CHEMICAL ENGINEERING TRANSACTIONS

VOL. 33, 2013

Guest Editors: Enrico Zio, Piero Baraldi

ISBN 978-88-95608-24-2; **ISSN** 1974-9791

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1333091

Quartz Flexible Accelerometer Stability Duration Prediction on Storage Condition Based on Accelerated Degradation Test

Dan Xu*, Yunxia Chen, Rui Kang

School of Reliability and Systems Engineering, Beihang University, No.37 Xueyuan Road, Haidian District, Beijing 100191, China
xudan@buaa.edu.cn

The zero bias and the scale factor which are the important parameters of the accelerometer change with temperature and time due to the influence of material degradation and residual stress changing in the process of storage and use. For studying the stability duration of the parameters of the accelerometer on the storage condition, the accelerated degradation test is designed and applied. First, through analyzing the storage section and the mechanism of parameters changing on account of the environmental stress, the type of the stress in the accelerated degradation test is determined. Moreover, the working range of the stress of the accelerometer is obtained by implementing the enhancement test. Based on the type and the range of the stress, the constant temperature accelerated degradation tests are conducted under different levels of the thermal stress. The changing tendencies of the zero bias and the scale factor of the accelerometer subjected to the thermal stress are performed, and the models of key parameters of the accelerometer changing with time are separately built under different levels of ADT. Then the pseudo life of every level of the temperature test is extrapolated by regression models according to the failure threshold. Finally, the stability duration on the normal temperature is predicted by an accelerated function and the pseudo life on the high stress.

1. Instruction

Accelerometer is a kind of mechanical and electrical product which measures acceleration into electrical signal by various measuring methods. Quartz flexible accelerometer has the advantages of small volume, quickly response and high sensibility, thus they are rapidly applied in many fields such as transportation, aeronautics and astronautics, and very popular in some precision guided fields such as military field.
The main parameters of the accelerometer are the zero bias and the scale factor. Due to the influences of time and external environment, the main parameters are led into drift, which influence the stability duration of the accelerometer in the storage. The related researches are mainly about impact factors on measurement error of accelerometer (Liu, et al, 2002), environmental error modeling and compensation (Guo, et al, 2007).The parameters changing can be attributed to two factors: internal factors and environmental factors. The internal factors include the material, structure, component, circuit, manufacturing and other things; and specifically, factors of making accelerometer model coefficients instable are mainly as follows: residual stress of the internal structural material, magnetization and demagnetization effect of the torquer, internal stress by processing and assembly of mechanical structure and so on. Among the environmental factors which influence the accelerometer parameters changing, the temperature is one of the most important factors on the effect of the precision.
Generally, the storage stability duration of the accelerometer is comparatively long. It is an important problem to predict the stability duration in a short time. As for the slow degradation of high-reliability and long-life products, the accelerated degradation test provides a new method for predicting the reliability and life of these products. Boulanger and Escobar (1994) have researched ADT plan design for a kind of class degradation model. Wang (2009) has reported a kind of reliability assessment method for the functional unit based on ADT. In the data processing, Zhao and Elsayed (2004) have reported the degradation

Please cite this article as: Xu D., Chen Y., Kang R., 2013, Quartz flexible accelerometer stability duration prediction on storage condition based on accelerated degradation test, Chemical Engineering Transactions, 33, 541-546 DOI: 10.3303/CET1333091

process modeling by the random process. Bluvband (1995), Sun (2004) and Huang (2005) has studied the degradation modeling and parameters evaluation method for the ADT. And the ADT method has been gradually applied on various products, such as aerospace electrical connector (Chen, et al, 2011), LED (Wang, et al, 2012), induction motor (Wang, 2002).

This paper firstly applies the accelerated degradation test to predict the storage stability duration of the accelerometer. The constant high temperature accelerated degradation tests are conducted. The changing tendencies of the zero bias and the scale factor of the accelerometer under multi-temperature levels are performed. Then the pseudo life of every level of the temperature test is extrapolated by regression models according to the failure threshold. Finally, the stability duration on the normal temperature is predicted by an accelerated function and the pseudo life on the high stress.

2. Mechanism analysis of parameters changing

Quartz flexible accelerometer is composed of two parts, the header body and the servo circuit. Specifically, it is mainly composed of the soft magnet, alnico, flexible beam, torque coil and servo amplifier circuit.

Through analyzing the storage section and the mechanism of parameters changing on account of the environmental stress, the mechanism analysis results including weak taches, degradation mechanism and the type of the sensitive stress are shown in table 1. Considering the storage condition where the main stress is the temperature stress, the stress of the test is firstly determined to be temperature.

Table 1: Main Mechanism Analysis of the Accelerometer

No.	Parts	Weak tahces	Sensitive stress	Degradation mechanism	Key parameters
1	Pre-load loop close to two soft magnets	Welding stress relief	Vibration, temperature	Welding stress relief with time	Zero bias
2	Glue between pendulum and framework	Relative motion between pendulum and framework	Vibration, temperature	Glue creep	Zero bias, scale factor
3	Alnico	Demagnetization	Temperature, external magnetic field	Magnetic aging	Scale factor

3. Constant temperature accelerated degradation tests

3.1 Test Profile Design

Based on the enhancement test, the working range of the stress of the accelerometer is obtained. It is concluded that the high temperature working limit is 90°C through the high temperature step stress test. Then the constant temperature accelerated degradation tests are conducted under different levels of the thermal stress to predict the stability duration in the storage.

The temperature values of the experiment are designed as 70°C, 80°C and 90°C. In each temperature, at the beginning the accelerometers are maintained for 4 h in the chamber. Then the temperature is lowered to the normal temperature and the parameters of accelerometers are tested. In the experimental process, the changing tendencies of parameters need to be mainly observed in order to appropriately extend the holding time at the high temperature to be 8 h, 16 h or 20 h.

3.2 State and quantities of the samples

Due to high cost and limitation of the pilot samples, nine newly-produced accelerometers are adopted, which are only through one functional test. Five of them (1 #, 2 #, 3 #, 4#, 5#) are for 70°C accelerated degradation test, five (6 #, 7 #, 8 #, 9#, 10#) for 80°C accelerated degradation test and other five (11 #, 12 #, 13 #, 14#, 15#) are for 90°C accelerated degradation test.

3.3 Experimental parameters testing and termination conditions

After going through each cycle section, the accelerometer would be taken out of the test chamber and installed on the precision test bench. Then its zero bias K_0 and scale factor K_1 can be obtained according to the four-point testing method. The variations of these two parameters are used to represent the accelerometer stable state.

The accelerated degradation test is terminated when the variations of the zero bias and the scale factor meet the following conditions as equation (1) for three consecutive times.

$$\begin{cases} \left| K_0^i - K_0^0 \right| \geq 3000 \mu g \\ \left| \dfrac{K_1^i - K_1^0}{K_1^0} \right| \geq 3500 ppm \end{cases} \tag{1}$$

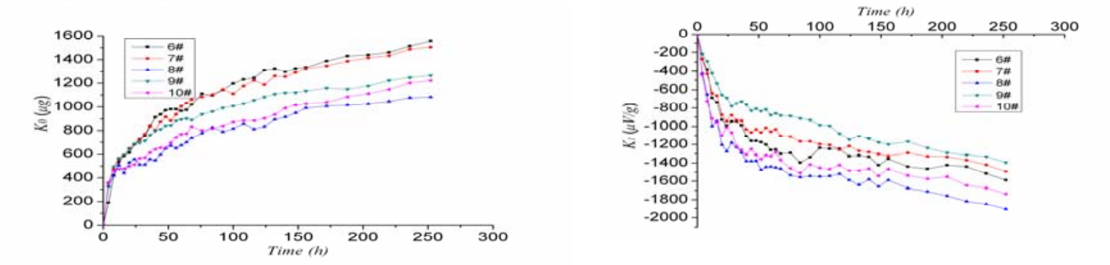
In the formula, K_0^i and K_1^i are respectively the zero bias and the scale factor after the *i*th experiment; the superscript *i* is the *i*th experiment. K_0^0 and K_1^0 are respectively the initial test value for zero bias and the initial test value for the scale factor before the experiment; the superscript '0' expresses the initial test before the experiment. If both the above-listed two criteria are not met, the ADT is terminated after 250 h.

4. Storage stability duration prediction

After the ADT, the data is analyzed based on the pseudo life at the normal storage temperature to predict the stability duration at a given reliability value and a confidence level. The prediction process for the stability duration is divided to three steps. First, the degradation models of the zero bias and the scale factor changing with time are separately built, and then the pseudo life of each accelerometer at every level of the temperature test is extrapolated by regression models according to the failure threshold. Second, the accelerated model is built by fitting the pseudo life, and the parameters of the model are obtained. Finally, the lower limit of the stability duration is extrapolated under normal temperature condition at a given reliability value and a confidence level on the basis of the accelerated model.

4.1 Degradation model fitting

The degradation paths of the variation of the zero bias under different stress show a common increasing trend (Figure 1(a)), so do degradation paths of the scale factor which are performed in Figure 1(b).



(a) K_0(μg)　　　　(b) K_1(μV/g)

Figure 1 Degradation paths of the variation of the zero bias and the scale factor at 80℃

The degradation paths describe the variation of parameters with time. The changing tendencies of the zero bias and the scale factor of the accelerometer subjected to the thermal stress are monotonic, and the rate of the variation is gradually reduced; therefore, the degradation paths can be fitted by the power model, namely,

$$y = y_0 + bt^{\alpha} \tag{2}$$

where *y* is the value of the parameter (as the zero bias or the scale factor) under the time *t*; y_0 is the initial value of the parameter; *b* is the rate of the variation; α is the correction constant, and it should meet $0 < \alpha < 1$.

The formula for linearization should be first done. The regression model is as follows,

$$y = y_0 + bx + \varepsilon \ , \ \varepsilon \sim N(0, \sigma^2) \tag{3}$$

where $x = t^{\alpha}$.

And q_i accelerometers at the *i*th temperature which is T_i ($T_1 < T_2 < T_i < \cdots < T_p$) are applied in the ADT. y_{ijk} is the parameter value of the *j*th accelerometer at the *k*th test time at the temperature T_i; $i = 1, 2, \cdots, p$; $j = 1, 2, \cdots, q_i$; $k = 1, 2, \cdots, n_{ij}$. The parameter y_{0ij} and b_{ij} in the degradation path model of the *j*th accelerometer at the temperature T_i can be estimated by virtue of the following formula,

$$\hat{y}_{0ij} = \overline{y}_{ij} - \hat{b}_{ij}\overline{x}_{ij} \quad (4) \qquad \hat{b}_{ij} = \frac{l_{\mathrm{xy}ij}}{l_{\mathrm{xx}ij}} \quad (5)$$

The correlation coefficient can be calculated as follows,

$$r_{ij} = \frac{l_{\mathrm{xy}ij}}{\sqrt{l_{\mathrm{xx}ij} l_{\mathrm{yy}ij}}} \quad (6)$$

where

$$x_{ijk} = t_{ijk}^{\alpha} \quad (7) \qquad \overline{x}_{ij} = \frac{1}{n_{ij}} \sum_{k=1}^{n_{ij}} x_{ijk} \quad (8)$$

$$\overline{y}_{ij} = \frac{1}{n_{ij}} \sum_{k=1}^{n_{ij}} y_{ijk} \quad (9) \qquad l_{\mathrm{xx}ij} = \sum_{k=1}^{n_{ij}} (x_{ijk} - \overline{x}_{ij})^2 \quad (10)$$

$$l_{\mathrm{xy}ij} = \sum_{k=1}^{n_{ij}} (x_{ijk} - \overline{x}_{ij})(y_{ijk} - \overline{y}_{ij}) \quad (11) \qquad l_{\mathrm{yy}ij} = \sum_{k=1}^{n_{ij}} (y_{ijk} - \overline{y}_{ij})^2 \quad (12)$$

It is assumed that the degradation path at the maximum stress level can better reflect the degradation tendency of the parameter. According to the principle called the maximum average correlation coefficient at the maximum stress level, the exponential parameter is determined (Ma, 2012) by virtue of the following formula,

$$\alpha = \arg\max\left\{\overline{r^2(S_{\max})} : \alpha \in \{\alpha \mid 0 < \alpha < 1\}\right\} \quad (13)$$

where $S_{\max}$ is the maximum stress level, in this experiment $S_{\max}$ is namely $T_{p-1} = 90$ °C.

The maximum average correlation coefficient meets $\overline{r^2(S_{\max})} = \overline{r^2(T_{p-1})}$ and can be calculated as follows,

$$\overline{r^2(T_{p-1})} = \sum_{j=1}^{q_p} r_{(p-1)j}^2 \Big/ q_{p-1} \quad (14)$$

4.2 Pseudo life estimation

After obtaining the parameter of the degradation model, the pseudo life at each stress level can be obtained by the end of the failure threshold.

The failure threshold of the zero bias under the storage condition is $|\Delta K_0| = 3\mathrm{mg}$.

Then the pseudo life estimation of the zero bias is $\hat{t} = \sqrt[\alpha]{3 / |\hat{b}|}$

The failure threshold of the scale factor under the storage condition is $\left|\frac{\Delta K_1}{K_1^0}\right| = 0.0035$

where K_1^0 is the initial test value for the scale factor; ΔK_1 is the difference between the failure value and the initial value for the scale factor.

Then the pseudo life estimation of the scale factor is $\hat{t} = \sqrt[\alpha]{0.0035|\hat{y}_0| / |\hat{b}|}$

4.3 Parameters estimation of the accelerated model

Due to the accelerated stress is the temperature stress, the Arrhenius model is applied for the accelerated model as follows,

$$t = C\exp\left(\frac{B}{T}\right) \quad (15)$$

where *T* is the absolute temperature (unit: K); *C* is a constant; $B = E/k_B$, and *E* is the activation energy; k_B is the Boltzmann constant.

The goodness-of –fittest under each stress level shows that the pseudo life of the zero bias of the accelerometer follows the Lognormal distribution, and the pseudo life of the scale factor follows the Weibull distribution where the software ALTA is applied.

The accelerated model of the zero bias is $t_{K_0} \sim LN(\ln C_{K_0} + \frac{B_{K_0}}{T}, \sigma_{K_0}^2)$

The accelerated model of the scale factor is $t_{K_1} \sim Weibull(C_{K_1}\exp(\frac{B_{K_1}}{T}), m)$

Then we conduct the maximum likelihood estimation (MLE) method to estimate the parameters. And the results are shown in Table 2 and Table 3.

Table 2: Parameter Estimation of Accelerated Model of the Zero Bias

Parameter	MLE	Fisher Matrix		
		σ_{K_0}	B_{K_0}	C_{K_0}
σ_{K_0}	1.4387	0.0517	4.33E-10	-6.00E-22
B_{K_0}	1.0923E+4	4.33E-10	1.24E+07	-1.72E-05
C_{K_0}	4.8392E-10	-6.00E-22	-1.72E-05	2.39E-17

Table 3: Parameter Estimation of Accelerated Model of the Scale Factor

Parameter	MLE	Fisher Matrix		
		β	B_{K_1}	C_{K_1}
β	1.9768	0.0854	-28.5842	2.3379E-09
B_{K_1}	9390.7254	-28.5842	3.2053E+06	-0.000236
C_{K_1}	2.62E-08	2.3379E-09	-0.000236	1.7424E-14

4.4 Stability duration evaluation

Because the pseudo life of the zero bias follows a Lognormal distribution and that of the scale factor follows a Weibull distribution, the stability duration with the reliability *R* of the zero bias and the scale factor can be separately written as follows,

$$t_{K_0,R} = C_{K_0}\exp(\frac{B_{K_0}}{T} - u_R\sigma_{K_0}) \quad (16)$$

$$\ln t_{K_1,R} = \ln C_{K_1} + \frac{B_{K_1}}{T} + \frac{1}{m}\ln(\ln\frac{1}{R}) \quad (17)$$

where $t_{K_0,R}$ is the stability duration with a predefined reliability level of the zero bias; $t_{K_1,R}$ is the stability duration with a predefined reliability level of the scale factor; $u_R = \Phi^{-1}(R)$.

For the Lognormal distribution and the Weibull distribution, the lower bounds of the reliability stability duration $t_{R,\gamma}$ can be separately obtained by the following formula,

$$t_{K_0,R,\gamma} = t_{K_0,R} - u_\gamma\sqrt{Var(t_{K_0,R})} \quad (18)$$

$$\ln t_{K_1,R,\gamma} = \ln t_{K_1,R} - u_\gamma\sqrt{Var(\ln t_{K_1,R})} \quad (19)$$

Where the index γ indicates the confidence level and $Var(\cdot)$ is the variance and can be calculated by the following formula,

$$\begin{aligned} Var(t_{K_0,R}) = & \frac{\partial^2 t_{K_0,R}}{\partial^2\sigma_{K_0}}Var(\sigma_{K_0}) + \frac{\partial^2 t_{K_0,R}}{\partial^2 B_{K_0}}Var(B_{K_0}) + \frac{\partial^2 t_{K_0,R}}{\partial^2 C_{K_0}}Var(C_{K_0}) + 2\frac{\partial^2 t_{K_0,R}}{\partial\sigma_{K_0}\partial B_{K_0}}Cov(\sigma_{K_0}, B_{K_0}) \\ & + 2\frac{\partial^2 t_{K_0,R}}{\partial\sigma_{K_0}\partial C_{K_0}}Cov(\sigma_{K_0}, C_{K_0}) + 2\frac{\partial^2 t_{K_0,R}}{\partial B_{K_0}\partial C_{K_0}}Cov(B_{K_0}, C_{K_0}) \end{aligned} \quad (20)$$

$$Var(\ln t_{K_1,R,\gamma}) = \frac{\partial^2 \ln t_{K_1,R}}{\partial^2 B_{K_1}} Var(B_{K_1}) + \frac{\partial^2 \ln t_{K_1,R}}{\partial^2 C_{K_1}} Var(C_{K_1}) + \frac{\partial^2 \ln t_{K_1,R}}{\partial^2 m} Var(m) + 2\frac{\partial^2 \ln t_{K_1,R}}{\partial B_{K_1}\partial C_{K_1}} Cov(B_{K_1}, C_{K_1}) + 2\frac{\partial^2 \ln t_{K_1,R}}{\partial B_{K_1}\partial m} Cov(B_{K_1}, m) + 2\frac{\partial^2 \ln t_{K_1,R}}{\partial C_{K_1}\partial m} Cov(C_{K_1}, m) \quad (21)$$

Therefore, under the given storage condition (T=293°C) of the accelerometer, the lower bound of the reliable stability duration at the given confidence level $\gamma = 0.9$ and reliability value $R = 0.9$ is calculated as follows,

The reliable stability duration of the zero bias is $t_{K_0,R,\gamma} = 4995$ h;
The reliable stability duration of the scale factor is $t_{K_1,R,\gamma} = 115219$ h.
Therefore, the stability duration of the accelerometer is 4995 h (about 0.57 y) according to the shorter reliable stability duration between the two parameters.

5. Conclusions

In this paper, we first analyze the main mechanism of parameters changing of the accelerometer. Based on the main mechanism, we attempt to apply the constant temperature accelerated degradation test to predict the stability duration of the accelerometer on the storage condition. Two step analysis method can be applied in the data processing of the ADT of the accelerometer to predict the reliability and lifetime, which is first to extrapolate the pseudo life on the high stress and then estimate the parameters of the accelerated model. By virtue of analyzing the test data by this method, the lower bound of stability duration at the normal temperature is predicted by the accelerated model at the given reliability value and confidence level.

References

Bluvband Z., Peshes L., 1995, Accelerated Life Testing for Products Without Sequence Effect, Proceedings Annual Reliability and Maintainability Symposium, New Orleans, LA, USA, 16-19 Jan, pp.341-347.

Boulanger M., Escobar L. A., 1994, Experimental design for a class of accelerated degradation tests, Technometrics, Vol.36, No.3, pp.260-272.

Chen WH, Liu J, Gao L, Pan J, Zhou SJ, 2011, Accelerated degradation reliability modeling and test data statistical analysis of aerospace electrical connector, Chinese Journal of Mechanical Engineering, Vol.24, No.6, pp.957-962.

Guo RQ, Zheng XD, Wang C, 2007, Study of the identification for the static temperature model and the method for compensating temperature of the accelerometer, Journal of Xidian University : natural science edition, Vol.34, No.3, pp.438-442. (in Chinese)

Huang W, Dietrich D. L., 2005, An Alternative Degradation Reliability Modeling Approach Using Maximum Likelihood Estimation, IEEE Transactions on Reliability, Vol. 54, No. 2, pp.310-317.

Liu XD, Ding XP, Lei LM, 2002, Influence factors and theoretic analysis for model coefficient of accelerometer, Journal of Transducer Technology, Vol. 21, No. 2, pp.29-32. (in Chinese)

Ma XB, Chang SH, Chen YX, 2012, Method for linearize power function with three parameters of incomplete accelerated degradation data, Journal of Beijing University of Aeronautics and Astronautics (network edition).

Sun Q, Zhou JL, Zhong Z, Zhao JY, Duan XL, 2004, Gauss–Poisson Joint Distribution Model for Degradation Failure, IEEE Transactions on Plasma Science, Vol. 32, No. 5, pp.1864-1868.

Wang YM, Cai JY, 2009, Reliability assessment of functional unit based on accelerated degradation data, Proceeding of 2009 8th international conference on reliability, maintainability and safety, Chengdu, Sichuan province, China, 21-25 July, pp.1297-1301.

Wang FK, Chu TP, 2012, Lifetime predictions of LED-based light bars by accelerated degradation test, Microelectronics Reliability, Vol. 52, No. 7, pp.1332-1336.

Wang WD, 2002, Reliability quantification of induction motors- accelerated degradation testing approach, Annual Reliability and Maintainability Symposium, 2002 Proceedings, Settle, WA, USA, 31 Jan, pp.325-331.

Zhao WB, Elsayed E. A., 2004, An Accelerated Life Testing Model Involving Performance Degradation, Annual Reliability and Maintainability Symposium, 2004 Proceedings, 26-29 Jan, pp.324-329.