Failure Analysis and Experimental validation of MEMS Gyro under random Vibration condition

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***Abstract*—MEMS gyros installed in modern complex systems, like aircraft systems and industrial control system, are mainly subjected to mechanical vibrations in applications. Therefore, the failure of the MEMS gyro under random vibration was studied by the finite element method (FEM) and step test in this paper. Firstly, the mechanism of the output accuracy reduction of MEMS gyro under random vibration was analyzed. Then the displacement variation of MEMS gyro's sensitive structure in three different directions and the stress distribution under random vibration was analyzed by FEM, and the results showed that the key failure location of the MEMS gyro is the intersection of the slanted beam and the trapezoidal beam. MEMS gyros have been tested to failure by subjecting to a wide-band (15Hz-2KHz) random vibration step test with root mean square accelerations of 3g, 6g, 25g, 30g, 35g, 45g, 50g, 55g, 60g and 62.5g. The test results showed that the MEMS gyro can withstand a limit root mean square acceleration of 62.5g, and the failure position is consistent with simulation results by FEM, the reason of the failure was analyzed.**

Keywords- MEMS gyro; random vibration; failure; FEM; step test

I. INTRODUCTION

MEMS Gyro is the core component of inertial navigation with its advantages of small size, mass production and easy integration, etc. It has become one of the most promising inertial components and widely used in aerospace. However, MEMS Gyro will inevitably withstand external random vibration in operation, where the accuracy of MEMS' output can be reduced or even failure, such as silicon structure fracture, electrode lead drop, etc[1-4]. Therefore, studying the failure of MEMS Gyro under random vibration condition is of great significance to the reliability of MEMS Gyro.

Many scholars have studied the reliability of MEMS devices such as MEMS microphone, MEMS accelerometers, and MEMS gyros under shock impact. Jue studied the reliability evaluation method of MEMS microphone under shock impact through experiments and FEM [5]. Torsten studied the stress analysis of the MEMS accelerometer during the drop process by FEM [6]. Jue studied the reliability evaluation method of three-axis MEMS gyro under shock impact [7,8]. At present, there are many researches and experiments on the MEMS devices under the shock impact.

Many scholars studied the characterization of the MEMS gyro output voltage under vibration condition. Sang studied the vibration-induced errors in MEMS tuning fork gyro [10]. Especially for MEMS gyros, the vibration can easily affect the output of the MEMS gyros under high vacuum [11]. Federico studied the signal integrity in capacitive and piezoresistive single-axis and multi-axis MEMS gyroscopes under vibrations [12]. Dean studied the performance characterization of MEMS gyros in extreme environments [13]. Presently, there are few researching articles on the failure of MEMS gyro under vibration condition.

The aim of this paper is to describe the failure behavior of MEMS gyro under random vibration based on FEM and random vibration step test, to find the key failure location of MEMS gyro, to analyze the cause of failure, which are the foundation of reliability evaluation for MEMS gyro under random vibration condition.

II. MECHANISM OF THE INFLUENCE OF VIBRATION ON MEMS GYRO'S BIAS

The MEMS gyro architecture consists of a single crystal silicon resonator, and a Pyrex glass base with patterned electrodes. The silicon resonator comprises four proof masses and a slanted suspension beam, as shown in Figure 1. The slanted beam with an asymmetric cross section so that vertical electrostatic forces bend the beams both vertically and horizontally. The excitation mode is the flexural vibration of the slanted beam, the detection mode is the torsional vibration of the slanted beam. The excitation mode and the detection mode are two perpendicular degenerate modes of the axially symmetric elastic body. When an angular rate inputs, there will be a sinusoidal oscillation in detection axis direction due to the Coriolis Effect.

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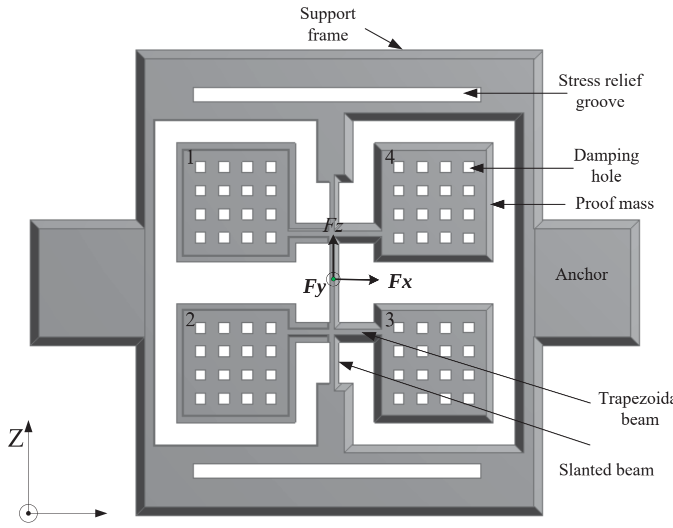


Figure 1. Schematic diagrams of the MEMS gyro

The differential capacitance on detection electrodes of MEMS gyro is

$$\begin{aligned}\Delta C_s &= \left(C_{s1}+C_{s3}\right)-\left(C_{s2}+C_{s4}\right)\\ &= \left(\frac{\varepsilon\varepsilon_o w_s l_s}{d_1+\Delta d_1}+\frac{\varepsilon\varepsilon_o w_s l_s}{d_3+\Delta d_3}\right)-\left(\frac{\varepsilon\varepsilon_o w_s l_s}{d_2+\Delta d_2}+\frac{\varepsilon\varepsilon_o w_s l_s}{d_4+\Delta d_4}\right)\\ &= \frac{\varepsilon\varepsilon_o w_s l_s}{d^2}\left(\Delta d_1+\Delta d_3-\Delta d_2-\Delta d_4\right)\end{aligned} \quad (1)$$

where C_{s1}、C_{s2}、C_{s3} and C_{s4} are, respectively denoted as the capacitance, w_s、w_l are, respectively denoted as the width and length of the detecting electrode, d_1、d_2、d_3、and d_4 are the initial gaps between the proof mass and the detecting electrodes on the glass substrate, Δd_1, Δd_2, Δd_3 and Δd_4 are respectively the vibration displacement of the proof mass in Y direction.

In the ideal case, the differential capacitance in (1) is 0 when there is no external angular velocity. However, in practice, even if there is no external angular velocity, the four proof masses will be displaced in Y direction under the driving torque due to the machining error, which is the reason of the bias. The coupling capacitance that produces the zero bias can be expressed as

$$\Delta C_{cs} = \frac{\varepsilon\varepsilon_o w_s l_s}{d^2}\Delta d_{bias} \quad (2)$$

where $\Delta d_{\text{bias}}=\Delta d_1+\Delta d_2-\Delta d_3-\Delta d_4$.

Next, the influence of external vibration on bias is analyzed. For any spatial disturbance load F, it can be decomposed into three orthogonal components, F_x, F_y and F_z, as shown in Figure 1. The force that affects the displacement of the proof mass in Y direction is F_y, and the proof mass will be displaced by the inertial acceleration, and the direction is opposite to the direction of the external force. The differential capacitance under the external vibration can be expressed as

$$\Delta C_{fs} = \frac{\varepsilon\varepsilon_o w_s l_s}{d^2}\left(\Delta d_{bias}+y_1+y_2+y_3+y_4\right) \quad (3)$$

where y_1, y_2, y_3, y_4 are the displacements of the four proof mass caused by the external vibration load, and the direction is opposite to the direction of the external force.

Since the four proof masses in the silicon sensitive structure are double symmetric structures, the displacements of the four proof masses are equal under inertial acceleration, so (3) can be expressed as

$$\Delta C_{fs} = \frac{\varepsilon\varepsilon_o w_s l_s}{d^2}\left(\Delta d_{bias}+4y\right) \quad (4)$$

where $y = y_1= y_2= y_3= y_4$.

After the differential capacitance demodulated by the high frequency carrier signal, the output voltage of the detected mode can be expressed as

$$V_{seo} = -\frac{K_h K_{se} E_{fs}^2 \Delta C_{fs}}{2C_f} \quad (5)$$

where K_h and K_{se} are circuit amplifier coefficients, and E_{fs} is the high frequency carrier amplitude of the detection electrode, C_f is the capacitance in C/V conversion circuit.

So, substituting (4) into (5), the output voltage of the detected mode can also be written as

$$V_{seo} = -\frac{K_h K_{se} E_{fs}^2 \varepsilon\varepsilon_o w_s l_s}{2C_f d^2}\left(\Delta d_{bias}+4y\right) \quad (6)$$

Equation (6) is the output voltage of the MEMS gyro under the vibration load. It shows that the vibration load can affect the gap of the differential electrode plate, which in turn affects the differential capacitance and finally affects the MEMS gyro's output voltage.

III. FINITE ELEMENT SIMULATION OF MEMS GYRO UNDER RANDOM VIBRATION

In this section, we analyze the influence of vibration load on the displacement of the proof mass and the stress distribution by FEM. The simulation parameters are shown in Table 1.

MEMS gyros installed on Jet aircraft are widely used in civil aviation and military fields, so we selected the random vibration spectrum of jet aircraft, as shown in Figure 2, which is widely representative.

The excitation mode and detection mode are shown in Figure 3. The resonant frequency of excitation mode and detection mode are 3514.9 Hz and 4487.6 Hz respectively. The results are closer to the theoretical calculation of the MEMS gyro [13].

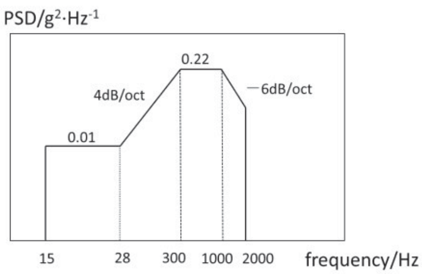
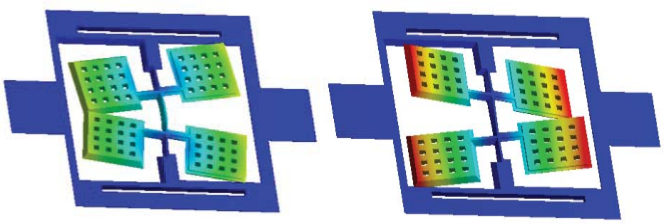


Figure 2. Vibration Spectrum of MEMS Gyroscope in Jet Aircraft

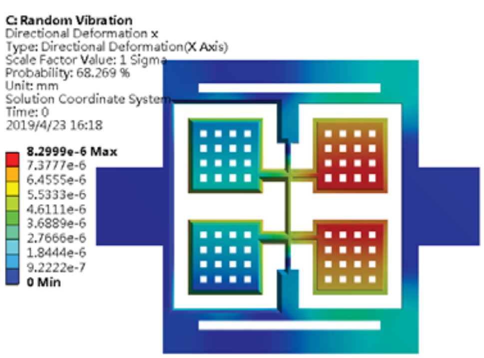
TABLE I. PHYSICAL CONSTANT OF SINGLE CRYSTAL SILICON

Physical constant	Density (kg/m^3)	Modulus of elasticity(GPa)	Poisson's ratio	Shear modulus of elasticity(GPa)
value	2330	2.6×10^{-6}	0.22	67.623



(a) Excitation mode (b) Detection mode

Figure 3. The excitation mode and detection mode of MEMS gyro



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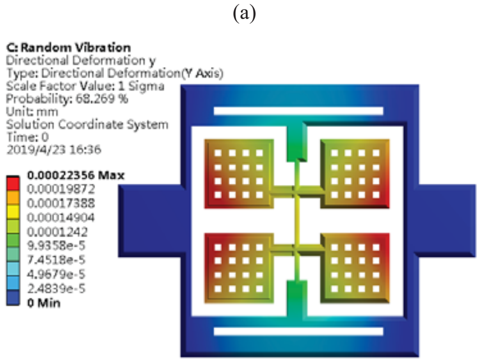

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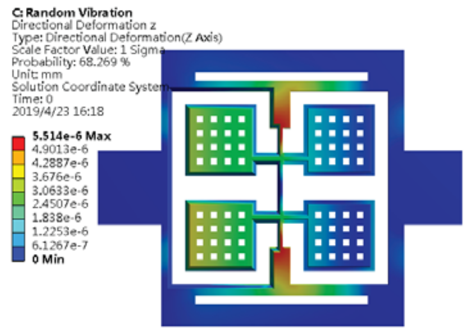

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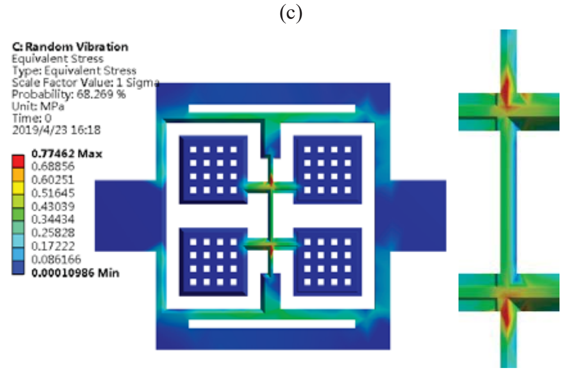


(d)

Figure 4. The displacement and stress distribution of MEMS gyro's proof mass under random vibration

The displacement of MEMS gyro's proof mass under random vibration are simulated by FEM, as shown in Figure 4 (a) (b) and (c). It shows that the displacement in Y direction is much larger than the displacements in X and Z direction under random vibration condition, and the displacement in Y direction is symmetrically distributed. The displacement will affect the differential capacitance, and change the output voltage of MEMS gyro. If the acceleration of random vibration is too large, the displacement of the proof mass caused by inertia acceleration in Y direction will be much larger than the displacement generated by the Coriolis force, which will cause the differential capacitance (voltage) generated by the vibration "cover" differential capacitance by Coriolis force. It will reduce the accuracy of the MEMS gyro, as shown in Figure 5. It shows that the peak to peak of voltage under random vibration at 25g is 10 times of the condition at no vibration condition.

It can be shown that the MEMS gyro has the greatest stress at the intersection of the support beam and the trapezoidal beam from the stress distribution in Figure 4 (d). When the root mean square acceleration of the random vibration is further increased, the maximum stress will gradually approach the fracture limit of the silicon material, and eventually the fracture will occur at the location with the greatest stress.

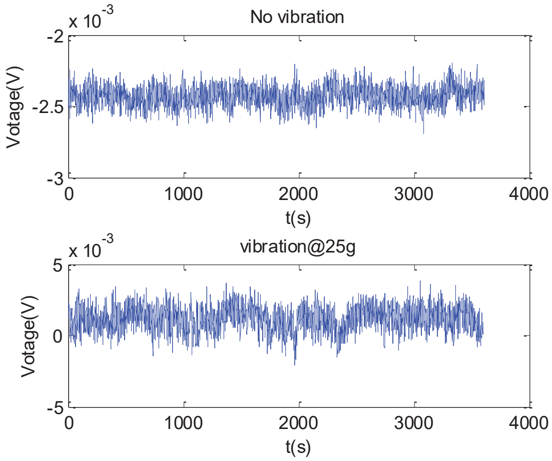


Figure 5. Voltage output under random vibration conditions

IV. STEP TEST OF THE MEMS GYRO UNDER RANDOM VIBRATION

The step test of MEMS gyro used in jet aircraft are carried out. As shown in Figure 6, the test platform consists of vibration system and signal acquisition system. The vibration system consists of a controller, a power amplifier and a vibration table. The signal acquisition system consists of a power supply, a NI acquisition device and the LabVIEW application software. In the vibration system, the controller is the control part of the vibration signal. The parameters of the vibration signal are designed and the feedback signal of the vibration table is received through the controller. The power amplifier is used to amplification the power of the system signal. The MEMS gyroscope is fixed on the vibration table to withstand the random vibration. In the signal acquisition system, the power supply provides a stable power supply for the gyroscope test circuit. The acquisition, processing and real-time display of the voltage signal of the MEMS gyroscope can be automatically completed combining NI acquisition device and LabVIEW application software.

According to the investigation of the vibration environment of the MEMS gyroscope in the jet aircraft, the vibration environment of the MEMS gyroscope is set by the vibration controller in this section. The spectrum is shown in Figure 4. The experimental steps are as follows:

(1) Fix the gyroscope on the vibration table and place the instrument as shown in Figure 6.

(2) Turn on the power supply and start to collect the voltage signal of the MEMS gyro.

(3) Open the computer control software and set parameters to make the vibration environment spectrum as shown in Figure 4, and the initial total root mean square acceleration is 3g.

(4) Open vibration, the gyroscope is forced to vibrate in Y direction.

(5) Processing the collected signals.

(6) If the performance parameters of the MEMS gyro are normal after the acquisition is stopped, the parameters will be adjusted to increase the RMS acceleration. Otherwise, stop the test.

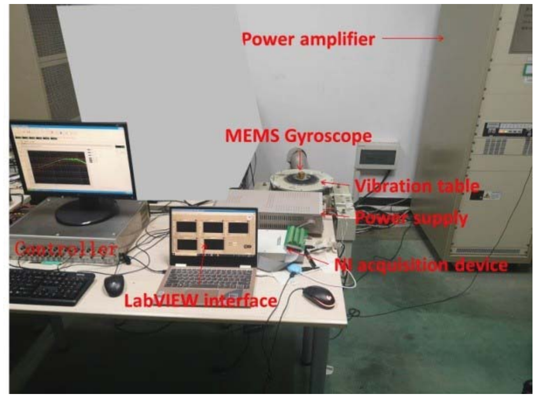
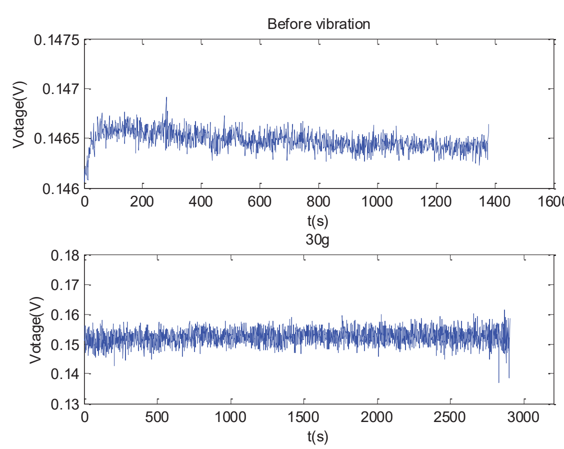


Figure 6. Test platform

Set the root mean square acceleration are 3g, 6g, 25g, 30g, 35g, 45g, 50g, 55g, 60g and 62.5g, respectively. The method for judging the abnormal voltage output of the MEMS gyro is: Step 1, The voltage of the gyro under random vibration is far greater than the voltage of no vibration. Step 2, The oscilloscope does not display the start-up waveform, indicating that the MEMS gyro cannot start to vibrate.

The output voltage signal of the MEMS gyro without the random vibration is collected as shown in Figure 7(a). The peak-to-peak of the output voltage of the MEMS gyro obviously increases under the random vibration. However, when the random vibration disappears, the voltage signal of the MEMS gyro returns to the normal level, as shown in Figure 7(b) (c) (d) (e) (f), which indicates that the random vibration will reduce the output precision of the MEMS gyro, but it does not make the MEMS gyro completely invalid. After the root mean square acceleration reaches to 62.5g, as shown in Figure 7(g), which is close to the working limit of the vibrating table, MEMS gyro still does not completely invalid. So after the random vibration at 62.5g for 14 hours, as shown in Figure 7(h), it can be shown that the voltage of MEMS gyro has been abnormal at no random vibration, which means the MEMS gyro failed.



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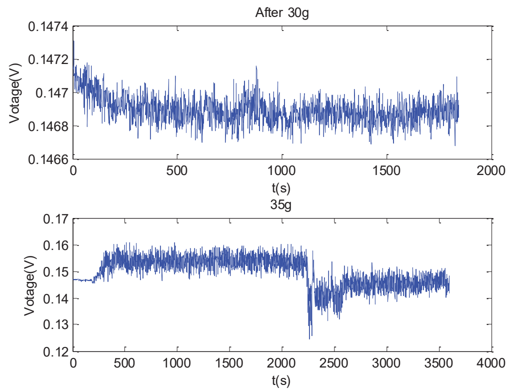

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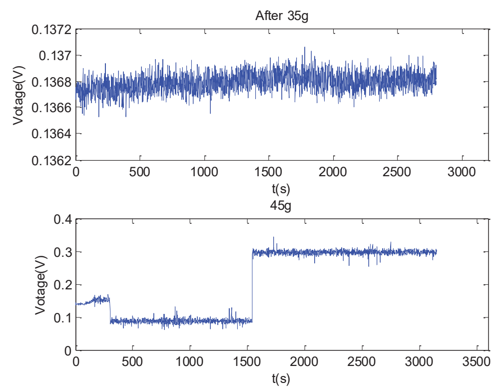

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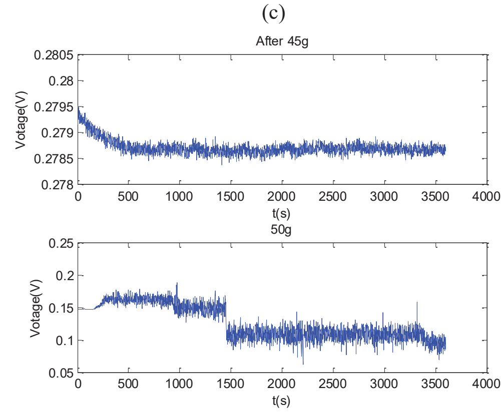

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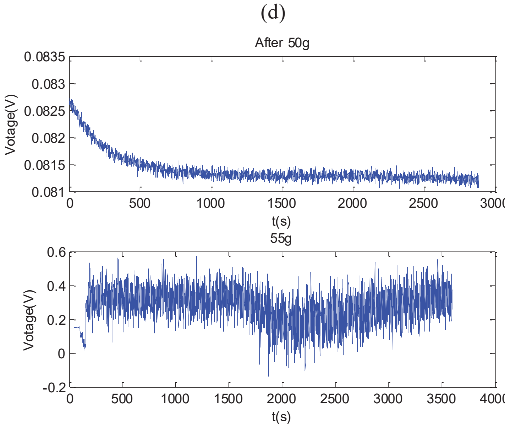

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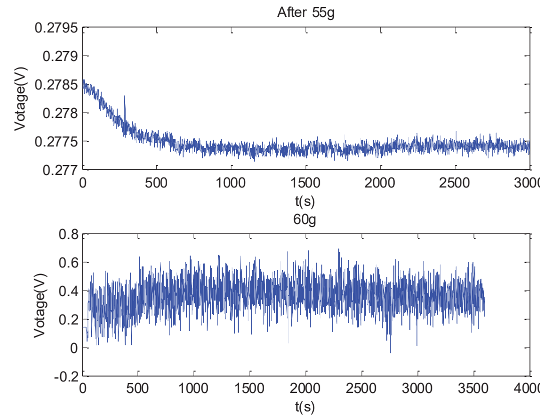

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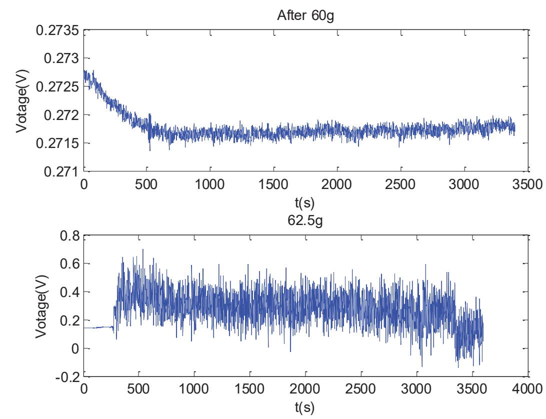
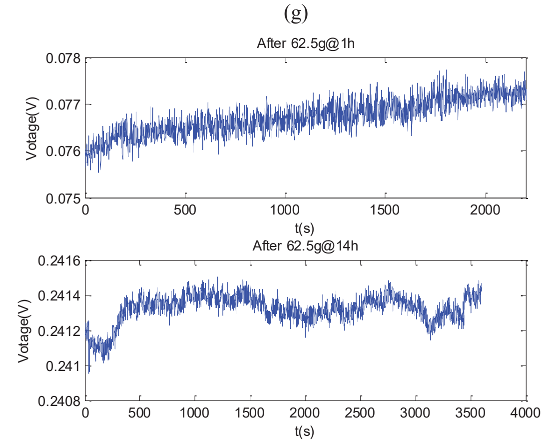


(g)



(h)

Figure 7. MEMS gyro voltage signal before and after random vibration test

In order to further determine the failure location of the MEMS gyro, the MEMS chip and circuit board should be separated by melting the surrounding solder joints, then checking the function of the chip and circuit board separately.

Firstly, check whether the function of the board is normal. The steps are: Connect another normal chip to the circuit board, use a multimeter to observe whether the output voltage of MEMS gyro is normal, use the oscilloscope to detect the starting voltage and observe whether the oscilloscope has a starting waveform. It is found that the output voltage of MEMS gyro is normal and there is a vibration waveform after connecting the normal chip and the circuit board. Therefore, the circuit board functions normally after the random vibration of 62.5g for 14 hours.

Secondly, check whether the function of the chip is normal. The steps are: Open the package of the chip and check if the silicon structure is broken. It is found that the silicon structure of the chip has a fracture at the intersection of the slanted beam and the trapezoidal beam, as shown in Figure 8, which is consistent with the FEM results at previous section. This is due to the existence of crack defects in the silicon material itself. Defects may occur in the processing of silicon wafers during heat treatment, etching, dicing, and etc. Due to the existence of these defects, when the structure is subjected to the random vibration, the stress concentration in the structure where the crack exists is easy to occur, and the possibility of failure is increased. In the high overload condition, the fractures occur on the intersection of the slanted beam and the parallelogram beam cause fracture.

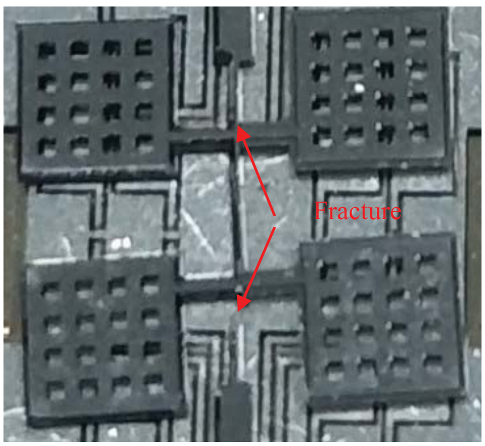


Figure 8. MEMS gyro structure fractures under random vibration condition

V. Conclusion

In this paper, the failure analysis of the MEMS gyro under random vibration was studied by FEM and step test. The following conclusions can be drawn:

(1) The vibration load can affect the gap of the differential Electrode plate, which in turn affects the differential capacitance and finally affects the MEMS gyro's output voltage.

(2) The displacement variation and stress distribution of MEMS gyro sensitive structure in three different directions under random vibration condition are analyzed by FEM. The simulation results show that MEMS gyro's failure position is the intersection of the slanted beam and the trapezoidal beam.

(3) Step test of the MEMS gyro under random vibration are carried out. The test results show that the MEMS gyro can withstand a limit root mean square acceleration of 62.5g, and the fracture location is the intersection of the slanted beam and the trapezoidal beam, which is consistent with the FEM results.

Acknowledgment

The authors would like to acknowledge the financial supports provided by the National Key Research and Development Program of China (Grant No.2017YFC0806302) , and the National Natural Science Foundation of China under Grant(51705526).

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