Storage Life Evaluation of Quartz Accelerometer Servo Circuit Based on Drift Brownian Movement

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Abstract. The research object of this paper was the servo circuit of quartz accelerometer. The evaluation method based on drift Brownian movement was proposed to evaluate the storage reliability and storage life of servo circuit. Based on the characteristic of the servo circuit of quartz accelerometer, an accelerated model was established. Then, the reliability evaluation model was generated combined with linear drift Brownian movement. Using the degradation data of servo circuit acceleration storage, the storage life of servo circuit was evaluated. The evaluated results were reasonable, and the feasibility of the method was validated.

Introduction

Quartz accelerometers are typical high-precision mechanical and electrical products that are widely used in aerospace, transportation, and other fields in China. The quartz accelerometer consists of a servo-integrated hybrid circuit part, a process structure part (quartz pendulum), and a basic material part (viscose, magnetic material) [1][2]. The composition material and the process are complex, and the accuracy is required to be high. Quartz accelerometers have characteristics that degrade over time. Various factors, such as aging, magnetic degradation, and circuit drift, can cause degradation of their accuracy. Among them, degradation of parameters such as circuit voltage and current caused by degradation of the servo circuit performance will directly lead to the failure of the accelerometer.

In general, degradation of servo circuit performance is a slow process, and accelerating methods are used in engineering to evaluate its degradation process. However, due to the high degree of uncertainty in the degradation of servo circuit performance, it poses a challenge for reliability evaluation.

In order to evaluate the storage life and reliability index of quartz accelerometer servo circuit, the accelerated degradation test method can be used to shorten the test time and save cost. According to a large number of documents, the reliability evaluation method based on drift Brownian motion is more suitable for reliability evaluation based on performance degradation data. Therefore, this article accelerates the test data obtained by the storage degradation test through the servo circuit and uses the reliability evaluation method based on the drift Brownian motion to evaluate the storage life of the quartz accelerometer servo circuit.

Composition and the Main Performance Parameter of Servo Circuit

At present, the servo circuit commonly used by domestic quartz flexible accelerometer manufacturers is the hybrid integrated servo circuit HB309. The HB309 is a dedicated capacitive sensor servo circuit that is connected to a quartz meter to form a complete accelerometer. The HB309 hybrid servo circuit
consists of a dual-regulator power supply CW, a differential capacitor voltage converter LZF15, a power amplifier circuit LB314, and a calibration network. The main characteristics of this circuit are: large dynamic range, good linearity, wide frequency response, and large output power. It can be widely used to measure the acceleration and lateral displacement of aircrafts and ships. It can also be widely used to measure swing, vibration, and tilt, etc. Physical quantities in the civil industry. The HB309 hybrid integrated servo circuit is shown in Figure 1.

![Figure 1. HB309 hybrid integrated servo circuit diagram.](image)

The main parameters of quartz accelerometer servo circuit performance are regulator output voltage, quiescent current, output voltage, maximum output DC saturation voltage, output noise voltage, and so on. In Figure 1, the 9th and 10th sides are the output terminals of the regulated power supply in the circuit. Generally, there are three roles. First, as a self-test power supply; second, external power supply within the power allowable range; thirdly, it is used to detect whether the circuit regulated power supply works normally. The output voltage of the regulator can reflect the performance degradation of the servo circuit and is the main accuracy index of the servo circuit. Therefore, the output voltage of the regulator is selected as the performance parameter of the degradation test of the accelerometer servo circuit.

**Accelerated Life Model of Servo Circuit**

**Basic Assumptions**

Combining domestic and foreign relevant research literature [3][4], the following hypotheses are proposed for accelerated degradation tests of servo systems.

Hypothesis 1: The performance degradation process of the product is monotonic, that is, the degradation of performance is irreversible;

Hypothesis 2: Random variables of the system performance are subject to the same parameter family distribution at different stress levels, i.e., the failure mechanism of the product remains unchanged at each stress level;

Hypothesis 3: The residual life of the product depends only on the part of the cumulative failure and the stress level at that time, but not on the cumulative method;

Hypothesis 4: The product performance degradation process can be described by linear drift Brownian motion;
Hypothesis 5: The diffusion coefficient in this drift Brownian motion does not vary with stress level and time and is a constant.

**Acceleration Model Based on Drift Brownian Motion**

The temperature is the main factor affecting the output characteristics of the servo circuit of the accelerometer, and the components that constitute the servo circuit are all sensitive to the temperature and can be accelerated. Therefore, the temperature stress is selected as the accelerating stress and the Arrhenius model is selected as the acceleration model of the accelerometer servo circuit [5][6].

\[
\frac{\partial M}{\partial t} = L = Ae^{-E/KT}\tag{1}
\]

- \(M\) — a specific value or a degenerate amount;
- \(L\) — the characteristic life;
- \(A\) — the coefficient;
- \(E\) — activation energy;
- \(K\) — Boltzmann’s constant;
- \(T\) — the absolute temperature.

This paper uses a logarithmic nonlinear drift Brownian motion [7] to fit.

\[
Y(t) = \sigma B(t) + d(s)t + y_0\tag{2}
\]

\(Y(t)\) is product performance and \(t\) is a time scale. For example, for a linear degenerate process, \(t\) is the actual time \(\tau\). For a non-linear degenerate process, \(t\) can represent the actual time \(\ln(\tau)\). For different actual times, the function of \(\tau\) is different. \(y_0\) is the starting point of the drift Brownian motion, and the product performance is the initial value of the initial time \(t_0\). \(B(t)\) is the standard Brownian movement \(B(t) \sim N(0,t)\). \(d(s)\) is the drift coefficient. It is a stress-only function. \(\sigma\) is the diffusion coefficient. The coefficient describes the influence of random factors such as inconsistency and instability on the product performance during the production process. Usually, these random factors do not change with time and stress conditions, so the diffusion coefficient does not change with stress and time. \(\sigma\) is a constant.

Since the Brownian motion belongs to a normal process, the degenerate increment \((Y_i - Y_{i-1})\) obeys the normal distribution with mean \(d(s)\Delta t\) and variance \(\sigma^2\Delta t\). Take the degradation rate for the Arrhenius model as an example. Its probability density function is shown below [8].

\[
f_{i,i-1} = \frac{1}{\sigma\sqrt{\Delta t}} \Phi\left(\frac{Y_i - Y_{i-1}}{\sigma^2\Delta t} - d(s)\Delta t\right)\tag{3}
\]

\(\Phi\) represents the probability density function of the standard normal distribution.

When the product performance degradation process is a drift Brownian motion, performance exceeds its critical value and the product is considered to be a failure. That is, the lifetime of the product corresponds to the value \(T_a\) of the drift Brownian motion \(Y(t)\) that traverses \(a\) for the first time. Therefore, through the life distribution, life information related to product degradation failure can be obtained. The life of the product obeys inverse Gaussian distribution. As follows.

\[
f(t; y_0, a) = \frac{a - y_0}{\sigma\sqrt{2\pi t}} \exp\left\{-\frac{[(a - y_0) - d(s)t]^2}{2\sigma^2t}\right\}\tag{4}
\]

The reliability of the servo circuit is shown as follows.

\[
R(t) = \Phi\left[\frac{a - y_0 - d(s)t}{\sigma\sqrt{t}}\right] - \exp\left(\frac{2d(s)(a - y_0)}{\sigma^2}\right)\Phi\left[\frac{a - y_0 + d(s)t}{\sigma\sqrt{t}}\right]\tag{5}
\]
Estimation of Model Parameter

There are $n$ servo circuits for $K$ level temperature step stress acceleration degradation tests. The product was energized once every interval $\Delta t$ during the test. The number of performance tests at each stress level is $M_i$, and the total number of detections is $M$. For each stress level, the test time is $M_i \Delta t$, and the total test time is $M \Delta t$. Each monitoring time is $t_{ij}$, and the detected performance value is $y_{ij}$.

The maximum likelihood function of accelerated degradation test is shown as follows.

$$L = \prod_{i=1}^{K} \prod_{j=1}^{n} \prod_{l=1}^{M_i} \frac{1}{\sqrt{2\pi \sigma^2 \Delta t}} \exp \left\{ -\frac{(y_{ij} - y_{(i-1)j}) - d(T_i) \Delta t}{2 \sigma^2 \Delta t} \right\}$$

(6)

$$\ln L = -\frac{1}{2} \sum_{i=1}^{K} \sum_{j=1}^{n} \sum_{l=1}^{M_i} \left[ \ln(2\pi \sigma^2) + \ln(\sigma^2) \right] + \frac{(y_{ij} - y_{(i-1)j}) - A \exp(-E_a / kT_i) \Delta t}{\sigma^2 \Delta t}$$

(7)

Calculate the partial derivative of each parameter in the above equation and make it equal to zero, then we can get the maximum likelihood estimation of each parameter. The estimation of the diffusion coefficient $\sigma$ for solving the drift Brownian motion is as follows.

$$\sigma^2 = \frac{1}{\Delta t \sum_{i=1}^{K} \sum_{j=1}^{n} \sum_{l=1}^{M_i}} \sum_{i=1}^{K} \sum_{j=1}^{n} \sum_{l=1}^{M_i} \left[ (y_{ij} - y_{(i-1)j}) - A \exp(-E_a / kT_i) \Delta t \right]^2$$

(8)

The maximum likelihood method is used to solve the parameters $A$ and $E$ in the accelerated model.

$$A = \frac{\sum_{i=1}^{K} \sum_{j=1}^{n} \sum_{l=1}^{M_i} (y_{ij} - y_{(i-1)j}) e^{E_a / kT_i}}{\sum_{i=1}^{K} \sum_{j=1}^{n} \sum_{l=1}^{M_i} \Delta t \cdot e^{E_a / kT_i}}$$

(9)

The parameter $A$ appears as an algebraic multiplier in the Arrhenius model and is a dimensionless adjustment factor. Product reliability is minimally affected by $A$.

The activation energy $E_a$ is the barrier that exists during the transition from the normal non-failure state to the failure state of the accelerometer servo circuit. The smaller the activation energy, the easier the physical process of failure. The greater the activation energy, the greater the acceleration factor and the easier the product is to accelerate and fail.

The parameter $\sigma$ is the diffusion coefficient of the servo circuit and its size mainly describes the inconsistency of the same batch of products. The larger the value, the worse the consistency of the product.

Accelerated Life Model of Servo Circuit

Use temperature for accelerated stress. Accelerated degradation test is performed for a certain type of accelerometer servo circuit to obtain performance degradation data of the servo circuit. Three levels of temperature stress are applied in accelerated degradation tests. They are 125°C, 135°C, and 140°C. The number of test samples for each set of temperature stress is 8 and the total test time is 1800 hours without failure. The servo circuit is tested under the condition of temperature accelerated stress. During the test, the servo circuit is kept in a non-operating state. The performance of the voltage regulator output voltage of the servo circuit is tested through the test equipment every 300 hours. The total number of trials is 6 times. By processing the test data, the curve of the output voltage of the servo circuit regulator over time is obtained. As shown in Figure 2.
The parameters of the reliability model are estimated using the least squares estimation method. The estimated values of the three parameters $A$, $E_a$ and $\sigma$ are shown in Table 1. Substituting the parameter estimation result in Table 1 into the reliability evaluation model can obtain the reliability curve of the servo circuit under the normal stress level. As shown in Fig. 3, the reliability of the servo circuit for storing 30000h is 0.89.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$A$</th>
<th>$E_a$ (eV)</th>
<th>$\sigma$</th>
</tr>
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<tbody>
<tr>
<td>Value</td>
<td>34.6</td>
<td>0.55</td>
<td>0.01</td>
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</table>

**Summary**

Accelerometer test of quartz accelerometer’s servo circuit has a long measuring period and difficult measurement of performance parameters. This paper proposes a storage life evaluation method for quartz accelerometer servo circuit based on drift Brownian motion, and combines the test data to carry out the method application. This method can provide the basis for the life evaluation of quartz accelerometer servo circuit.

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