Reliability Prediction for MEMS Accelerometer under Random Vibration Testing

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Abstract

MEMS accelerometer can measure acceleration information for carrier in movement, mainly used in the inertial navigation field of aerospace and aviation accompanied with vibration interference. In order to analyze the reliability of MEMS accelerometer in vibration environment, the method of MEMS accelerometer’s reliability testing and life prediction under accelerated constant stress were proposed. Aiming at analyzing the typical failure modes of accelerometer with bilateral four beam structure, the paper adopted the accelerated constant stress testing and analyzed testing data by statistical method. The shape parameter’s estimation value under each accelerated stress agrees with constraint theory that Weibull distribution parameters are almost identical. Therefore the reliability prediction model of MEMS accelerometer was established by the inverse power law model, and the work condition under design vibration stress was predicted. The prediction results show that the reliability index of bilateral four beams MEMS accelerometer is better than 0.9 under design vibration stress, and its life can reach 83 h.

Key Words: Bilateral Four Beams, MEMS Accelerometer, Random Vibration, Reliability Index Prediction

1. Introduction

MEMS accelerometer is an indispensable part in the precision-guided weapons system as the inertial measurement unit, which can measure acceleration information for carrier in movement, while there is still great vibration in the application, such as in launch and flight process of guided missiles. External environment vibration may influence the accelerometer’s performance, and lead to device failure if continuous vibration makes it unable to obtain measurement information. In order to ensure the MEMS accelerometer to work normally in the vibration environment, carrying out simulation testing and life prediction for the MEMS accelerometer in the vibration environment is one of the most important means to evaluate the anti-vibration reliability. Some design parameters of MEMS accelerometer can be constrained by reliability analysis and life prediction, therefore, which can be of great help in the research and development of inertial sensors and make it work in the vibration environment with higher reliability.

At present, there are some studies about MEMS accelerometers as follows. Zhou Xiaofeng presented a MEMS capacitive accelerometer with fully symmetrical double-sided H-shaped beam structure [1]. Peng Peng designed a new structure accelerometer with axially deformed tiny beams [2]. Jiao Xin-Quan presented a new package method for MEMS accelerometer, which adopts glass-sili-
con-glass structure at wafer level and introduces an alu-
minum shell filled with two-component epoxy resin at
system level [3]. Li Ping verified that accelerometers
with stainless steel package have higher sensitivities and
better anti-overload capabilities compared with the ac-
celerometers with ceramic package [4]. Mohd-Yasin F.
developed a special measurement system to measure the
combined noise and reliability of a three-axis micro-ac-
celerometer [5]. Ma Xihong designed the test profile of
step stress and sustained stress on micro-accelerometer
in order to quickly determine the weak links of micro-
accelerometer in vibration environment [6]. Yuan Hong-
Jie utilize the method of step-stress accelerated degra-
dation testing to evaluate the storage reliability and life
of accelerometer [7]. It was focused on the new structure
design, novel package technology and reliability mea-
surement and so on. While researches of reliability pre-
diction in the vibration environment for MEMS acceler-
ometer which aim at improving the testing precision in
inertial navigation system are few. Based on such re-
search background, this thesis studies a kind of random
vibration step accelerated constant stress testing and life
prediction method of MEMS device, which is applied
in the MEMS accelerometer, and obtains the high credi-
bility predict results.

2. Failure Analysis of MEMS Accelerometer

The working principle of MEMS accelerometer is
based on piezoresistive effect of semiconductor materials,
which used the beam-mass structure and made the pie-
zoresistor at the root of the beam by doping process, then
connected piezoresistors to form a Wheatstone bridge,
we can obtain acceleration value according to the change
of output voltage on the Wheatstone bridge. The struc-
ture is equivalent to second order linear system con-
sisting of spring, damper and sensitive mass. MEMS ac-
celerometer chip in this research is bilateral four beams
structure, the packaged model is shown in Figure 1. Sen-
tive chip after packaged is installed inside the sensor
shell by potting, which makes sensitive chip and sensor
shell connected well. The overall dimension is 32 mm ×
30 mm × 23 mm, whole model is shown in Figure 2 and
the model after potting is shown in Figure 3.

Piezoresistive MEMS accelerometer in the external
vibration environment may lead to structural damage,
surface adhesion or fracture, the main failure mechanism
is fatigue failure of accelerometer’s beam because of the
long time environment vibration, which eventually leads
to cantilever beam fracture.

When the output of MEMS accelerometer was fai-
lure under the long time constant vibration stress, the de-
tailed information of structure fracture can be explored
and examined by microscope, which is shown in Figure
4 examination. It can be concluded that the influence
caused by long time vibration is deadly for the MEMS
accelerometer, so it is necessary to examine how to assess
the vibration reliability of MEMS accelerometer through
the simulation testing.

Figure 1. Packaged model of accelerometer chip.

Figure 2. The overall model of sensor.

Figure 3. The model after potting.

MEMS accelerometer’s fatigue failure is a gradual and cumulative process under the vibration environment, which will partially consume the life of accelerometer. And its fatigue properties is based on the cumulative damage theory. When the damage value reaches a certain degree, MEMS accelerometer’s structure will be fractured, which can be described as the relationship between the stress and the fatigue life, and the S-N curve is shown in Figure 5, with the increase of cycling times, the breaking strength decreases gradually.

In order to assess and predict the fatigue life of MEMS accelerometer quantitatively, it is necessary to analyze the feasibility of accelerated testing under vibration environment, and establish the relationship between external stress and life according to the testing results. With reference to the literature [8] and statistical theory, when the failure mechanism is not changed, the failure probability for the same sample under different acceleration stress is equal. Namely, the accelerated and the normal stress testing have the same testing ability in statistical sense, making these two testing methods equivalent. Therefore accelerated stress testing can be carried out on the MEMS accelerometer under vibration environment [9,10].

According to the principle of Miner, the cumulative damage of variable stress amplitude is expressed as:

\[ D_r = \sum \frac{\sigma_r \cdot N_i}{C} \]  

(1)

Assume that the same testing times under the equivalent constant stress amplitude and variable stress amplitude have the same damage, as is shown:

\[ D_r = \frac{\sum \sigma_r^k \cdot N_i}{C} \]  

(2)

Combining the expression (1) and (2) leads to the following equation:

\[ S_r = \left( \frac{1}{D_r} \right)^{\frac{1}{k}} \left( \frac{\sum \sigma_r \cdot N_i}{C} \right)^{\frac{1}{k}} \]  

(3)

The accelerated model of random vibration as accelerated stress conforms to the fatigue characteristics of S-N curve and its approximated formula can be represented as follows:

\[ NS^k = C \]  

(4)

where, \( k \) and \( C \) are material constants; \( S \) is the root mean square value of the stress, the \( N \) is the life of \( S \) stress.

Hypothesize the formula \( \eta = N/N_f \) (\( N_f \) is the constant value and the average life per unit time), then we can obtain the expression \( \eta = CS^{-k} \) from the formula (3) and (4). Take natural logarithm on both sides of the expression, we then have:

\[ \ln \eta = \alpha + \beta \ln S \]  

(5)

where \( \alpha = \ln C \), \( \beta = -k \). Therefore the failure physics equation of MEMS accelerometer under vibration stress can be described by using the inverse power law model, and the coefficient can be determined by \( \alpha \) and \( \beta \) according to the testing data, then the reliability informa-

Figure 4. Cantilever beam of MEMS accelerometer was fractured.

Figure 5. S-N curve.
tion of MEMS accelerometer can be predicted and evaluated via statistical methods.

4. Acceleration Testing under Random Vibration

4.1 Experiment Design

In order to simulate the vibration environment produced by guided missile, high-speed aircraft, and the rocket engine device, random vibration load is provided by digital electric vibration testing system. According to the designing principle of acceleration life testing under vibration environment, eighteen MEMS-accelerometers of low range with the same structure and batch processing are used as the testing samples. Based on the actual work stress and selection principle of stress levels, step accelerated constant stress testing are carried out under five high accelerated stresses in vibration environment. By adopting the complete life method, if the sample failure was found, failure time and failure mode will be recorded and analyzed. And after the sample all failed under one stress level, the next level stress testing was performed.

4.2 Testing Results

In accordance with the scheme of accelerated random vibration testing, the standard input spectral shape is adopted, as shown in Figure 6. Input acceleration spectral density under different vibration value is the same spectral shape (spectral shape includes frequency range, frequency conversion point and slope factor). The step constant stress vibration testing was carried out according to testing condition under five acceleration stress of different Grms as listed in Table 1. Because the standard value of accelerometer’s zero output is 2.5 V and the failure threshold is set to 0.1 V combing with application requirement, so if the MEMS accelerometer’s zero output exceeded the range from 2.4 V to 2.6 V or when there is obvious deviation about output curve or no output, MEMS accelerometer failure can be confirmed. And the failure time is recorded as shown in Table 1.

4.3 Statistical Analysis of Testing Data

The testing on distribution hypothesis was completed by statistical method in which the best distribution form with smaller value of the Anderson-Darling statistics was chosen. Because the statistics of Anderson-Darling measures the distance between data point and fitting line in the probability diagram, the smaller AD value, the better distribution of life data’s fitting [11,12]. The hypothesis testing results are shown in Figure 7. The distribution lines under each constant stress are approximately parallel, which verified not only no change in

<table>
<thead>
<tr>
<th>Stress level</th>
<th>Grms (g)</th>
<th>Failure time (hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>12</td>
<td>20.2 25.9 32.8 34.9 40.8 42.5</td>
</tr>
<tr>
<td>$S_2$</td>
<td>14</td>
<td>18.4 19.8 21.9 22.4 28.1 32.3</td>
</tr>
<tr>
<td>$S_3$</td>
<td>17</td>
<td>12.9 13.4 14.4 16.6 20.8 22.6</td>
</tr>
<tr>
<td>$S_4$</td>
<td>20</td>
<td>10.4 11.5 11.7 13.1 14.2 18.1</td>
</tr>
<tr>
<td>$S_5$</td>
<td>25</td>
<td>5.5 5.7 5.9 6.3 8.3 9.5</td>
</tr>
</tbody>
</table>

Figure 6. Spectrum of random vibration testing.

Figure 7. The distribution fit testing of failure time.
MEMS accelerometer’s failure mechanism even in the process of different accelerated testing under random vibration but also the basic assumptions of accelerated life testing. Therefore, MEMS accelerometer’s reliability index can be predicted in the designed stress environment by establishing a universal accelerated model.

5. Reliability Prediction for MEMS Accelerometer under the Designed Vibration Environment

According to the result of distribution hypothesis testing and because of the samples less than twenty-five, the point estimation value of shape parameter and scale parameter were solved using Best Linear Unbiased Estimation when the failure time obeys Weibull distribution, as shown in Table 2. The estimation value of the shape parameter looks consistent, which agrees with the constraints condition that distribution parameters are almost identical. Therefore we can analyze the reliability of MEMS accelerometer in the vibration environment based on the cumulative failure model.

The five data points of \((\ln S_k, \ln \eta_k)\) \(k = 1, 2, 3, 4, 5\) under each constant stress are plotted their linear fitting follows, as shown in Figure 8. It can be observed that the failure process of MEMS accelerometer in the vibration stress satisfies the inverse power law model with parameters \(\alpha = 8.7430\) and \(\beta = -2.062\), making the equation \(\ln \eta = 8.7430 - 2.062 \ln S\).

Based on the accelerated life equation, we can calculate the distribution parameters on failure life of MEMS accelerometer working under the designed vibration environment with \(S_0 = 6.06\) g. They are:

\[
m_0 = \sum_{k=1}^{5} n_k \hat{m}_k / \sum_{k=1}^{5} n_k = 3.768
\]

\[
\eta_0 = \exp(\alpha + \beta \ln S_0) = 152.6
\]

Therefore, the point estimation value of the reliability \(R(t)\) is:

\[
R(t) = \exp \left( -\frac{t}{\eta_0} \right) = \exp \left( -\left( \frac{t}{152.6} \right)^{1.708} \right)
\]

According to the equation of reliability \(R(t)\), reliability curve of MEMS accelerometer under the design vibration stress is plotted as shown in Figure 9. Considering the application background, failure criterion was set at \(R = 0.9\), and its reliability life was calculated as follows: \(t(R) = \eta_0 (-\ln R)^{(1/\beta)} = 83\) hours. It means that reliability will be less than 0.9 and more than 10% of MEMS accelerometers will fail after working 83 hours under the design vibration stress.

6. Conclusions

According to the application background of piezoresistive MEMS accelerometer with bilateral four beams
structure, this paper analyzed its failure mode in the vibration environment and analyzed the feasibility of random vibration accelerated testing method. In order to ensure the validity of parameter estimation and the robustness of accelerated testing, the step accelerated constant vibration stress testing was designed and sample’s failure time under each stress level based on the failure criterion was recorded. Besides, the research verified the distribution hypothesis of failure data by choosing the best distribution form with smaller value of Anderson-Darling statistics and estimated the shape parameter and scale parameters which obey Weibull distribution by using the Best Linear Unbiased Estimation. Because of the consistency of shape parameter, it was verified that the failure mechanism under each acceleration vibration stress almost holds, which confirmed to the feasibility of accelerated vibration testing. We can predict MEMS accelerometer reliability index under the design vibration stress by the method of establishing accelerated model. The accelerated step constant stress testing scheme under random vibration environment proposed in the paper saved testing time greatly and the statistical analysis method on testing data improved the credibility of life and reliability prediction effectively.

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