A Vertically Supported Ring-Type MEMS Gyroscope Utilizing Electromagnetic Actuation and Sensing

C. N. Yeh, J. J. Tsai, R. J. Shieh, F. G. Tseng, C. J. Li, and Y. C. Su

Abstract – **In this paper, we present the design and fabrication of a ring-type MEMS gyroscope, which is composed of a soft polymer-structure and 8 separate driving and sensing coils. The bottom side of the ring structure is mounted, while the upper portion vibrated freely by the actuation of electromagnetic and inertial forces. For the prototype demonstration, a polymer molding, metal printing, and multilayer packaging process is developed. Realized by the highly flexible structure, the device is expected to greatly amplify the vibratory motion and therefore the resulting output signal. As such, the proposed device could be low cost and readily serve as a motion detector for a variety of applications.**

I. INTRODUCTION

Gyroscopes, which measure the rate and angle of rotation, have a wide range of applications in many fields, such as military, automotive, leisure, and robotics. The applications of traditional gyroscopes are limited, mainly due to its structural complexity, high cost, and bearing-wear problems. Because of their great potential for wide-spread application, MEMS gyroscopes have received great attention in recent years [1-5]. Among the various types of MEMS gyroscopes, almost all of them are vibratory ones, which use vibrating structures (instead of complicated spinning and lubricated assemblies) to sense rotation. For the driving and sensing of vibration, electrostatic and piezoelectric forces are widely utilized to actuate the structures, while the variations in measured capacitance and piezoresistance are commonly employed to monitor the motion. It seems that silicon-based MEMS gyroscopes are advantageous, for example, they can be batch-processed with IC fab technology while their sizes and costs could be reduced significantly. However, there might be some remaining problems related to the fabrication of MEMS gyroscopes. In order to improve their sensitivity, many devices employ narrow gaps, 3D structures, or vacuum packaging, which make the fabrication process complicated, high cost, and usually low yield.

In this paper, we present a novel ring-type MEMS gyroscope, which utilize electromagnetic forces to drive a soft polymer structure and sense its rotation by monitoring the variation in induced electro-motive forces. The device is easy to fabricate and expected to amplify the induced vibration and therefore the resulting output signal. As such, the proposed device could be low cost and readily serve as a motion detector for a variety of applications.

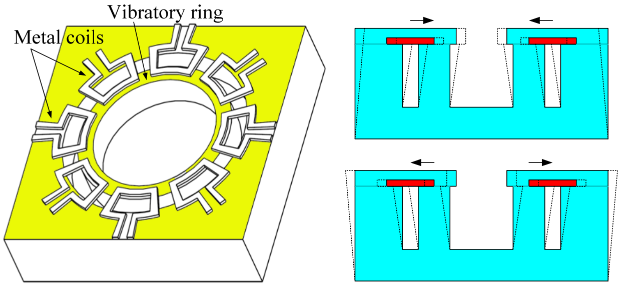

Fig. 1. Schematic illustration of the gyroscope.

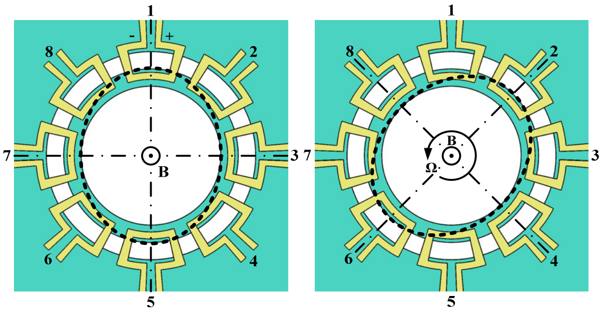

Fig. 2. Operating scheme of the gyroscope.

II. OPERATING PRINCIPLE

A vibratory gyroscope takes advantage of the Coriolis effect to measure the angular motion of an object. It consists of a proof mass and a pair of driving and sensing elements. The proof mass is forced to harmonically vibrate by the driving element. When the mass is subjected to rotation, the induced Coriolis force would cause the mass to vibrate along the sensing direction. One can obtain the angular velocity by detecting the vibration in the sensing direction. Figure 1 is a schematic illustration of the proposed MEMS gyroscope, which is composed of a soft ring- structure and 8 separate driving and sensing coils

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around the ring. The bottom side of the ring structure is mounted, while the upper portion is vibrated freely by the actuation of electromagnetic and inertial forces. Since a polymer structure is much softer than a silicon one, the required driving forces could be greatly reduced. In case that a magnetic field normal to the ring is applied, Lorentz forces are induced when currents passing through the metal coils. As illustrated in Figure 2, the Lorentz force acting on coil #1 would pull the ring-structure away from its center, if a current is fed through the indicated direction. Typically, coils #1 and #5 work as a pair to stretch the ring-structure, while coils #3 and #7 work oppositely to compress the ring-structure. AC currents that match the resonant frequency of the ring-structure are utilized to induce an amplified primary vibration. Meanwhile, the rotation of the device (with an angular velocity of Ω) around an axis normal to the ring would result in a secondary vibration, as illustrated in Figure 2. A Coriolis force is induced and the resultant force is expected to be 45° from the primary vibration. In addition, the two vibration modes are mutually independent and spatially orthogonal. Monitoring of both the primary and secondary vibration is realized by detecting the induced electro-motive forces in the 8 metal coils. Usually, coils #1, #3, #5, and #7 are used to monitor the primary vibration, while coils #2, #4, #6, and #8 are utilized to sense the secondary vibration.

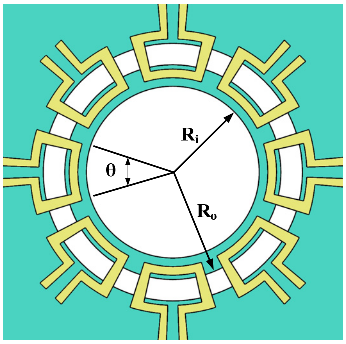

Fig. 3. Design parameters of the gyroscope.

TABLE I
MATERIAL PROPERTIES USED FOR ANALYSIS

	PDMS	Silicon
Density (g/cm^3)	1.0	2.4
Young's Modulus (Pa)	750 k	180 G
Poisson's Ratio	0.45	0.35

III. STRUCTURAL DESIGN

As illustrated in Figure 3, the main design parameters of the proposed ring-type gyroscope are the height, inner, and outer diameters of the ring structure, and the effective length of the coils. In order to investigate the dynamics and facilitate the design of the ring-type gyroscope, numerical simulation utilizing ANSYS (ANSYS, Inc.) is performed. The material properties used in the simulation are listed in Table I. It is noticed that the Young's modulus of PDMS is about quarter million times of that of silicon, so it is feasible to deform a PDMS microstructure with some weak force. The first few mode shapes of the ring-structure is illustrated in Figure 4, while the actual order is determined by the aspect-ratio of the ring-structure. Among these vibration modes, mode (b) is intentionally induced to facilitate the sensing of rotation. If the inner and outer diameters of the ring-structure are fixed at 500 and 1000 μm, respectively, the relationship between the height and the resulting resonant frequency of the ring-structure is shown in Figure 5. It is found that the resonant frequency drops rapidly from 40 to less than 10 kHz, when the height decreases from 100 to 400μm. Meanwhile, the increase of the outer diameter and the decrease of the inner diameter both raise the stiffness of the ring-structure, and therefore raise the resonant frequency.

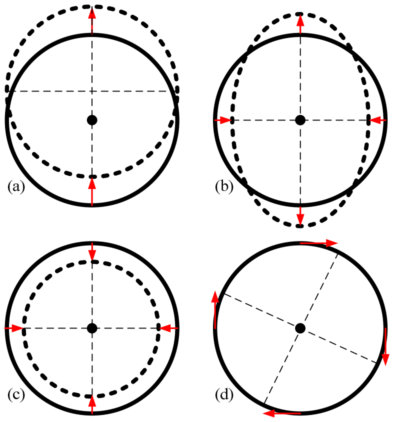

Fig. 4. Expected mode shapes of the vibratory ring.

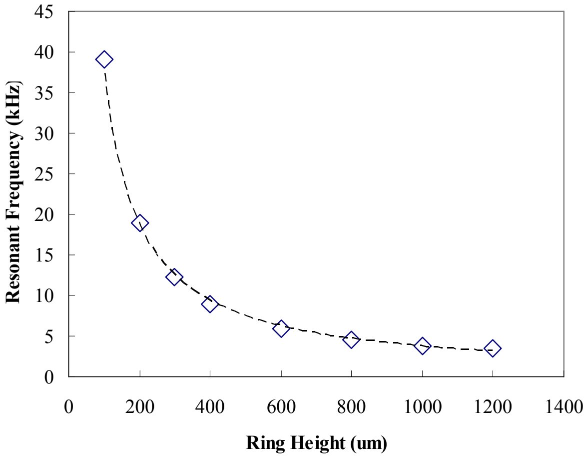

Fig. 5. Relationship between the height and the resulting resonant frequency of the ring-structure.

In addition to resonant frequency, the amplitude of the forced vibration is also investigated. The amplitude of the primary vibration at resonance (P) can be determined by Equation 1:

$$P = CQ_P IB \qquad (1)$$

where Q_P is the quality factor of the primary vibration, I is the amplitude of the AC driving current, B is the magnetic flux density, and constant C is determined by the geometries and material properties of the ring-structure. With the aid of ANSYS simulation, the values of constant

C can be estimated numerically. Figure 6 shows the simulation result of a ring structure with inner and outer diameters equal to 600 and 1000 μm, respectively, and a height of 600 μm. Meanwhile, if the secondary vibration is induced, the amplitude of the secondary vibration (S) can be estimated by Equation 2:

$$S = 2kQ_S P\Omega / \omega \qquad (2)$$

where k is the gyroscopic coupling factor determined by the mode shapes of the radial and tangential displacements, Q_S is the quality factor of the secondary vibration, and ω is the angular frequency of the matched mode. Furthermore, the induced electro-motive force along a metal coil can be calculated by Equation 3:

$$EMF = (P \text{ or } S)\ BLw \qquad (3)$$

where L is the effective length of the coil. The output signal is usually quite small, therefore auxiliary exciting, controlling, and sensing circuitry is often employed to ensure stable operation and amplified signal output.

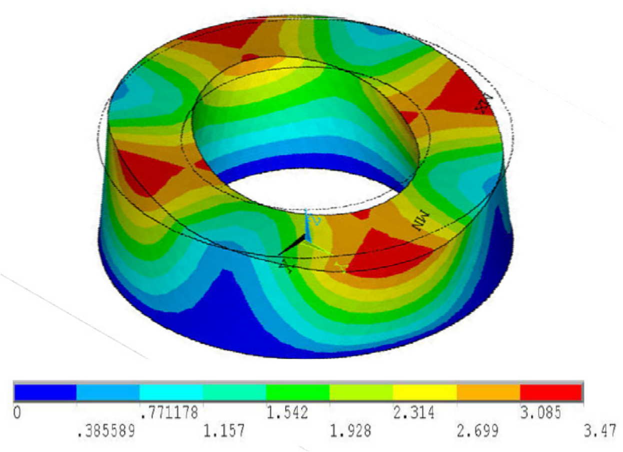

Fig. 6. Resulting deformation of a ring structure with R_i = 600μm, R_o = 1000 μm, and a height of 600 μm.

IV. FABRICATION PROCESSES

As illustrated in Figure 7, a polymer molding, metal printing, and multilayer bonding/packaging process is developed to fabricate the prototype ring-type gyroscope for demonstration. First of all, a layer of 200 μm thick negative photo-resist (SU-8, MicroChem) was spin-coated and patterned on top of a clean silicon wafer to fabricate the mold used for duplicating the ring structure. After the SU-8 mold was fully cured, it was placed in a desiccator with a vial containing a few drops of 1H,1H,2H,2H-perfluorooctyl-trichlorosilane (Fluka) under vacuum for 2 hours to silanize the surfaces. The purpose of silanization is to facilitate the removal of polymeric replicas (from the molds) after the following casting process. Meanwhile, a mixture of 10:1 PDMS pre-polymer and curing agent (Sylgard 184, Dow-Corning) was stirred thoroughly and then degassed under vacuum to remove trapped air bubbles. The casting and bonding process started with the deposition of a thin PDMS film on top of a clean silicon wafer. About one tenths of the PDMS mixture was spin-coated on the wafer at 2500 rpm for 30 seconds, which yielded a thickness of roughly 15 μm, and cured for 15 minutes at 85ºC. Afterward, the rest of the PDMS mixture was poured onto the SU-8 mold, degassed, and cured for 2 hours at 85ºC. Meanwhile, the metal coils were deposited on top of the 15 μm thick PDMS film by screen printing. A certain volume of the employed conducting silver paste (RF1008A, Hong How Technology) was printed and then baked for 30 minutes to solidify the coil structures. After thoroughly cured, the PDMS replica on the SU-8 mold was peeled off.

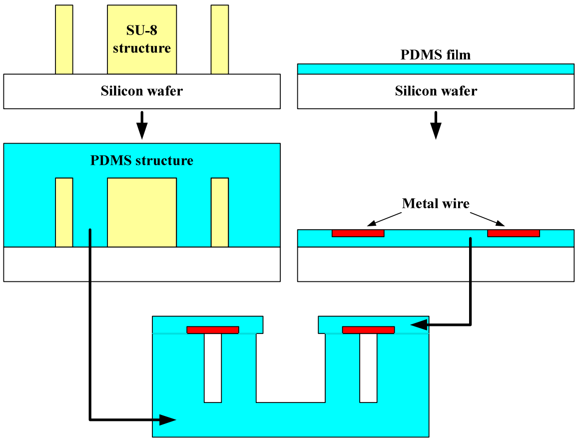

Fig. 7. Fabrication process of the ring-type gyroscope.

Once peeled off from the mold, the top side of the PDMS ring structure was then treated with a hand-held corona treater (BD-20AC, Electro-Technic Products), which ionizes surrounding air and creates localized plasma to activate the surfaces for irreversible bonding. The intensity of the corona was set at a relatively low level in order to produce a stable but soft corona with minimal crackling and sparking. The wire electrode was positioned roughly 3 mm above the treated surface, and scanned back and forth for 30 seconds to 1 minute, depending on the size of the surface. Meanwhile, the same surface treatment was also applied to the thin PDMS film. Afterward, the corona-treated surfaces were then pressed together and left undisturbed for at least one hour at 85°C for the bonding to take effect. At the end, the required interconnections for currents feed-in and electro-motive forces feed-out were made by punching holes through the structure and by mounting the device into a customized housing.

V. CONCLUSION

This paper presents the design and fabrication of a novel ring-type gyroscope, which is composed of a soft polymer-structure and 8 separate driving and sensing coils. The gyroscope utilizes electromagnetic forces to drive a soft polymer structure and sense its rotation by monitoring the variation in the induced electro-motive forces. The bottom side of the ring structure is mounted, while the upper portion is vibrated freely by the actuation of electromagnetic and inertial forces. Numerical simulation is performed to investigate the dynamics of the ring structure, and the effects caused by a variety of design parameters. It is found that the resonant frequency drops rapidly when the height decreases. Meanwhile, the increase of the outer diameter and the decrease of the inner diameter both raise the stiffness of the ring-structure, and therefore raise the resonant frequency. For the prototype demonstration, a polymer molding, metal printing, and multilayer packaging process is developed. Realized by the highly flexible structure, the device is expected to greatly amplify the vibratory motion and therefore the resulting output signal. In addition, auxiliary exciting, controlling, and sensing circuitry is employed to ensure stable operation and amplified signal output. As such, the proposed device could be low cost and readily serve as a motion sensor for a variety of applications.

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