Research on the Reliability Test of a Micromechanical Gyroscope with Full Symmetry Structure

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Abstract. The reliability of micromechanical gyroscope has a great influence on the performance of precision guided weapon. This paper studies the reliability test of a type of micromechanical gyroscope with full symmetry structure. From the perspective of equipment failure prevention, combined with the mapping relationship between the failure mode of micromechanical gyroscope and the external environment load, and referring to the requirements of the use environment of micromechanical gyroscope, designs the reliability test flow, and analyzes the reliability test flow. The test results provide a new design method of test flow for reliability test of MEMS gyroscope with full symmetrical structure, which is of great value for popularization and guidance.

1. Introduction
Gyroscope is one of the core components of the inertial instrument. It is a sensor used to measure the angular velocity or displacement of the moving carrier relative to the inertial space. It can control the attitude and trajectory of the moving carrier. The micromachined gyroscope based on the micromachining technology has been widely used in the full symmetrical structure market because of its small size, light weight, low power consumption, fast start-up, low cost and easy digitization. All kinds of UAV, self-propelled gun, stabilized fire platform and other new weapons and equipment need to achieve precise guidance when they are carrying out tasks, and the precise strike depends on the micromechanical gyroscope. However, due to the harsh wartime environment of weapons and equipment, especially the vast territory of our country, the large area of national defense, the different environment of each region, the reliability of the micromechanical gyroscope with full symmetrical structure is put forward strict requirements. Whether in the stage of design finalization or in the stage of mass production, the reliability test must be carried out. Due to the differences of manufacturing materials, processing technology, vacuum packaging form and other aspects of different MEMS gyroscopes, there is no unified standard for reliability test methods of MEMS gyroscopes. In this paper, the reliability test of a full symmetrical structure micromechanical gyroscope is studied, its failure mechanism is analyzed, and a reasonable reliability test flow is designed according to the requirements of the use environment, in order to accurately and efficiently complete the reliability acceptance and research of a full symmetrical structure micromechanical gyroscope [1-4].
2. Failure mode of MEMS gyroscope with full symmetry structure
The sensitive chip (header part) of a fully symmetrical micromachined gyroscope is made of monocrystalline silicon, pyrex7740 heat-resistant glass and inertia mass bar, as shown in Figure 1. The vibration mechanical structure was fabricated by anisotropic wet etching, and a metal film with uniform thickness was formed on the preset area of Pyrex 7740 heat-resistant glass surface by metal coating process. After the anodic bonding process of silicon structure and glass substrate structure is completed, the parallel plate capacitance \( C \) is formed between the metal film and the corresponding vibration part of silicon structure, and there is a micron scale spacing \( d \) between the plates. In the process of micromachined gyroscope operation, the change of electrode spacing \( \Delta D \), produces the change of capacitance, \( \Delta C \), and then the signal is detected by the back-end \( C / V \) conversion circuit. The angular vibration micromechanical gyroscope based on Coriolis effect uses four blades with symmetrical distribution and corresponding metal electrodes as working capacitance, and its working mode is electrostatic driving and capacitance detection.

This special structure design and working mode make the external environment factors have a great influence on its performance. When subjected to shock vibration or large driving voltage, due to the very small spacing \( d \) between the plates, the upper and lower plates are prone to adhesion. At the same time, because the micromachined gyroscope is in the state of high frequency resonance, there will be stress concentration in the lattice defects of the vibrating silicon structure. With the passage of time, the cyclic stress in the process of vibration may cause microcracks in the silicon structure to grow continuously, and the growth rate of cracks will accelerate, eventually leading to fatigue fracture of the structure. Another important external environment load, temperature, has a great influence on the performance of MEMS gyroscope.

Due to the wide range of temperature (-40°C ~ 85°C) and the great gradient of temperature change, the temperature reliability of a fully symmetric micromechanical gyroscope is strictly required. As the head of a full symmetrical micromachined gyroscope is assembled by two different materials, namely,
silicon structure and pyrex7740 heat-resistant glass through the anodic bonding process, when the ambient temperature changes rapidly, the thermal expansion coefficients of the two materials are different, as shown in Table 1. When the ambient temperature changes rapidly, there will be a huge thermal stress on the bonding surface, which will lead to chip cracking and gyro failure. The corresponding relationship between other failure modes, including chip pollution, corrosive gas, and external environmental load is shown in Table 2.

Table 2. Failure modes and external environmental loads of MEMS gyroscopes with full symmetry structure.

| External environmental load | Non working mode resonance | Plate adhesion | Fatigue fracture | Bond surface stratification | Encapsulate the failure | Aging failure |
|-----------------------------|-----------------------------|----------------|------------------|----------------------------|-------------------------|--------------|
| High frequency vibration    | √                           | √              |                  | √                          |                         |              |
| The instantaneous impact    |                            |                |                  |                            |                         |              |
| High and low temperature cycle |                          |                |                  |                            |                         |              |
| Instantaneous high pressure |                            |                |                  |                            |                         |              |
| The corrosion of gas        |                            |                |                  |                            |                         |              |
| Chip pollution              |                            |                |                  |                            |                         |              |

3. Reliability test process design and test result analysis
The fully symmetrical structure micromachined gyroscope must consider the reliability issues during its use after the troops are installed in the product design and finalization stage and before entering the mass production stage. For this reason, it is necessary to test the reliability of a batch of micromechanical gyros. According to the corresponding relationship between the failure mode and the external environmental load in Table 2, it can be seen that there is a certain mapping relationship between each failure mode of a certain type of fully symmetric structure micromechanical gyro and the external environmental load. Therefore, according to the principle of equivalent load of the external environment, the reliability test process of a certain type of fully symmetrical structure micromachined gyroscope can be rationally designed.

3.1. High frequency vibration
High frequency vibration has a great influence on the performance of micromachined gyros. Because the working mode (driving mode and detecting mode) frequency of the micromachined gyroscope is about 3KHz, other non-working mode frequencies are far away from the working mode frequency, and the high frequency vibration in the environment will excite the non-working under certain conditions. The modal vibration causes the gyroscope to fail. In order to test the reliability of the gyroscope under high-frequency vibration conditions, a random vibration platform can be used to load the micromechanical gyroscope, so that the random vibration platform generates signals of different frequencies, and the external high-frequency vibration signal is used to excite the gyroscope, and the average failure interval of the micro gyroscope is tested. Time (MFBT), you can get the key frequency data and reliability comparison data. Through a high-frequency vibration reliability test on a batch of 10 gyro instrument heads, it is concluded that a certain type of fully symmetrical structure micromechanical gyroscope resonates when the platform vibration frequency is 3KHz, and its average failure occurs when the platform vibration frequency exceeds 10KHz. The interval time (MFBT) is less
than 30% of the design index, at which time structural fatigue fracture or delamination failure mode of the bonding surface will occur.

3.2. **Instantaneous shock**

The instantaneous shock is similar to the input of the pulse signal to the system for the micromachined gyroscope. This limit input will cause irreparable damage to the structure of the micromachined gyroscope. Because the spacing \( d \) of the polar plates of a certain type of fully symmetrical micromachined gyroscope is small, when the acceleration value of the instantaneous impact applied to the vibration structure exceeds its maximum threshold, the spacing \( d \) between the upper and lower polar plates suddenly drops to zero. When the instantaneous impact load disappears, the upper and lower plates are stuck due to surface effects and electrostatic adsorption. If the instantaneous load is further increased, the instantaneous impact may even damage the packaging system of the micromechanical gyro, causing the gyro vacuum to change, so that the gyro cannot work normally. Because a certain type of fully symmetrical structure micromachined gyroscope is a typical Z-axis gyroscope, its angular velocity sensitive direction is shown in the \( \Omega_z \) direction shown in FIG. 1, the micromechanical gyroscope can be fixed on the impact platform with a tooling fixture, and the angular velocity sensitive direction. Refers to the sky, the gradient sets the acceleration value of the instantaneous impact, from 2g to 200g. In the test process, the interface circuit is used to track and collect the capacitance change value in real time, thereby judging the instantaneous impact acceleration threshold of different batches of micromechanical gyros. The test results show that the instantaneous impact acceleration threshold of a certain type of fully symmetrical micromachined gyroscope in the Z-axis direction is 150g, and the transient impact acceleration threshold of other non-angular velocity-sensitive directions reaches 800g.

3.3. **High and low temperature cycle**

The high and low temperature cycle test is mainly to test the reliability of the micromechanical gyro in the full temperature range. The temperature range of a fully symmetrical micromachined gyroscope is \(-40^\circ C\) to \(85^\circ C\). A wide range of temperature changes leads to irregular changes in the performance parameters of the microgyroscope, especially the key performance parameters such as the scale factor and zero drift of the micromachined gyroscope change with temperature And a drastic change. The temperature cycle leads to the periodic generation of thermal stress on the bonding surface, and the device ages and fails. In order to collect the high and low temperature cycle test data, the micromachined gyroscope head can be placed in the high and low temperature cycle test furnace. Under the condition of zero angular rate input, the gradient setting temperature range is \(-40^\circ C\) to \(85^\circ C\), through the subsequent interface circuit The static output of the test gyro can be tracked in real time to obtain the gyro failure range in the full temperature range.

3.4. **Transient high pressure**

The instantaneous high-voltage reliability test is mainly used to test the impact of the high-voltage impact on the gyro caused by the instantaneous power-on of the micromechanical gyro and other reasons. When the instantaneous high voltage value exceeds the voltage threshold of the micromachined gyro, it will cause the breakdown of the blade capacitance and cause damage to the device. This test is a destructive test. Under the instantaneous high-pressure impact, the blade electrode of a certain type of fully symmetric structure micromechanical gyroscope attracts and the electrode spacing \( d \) decreases rapidly. When the instantaneous high voltage reaches 200V, the blade capacitance breaks down and the gyro is completely invalid.

3.5. **Corrosive gas**

Corrosive gases mainly include water vapor generated during the packaging process, and gases generated by cracking of the packaging material when the temperature changes. At present, the detection of the corrosive gas of the micromachined gyroscope after vacuum packaging mainly uses an
indirect test method, that is, the presence of corrosive gas is checked by measuring the change of the vacuum degree in the vacuum packaging tube. Because the Q value (quality factor) of the micromachined gyroscope is closely related to the vacuum degree in the package tube, the Q value of the micromachined gyroscope can be selected as the detection object. Curve to judge the change of vacuum degree, and then test the corrosive gas. After a period of time (120 days to 180 days) follow-up test, if the Q value of the micromechanical gyro has not decreased significantly, it can be determined that there is no corrosive gas in the package tube.

3.6. Chip contamination

Chip contamination mainly occurs in the manufacturing process of micromachined gyros. Because the scale of the microstructure is small, tiny dust and lobes may cause the vibrating microstructure to get stuck and not work properly. Whether it is dry processing or wet processing, the surface of the vibrating silicon structure is easily contaminated, making the plate adhesion or packaging failure. The chip pollution reliability test mainly tests the voltage between the electrodes of the micromechanical gyro by sampling. If there is no obvious difference in the voltages of the electrodes, it can be determined that the chip is not polluted.

4. Conclusion

Improving the reliability of micromachined gyros is of great significance to the performance of the system. At present, the standards for the reliability test of fully symmetrical structured micromachined gyros have not been unified. Generally, the design of the reliability test process of micromachined gyros refers to the IC device test standards. Although IC devices are similar to micromachined gyros in terms of packaging, fabrication, materials, etc., due to the special structural design and processing technology of micromachined gyros, which have a significant impact on their subsequent reliability tests, different structural designs and processing techniques correspond to different Failure mode, when designing the micromachined gyro reliability test process, different types of micromachined gyros must be specifically analyzed, so IC device test standards cannot be fully applied. This paper analyzes the corresponding relationship between the special failure mode and the external environmental load of a certain type of fully symmetrical micromechanical gyroscope. The reliability test process is designed according to the principle of equivalent external environmental load, and the reliability test is obtained. The results provide a test basis for the subsequent mass production and operation of a certain type of fully symmetrical structure micromachined gyroscope. At the same time, it provides new research ideas for the reliability tests of other types of micromachined gyros, and has important promotion value and guiding significance.

Acknowledgments

This work was financially supported by National Natural Science Foundation.

References

[1] IEEE Aerospace and Electronic Systems Society. IEEE Std 528-2001 IEEE Standard for Inertial Sensor Terminology. New York: The Institute of Electrical and Electronics Engineers, Inc, 2001.

[2] Lei Xin, Xie Jinsong. Research on Reliability Test Method of MEMS Inertial Sensor[J]. Reliability and Environmental Test of Electronic Products. 2009(6), 13-18.

[3] "Reliability Appraisal and Acceptance Test" (GJB 899-90), National Defense Science and Technology Industry Commission, 1991.04.01.

[4] He Chunhua, Zhao Qiancheng, etc. Research on Impact Characteristics and Reliability of Micromechanical Gyroscope [J]. Journal of Sensing Technology. 2019 (5), 643-648.