Reliability evaluation of grating encoder based on the accelerated degradation test

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Abstract. In order to overcome the difficulty in evaluating the reliability of grating encoders in a short time for its high reliability level, a reliability evaluation method based on the accelerated degradation test is proposed. First, according to the accelerated model with two types of stresses, an accelerated test scheme is designed. Then, models of linear degradation paths under different stress levels are established based on characteristic degradation quantity. Furthermore, the pseudo time between failures is solved according to the failure threshold value. Afterwards, a reliability model of grating encoders with a variable of pseudo time between failures is developed. At the same time, mean time between failures is estimated under different stress levels by the maximum likelihood estimation method and simulated annealing algorithm. Finally, the parameters of the accelerated model are solved and the reliability of the grating encoder at the normal stress level is evaluated.

1. Introduction
For high reliability products, conventional reliability tests and accelerated reliability tests have difficulty in obtaining enough failure data in limited test time. In order to save test time and test cost, accelerated degradation test (ADT) is employed with the assumption that one or more performance characteristics are directly related to product life or reliability and have the trait of gradual declining with time [1]. The degradation data contains a lot of information about reliability and life of product, which can be applied to assess life or reliability of products [2, 3].

With the rapid development of ADT recently, the experimental stress has developed from single stress [4] to multi types of stresses [5, 6], and test object has developed from material or cell level to component or whole machine level [7, 8]. Many scholars employed step-stress accelerated degradation test (SSADT) to estimate model parameters and converted data based on equivalent degradation criterion [9-11]. For example, Haghighi and Bae carried out SSADT for newly developed products or very expensive products to evaluate reliability [12]. Although test time is short with low cost, the accuracy of established model is low compared with that under constant stress accelerated degradation test (CSADT) [13, 14]. Therefore, CSADT is widely employed for evaluating products’ reliability [15, 16].

This paper is devoted to establish the reliability model of grating encoder based on CSADT. The remainder of this paper is organized as follows: in section 2, an accelerated model with two stresses of temperature and humidity is selected. Section 3 designs the accelerated test scheme. In section 4, the power consumption degradation models of grating encoder are established. Section 5 assesses the
reliability of grating encoder under different stress levels. In section 6, reliability model of grating encoder under the normal stress level is established. Section 7 concludes this paper.

2. Accelerated model
Based on a certain rule of product life or reliability characteristic value under different stress levels, the accelerated model is a mathematical model reflecting the relationship between product life (or reliability characteristic value) and stress level. Currently, temperature, humidity, electrical stress and vibration are commonly used as accelerated stresses in ADT [17]. As known to all, the life of electronic products is highly influenced by working environment mainly including temperature and humidity. Therefore, temperature and humidity are selected as accelerated stresses for grating encoder in this paper.

The accelerated models with two types of stresses include T-H model, T-N model and Generalized Eyring model. T-H model, also namely double-Arrhenius model, is suitable for stresses about temperature and humidity; T-N model is widely employed for a temperature stress and a non-thermal stress mainly including mechanical and electronic stresses; and Generalized Eyring model is a complex model for a temperature stress and another stress including humidity and electronic stresses. Therefore, a simple and suitable model, T-H model, is employed in this paper for temperature and humidity stresses as shown in Equation (1).

\[ \eta=A\exp\left(\frac{B}{T} + \frac{C}{RH}\right) \]  

(1)

Where, \( \eta \) is characteristic life, \( T \) is absolute temperature, \( RH \) is relative humidity. A, B and C are model parameters.

3. Design of test scheme
Seen from Equation (1), there are at least three groups of stress levels and their characteristic life solving model parameters. In order to improve the efficiency of accelerated test, the values of temperature and humidity selected in the accelerated test are in a high level. Meanwhile, the test scheme is designed with uniform design method as shown in table 1.

| NO. | Stress level | Number of samples | 1/T  | 1/RH | Temperature (K) | Humidity (%RH) | Expected test time (h) |
|-----|--------------|--------------------|------|------|-----------------|----------------|-----------------------|
| 1   | S1           | 24                 | 0.0029 | 1.43 | 343             | 70             | 1000                  |
| 2   | S2           | 24                 | 0.0028 | 1.30 | 355             | 77             | 800                   |
| 3   | S3           | 24                 | 0.0027 | 1.17 | 368             | 85             | 600                   |

Twenty-four grating encoders from the same batch, fixed on the reliability test rig with modular design, are used as a group of test objects. The whole test rig is placed in the THV-600 Temp/Humid/Vibration chamber which is an equipment for loading temperature and humidity stresses shown in figure 1.

![Figure 1. Test equipment of grating encoders.](image)

![Figure 2. Power degradation model.](image)
4. Degradation model

In order to simplify the degradation model of grating encoders, dimensionality reduction of its multivariate degradation data is employed. After principal component analysis, it is obvious that the laws of degradation of electrical signals of grating encoders are similar. Thus, one of the typical electrical signals is selected as the main performance degradation feature. As shown in figure 2, the power consumption degradation path of sample 1 under stress level S1 is generally linear.

It can be seen from figure 2 that the power consumption degradation of grating encoder can be approximately described by the following linearized equation:

\[ I = -0.0015t + 119.93 \]

According to degradation path, when the failure threshold is 115mA, the corresponding running time is 3286.7h, which is also called pseudo time between failures (TBF). The pseudo TBF of the remaining samples can be calculated in the same way and the results are shown in empirical distribution figure with a fitting line as shown in figure 3.

5. Reliability assessment under different stress levels

Three groups of pseudo TBF are used to established reliability models respectively, and then characteristic life, mean time between failures (MTBF), is solved. Here, pseudo TBF can be regarded as TBF and take the group of TBF under stress level S1 as an example for estimation of MTBF.

First, TBF should be divided into several groups. The number of groups is determined by Equation (2).

\[ K = 1 + 3.322\log_{10}(n) \]  

(2)

Where, \( K \) is the number of groups, and \( n \) is the number of TBF.

When \( n = 24 \), \( K \approx 5.58 \). Here, \( K \) is set as 5. After division, frequency histogram and cumulative frequency histogram are drawn in figure 4 and figure 5, respectively.
Secondly, the group of TBF should be sorted from small to large: \( t_1, t_2, \ldots, t_n \). The median rank estimation of the empirical distribution function is described in Equation (3).

\[
F(t_i) = \frac{i - 0.3}{n + 0.4}, \quad i = 1, 2, \ldots, n
\]  

(3)

According to Equation (3), empirical distribution function can be calculated and drawn in figure 6.

Thirdly, Weibull distribution with two parameters is selected as TBF distribution of grating encoder according to figure 4-6. The Weibull distribution function is shown in Equation (4).

\[
F(t) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^\beta\right] \quad t \geq 0
\]  

(4)

Fourthly, distribution parameters should be estimated. In general, Weibull distribution is linearly changed firstly and linear regression is employed to solve its parameters. However, this method has larger error. Therefore, maximum likelihood estimation (MLE) and simulated annealing algorithm are employed for parameters estimation in the paper. The results are shown in table 2.

| Stress level | S1     | S2     | S3     |
|-------------|--------|--------|--------|
| \( \alpha \) | 5358.6 | 3844.6 | 3357.4 |
| \( \beta \)  | 2.1    | 1.4    | 1.2    |
| MTBF (h)    | 4747   | 3504   | 3165   |

Table 2. Results under different stress levels.

Seen from table 2, \( \beta \) is different under different stress levels, while \( \beta \) keeps same theoretically. It can be explained from three aspects: the samples of three reliability models are too small to establish accurate model; different test time causes different damaged degree of grating encoder resulting in different errors of pseudo TBF to true TBF; three groups of samples extracted from big samples must have difference from each other resulting in different \( \beta \). Therefore, with the error increasing, \( \beta \) may be different greatly under different stress levels.

Finally, the fitting models should be checked. The model checking is mainly divided into graphic method and analytic method. \( \chi^2 \) test method and K-S test method are main analytical method, suitable for discrete distribution and continuous distribution respectively. Moreover, \( \chi^2 \) test method is not suitable for small-sample situation. Hence, PP diagram is employed to check the reliability models shown in figure 7.

![Figure 6. Empirical distribution figure.](image)

![Figure 7. PP diagram.](image)

Seen from figure 7, the fitting curve can be nearly regarded as a line passing origin point with a slope of 1, so the reliability fitting model is reasonable.
6. Reliability assessment under normal stress level

Substituting MTBF and stress levels into accelerated model, the parameters of the accelerated model can be solved and the accelerated model are shown in Equation (5).

\[ \eta = 15.3 \times \exp \left( \frac{1707}{T} + \frac{53.3}{RH} \right) \] (5)

Substituting normal stress S\(0\) (313K, 30%RH) into accelerated model, MTBF of the Grating encoder under normal stress level is 21117h. Acceleration factor under different stress levels can be calculated through Equation (6) and the results are shown in table 3.

| Stress level | S1 | S2 | S3 |
|-------------|----|----|----|
| Acceleration factor | 4.45 | 6.03 | 6.67 |

\[ a = \frac{\text{MTBF}_{S0}}{\text{MTBF}_{S_i}} \] (6)

According to acceleration factor, the data of TBF under different stress levels can be converted to that under the normal stress level. Then the TBF under the normal stress level can be used to establish the reliability model. Distribution function and WPP diagram are shown in figure 8 and figure 9, respectively.

Model parameters and MTBF estimation of grating encoder under the normal stress level are shown in table 4.

| Item       | \(\alpha\) | \(\beta\) | MTBF | Interval estimation under different credibility levels | 0.95 | 0.9 | 0.8 |
|------------|----------|----------|------|-----------------------------------------------------|------|----|----|
| Value      | 23271    | 1.43     | 19444| \[18932,20008\] [19013,19917] [19109,19814] |      |    |    |

Therefore, the reliability function of grating encoder under the normal stress is shown in Equation (7).

\[ R(t) = \exp\left[ -\left( \frac{t}{23271} \right)^{1.43} \right] \quad t \geq 0 \] (7)

7. Conclusions

(1) CSADT is firstly applied to grating encoder: compared with degradation test, it greatly shortens the evaluation cycle; compared with SSADT, it has higher modelling accuracy with larger sample sizes.

(2) In order to evaluate the reliability of grating encoder in a short time, CSADT is carried out through improving its temperature and humidity stresses with employing linear degradation models to describe the power consumption degradation of grating encoders.
(3) According to the accelerated model established in the accelerated test with temperature and humidity stresses, acceleration factor is 4.45 under 343K and 70%RH; acceleration factor is 6.03 under 355K and 77%RH; and acceleration factor is 6.67 under 368K and 85%RH.

(4) Weibull distribution are selected as the reliability model of grating encoder under the normal stress level. The parameters of it are evaluated as $\alpha = 23271$ and $\beta = 1.43$. And MTBF under the normal stress level is estimated as 19444 hours.

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