ASEC 2022

Proceeding Paper

MEMS Vibrating Ring Gyroscope with Worm-Shaped Support Springs for Space Applications †

Waqas Amin Gill *, Ian Howard, Ilyas Mazhar and Kristoffer McKee

Department of Mechanical Engineering, Curtin University, Perth, WA 6845, Australia; email (I.H.); email (I.M.); email (K.M.)
* Correspondence: waqasamin.gill@postgrad.curtin.edu.au

† Presented at the 3rd International Electronic Conference on Applied Sciences; Available online: https://asec2022.sciforum.net/.

Abstract: Microelectromechanical systems (MEMS) devices have gained tremendous attention in the field of smart electronics applications. MEMS vibrating gyroscope is a rotational inertial sensor that is exhaustively used in many applications from GPS, household, smart appliances to space applications. The reliability of MEMS devices for space applications is a big concern. The devices need to be robust against harsh environments. This paper reports a double-ring MEMS vibrating ring gyroscope with sixteen worm-shaped support springs. The inclusion of the two rings with sixteen worm-shaped springs enhances the sensitivity of the gyroscope. The design symmetry and the worm-shaped springs increase the robustness, better mode matching, and gyroscopic sensitivity against harsh environments. The design modeling of the gyroscope is investigated on the ANSYSTM software. The design of the vibrating ring gyroscope incorporates two 10 μm thick rings, an outer ring radius of 1000 μm and the inner ring radius of 750 μm. Both the rings are attached with sixteen worm-shaped springs and a centrally placed anchor supports the whole structure with a radius of 260 μm. The proposed gyroscope operates at two identical shapes of wine glass modes. The first targeted resonant mode was recorded at 29.07 kHz, and the second mode of the same shape was recorded at 29.35 kHz. There is a low mode mismatch of 0.38 kHz observed between the two resonant frequencies which can be resolved with tuning electrodes. The initial modeling results show a good prospect design of a vibrating gyroscope for space applications.

Keywords: MEMS; vibratory ring gyroscope; mode matching; space applications; worm-shaped; IMU

Citation: Gill, W.A.; Howard, I.; Mazhar, I.; McKee, K. MEMS Vibrating Ring Gyroscope with Worm-Shaped Support Springs for Space Applications. **2022**, 4, x. https://doi.org/10.3390/xxxxx

Academic Editor(s):

Published: 1 December 2022

1. Introduction

The usage of smart devices in human life has risen enormously throughout from last decade. These smart devices need advanced and efficient sensors for working operations [1]. A gyroscope is one of those inertial sensors that is being used for sensing and controlling the rotational motion of these devices [2,3], and it is being extensively used in smartphones, digital cameras, military, biomedical, household, space applications and so on. The timeline history of the MEMS vibrating gyroscopes is presented [4].

Microelectromechanical systems (MEMS) vibrating gyroscopes [5,6] are widely used inertial sensors. The MEMS vibrating ring gyroscope usage is increased because of its best mode matching, symmetrical design features, higher sensitivity, and robust design for space applications [7,8]. There are various MEMS vibrating ring gyroscopes discussed by Jia et al. [9]. Cao et al. developed a double U-beam-shaped vibratory ring gyroscope with twenty-four control and tuning electrodes [10].

We present a double-ring MEMS vibrating gyroscope comprising sixteen worm-shaped springs with higher sensitivity for space applications. The paper discusses the modelling results by using ANSYS software. The modal and harmonic analysis have been discussed and effectiveness of the worm-shaped support springs. The worm-shaped support springs provide robust characteristics to the gyroscope design.

2. MEMS Vibrating Ring Gyroscope

MEMS vibrating gyroscopes have vibratory systems that need to oscillate continuously on the given resonant frequency. The working principle of the gyroscope is comprised of two vibrational modes. One vibration mode is used for driving the vibrating structure, and the second vibration mode is used for sensing the rotational movement of that vibrating structure.

The basic MEMS vibrating ring gyroscope has comprised a vibrating proof mass "m" with eight support springs having two degrees of freedom. The vibrating ring gyroscope vibrates along the driving direction with an elliptical shape of the ring. The schematic diagram of the vibrating ring mass system is shown in Figure 1.

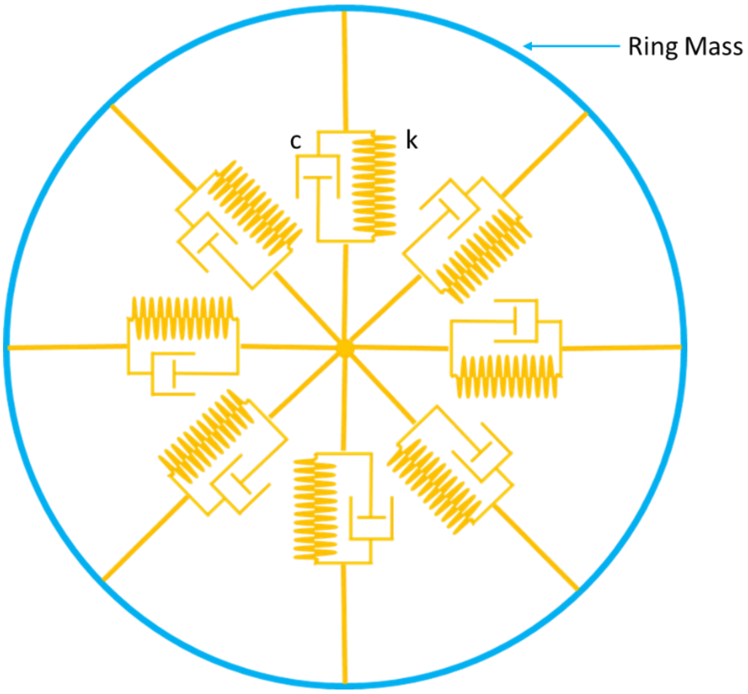

Figure 1. The schematic view of the vibrating ring mass system with spring and damping coefficient.

The general equations of motions for vibrating gyroscopes are shown below. The driving motion equation is written as Equation (1), the equation of motion detection along sensing direction is written as Equation (2), and the Coriolis motion equation is presented as Equation (3). The "m" represents proof mass, "c" is the damping coefficient, "k" represents the spring constant, "x" represents motion along the driving direction, "y" represents the motion along the sensing direction, and "Ω" represents the external rotation applied to the gyroscope. There F_d, F_s, and F_c are driving, sensing, and Coriolis forces applied to the gyroscope motion equations.

$$m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx = F_d \tag{1}$$

$$m\frac{d^2y}{dt^2} + c\frac{dy}{dt} + ky = F_s - F_c \tag{2}$$

$$F_c = -2m\Omega\frac{dx}{dt} \tag{3}$$

2.1. Basic Operating Mechanism

The basic operation of the vibrating ring gyroscope is described from steps a to d in Figure 2. There are eight driving and sensing electrodes placed around the ring structure. Continuous oscillation and excitation are provided to the ring structure by driving electrodes at the set resonant frequency. The ring structure oscillates as an elliptical shape by driving electrodes along the driving axis. At the same time, there is no displacement along the sensing axis. However, when the gyroscope is exposed to the external rotation, the Coriolis force generates and repels elliptical shape oscillation towards the sensing axis. The sensing electrodes sense the change in displacement.

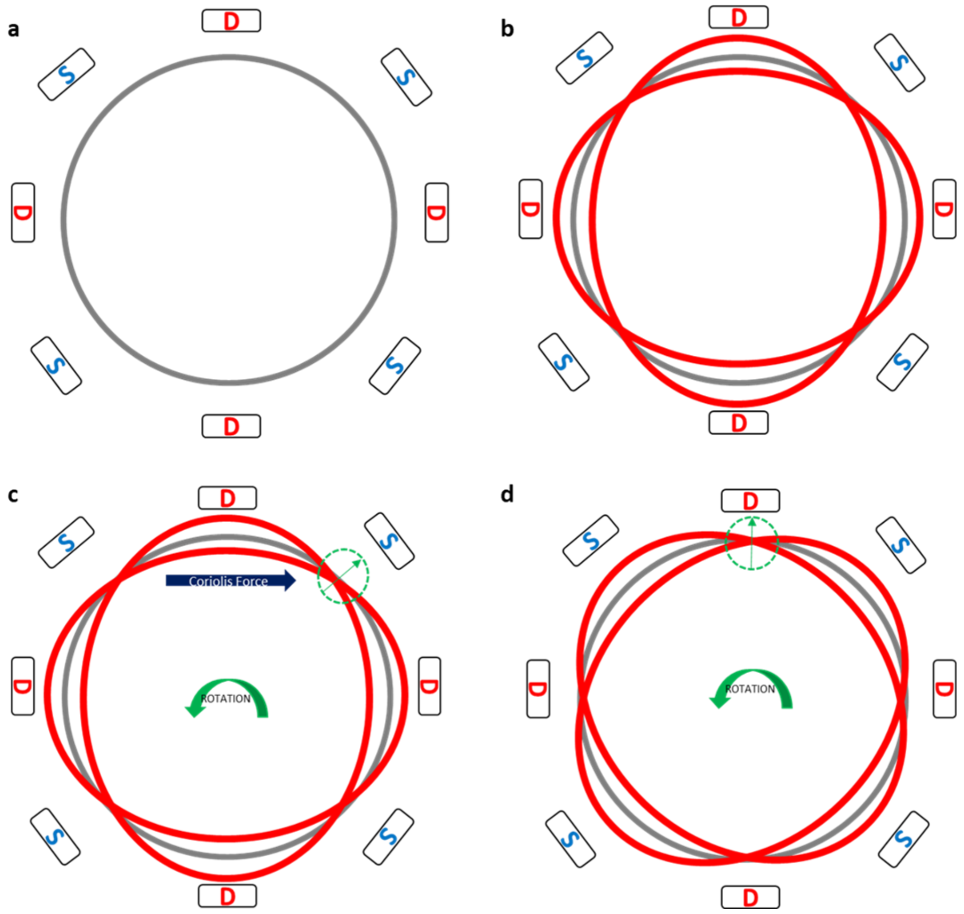

Figure 2. The vibrating ring gyroscope operation mechanism is represented from step a to step d [4].

3. Design Conceptualization

The proposed gyroscope design comprised double resonator rings, sixteen worm-shaped springs, and one centrally placed anchor. The sixteen worm-shaped springs were placed in two sets. The large sizes of the eight springs were placed with the internal set and attached to the internal ring and the centrally placed anchor. The small sizes of the eight springs are placed with the external set and attached to the external and internal rings of the gyroscope. The proposed vibrating ring gyroscope is shown in Figure 3.

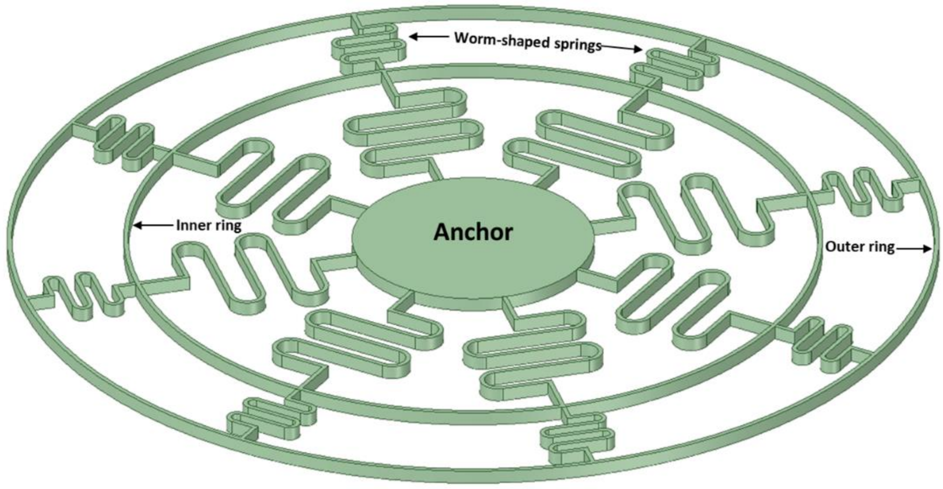

Figure 3. The schematic diagram of MEMS vibrating ring gyroscope with worm-shaped springs structure.

The concept of including two sets of sixteen worm-shaped springs enhances the gyroscope sensitivity and resistance to high-shock environments. The symmetric design of the proposed springs corroborates high shock absorbers for harsh environments. The gyroscope design must be robust enough to operate in the space environment and provide excellent performance for space applications. The complete design features of the proposed vibrating ring gyroscope are listed in Table 1. We have set the radius of the external ring resonator to 1000 µm, the reason to set this radius is to achieve operating resonant frequency within the range of double-digit kHz resonant frequency. If we decrease the device size, the gyroscope operational resonant frequency will be higher. Therefore, higher resonant frequencies provide a big split resonant frequency up to 100 s of kHz between driving and sensing resonant frequencies. If we increase the radius of the ring, then the operating resonant frequency will be lower, which means we need to increase the device size. Most of the MEMS vibrating gyroscopes operate in double-digit kHz resonant frequencies.

Table 1. Design parameters of MEMS vibrating ring gyroscope with worm-shaped springs.

Design Parameters	Value (µm)
External ring radius	1000
Internal ring radius	750
Ring thickness	10
Length of internal worm-shaped spring	480
Length of external worm-shaped spring	240
Arc radius of internal worm-shaped spring	30
Arc radius of external worm-shaped spring	12.5
Internal worm-shaped spring thickness	10
External worm-shaped spring thickness	10
Radius of anchor	260
Device width	40

4. Modelling Analysis of Worm-Shaped Springs Vibrating Ring Gyroscope

4.1. Modal Analysis

The finite element analysis of the proposed design has been done on the ANSYS software. The modal analysis describes the basic vibrational shapes of the selected design structure. The modal analysis provides information regarding natural frequencies, different vibrational shapes, structure displacement, and vibration stability of the structure. The modal frequencies for mode n = 1 are shown in Figure 4. The elliptical shapes of vibrations for the vibrating ring gyroscope can be seen in Figure 4.

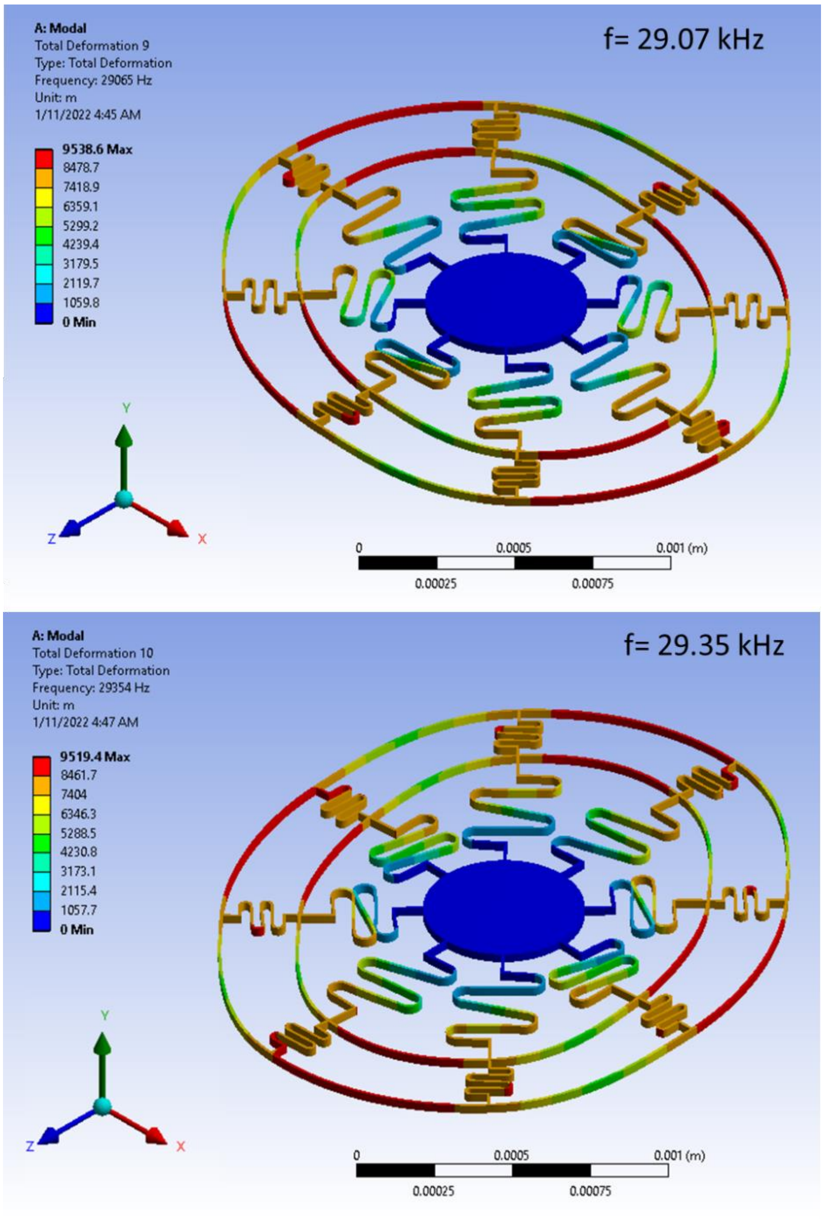

Figure 4. Modal frequencies for mode n = 1.

The driving and sensing resonant frequencies were measured at 29.07 kHz and 29.35 kHz, respectively. The frequency mismatch between driving and sensing resonant frequencies is recorded at 0.38 kHz.

5. Conclusions

This paper successfully demonstrated the initial development of the new worm-shaped springs vibrating ring gyroscope. Including two rings with sixteen worm-shaped springs enhances the performance reliability of the gyroscope for space applications. The 480 µm and 240 µm lengths of internal and external springs provide a higher compliance number which shows a good response as a shock absorber. The vibrating ring radius is 1000 µm with two elliptical shapes of resonant frequencies at 29.07 kHz and 29.35 kHz, respectively. The mode mismatch is recorded at 0.38 kHz. The proposed gyroscope design will be fabricated and dynamically tested for further investigation for space applications.

Author Contributions: The conceptualization and idea given by W.A.G. All the figures' designing, findings, and preparation done by W.A.G. Writing: the draft written by W.A.G. Writing: Review and editing the final draft done by I.H., I.M. and K.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Mohammed, Z.; Gill, W.A.; Rasras, M. Double-comb-finger design to eliminate cross-axis sensitivity in a dual-axis accelerometer. *IEEE Sens. Lett.* **2017**, *1*, 1–4.
2. Xia, D.; Yu, C.; Kong, L. The Development of Micromachined Gyroscope Structure and Circuitry Technology. *Sensors* **2014**, *14*, 1394–1473.
3. Lee, J.S.; An, B.H.; Mansouri, M.; Al Yassi, H.; Taha, I.; Gill, W.A.; Choi, D.S. MEMS vibrating wheel on gimbal gyroscope with high scale factor. *Microsyst. Technol.* **2019**, *25*, 4645–4650.
4. Gill, W.A.; Howard, I.; Mazhar, I.; McKee, K. A Review of MEMS Vibrating Gyroscopes and Their Reliability Issues in Harsh Environments. *Sensors* **2022**, *22*, 7405.
5. Pistorio, F.; Saleem, M.M.; Somà, A. A Dual-Mass Resonant MEMS Gyroscope Design with Electrostatic Tuning for Frequency Mismatch Compensation. *Appl. Sci.* **2021**, *11*, 1129.
6. Gill, W.A.; Ali, D.; An, B.H.; Syed, W.U.; Saeed, N.; Al-Shaibah, M.; Elfadel, I.M.; Al Dahmani, S.; Choi, D.S. MEMS multi-vibrating ring gyroscope for space applications. *Microsyst. Technol.* **2020**, *26*, 2527–2533.
7. Gill, W.A.; Ali, D.; An, B.H.; Syed, W.U.; Saeed, N.; Al-shaibah, M.; Elfadel, I.M.; Al Dahmani, S.; Choi, D.S. MEMS multi-vibrating ring gyroscope for space applications. *Microsyst. Technol.* **2020**, *26*, 2527–2533.
8. Syed, W.U.; An, B.H.; Gill, W.A.; Saeed, N.; Al-Shaibah, M.S.; Al Dahmani, S.; Choi, D.S.; Elfadel, I.A.M. Sensor Design Migration: The Case of a VRG. *IEEE Sensors J.* **2019**, *19*, 10336–10346.
9. Jia, J.; Ding, X.; Qin, Z.; Ruan, Z.; Li, W.; Liu, X.; Li, H. Overview and analysis of MEMS Coriolis vibratory ring gyroscope. *Measurement* **2021**, *182*, 109704.
10. Cao, H.; Liu, Y.; Kou, Z.; Zhang, Y.; Shao, X.; Gao, J.; Huang, K.; Shi, Y.; Tang, J.; Shen, C.; Liu, J. Design, fabrication and experiment of double U-beam MEMS vibration ring gyroscope. *Micromachines* **2019**, *10*, 186.