resonant frequency should be chosen carefully considering environmental vibration and shock. From Eq. (6), we obtain

$$\omega_1 = \sqrt{\frac{K_D}{2\pi\,\rho AR + \frac{4}{3}m_f}}. \tag{7}$$

2) $n = 2$ mode
   This mode is utilized to drive the resonator and sense the angular rate. Two nodal diameters and four antinodes are associated with this mode. From Eq. (6), the resonant frequency is given by the formula

$$\omega_2 = \sqrt{\frac{\frac{18EI\pi}{R^3} + \frac{K_D}{2}}{\frac{5}{2}\pi\,\rho AR + \frac{5}{3}m_f}}. \tag{8}$$

In most cases, R is restricted by the size requirement of the device. Therefore, the major design parameters for the ring resonator are the thickness and height (related to I and A in Eq. (8)) of the ring and stiffness of the flexure (Fig. 2).

Narrowing the ring thickness decreases the resonant frequency of the ring, which generally increases the sensitivity of the gyroscope,

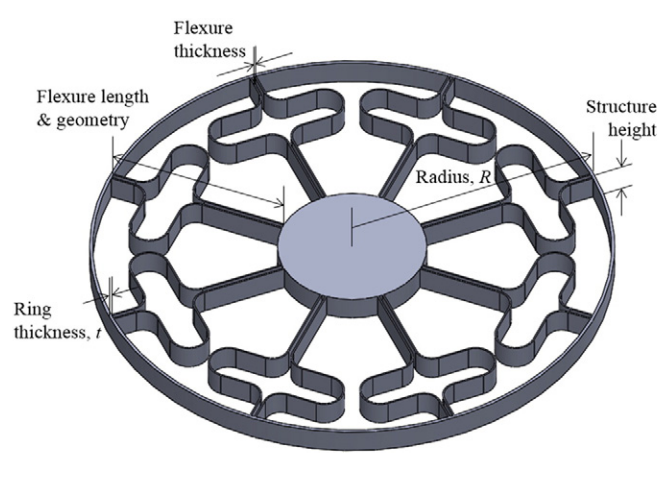

Fig. 2. Major design parameters of vibrating ring gyroscope.