Analysis of Electrostatic Driven Micromachined Gyroscope

Runyu Jiao, Zhaomin Luo, Jianming Wang and Xingming Xu*
Shandong University of Science and Technology, Taian, China

*Corresponding author e-mail: xxm1601@163.com

Abstract. Micromechanical gyroscopes are an important inertial instrument used to measure the angular or angular acceleration of an object. China's research in this field lags behind that of developed countries in the West. The research on the core components of high-performance micromachined gyroscopes is still in its infancy. In this paper, a fully symmetrical multi-ring vibration structure electrostatically driven micromachined gyroscope is proposed, which is studied from the theoretical basis, working principle, structural design, performance simulation, processing technology and device testing, including the following electrostatic drive micro Testing of mechanical resonant devices. The test methods of several main MEMS resonant devices are analyzed. Based on vector network analyzer, vacuum cavity, transimpedance amplifier and other equipment, the frequency sweep test is performed on the device, and the resonant frequency of the drive shaft is 23686.2 Hz. The resonant frequency of the sensitive axis is obtained. For the 23980 Hz based on the principle of electrostatic regulation, a 2.5V electrostatic adjustment voltage is applied to the device, and the frequency cracking of the two modes is reduced from 293.75 Hz to 6.25 Hz, which improves the performance of the device.

1. Introduction
A gyroscope is an instrument that measures the angular velocity or angle of an object's rotation in space. The gyroscope's English name "gyroscope" was created by the famous French scientist Foucault in the experiment of measuring the Earth's rotation. It is a combination of the Greek "skopeein" (meaning "see") and "gyros" (meaning "rotation"). The work of the gyroscope does not depend on the external reference signal, and can independently detect the change of the attitude of the moving object. In the aerospace, navigation, military guidance and other fields, the traditional gyroscope is widely used, including the mechanical rotor gyroscope, the laser gyroscope, Fiber optic gyroscopes, etc. Mechanical rotor gyroscopes rely on high-speed rotating mechanical rotors. Due to the uneven quality of the rotor itself, it is extremely susceptible to acceleration and the application range is limited. Moreover, the wear caused by the friction of mechanical parts also affects the performance of the gyroscope. And life effects affect the laser gyro, fiber optic gyroscope based on the Sagnac effect, through the interference of light to detect angular velocity; compared to mechanical rotor gyroscope, with no moving parts, simple structure, no need for preheating, long service life, etc. However, such gyroscopes are extremely expensive and are mainly used in some highly sophisticated fields.

Therefore, it is of great significance to study a micro-mechanical gyroscope based on fully symmetric vibration multi-ring structure. This paper studies the physical basis of micro-mechanical gyroscope: analyzes the method of improving the sensitivity of the device; in structural design, micro-machining
process, weak signal detection and device testing methods are explored to lay the foundation for the further development of micromachined gyroscopes. There is a lack of systematic research in these areas, and there is a great demand for high performance micromachined gyroscopes. This topic develops micromechanical inertia for China. The device and research mems micro-machining process have great practical significance and application value.

2. Design of micro machined gyroscope

2.1. Micro-mechanical gyroscope design

2.1.1. Structural Design. The early vibrating ring gyroscope was dominated by a single-ring structure. Later, it evolved from a single-ring structure to a multi-ring structure, also known as a disc structure. The design of multiple rings increases electrode coverage. The area increases the capacitance plate area of the sensitive electrode and the driving electrode, improves the sensitivity of the sensitive signal of the gyro, and increases the effective quality of the device. For the mems resonant device, increasing the effective quality is one of the important means to reduce the noise level.

The mems gyroscope designed in this paper is based on the main components of multi-ring structure design: vibration ring, drive electrode, sensitive electrode, repair electrode support block. The vibrating ring is the core of the device and is also used as the main part of the resonator for the angular velocity changes of sensitive systems. The drive electrode is used to apply an excitation signal to drive the device to move. Sensitive electrodes are used to detect the output signal. The trim electrode is used for frequency tuning of the device. The support block functions as a supporting substrate during the thinning process of the device process.

2.1.2. Working mode as mentioned above, the working mode of the mems vibrating ring type micromachined gyroscope is generally a high-order mode. The driving electrode and the detecting electrode are both around the vibrating ring structure. Therefore, the driving force acts in parallel with the device. The substrate is perpendicular to the direction of rotation. The vibration of the device is in the horizontal plane, and in theory there is no out-of-plane vibration of the device. Thus, we can obtain the vibration mode of the vibrating ring gyroscope. The vibration amplitude of the two working modes and the angular increase coefficient is different. In order to obtain greater mechanical sensitivity, for the vibrating ring type micromachined gyroscope, the orthogonal mode is 45 degrees.

The vibrating ring gyroscope designed in this paper mainly detects the angle or angular velocity by the vibration of two natural modes. Different gyroscopes can be designed with different modes. In this paper, the angular velocity is detected by two ellipse orthogonal to 45 degrees. In the reciprocating vibration of the vibrating ring from an ellipse to a circle and then to an ellipse, the structure is continuously bent, that is, the capacitor plate constantly moves and the capacitance constantly changes. The specific working mode is as follows: firstly, the driving electrode is energized, and the excitation signal is applied to make the gyroscope work in a resonance state, the vibration ring changes from a circular shape to an ellipse and continuously vibrates; when an external angular velocity is applied to the object, the energy of the gyroscope is driven. The axis is transferred to the sensitive axis. The vibration modes of the two vibration modes are the same, but the angle of the vibration axis is 45 degrees. When driving the mode, the diameter of the sensitive axis does not change, the capacitance gap at the sensitive electrode does not change, and there is no sensitive signal output. When an angular velocity input occurs, the vibration in the direction of the sensitive axis is excited to generate a displacement.
3. Micromachined gyroscope testing

3.1. mems resonant device test method

The micro-nano dynamic mechanical test of the mems resonant device is of great significance to the performance of the device design, process, reliability, etc. The micro-nano dynamic mechanical test generally includes the following parts: vibration excitation, dynamic vibration measurement Modal analysis. The excitation signal is applied to the mems resonant device. After the device generates the vibration response, the response is measured, and the relationship between the excitation and the response is analyzed to determine the resonant frequency and mode shape of the device.

Through the actual micro-nano dynamic response, the theoretical model is verified and the structure and process design optimization of the mems resonant device are guided.

Due to the extremely small size and high resonance frequency of the MEMS device, the conventional contact vibration test method (piezoelectric, photoelastic, strain, etc.) cannot be used. Generally speaking, there are two methods for measuring the mem device: Optical-based non-destructive testing techniques, such as laser Doppler vibrometry, stroboscopic optics, laser interferometry, etc.; electrical-based excitation feedback testing techniques. For mems micromachined gyroscopes, the vibration of the vibrating ring is in-plane Vibration (in-plane vibration), so this section will mainly analyze the in-plane vibration stroboscopic dynamic vision imaging technology and electrical frequency sweep testing technology.

3.2. Electrical test based on vector network analyzer

3.2.1. Experimental Equipment and Procedures Testing of MEMS micromachined gyroscope chips requires the design of a simple printed circuit board (PCB), which is used to extract the electrical signals of the chip; on the other hand, as the fixture and carrier of the chip. The platform provides a good environment for testing chips.

The device is mainly subjected to frequency sweep test by means of a vector network analyzer and the like. The test equipment mainly includes a vector network analyzer, a transimpedance amplifier, a vacuum chamber, a DC power supply, etc., and the device resonance frequency is obtained by performing a frequency sweep test on the device.

The specific test steps are as follows:

(1) Place the device in a vacuum chamber, make electrical connections, and test the electrical path with a multimeter.

(2) Using a mechanical pump, pump the vacuum chamber to about 5Pa.

(3) Set up the Agilent E55061B network analyzer: DC Bias port output 10 bias voltage, port1 port output 0dBmV excitation voltage, Port2 port connected transimpedance amplifier, input amplified signal, signal detection equivalent circuit as shown in Figure 1.

![Figure 1. Signal Detection Equivalent Circuit](image)
3.2.2. Experimental results. Based on the vector network analyzer and vacuum test environment, the frequency sweeping test of the mems micromachined gyroscope manufactured in this paper is carried out.

(1) The amplitude-frequency response and phase-frequency response curve of the drive shaft, it can be seen that the resonant frequency of the device is 23686.25Hz, as shown in Figure 2.

![Figure 2. Drive Axis Sweep Test (a) Amplitude-Frequency Response Curve (b) Phase-Frequency Response Curve](image)

(2) The amplitude-frequency response and phase-frequency response curve of the sensitive axis, it can be seen that the resonant frequency of the device is 23980 Hz, as shown in Figure 3.

![Figure 3. Sweep frequency test of sensitive axis (a) amplitude-frequency response curve (b) phase-frequency response curve](image)

Electrostatic adjustment experiment when the 2.5V adjustment voltage is applied to the drive shaft, the amplitude-frequency response curve is shown in Figure 4, and the resonant frequency of the device is 23986.25Hz. The frequency cracking of the two axes has dropped from 293.75Hz to 6.25Hz. From the previous analysis, the resonance frequency cracking of the two axes is greatly reduced, which can greatly improve the sensitivity of the device and lay a foundation for achieving better comprehensive performance of the device.

![Figure 4. Drive shaft amplitude response after applying 2.5v trimming voltage](image)
By comparing the experimental values with the simulated values, it can be found that the simulation frequency of the resonant frequency of the drive shaft is 21052 Hz, which is smaller than the experimental value of 2643.25 Hz; the simulation frequency of the sensitive axis is 21545 Hz, which is 2435 less than the experimental value. This is because the deep silicon etching in the process flow sheet has etching (side etching) on the sidewall of the device, and the deep silicon etching has unevenness. In some places, the side etching is large, and in some places, the side etching is small, affecting the device. The resonant frequency.

In the experiment of the relationship between the regulation voltage and the frequency shown in Figure 5.9, the frequency increases with the increase of the adjustment voltage, which is in line with the experimental expectation, and the electrostatic adjustment is realized. Therefore, on the one hand, the improvement of deep silicon etching technology is a key direction of future research; on the other hand, it also proves the importance of frequency adjustment.

4. Summary
Micromachined gyroscope is an important inertial measurement device widely used in consumer electronics, automotive, defense guided weapons, aerospace and other fields. This paper presents a micromechanical gyroscope based on multi-ring structure. In the theoretical analysis, structural design, simulation calculation, process design, key micro-nano processing technology test, test analysis and other aspects have been studied. The main research results are as follows:

1. Combining the application background of this subject, the advantages and disadvantages of common types of micromachined gyroscopes are compared, and the multi-ring structure gyroscope is established as the main design prototype and research object. The basic design parameters were determined. The high aspect ratio design was used. The modal analysis was performed on the device with a capacitance gap of 5 μm and a depth of 50 μm. The resonant frequency of the driving mode was determined to be 21052 Hz. The resonant frequency of the sensitive mode was 21545 Hz. The damping was analyzed, especially the effect of air damping on the operation of the device and the establishment of the device operating environment as a vacuum. Under different fixed damping ratios, the harmonic response analysis of the device is carried out to analyze the impact resistance of the device. The X-axis can withstand an acceleration of $8.842 \times 10^3$ g, and the E-axis can withstand an acceleration of $1.9 \times 10^2$ g, which meets the design requirements.

2. Established a test platform for micromachined gyroscopes, using a vector network analyzer, vacuum chamber, transimpedance amplifier and other equipment to perform frequency sweep testing. The resonant frequency of the drive shaft is 23686.25 Hz and the resonant frequency of the sensitive shaft is 23980 Hz. The effect of uneven etching of deep silicon on the device was analyzed. The device was subjected to an electrostatic adjustment experiment. After applying a 2.5 V trimming voltage, the frequency clearance of the two modes was reduced from 293.75 Hz to 6.25 Hz. Verify the effect of different trimming voltages on the resonant frequency of the device.

Acknowledgments
This work was financially supported by the overseas program of Shandong University of science and technology.

References
[1] ACAR C, SHKEL A M. An approach for increasing drive-mode bandwidth of MEMS vibra-tory gyroscopes [J]. Journal of microelectromechanica systems, 2005, 14 (3): 520-528.
[2] Lu Hao, Wei Xiaofeng, Pang Xiaozhi Application and Development of Inertial Technology in Precision Guided Weapons [J]. Electro-optical and Control, 2007, 14 (3): 45-47.
[3] Liang Geting, Hui Junjun, Li Yuping Gyro Development and Application. Flying Missile, 2006 (4): 108-110.
[4] SANDERS G, SZAFRANIEC B, LIU, et al. Fiber optic gyro for space, marine, and aviat-ion applications [C]//Fiber Optic Gyros-20th Anniversary Conference. DENVER, CO:SPIE,1996:
[5] PAVLATH G A. Fiber optic gyros: the vision realized [C]//Optical Fiber Sensors. San Diego, CA: SPIE, 2006: G3140.

[6] BEAN K E, BEAN K E. Anisotropic etching of silicon [J]. IEEE Transactions on electron devices, 1978, 25 (10): 1185-1193.

[7] SMITH C S. Piezoresistance effect in germanium and silicon [J]. Physical review 1954, 94 (25): 1185-1193

[8] FRENCH P J, Evans R. Polycrystalline silicon strain sensors [J]. Sensors and actuators, 1985, 8 (3): 219-225.