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STUDY OF AN ADAPTIVE ACCELERATED MODEL AND A DATA TRANSFER METHOD BASED ON A RELIABILITY ENHANCEMENT TEST

BADANIA ADAPTACYJNEGO MODELU PRZYSPIESZONEGO ORAZ METODY TRANSFERU DANYCH W OPARCIU O TEST POPRAWY NIEZAWODNOŚCI

To assess the reliability of a product using a Reliability Enhancement Test (RET), this study first considers the change process of the Arrhenius model parameters by combining the Arrhenius model with the Duane model and gives an adaptive accelerated model and a parameter estimation method. Then, the data transfer method from the RET to normal test stress are described based on the adaptive accelerated model. Finally, the differences observed when the RET is used for a reliability identity test or a reliability growth test are discussed, and an engineering case demonstrates a method for obtaining the reliability index of a product using the RET.

***Keywords**: reliability enhancement test, Arrhenius model, Duane model, adaptive accelerated model, acceleration factor.*

Aby ocenić niezawodność produktu za pomocą testu poprawy niezawodności (Reliability Enhancement Test, RET), w badaniach najpierw rozważano proces zmiany parametrów modelu Arrheniusa poprzez połączenie modelu Arrheniusa z modelem Duane'a oraz przedstawiono adaptacyjny model przyspieszony i metodę oceny parametrów. Następnie, na podstawie adaptacyjnego modelu przyspieszonego opisano metodę transferu danych z RET do badań przy normalnym oddziaływaniu czynników zewnętrznych. Wreszcie, omówiono różnice obserwowane przy zastosowaniu RET do badań identyfikacyjnych niezawodności i badań wzrostu niezawodności. Na przykładzie zagadnienia inżynierskiego przedstawiono także metodę obliczania wskaźnika niezawodności produktu za pomocą RET.

***Słowa kluczowe**: test poprawy niezawodności, model Arrheniusa, model Duane'a, adaptacyjny model przyspieszony, współczynnik przyspieszenia.*

1. Introduction

Reliability enhancement tests (RETs) can quickly stimulate the latent defects of a product by using the accelerated test stress in the product development stage, which is an effective approach for improving product reliability [2, 6, 14].

Since 1988, many researchers have studied this area, and RETs have been used in engineering. For instance, a RET was used in a Sidewinder development stage [7] and in a radar development stage [16]. Although RETs can effectively improve product reliability, the product reliability index cannot be quantitatively given. The development of methods for assessing product reliability have been the focus of RET research. Determining how to set up an accelerated model, and understanding how to transfer data from a RET to a normal stress test through an accelerated model, are the core problems of RET research. Mike Silverman [8, 9], Harry Mclean [4] and Pascal Lantieri [13] have done some researches on assessment of products in the RET.

In the process of conducting a RET, the design defects of a simulated product are improved to rapidly increase the product reliability. Thus, the parameters of the accelerated model also change as the product reliability increases. In focusing on the adaptive accelerated model of a RET, this study first considers the change process of the Arrhenius parameters and obtains an adaptive accelerated model by combining the Arrhenius model with the Duane model. Then, the parameter estimation and the data transfer method of the RET data are given based on the new model, and the difference observed when the RET is used for reliability assessment and reliability growth is analyzed. Finally, an engineering case verifies that the accelerated model is correct and useable.

This study first presents the adaptive accelerated model of a RET, by combining the Arrhenius accelerated model and the Duane increase model, examining the change process of the Arrhenius accelerated model parameters, and setting up the adaptive accelerated model. Next, it presents the estimated measure of the adaptive accelerated model parameter, and the enhancement step in the test data transfer of the adaptive accelerated model. Finally, analyses are presented of the differences observed due to RET technology used in a reliability identity test and a reliability growth test.

2. Model hypotheses

(1) Product life is assumed to follow an exponential distribution for each stress level, and after the product is improved, the parameters of the product life distribution change, but the distribution function type does not change.

(2) Product life and the accelerated test stress follow the Arrhenius model, and the test data transferred from the RET test stress to the normal test stress follow the Duane model.
(3) The residual life of the product only depends on the current accumulated failure and the current stress value and is not dependent on the cumulative method.

For most electronic and mechatronical products, the life distribution follows an exponential distribution. Product improvements are generally only partially carried out so that the basic attributes of the product are not changed, i.e., after the improvement, they are still mechatronical products, so hypothesis 1 is satisfied.

The Arrhenius model is generally used in accelerated life tests of products. Generally, for product failure under different stress test levels, the same corrective measures are employed, so data transferred to the normal stress test will follow the Duane model, i.e., hypothesis 2 is satisfied.

Hypothesis 3 was proposed by Nelson based on the physics-of-failure (POF), and for the data transfer problem in the step stress test, hypothesis 3 is satisfied.

3. Adaptive accelerated model

the product life varies under different temperature stresses. For a product whose life follows an exponential distribution, the characteristics of the product life can be described by the Arrhenius accelerated model [10, 15]:

$$L = Ae^{\frac{Ea}{kT}} \tag{1}$$

Here, ***A*** is a constant that depends on the product geometry, the specimen size and fabrication, the test method, and other factors. E_a is the activation energy of the reaction, usually in electron-volts. ***k*** is Boltzmann's constant, 8.6171×10^{-5} electron-volts per °C. ***T*** is the absolute temperature in Kelvin, which is equivalent to the Centigrade temperature plus 273.16 degrees.

Obviously, according to Equation (1), the relation of the product life under different temperature stresses is expressed as follows:

$$A_F = \frac{L_0}{L_1} = \frac{A\ e^{\frac{Ea}{kT_0}}}{A\ e^{\frac{Ea}{kT_1}}} = e^{\frac{Ea}{K}(\frac{1}{T_0}-\frac{1}{T_1})} \tag{2}$$

Here, L_1 is the product life under the accelerated test stress, L_0 is the product life under the normal test stress, T_0 is the normal test temperature stress, and T_1 is the accelerated test temperature stress.

A_F is generally called the acceleration factor [5] and is used in the transfer of failure data for a product at two stress levels. After obtaining failure data for a product in an accelerated test, the test data for normal stress can be transferred through the acceleration factor using the following equation:

$$L_{0i} = L_{1i}e^{\frac{Ea}{K}(\frac{1}{T_0}-\frac{1}{T_1})} \tag{3}$$

When carrying out the RET, the product should be continuously improved to determine its reliability growth. This process causes the activation energy E_a of failure due to the stimulated latent defects to grow as the product reliability increases. Thus, it is necessary to ensure that the evolution of the activation energy E_a of the acceleration factor during the test time allows the RET data to be transferred to normal test stress data; such a change process can be obtained by combining the Arrhenius model with the Duane model.

In a traditional reliability growth test that simulates the practical stress of a product, the Duane growth model [1, 11] has shown that the cumulative failure rate plotted against the cumulative test time in a log-log space exhibits an almost linear relationship and can give the instantaneous MTBF of the product because the mean life of the product can be expressed by the MTBF for an exponential product, namely, the instantaneous MTBF of the product is equal to the product mean life at the current moment. Therefore, based on the Arrhenius accelerated model and the Duane growth model, the following equation can be found:

$$M\hat{T}BF = \frac{{t_0}^m}{a(1-m)} = L_0 = Ae^{\frac{E_a(t)}{kT_0}} \tag{4}$$

Here, ***a*** is a scale parameter, ***m*** is the growth rate(0<m<1), t_0 is the cumulative test time for the normal stress, $M\hat{T}BF$ is the instantaneous MTBF at t_0, and L_0 is the mean life at t_0.

According to Equation (4), the activation energy E_a can be expressed as a function of the cumulative test time under the normal test stress,

$$E_a(t_0) = kT_0 \times Ln\frac{{t_0}^m}{B(1-m)} \tag{5}$$

where $B = A\times a$.

In the RET, the reliability of the product increases at each stress level with product improvement, and thus, the activation energy E_a will increase as well. Obviously, the activation energies of the RET for the time interval $(t_{1i},\ t_{1(i+1)})$, from the i^{th} to the $(i+1)^{th}$ failure, and that for the time interval $(t_{0i},\ t_{0(i+1)})$ transferred to the normal stress test E_{ai} are equal. Therefore, the activation energy at any moment t_1 under the accelerated stress test is equivalent to that at t_0 under the normal stress test. The data transfer process from the RET to the normal test is shown in Figure 1.

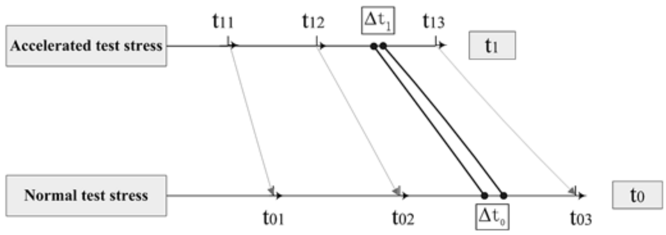

Fig. 1. The data transfer process

Figure 1 shows that the activation energy E_a is constant in the minimal interval $\Delta t_1 \to 0$ and $\Delta t_0 \to 0$. Assuming that the value of E_a is $E_a(t_0)$, then Δt_1 and Δt_0 follow Equation (3):

$$\Delta t_0 = \Delta t_1 \times e^{\frac{E_a(t_0)}{K}(\frac{1}{T_0}-\frac{1}{T_1})} \tag{6}$$

According to Equation (6), can be expressed by Equation (7).

$$t_1 = \int_0^{t_0} e^{\frac{Ea(t_0)}{K}(\frac{1}{T_1}-\frac{1}{T_0})} dt_0 \tag{7}$$

Based on Equations (7) and (5), the relation between the cumulative time t_1 of the accelerated stress test and the cumulative time t_0 of the normal stress test is described by the following expression:

$$t_0 = \left\{ t_1 \left[(\frac{1}{T_1}-\frac{1}{T_0})T_0 m+1 \right] \times \left[B(1-m) \right]^{(\frac{1}{T_1}-\frac{1}{T_0})T_0} \right\}^{\frac{1}{(\frac{1}{T_1}-\frac{1}{T_0})T_0 m+1}} \tag{8}$$

Equation (8) is obtained by replacing t_0 in Equation (5), and the activation energy E_a for the cumulative test time of the RET is expressed as Equation (9):

$$E_a(t_1) = kT_0 \times Ln \frac{\left\{ t_1 \left[(\frac{1}{T_1}-\frac{1}{T_0})T_0 m+1 \right] \times \left[B(1-m) \right]^{(\frac{1}{T_1}-\frac{1}{T_0})T_0} \right\}^{\frac{m}{(\frac{1}{T_1}-\frac{1}{T_0})T_0 m+1}}}{B(1-m)} \tag{9}$$

After finding the expression for $E_a(t_1)$, the Arrhenius model can be rewritten as follows for the RET:

$$L = \mathrm{A} e^{\frac{Ea(t_1)}{kT}} \tag{10}$$

Moreover, the acceleration factor of the RET is expressed by Equation (11):

$$A_{Fi} = \frac{L_{0i}}{L_{1i}} = e^{\frac{E_a(t_1)}{k}(\frac{1}{T_0}-\frac{1}{T_1})} \tag{11}$$

4. RET data transfer method

4.1. Parameter estimation of the acceleration factor

based on the accelerated model assumption and assuming that the RET is conducted under different accelerated stresses, the parameters of the adaptive accelerated model can easily be estimated by Equation (11), i.e., the conversion factor for any two accelerated stress data sets is described as follows:

$$A_{F12i} = \frac{L_{1i}}{L_{2i}} = e^{\frac{E_a(t_1)}{k}(\frac{1}{T_1}-\frac{1}{T_2})} \tag{12}$$

Using Equation (9), we can rewrite Equation (12) in logarithmic form,

$$\ln\frac{L_{1i}}{L_{2i}} = \frac{Dm}{Cm+1}\ln t_{1i} + \frac{Dm}{Cm+1}\ln(Cm+1) - \frac{D}{Cm+1}\ln B - \frac{D}{Cm+1}\ln(1-m) \tag{13}$$

where $C = (\frac{1}{T_1}-\frac{1}{T_0})T_0$, $D = \left(\frac{1}{T_1}-\frac{1}{T_2}\right)T_0$.

Obviously, by using Equation (13), the acceleration factor can be estimated by the least squares method.

4.2. RET test data transfer method

obviously, the product reliability is improved step by step in the RET, and the activation energy E_a increases as well. When transferring the RET data to normal test data for the time interval between the i^{th} failure and the $i+1^{th}$ failure, the cumulative time for Equation (9), t_1, should be the total test time before the i^{th} failure.

The Duane model makes the activation energy infinitesimal when the initial time is zero[11]. Therefore, when we first transfer the failure data for each stress level, the activation energy E_a is the value of the last stress level at the last time step. For the first test stress level, the first failure data point will be used to calculate the E_a of the second failure data point. Thus, the data transfer process will begin from the second failure data point.

Through the above analysis, the steps of transferring the RET test data to normal test stress data based on the adaptive accelerated model (10) are described as follows:

$$L_{0j} = L_{ij} A_{Fij} \tag{14}$$

where $L_{ij} = t_{ij} - t_{i(j-1)}$ is the time interval from the $j-1^{th}$ failure to the j^{th} failure at the i^{th} stress level. $L_{0j} = t_{0j} - t_{0(j-1)}$ is the time interval from the j-1^{th} failure to the j^{th} failure after the RET data are transferred to the normal test stress. A_{Fij} is the acceleration factor for the translation of L_{ij} to L_{0j}.

When $j>1$, Equation (11) is used by replacing the cumulative time of the $j-1^{th}$ failure under this test stress, and the acceleration factor is given by Equation (15):

$$A_{Fij} = e^{\frac{E_a(t_i)_{j-1}}{k}(\frac{1}{T_0}-\frac{1}{T_i})} \tag{15}$$

When $j=1$, Equation (11) is used by replacing E_a for the final time step of the previous test level, and the acceleration factor is given by Equation (16):

$$A_{Fi1} = e^{\frac{Ea'}{K}(\frac{1}{T_0}-\frac{1}{T_i})} \tag{16}$$

For the first accelerated stress, Equation (9) is used by replacing the first failure data set, and then the activation energy $E_a''(t)$ is found, which is used for the second failure data transfer. Equation (11) is used by replacing $E_a''(t)$, and then A_{F11} is found by Equation (17):

$$A_{F11} = e^{\frac{Ea''}{K}(\frac{1}{T_0}-\frac{1}{T_i})} \tag{17}$$

Therefore, the RET failure data can be transferred to the normal test failure data using the data transfer method, the transferred failure data can be used as the reliability growth test (RGT) failure data, and the product reliability value can be given by the RGT assessment method.

5. Illustrative example

5.1. Design of the RET Project

The traditional RET focuses on how to stimulate product defects, which cannot give the reliability index of a product. If we wish to obtain the reliability index by RET, it is necessary to modify the traditional RET [3,17] project based on the adaptive accelerated model.

(1) For a traditional RET, one or two samples is sufficient. If the RET is used for product reliability assessment, the number of samples is usually three to five, which allows one to obtain more accurate parameter estimate values of the adaptive accelerated model.

(2) There are several temperature stress levels in a RET, such as $S_1 < S_2 < \cdots < S_K$. Here, S_1 is the initial temperature. When a RET is used for reliability assessment, the number of stress levels is smaller, and the stress step is larger.

(3) In the parameter estimating process for the adaptive accelerated model, the RET must be conducted under two accelerated stresses at the same time, and the same corrective measures should be applied to the products.

Based on the above analyses, the adaptive accelerated model is suitable for a step-up-stress temperature test for samples under different accelerated stresses at the same time, and the test profile is shown in Figure 2.

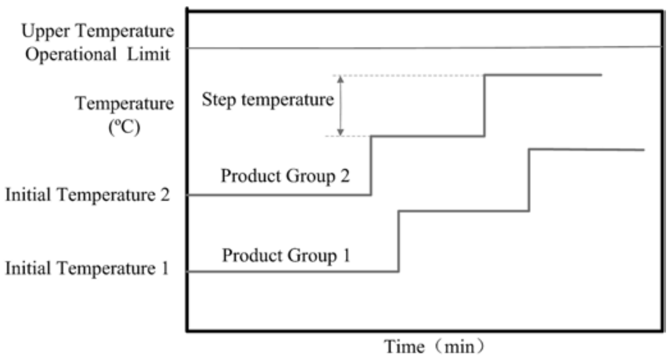

Fig. 2. Test profile sketch map

5.2. Case Analyses

Consider a special case, i.e., where the acceleration factor is equal to 1, so the accelerated test stress is equal to the normal test stress, namely $T_1 = T_0$. According to Equation (8), $t_1 = t_0$. Therefore, the data transfer method is correct when the acceleration factor is 1.

When the acceleration factor is greater than 1, the following case demonstrates the analysis process.

Table 1. RET failure data

Stress level	RET failure data
S_1=1.2S_0	12.5, 39.4, 92.3, 170.2, 289.4, 454.8, 679.3, 952.6, 1311.4
S_2=1.3S_0	5.6, 17.4, 39.9, 71.6, 117.8, 178.8, 257.3, 350.9, 470.1

Table 2. Estimation of parameters and transferred data

M	B	Transferred data
0.13	4.02×10^{-4}	110.4, 332.9, 667.3, 1185.4, 1912.5, 2909.9, 4135, 5755.3

In the development process of a new product, a RET was conducted in which the accelerated stress levels were $S1$=1.2$S0$ and $S2$=1.3$S0$ and the number of samples was 3 for each level. For failures in the RET, the same improvement measure was used for each product failure, and the test was stopped once the product had failed 9 times.

To improve the precision of the parameter estimate, the average of the failure data for three products under the same stress level was used as the final analysis data, as shown in Table 1.

Based on the failure data given in Table 1, the parameter estimate of the adaptive accelerated model and the transferred data were determined, as shown in Table 2.

In the data transfer process employed in this study, the first failure data point of both accelerated stresses is used to calculate the acceleration factor, so the data transfer process begins from the second failure data point. Therefore, we can obtain eight transferred failure data points.

Treating the transferred failure data as a set of RGT data, the MTBF of the product is 2004.3 (h) based on the Duane model. This case shows that the adaptive accelerated model given by this study can realize RET data transfer, and that the MTBF of a product can be calculated by the RET.

6. Conclusion

By focusing on the reliability assessment of a RET, the change process of the Arrhenius model parameters was examined, an adaptive accelerated model was developed by combining the Arrhenius model with the Duane model, and the RET data transfer method was described. Through an engineering case, this study showed that the adaptive accelerated model is correct and useable in practice. A new assessment method is given for the reliability index based on a RET.

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