Research on typical failure modes of hybrid integrated quartz flexible accelerometer servo circuit caused by multi-layer ceramic capacitors

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Abstract. The quartz flexible accelerometer servo circuit is one of the key components in the inertial measurement system, and the multi-layer ceramic capacitor is an important electronic component in the quartz flexible accelerometer servo circuit. This paper introduced the typical failure modes of hybrid integrated quartz flexible accelerometer servo circuit caused by multi-layer ceramic capacitors. These phenomena are analysed and studied using the circuit failure mode matching method, and improvements are proposed. The measures are of guiding significance for improving the failure analysis technology and enhancing the reliability of hybrid integrated circuit.

1. Introduction

The quartz flexible accelerometer servo circuit is a signal processing circuit that detects the change in the differential capacitance signal of the acceleration sensor and converts it into a current. This circuit is used to measure the acceleration of the carrier together with sensor, which has the characteristics of small size, high reliability, and good matching. It is widely used in the measurement of acceleration and displacement of rockets, airplanes, missiles, spacecrafts, and ships. It is one of the key components of inertial measurement system[1, 2, 3]. As one of the main components of the hybrid integrated quartz flexible accelerometer servo circuit, the multi-layer ceramic capacitor provides filtering, compensation, vibration elimination, frequency selection, and vibration in the circuit. Although multi-layer ceramic capacitors are basic electronic components and have excellent inherent reliability, they are still an electronic material with a high failure rate in engineering applications[4]. According to statistics, the failures caused by multi-layer ceramic capacitors accounted for 51.4% of the total number of component failure samples in the quartz flexible accelerometer servo circuit. Therefore, the failure analysis of multi-layer ceramic capacitors is of great significance to the reliability research of hybrid integrated quartz flexible accelerometer servo circuit.

2. Failure modes and mechanisms of multi-layer ceramic capacitors

Multi-layer ceramic capacitor is a type of chip capacitor, which is formed by stacking multi-layer ceramic dielectrics printed with internal electrodes in a staggered manner, sintered at high temperature, and then sealed with terminal electrodes at both ends. It has the characteristics of small size, compact structure, low loss, non-polarity, convenient storage, and suitable for surface mounting. It is widely used in aerospace, aviation, weapons and consumer electronics products[5]. The structure of a multi-
layer ceramic capacitor is shown in Figure 1, which mainly includes three parts: ceramic dielectrics, internal electrodes, and terminal electrodes. The failure modes of multi-layer ceramic capacitors are mainly short-circuit, open-circuit, and parameter drift[6]. The failure mechanisms mainly include metal ion migration, voids, delaminations, electrode tumours, microcracks, over-electrical stress, mechanical stress, environmental stress, and contamination[7, 8, 9, 10].

Figure 1. Structure diagram of multi-layer ceramic capacitor

3. Typical failure modes analysis of quartz flexible accelerometer servo circuit caused by multi-layer ceramic capacitors

The multi-layer ceramic capacitors used in the quartz flexible accelerometer servo circuit include the power filter capacitors, the triangle wave generator starting capacitor, the integration capacitors, the damping capacitor, and the frequency selection capacitors. The circuit is made by hybrid integration technology, in which the multi-layer ceramic capacitors are fixed to the pad by reflow soldering technology, and the circuit is encapsulated by a metal shell and a semicircular ceramic cover plate with the cap epoxy glue.

The parameter drift and functional failure of the hybrid integrated quartz flexible accelerometer servo circuit caused by the failure of the multi-layer ceramic capacitor will affect the measurement accuracy and stability of the inertial measurement system, and may cause the system to fail in severe cases. In order to analyze these failure modes of hybrid integrated quartz flexible accelerometer servo circuit, a failure mode matching method based on the role of multi-layer ceramic capacitor is established, which is used to quickly locate the failed multi-layer ceramic capacitors. With the help of test analysis technology and failure analysis program, the failure modes and failure mechanisms are distinguished, and the screening and improvement measures are proposed. The typical failure analysis process of the hybrid integrated quartz flexible accelerometer servo circuit is shown in Figure 2.

Figure 2. Flow chart of typical failure analysis of hybrid integrated quartz flexible accelerometer servo circuit

3.1. Quartz flexible accelerometer servo circuit output noise voltage abnormal mode

It is found that the output noise voltages of hybrid integrated quartz flexible accelerometer servo circuits are greater than the typical value during testing. The test data is shown in Table 1. Nos. 1, 2, 3 and 4 circuits are samples of abnormal output noise voltage, Nos. 5 and 6 circuits are good samples. The output noise voltages of the abnormal samples are both greater than 3mV. This failure mode has a matching correlation with the failure of the filter capacitor in the circuit.

Table 1. Test data of circuit samples output noise voltage

| Serials numbers of circuit samples | Output noise $V_N$ (mV) |
|-----------------------------------|-------------------------|
| No. 1                             | 6.7                     |

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The capacitance value of the relevant filter capacitors of the above Nos. 1, 2, 3, 4, 5 and 6 circuits are tested with a capacitance tester. The capacitance values of the low-end filter capacitor of the torque device (No. C15) in the faulty circuit were found to be abnormal, the test data is shown in Table 2.

| Serials numbers of capacitor samples | Capacitance value (pF) | Typical value range (pF) |
|-------------------------------------|------------------------|--------------------------|
| No. 1                               | 34                     | 8500~11500               |
| No. 2                               | 3440                   |                          |
| No. 3                               | 29                     |                          |
| No. 4                               | 6340                   |                          |
| No. 5                               | 10100                  |                          |
| No. 6                               | 9800                   |                          |

The circuit samples of Nos. 1 and 2 are potted and polished as a whole, and the No. C15 capacitors in the circuit of Nos. 3 and 4 are taken off with the protective measures and then polished in the direction perpendicular to the capacitor plate. It is found that the four capacitor ends have different degrees of microcracks, and there are no abnormal phenomena such as breakdown, voids, and manufacturing defects in the dielectric layer. The cracks positions are all at the end of the capacitor metal, and the cracks morphology is shown in Figures 3, 4, 5 and 6.

![Figure 3](image1.jpg) ![Figure 4](image2.jpg)

![Figure 5](image3.jpg) ![Figure 6](image4.jpg)

After failure analysis, it is believed that capacitors cracks are caused by mechanical stress. The test shows that the abnormal No. C15 multi-layer ceramic capacitors in the quartz flexible accelerometer...
servo circuit can be effectively eliminated through the temperature cycle test. Using the multi-layer ceramic capacitor with a thickness greater than 1.0 mm, the similar situation can be avoided.

3.2. Dynamic parameter abnormal mode of quartz flexible accelerometer servo circuit

In the test of hybrid integrated quartz flexible accelerometer servo circuits, it is found that the resonance frequency, oscillation degree and overshoot have parameter drift or over-tolerance. The test data is shown in Table 3. Among them, Nos. 7, 8, 9 and 10 circuits are samples of abnormal dynamic parameter circuits, Nos. 11 and 12 are good samples. The typical values of resonant frequency are 425 Hz to 445 Hz, the oscillation degree are 1.314 to 1.368, the overshoot are 22% to 24%, and the bandwidth are 1130 Hz to 1303 Hz. The abnormal circuit sample parameters are drifting compared with the intermediate electrical test parameters. The failure mode of the circuit has matching correlation with the failure of filtering, frequency selection, and integrating capacitor in the circuit.

| Serials numbers of circuit samples | Resonance frequency(Hz) | Oscillation degree | Overshoot (%) | Bandwidth (Hz) |
|-----------------------------------|-------------------------|--------------------|--------------|----------------|
| No. 7                             | 480                     | 1.735              | 35           | 942            |
| No. 8                             | 500                     | 1.777              | 39           | 977            |
| No. 9                             | 460                     | 1.534              | 30           | 964            |
| No. 10                            | 465                     | 1.646              | 33           | 934            |
| No. 11                            | 440                     | 1.356              | 22           | 1235           |
| No. 12                            | 445                     | 1.345              | 22           | 1286           |

After experimental analysis and component replacement experiments, the drift of the dynamic parameters of Nos. 7, 8, 9 and 10 circuit samples are caused by the failure of No. C14 capacitors. The cross-sectional analysis of No. C14 capacitor in No. 7 circuit is shown in Figures 7. It can be seen from the figure that there is a crack at the end of the circuit.

Figure 7. Sectional morphology of No. C14 capacitor in No. 7 circuit sample

It is observed that in the Nos. 7, 8, 9 and 10 circuit samples, one ends of the No. C14 capacitors are more than 1/3 of the height covered by the cap epoxy glue, while the other ends of No. C14 capacitors are not covered by the epoxy glue. No. C14 capacitor end is shown in Figure 8.

Figure 8. Schematic diagram of failed No. C14 capacitor

According to technical analysis, the failure of the No. C14 capacitor in the Nos. 7, 8, 9 and 10 circuit samples is because the cap epoxy glue does not match the thermal stress of the capacitor
terminal and the capacitor strength is poor. In the subsequent screening process, the stress is concentrated on one side of the capacitor terminal, resulting in cracks on its ends.

The following tests were carried out. Firstly, 35 thin capacitors’ ends were coated with the cap epoxy. After 50 times temperature cycle tests, 3 capacitors failed. The topography and partial enlargement of the capacitor are shown in Figures 9. Secondly, 35 thick capacitors’ ends were coated with the cap epoxy. After 50 times temperature cycle tests, no capacitor failure occurred. Finally, capacitors’ ends were first coated with flexible epoxy glue to reinforcing the capacitors’ ends, and then coated with the cap epoxy. After the temperature cycle test, no capacitor failure occurred. It can be seen that the temperature cycle test can effectively eliminate the quartz flexible accelerometer servo circuit with parameter drift caused by the abnormality of the No. C14 multi-layer ceramic capacitors. By improving the packaging process parameters, optimizing the reinforcement process of multi-layer ceramic capacitors, and selecting multi-layer ceramic capacitors with a thickness greater than 1.0 mm, the similar situation can be avoided.

![Figure 9. Topography of failed capacitor terminal](image)

3.3. Quartz flexible accelerometer servo circuit output saturation mode

It is found that the outputs of hybrid integrated quartz flexible accelerometer servo circuit are saturated and the static currents are abnormal. The static parameter test data is shown in Table 4. Among them, Nos. 13 and 14 are output saturation circuit samples, and Nos. 15 and 16 are good circuit samples. After the failure modes caused by the chips, bonding and conductor interconnection are eliminated by using the circuit failure mode matching method, it is confirmed that the circuit failure mode has a matching correlation with the No. C8 damping capacitor.

![Table 4. Test data of circuit samples static parameters](image)

Remove No.C8 capacitors of the Nos. 13 and 14 circuit samples, and the functions of two circuits return to normal. At the same time, No. C8 capacitors of Nos. 15 and 16 good circuits are removed. There is no visible damage to the appearance of the four capacitors. Test No. C8 capacitances of Nos. 13, 14, 15 and 16 circuit samples by the capacitance tester and the insulation resistance meter. The test data is shown in Table 5. From the data in Table 5, it can be seen that the capacitance values of the No. C8 capacitor of the Nos. 13 and 14 circuits are normal, but dissipation factor values are slightly larger than that of the Nos. 15 and 16 circuits, and the values of insulation resistance are smaller than that of the Nos. 15 and 16 circuits.

![Table 5. Test data of the No. C8 capacitor in the circuit samples](image)
Grinding and observing the No. C8 capacitors of the Nos. 13 and 14 circuits, it is found that there are slight breakdown points and cracks between dielectric layers inside the capacitors. The internal morphology is shown in Figures 10, 11. After failure analysis, the output saturation and abnormal quiescent current of the Nos. 13 and 14 circuits are due to the defect of the No. C8 capacitor. With the action of subsequent electrical stress and environmental stress, the defect is degraded and the capacitor is broken down and short-circuited.

|     |     |     |     |
|-----|-----|-----|-----|
| No. 13 | 56.86 | 0.0016 | 3.99 |
| No. 14 | 56.37 | 0.0020 | 5.72 |
| No. 15 | 55.85 | 0.0004 | >1000 |
| No. 16 | 56.14 | 0.0004 | >1000 |

Figure 10. Topography of the No. C8 capacitor in No. 13 circuit sample

Figure 11. Topography of the No. C8 capacitor in No. 14 circuit sample

The experiment shows that the temperature cycle test can effectively eliminate the circuit functional failure caused by the abnormality of the multi-layer ceramic capacitor, and the abnormal situation can be avoided by selecting the multi-layer ceramic capacitor after withstand voltage test, aging and screening.

4. Conclusion

Through the analysis of the typical failure modes about quartz flexible accelerometer servo circuit caused by multi-layer ceramic capacitors, it is shown that the circuit failure mode matching method is beneficial to quickly locate the failure locations of the multi-layer ceramic capacitors and distinguish the failure modes and failure mechanisms. The test verification shows that the temperature cycle test can effectively eliminate the parameter drift and functional failure of the quartz flexible accelerometer servo circuit caused by the multi-layer ceramic capacitors. At the same time, it is found that the typical failure modes of hybrid integrated quartz flexible accelerometer servo circuit can be effectively avoided by selecting thick multi-layer ceramic capacitors, optimizing the manufacturing process and strengthening the screening of multi-layer ceramic capacitors. The methods and measures mentioned in this paper improve the level of failure analysis technology and reliability of hybrid integrated circuit.
References

[1] Hathi, B., Ball, A.J., Colombatti, G., et al. (2009) Huygens HASI servo accelerometer: A review and lessons learned. Planetary & Space Science., 57(12): 1321-1333.

[2] Zhang, M., Wan, H.H., Xu, X., Ruan, X.M. (2020) Servo circuit of quartz flexible accelerometer with low power consumption and high integration. In: International Conference on Optoelectronic Materials and Device. Guangzhou. pp: 117670O1-117670O6.

[3] Yu, G.Q., Wang, J.X., Wang, W.J. (2007) Research and application of inclinometer Based on servo-accelerator of quartz flexibility. In: International Conference on Electronic Measurement and Instruments. Xi’an. pp: 4.256-4.260.

[4] Gu, J., Azarian, M.H., Pecht, M.G. (2008) Failure prognostics of multilayer ceramic capacitors in temperature-humidity-bias conditions. In: International Conference on Prognostics and Health Management. Denver. pp: 1-7.

[5] Pan, M.J., Randall, C. (2010) A brief introduction to ceramic capacitors. IEEE Electrical Insulation Magazine., 26: 44-50.

[6] Gui, L., Bao, S.X., Zhang, X.W., Wang, Z.W.; Zhang, C.S., Shi, G.H. (2012) Failure analysis on multilayer ceramic capacitor (MLCC) with leakage failure caused by silver (Ag) migration in molded plastic package. In: 13th International Conference on Electronic Packaging Technology and High Density Packaging. Guilin. pp: 1190-1193.

[7] Ng, K.K., Rajaratnam, M. (2012) Failure analysis on multilayer ceramic capacitor (MLCC) with leakage failure caused by silver (Ag) migration in molded plastic package. In: 19th IEEE International Symposium on the Physical and Failure Analysis of Integrated Circuits. Singapore. pp:1-6.

[8] Li, J.L., Zhao, J.H., You, Z. (2018) Failure analysis of multi-layer ceramic capacitors under board level shock environment. In: IEEE International Conference on Electron Devices and Solid State Circuits. Shenzhen. pp: 1-2.

[9] Andersson, C., Kristensen, O., Miller, S., Gloor, T. and Iannuzzo, F. (2018) Lock-in thermography failure detection on multilayer ceramic capacitors after flex cracking and temperature–humidity–bias stress. IEEE Journal of Emerging and Selected Topics in Power Electronics., 6: 2254-2261.

[10] Yeung, F., Chan, Y.C. (1994) Electrical failure of multilayer ceramic capacitors caused by high temperature and high humidity environment. In: Electronic Components and Technology Conference. Washington, DC. pp: 847-853.