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Study on Parameter Drift Mechanism of a Quartz Accelerometer with a System Analysis Method

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A quartz accelerometer is a chief sensitive device of the inertial navigation system. However, there exists parameter drift during the process of transportation, storage or in work condition, which has a bad influence on the navigation accuracy.
In this article, a system analysis method, the combination of FTA (Fault Tree Analysis) and FMEA (Failure Mode and Effects Analysis), is conducted to study the parameter drift mechanism of a quartz accelerometer and the conclusion is drawn that the mechanism mainly lies in the homogenization effect of vibration on welding residual stress. Finally, FEA (Finite Element Analysis) simulation is perceived to confirm the homogenization effect and demonstrates the correctness of the analysis results.

1. Introduction

A quartz accelerometer is a chief sensitive device of the inertial navigation system, which can be used to measure the linear acceleration of the object and further to obtain its trajectory, including the speed and distance. Due to the impact of materials, variation of manufacturing process, its parameter such as scale factor drifts during the process of transportation, storage or in work condition, which has a bad influence on the navigation accuracy.
At home and abroad the studies on parameter drift of a quartz accelerometer mainly focus on the mathematical modelling and the compensation of the various parameters identified by the system identification methods. Theodore (1971) has given the static error formula of an accelerometer through the test data fitting method. Fuhrman (1977) has given a method of obtaining the characteristic curve of the accelerometer to estimate the deviation of the scale factor and zero bias. Cline (1982) has used the time-constant interference equation to analyse the deviation of the inertial navigation system and clearly demonstrated the importance of choosing the proper coordinate frame for specifying shaping filters to model instrument error sources. Meskin and Itzhack (1992) have presented a new method for developing INS (Inertial Navigation System) error models which also puts all the known models in the framework and shows the equivalence among them and the method is based on several choices which uniquely define the error model. Linear error models have been presented and discussed and their eigenvalues have been computed in several special cases (Itzhack and Berman, 1987). Tiejun Qu etal (2006) has improved a self-compensation algorithm for drift of platform inertial navigation system and a simulation example has demonstrated the efficiency of the proposed approach. The dynamic separation method of inertial navigation instrument error during the missile's flight phase has been studied, the transfer model of inertial navigation instrument error has been analysed systemically and the SINS /Global Positioning System (GPS) Kalman filter for error separation has been designed (Gang Li etal, 2010).
In this article a system analysis method of combing FTA and FMEA is conducted to study the internal and external factors that have an influence on the parameter drift of the quartz accelerometer and reveal the mechanism of the parameter drift, so as to lay the foundation for improvement of design and control of process. First of all, FTA method is used to find out the structural parameters that associated with scale factor according to its working principle. Then FMEA method is employed with regard to the assembling process to

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find out the mechanism that affects the structural parameters relating to scale factor under vibration. Finally, FEA simulation is carried out to demonstrate the correctness of the results of the system analysis method.

2. FTA of scale factor drift

The scale factor is one of the important parameters of the quartz accelerometer. It is defined as the output current when subjecting to unit acceleration, which can be described by the following equation.

$$K_I = \frac{p}{K_{tg}} \tag{1}$$

Where p represents pendulosity and K_{tg} represents torque coefficient.

2.1 Torque coefficient

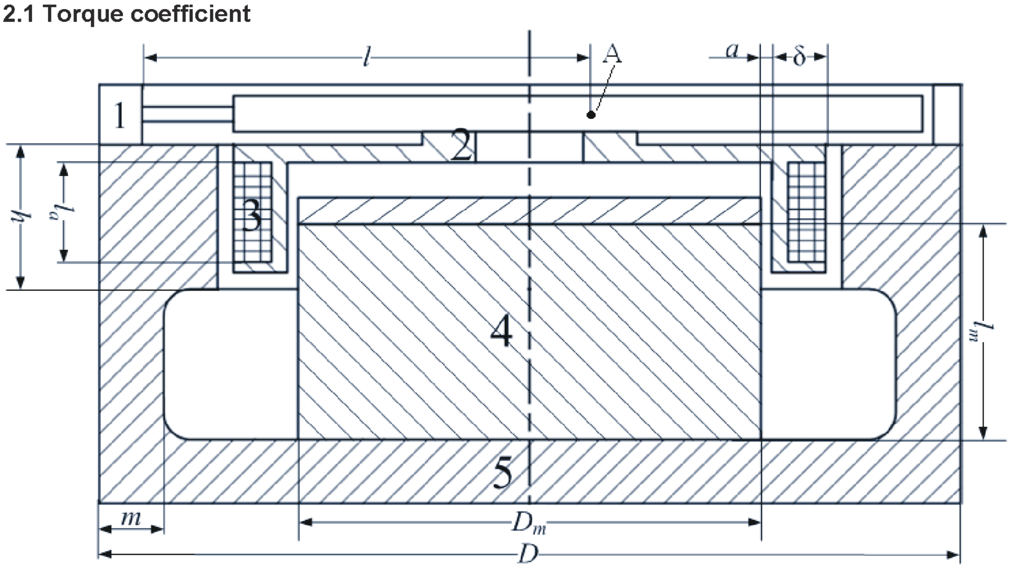

Figure 1: torquer structure of the quartz accelerometer

The torquer is one basic and important unit of the quartz accelerometer. As is shown in Figure 1, the torquer structure consists of five parts: part 1 represents quartz components, part 2 coil skeleton, part 3 coil, part 4 magnetic steel and part 5 soft magnet. When the quartz accelerometer is subjected to the acceleration excitation, the feedback torque is generated by the torque to balance the external torque caused by the acceleration excitation. The torque coefficient can be calculated by the following equation.

$$K_{tg} = B_\delta \bullet l_a \bullet L \tag{2}$$

Where l_a represents the effective length of the torque coil, B_δ represents the magnetic flux density of the torque working air gap and L represents the distance from the centre of the torquer coil to the flexible pivot along the direction of the output shaft.

According to the principle that total magnetic flux equals, B_δ can be described by the following equation.

$$B_\delta = \frac{B_m \bullet S_m}{S_\delta \bullet \sigma} \tag{3}$$

Where σ is the coefficient of magnetic leakage, B_m is the magnetic induction of magnetic steel, S_m is the cross-sectional area of magnetic steel and S_δ is the cross-sectional area of working air gap. And the two following equations can be drawn from Figure 1.

$$S_m = \frac{\pi}{4} \bullet D_m^2 \tag{4}$$

$$S_\delta = \pi \bullet \frac{D_m + 2a + (D_m + 2a + 2\delta)}{2} \bullet h \tag{5}$$

Where D_m is the diameter of soft magnetic, δ is the width of the torquer working air gap, a is the gap width between the magnetic steel and the coil skeleton and h is the height of the torquer working air gap.
As to the effective length of the torque coil, it can be obtained by the following equation.

$$l_a = 2\pi \bullet d_{cp} \bullet \omega \tag{6}$$

Where d_{cp} represents the average diameter of the torquer coil and ω represents the turns of the torquer coil.

2.2 Pendulosity

Pendulosity is determined by the mass of the quartz components and the distance from its centroid to the flexible pivot, which can be expressed by the following equation.

$$p = m \bullet l \tag{7}$$

Obviously, m is the mass of the quartz components and l is the distance from the centroid of the quartz components to the flexible pivot.

2.3 Fault Tree of scale factor drift

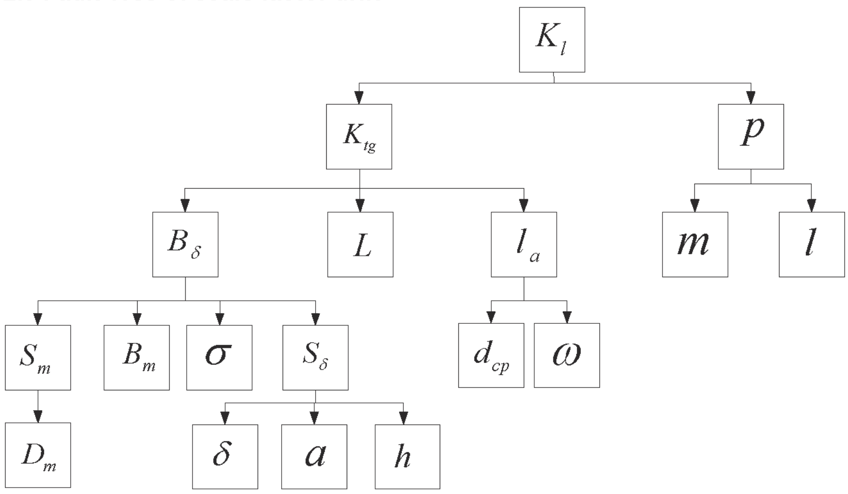

Figure 2: 'Fault Tree' of scale factor drift

From the analysis above, it is can be seen that structural parameters that related to the scale factor include D_m, δ, a, h, d_{cp} and l, as is shown in Figure 2. However, under the condition of vibration, slight variations of the diameter parameters such as D_m and d_{cp} can be ignored. Therefore, the parameters such as δ, a, h and l are considered to be affecting factors of the scale factor drift under vibration, δ, a and h being the dimensions of the working air gap while l having relationship with the centroid of the quartz components.

3. FMEA of quartz accelerometer under vibration

Vibration affects the output parameter of the quartz accelerometer by the influence on the mechanical structure. Assuming that the instability of the materials and components under vibration is not taken into account, the effects on the structure by vibration lie in the homogenization of the assembling process residual stress.

There are two kinds of assembling process used among the quartz accelerometer, welding process and cementation process. As is shown in Figure 3, the quartz components and coil skeleton, the soft magnet and magnetic steel, the soft magnet and isolation ring, the isolation ring and shell, are all assemble by cementation process, while the soft magnet and pre-load ring are assembled by laser spot welding.

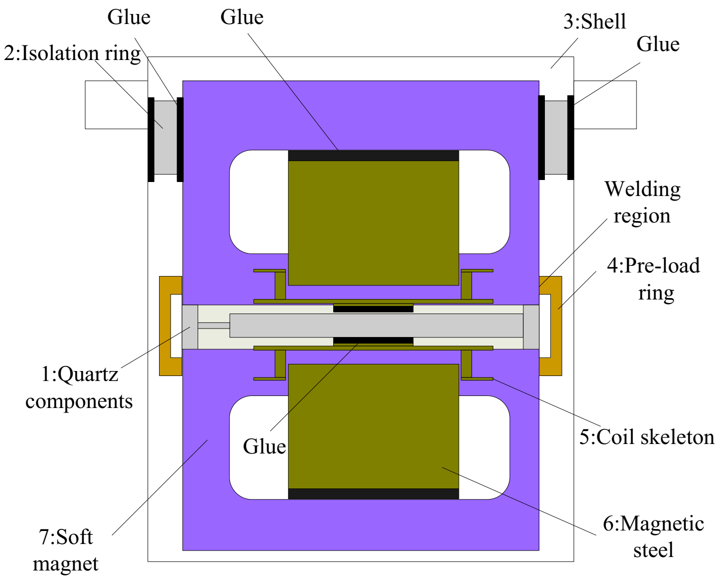

Figure 3: schematic diagram of assembling

With regard to the assembling process under vibration, FMEA is carried out and the results are shown in Table 1.

Table 1: FMEA results regarding to the assembling process under vibration

Assembling parts	Assembling process	Destabilizing factors	Effects on structure	Mechanism of effects	influenced structural factors	Effects on scale factor
1 and 5	Glue	Cementation residual stress	Dimensional changes	Homogenization in cementation residual stress	δ , a , h , l	Parameter drift
6 and 7	Glue	Cementation residual stress	Dimensional changes	Homogenization in cementation residual stress	δ , a , h	Parameter drift
4 and 7	Welding	Welding residual stress	Dimensional changes	Homogenization in welding residual stress	δ , a , h	Parameter drift
2 and 7	Glue	Cementation residual stress	Dimensional changes	Homogenization in cementation residual stress	δ , a , h	Parameter drift
2 and 3	Glue	Cementation residual stress	Dimensional changes	Homogenization in cementation residual stress	δ , a , h	Parameter drift

From Table 1, it can be seen that vibration can homogenize the cementation and welding residual stress, which cause the relating structural parameters to change, thus leading the parameter drift. In fact, vibration has less influence on cementation residual stress than welding residual stress. Therefore, the parameter drift mechanism of quartz accelerometer under vibration mainly lies in its homogenization effect on welding residual stress.

4. FEA simulation

FEA simulation is conducted to demonstrate the homogenization effect of vibration on welding residual stress. In order to simplify the problem, only half of the quartz flexible accelerometer is modelled. Figure 4 shows the finite element mesh created on the weld component. The weld position was accurately represented with fine mesh. In the finite element mesh, radial direction is the welding direction and direction Z is the through thickness direction which is also vibration direction.

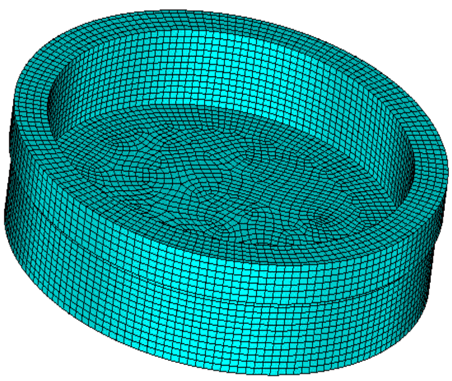

Figure 4: finite element model of welding region

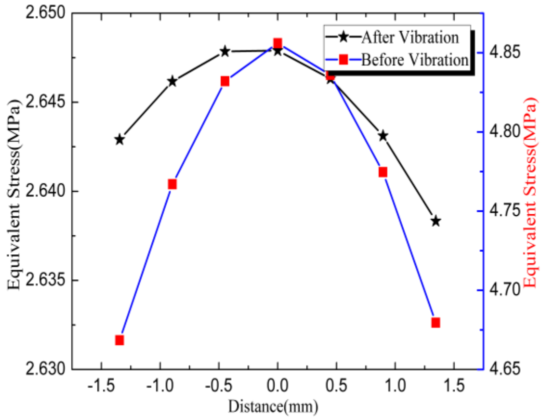

Figure 5: residual stress before and after vibration

In the simulation, the welding process is simulated firstly to get welding residual stress distribution and then vibration is exerted to see the change of residual stress distribution. From the Figure 5, Figure 6 and Figure 7, it can be obviously obtained that the residual stress after vibration is reduced and homogenized than that before vibration, indicating the homogenization effect of vibration on welding residual stress.

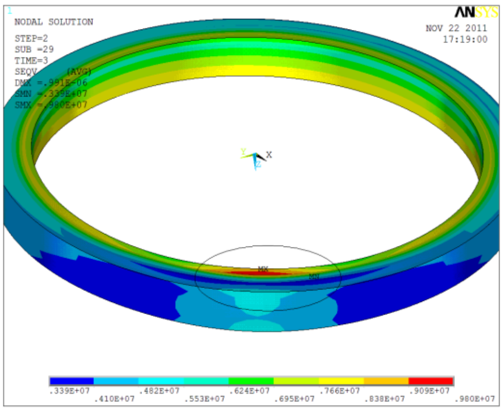

Figure 6: residual stress distribution before vibration

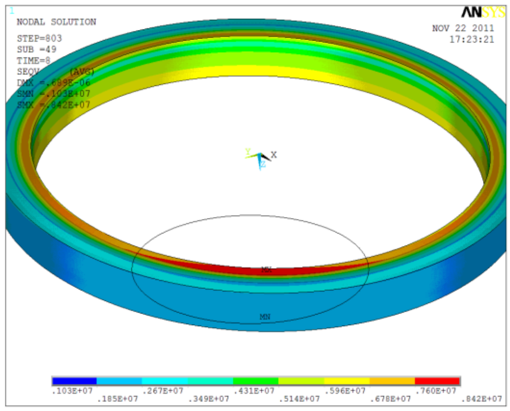

Figure 7: residual stress distribution after vibration

5. Conclusion

In this article, a system analysis method, the combination of FTA and FMEA, is used to study on parameter drift mechanism of a quartz accelerometer and FEA simulation is perceived to demonstrate the correctness of the analysis results. The conclusion can be drawn from the analysis and the simulation that the parameter drift mechanism of a quartz accelerometer under vibration mainly lies in its homogenization effect on welding residual stress, which lays the foundation for further study on improvement of design and control of process

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