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Accelerated Degradation Reliability Modeling and Test Data Statistical Analysis of Aerospace Electrical Connector

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Abstract: As few or no failures occur during accelerated life test, it is difficult to assess reliability for long-life products with traditional life tests. Reliability assessment using degradation data of product performance over time becomes a significant approach. Aerospace electrical connector is researched in this paper. Through the analysis of failure mechanism, the performance degradation law is obtained and the statistical model for degradation failure is set up; according to the research on statistical analysis methods for degradation data, accelerated life test theory and method for aerospace electrical connector based on performance degradation is proposed by improving time series analysis method, and the storage reliability is assessed for Y11X series of aerospace electrical connector with degradation data from accelerated degradation test. The result obtained in this paper is basically consistent with that obtained from accelerated life test based on failure data, and the two estimates of product's characteristic life only have a difference of 8.7% ,but the test time shortens about a half. As a result, a systemic approach is proposed for reliability assessment of highly reliable and long-life aerospace product.

Key words: electrical connector; performance degradation; reliability; accelerated degradation test

1 Introduction

As a kind of electro-mechanical components, electrical connector is applied to transmission and control of electric signals as well as electrical connection between electronics and electrical equipment. It is widely used in aerospace area with large amounts and plays an important role. As the reliability of aerospace systems is gradually improving, it requires that aerospace electrical connectors have increasingly high reliability even after long periods of time, some types of aerospace systems even ask for 21 years for the storage life of electrical connector. It is difficult to obtain failure data during a rather short period of time even under accelerated life tests (ALT), which brings many problems for reliability assessment with traditional life tests that record only time to failure. As there is a product characteristic of electrical connector whose degradation over time can be related to reliability in life tests, it is possible to obtain degradation measurements. Then, alternative approaches appeared which collects the degradation data at higher levers of stress and then use these data to predict the product's lifetime at a use-stress. Such an experiment is called an accelerated degradation test (ADT). Actually, these degradation measurements may contain useful information about product reliability, and there will be more useful information in degradation data than in time-to-failure data unless there is a large amount of measurement error [1]. The key to analysis degradation data is the degradation modeling and the perceived link between the degradation measurements and the failure time. Nelson[2] reviewed the degradation literature, surveyed applications, described basic ideas and showed how to analyze a type of degradation data using a specific example. Meeker [3-6] offered a comprehensive guide to degradation analysis for various life tests, including accelerated degradation test (ADT), and show that degradation analysis has great potential to improve upon reliability analysis. Deng [7] briefly compared ADT and ALT technologies, described related background, degradation models, data analysis methods and design and optimization of ADT and summarized the recent statuses of ADT technology and engineering application. Wang [8-11] studied model and method to analyze degradation data obtained in step-stress ADT with two accelerating stresses, and presented a new method of Monte Carlo simulation-based optimal design for degradation test (DT) and ADT.

In recent years, degradation analysis is gradually applied to engineering field. Marta [12] used the degradation data to assess reliability of train wheel. Ma[13] investigated degradation performance of long-life satellite thermal

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coating and its influence on satellite's thermal character. Meng[14] presented a methodology of designing for time-varying performance of complex products through performance degradation analysis. Ma[15] presented a performance reliability analysis method for piston pump affected by random degradation.

In order to assess the reliability of aerospace electrical connector rapidly, degradation analysis method is applied here. The reliability statistical modeling and the statistical analysis methods for test data based on performance degradation will be discussed and the storage reliability for Y11X series of aerospace electrical connector will be assessed in this paper. Section 2 analyzes the failure mechanism of electrical connector. Section 3 presents the degradation model and the failure model. Section 4 describes the method to estimate parameters of degradation model and the distribution function. Section 5 analyzes the degradation data, and section 6 presents discussions and conclusions.

2 Failure Mechanism Analysis of Aerospace Electrical Connector

There are three kinds of failure modes for aerospace electrical connector (shown in Figure 1[16]), that is, contact failure, insulation failure and mechanical connection failure. Field services and tests in earlier stages show that the main failure mode is contact failure [17].

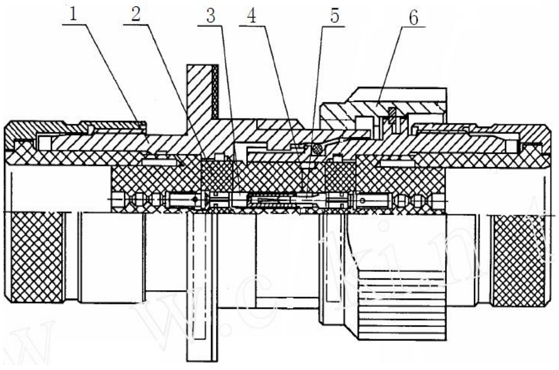

Fig 1. sketch map of primary structure for electrical connector

1- shell 2- insulation install panel 3- jack 4- insulator
5- contact pin 6- connect circle

The contact life of electrical connector depends on the growth rate of contact resistance, which depends on the growth of the corrosion on the contact surface in the atmosphere. As for electrical connector with copper-base contacts of gold-plated surface, like Y11X series of circular electrical connector, as the gilt crystallizes to a network structure and its thickness being only 0.7 μm, there will be some micropores and cracks inevitably during the gilding process; the wet gas in the atmosphere may come into contact with base metal copper through micro-capillarity of the gold-plated surface, and deposits to form the electrolyte. The potential difference between aurum and cuprum forms micro-cells on the interface between the gold-plated surface and copper-base material, and oxidation reaction generates

$$\mathrm{Cu} \rightarrow \mathrm{Cu}^{+} + \mathrm{e}$$

As it is much easier for Cu^{+} to diffuse from Au-Cu interface to the gold-plated surface than oxygen and water molecules to diffuse from the reverse direction, the reduction reaction of electrochemical reaction mainly happens on the gold-plated surface, namely, the contact surface, and an oxide film layer of extremely high resistance generates.

According to Holm electrical contact theory, the current through the oxide film is accomplished by tunnel effect, and the growth of the thickness of oxide film may increase the tunnel resistivity gradually, which results in the increase of contact resistance. According to the study[18] of the relationship between the tunnel resistivity σ and the film thickness h, when the film thickness is less than 20A, the tunnel resistivity increases basically linearly as the film thickness increases, that is $\sigma = \lambda h$, where λ is the proportional constant; as the film resistance can be expressed as $R = \sigma / S$ [18], the relationship between the contact resistance increment x_t and the film thickness h satisfies $x_t = \lambda (h - h_0)/S$, where, S is the actual contact area, and h_0 is the initial thickness of the film.

The analysis above shows, the contact performance degradation of electrical connector in storage environment on the ground is mainly caused by the growth and accumulation of the oxide on the contact surface, and the growth rate of oxide directly reflects the degradation condition of electrical connector's contact performance. The higher the ambient temperature is, the faster the oxide grows. Temperature is the most important environmental factor that affects the storage reliability of electro-mechanical components. When the accumulation of oxide causes the two contact surfaces to separate about 20Å, the contact resistance exceeds the allowable threshold value and the contact performance no longer meets the requirements, namely, degradation failure occurs.

3 Degradation Failure Modeling for Aerospace Electrical Connector

According to the analysis mentioned above, the probability that the contact failure occurs sometime equals to that of the contact resistance exceeding the threshold. In the following contents, the probability distribution of contact failure will be determined based on the statistical distribution of the contact resistance at each observation time, and then the life distribution of electrical connectors will be determined.

3.1 Performance Degradation Modeling for Aerospace Electrical Connector

According to the literature[17], the oxide film thickness *h* at time *t* follows a log-normal distribution, that is

$$H \sim LN(\mu_h(t), \sigma_h^2(t))$$

Assuming that the initial thickness of the oxide film is $h_0=0$, then the contact resistance increment caused by the increase of the film thickness at time *t* can be expressed by

$$x_t = \lambda h / S \qquad (1)$$

As equation (1) is a strictly monotone increasing function, the probability density function of the contact resistance increment at time *t* can be expressed as

$$f(x_t) = \frac{1}{\sqrt{2\pi}\sigma_h(t)\cdot x_t}\exp\left[-\frac{1}{2}\left(\frac{\ln x_t - [\mu_h(t) + \ln(\lambda/S)]}{\sigma_h(t)}\right)^2\right]$$

Assuming that $\mu_x(t) = \mu_h(t) + \ln(\lambda/S)$, $\sigma_x(t) = \sigma_h(t)$, the equation above can be simplified as

$$f(x_t) = \frac{1}{\sqrt{2\pi}\sigma_x(t)\cdot x_t}\exp\left[-\frac{1}{2}\left(\frac{\ln x_t - \mu_x(t)}{\sigma_x(t)}\right)^2\right] \qquad (2)$$

Equation (2) indicates that the contact resistance increment x_t at time *t* is a random variable that follows a log-normal distribution, that is $x_t \sim LN(\mu_x(t), \sigma_x^2(t))$.

As the oxide on the contact surface grows continually, the ion, able to go through the oxide film, becomes fewer and subsequently the oxide growth rate becomes slow. Thus it shows an inversely-proportional relationship between the growth rate and the thickness of the film, and the law for the film thickness growing over time can be expressed as[17]

$$h^2 = Kt$$

Here, *K* is the reaction rate, which is assumed to be constant over time but depends on temperature as described below

$$K = \Lambda \exp(-\Delta E/\kappa\theta)$$

Where, ΔE is the activation energy of the reaction (eV), κ is Boltzmann's constant（8.617×10^{-5} eV/K）, θ is the absolute Kelvin temperature (K), and Λ is the frequency factor.

According to equation (1), the relationship between the contact resistance increment x_t and time *t* can be expressed as

$$x_t = \lambda\sqrt{Kt}/S \qquad (3)$$

Let $\rho = \lambda\sqrt{K}/S$, instead *K* by $\Lambda\exp(-\Delta E/\kappa\theta)$, then $\rho = \lambda\sqrt{\Lambda\exp(-\Delta E/\kappa\theta)}/S$; then let $\rho = \exp(\alpha+\beta/\theta)$, here $\alpha = \ln(\lambda\sqrt{\Lambda}/S)$ and $\beta = -\Delta E/2\kappa$ are constants that do not depend on temperature or time. Therefore, equation (3) can be simplified as

$$x_t = \rho\cdot\sqrt{t} = \exp(\alpha + \beta/\theta)\cdot\sqrt{t}$$

The equation above reflects the relationship between the contact resistance increment and time as well as temperature. As x_t at time *t* follows a log-normal distribution, the logarithmic mean of x_t can be expressed as

$$\mu_x(t) = (\alpha + \beta/\theta) + \frac{1}{2}\ln t$$

As the differences of contact resistance among products are mainly caused by its initial performance, the log standard deviation of contact resistance increment is generally assumed constant over time and temperature stress[2], that is $\sigma_x(t) = \sigma_x$.

Therefore, the performance degradation process of electric connector can be described by a log-normal random process, that is

$$\begin{cases} x_t \sim LN(\mu_x(t), \sigma_x^2) \\ \mu_x(t) = (\alpha + \beta/\theta) + \frac{1}{2}\ln t \end{cases} \qquad (4)$$

3.2 Degradation Failure Modeling for Aerospace Electrical Connector

Suppose that x_0 is the initial value of contact resistance at t=0, the contact resistance at time *t* is $z_t=x_0+x_t$. Failure occurs when the contact resistance exceeds the threshold R_f, the failure probability at time *t* can be determined by $\Pr\{z_t \geq R_\mathrm{f}\}$, namely, $\Pr\{x_t \geq R_\mathrm{f} - x_0\}$. Generally, the initial value of contact resistance is a random variable, and then the transformed failure threshold $R_\mathrm{f} - x_0$ is also a random variable. As the analysis of random failure threshold is relatively complex in the process of data analysis, to simplify it, the initial value of contact resistance is taken as a constant, and then the contact failure probability at time *t* can be described by

$$\begin{aligned} F_e(t) &= \Pr\{x_t \ge R_{\mathrm{f}} - x_0\} \\ &= \Phi\{[\ln t - 2\ln(R_{\mathrm{f}} - x_0) + 2(\alpha + \beta/\theta)]/2\sigma_x\} \end{aligned}$$

Where Φ[] is the distribution function of standard normal distribution;

Let μ_e=2ln(R_{f}−x_0)-2(α+β/θ) and $\sigma_e = 2\sigma_x$, the equation above can be simplified as

$$F_e(t) = \Pr\{x_t \ge R_{\mathrm{f}} - x_0\} = \Phi[(\ln t - \mu_e)/\sigma_e]$$

Obviously, the contact life distribution yielded from the performance degradation statistical law follows a lognormal distribution (base *e*), that is

$$F_e(t) = \int_0^{\infty} \frac{1}{\sqrt{2\pi}\sigma_e t} \exp\{-\frac{1}{2}[(\ln t - \mu_e)/\sigma_e]^2\}\mathrm{d}t \quad (5)$$

Suppose there are *N* contacts in a electrical connector and the lifetime of the *i* th contact is $T_i (i = 1,2,\cdots,N)$, the lifetime T of electrical connector can be determined by the contact whose resistance reaches the failure threshold first, namely $T = \min\{T_1, T_2, \cdots, T_N\}$, and the life distribution function of electrical connector can be determined by

$$F(t) = 1 - \Pr\{T > t\} = 1 - [1 - F_e(t)]^N$$

It can be proved that[17], when $N \to \infty$, if $F_e(t)$ has a lognormal distribution, then the progressive distribution of $F(t)$ follows a Weibull distribution with two parameters. Replacing the strict minimum distribution by progressive minimum distribution of $F(t)$, it can be obtained that the lifetime of electrical connector follows a Weibull distribution with two parameters, and the probability distribution function is

$$F(t) = 1 - \exp[-(t/\eta)^m] \quad (t > 0, m > 0, \eta > 0) \quad (6)$$

Where *m* is shape parameter and η is the characteristic life.

4 Accelerated Degradation Test and Test Data Statistical Analysis Method

4.1 Accelerated Degradation Test Data

Select *n* specimens randomly from the same batch of products, and subject them to constant-stress ADT with *l* stress levels separately, allocate n_i (*i*=1,2,…,*l*) specimens to stress level θ_i. As it is difficult to monitor the contact resistance continuously, ADT under periodic inspection is adopted in this test, and the contact resistance is measured at times $t_{i,1}$, $t_{i,2}$, $\cdots$, t_{i,m_i} , and the performance degradation data can be described as

$$\{x_{ijk};\ i=1,2,\ldots l;\ j=1,2,\ldots n_i;\ k=1,2,\ldots m_i\} \quad (7)$$

Where, x_{ijk} is the contact resistance increment in the *k* th measurement for the *j* th specimen under temperature θ_i.

4.2 Test Data Statistical Analysis Method

Denoting the probability distribution density of the contact resistance increment x_t at time *t* by $f(x_t;\xi(t))$, where $\xi(t)$ is the unknown parameter vector of the distribution function, namely $\xi(t) = (\mu_x(t), \sigma_x)$. According to the performance degradation model (4) and the characteristic of degradation data in equation (7), time series analysis method[19] is adopted here to analysis degradation data.

For $t_{i,1}$< $t_{i,2}$<…<t_{i,m_i} , if the strict form of degradation condition is satisfied, namely, $0 \le x_{ij1} \le x_{ij2} \le \ldots \le x_{ijm_i} \le +\infty$, the probability distribution density function of degradation at certain time can be described as

$$\begin{gathered} t_{i,1}, f(x;\xi(t_{i,1})), x \ge 0 \ ; \\ t_{i,2}, f(x;\xi(t_{i,2})), x \ge x_{ij1} \ ; \\ \vdots \\ t_{i,m_i}, f(x;\xi(t_{i,m_i})), x \ge x_{ijm_i} \end{gathered}$$

Similar to the sequence random variable, the joint distribution of $x_{ij1}, x_{ij2}, \cdots, x_{ijm_i}$ is

$$f(x_{ij1}, x_{ij2}, \cdots, x_{ijm_i}) = \frac{1}{A_{ij}} \prod_{k=1}^{m_i} f(x_{ijk};\xi(t_{i,k})) \quad (8)$$

Here, $A_{ij} = \int_0^{+\infty} f[x_{ij1};\xi(t_{i,1})]dx_{ij1} \cdot \int_{x_{ij1}}^{+\infty} f[x_{ij2};\xi(t_{i,2})]dx_{ij2}$

$$\cdots \int_{x_{ijm_i-1}}^{+\infty} f[x_{ijm_i};\xi(t_{i,m_i})]dx_{ijm_i}$$

Assuming that all of the performance observations are statistically independent; the likelihood function for all of the specimens can be expressed by

$$\begin{aligned} L(\xi) &= \prod_{i=1}^{l} \prod_{j=1}^{n_i} f(x_{ij1}, x_{ij2}, \cdots, x_{ijm_i}) \\ &= \prod_{i=1}^{l} \prod_{j=1}^{n_i} \prod_{k=1}^{m_i} f[x_{ijk};\xi(t_{i,k})] \Big/ \prod_{i=1}^{l} \prod_{j=1}^{n_i} A_{ij} \end{aligned} \quad (9)$$

The maximum likelihood estimates of the unknown parameters can be obtained by maximizing $\ln L(\xi)$. The method above requires the degradation values to increase monotonically, but generally, due to the measurement errors or other random factors, the strict form of degradation condition is difficult to be satisfied. Therefore, this method has some limitations in application, and the following improvements are made to meet the actual demand.

According to the irreversibility of degradation process, as performance degrades, for $t_{i,k}<t_{i,k+1}$, $0 \le x_{ijk}, x_{ijk+1} \le +\infty$ and $0 \le E(x_{ijk}) \le E(x_{ijk+1})$ are always established, as $E(x_{ijk}) = \exp(\mu_x(t_{i,k}) + \sigma_x^2/2)$ is always established in lognormal distribution, $\mu_x(t_{i,k}) \le \mu_x(t_{i,k+1})$ can be inferred from the analysis above. Let $y_{i,k} = \mu_x(t_{i,k})$, then $y_{i,k}$ forms a new sample following normal distribution $N(\mu_x(t_{i,k}), \sigma_x^2/M_i)$, where $M_i = N \cdot n_i$ stands for the total number of the contacts at stress θ_i. Denote the probability distribution density function of $y_{i,k}$ by $g(y;\varphi(t))$, here $\varphi(t) = (\mu_x(t), \sigma_x^2/M_i)$, the joint distribution of $y_{i,1}, y_{i,2}, \cdots y_{i,m_i}$ can be described by

$$g(y_{i,1}, y_{i,2}, \cdots y_{i,m_i}) = \frac{1}{B_i}\prod_{k=1}^{m_i} g(y_{i,k};\varphi(t_{i,k}))$$

Here, $B_i = \int_0^{+\infty} g(y_{i,1};\varphi(t_{i,1}))dy_{i,1} \cdot \int_{y_{i,1}}^{+\infty} g(y_{i,2};\varphi(t_{i,2}))dy_{i,2}$

$$\cdots \int_{y_{i,m_i-1}}^{+\infty} g(y_{i,m_i};\varphi(t_{i,m_i}))dy_{i,m_i}$$

As the specimens at all of the stress levels are statistically independent, the likelihood function for all specimens can be expressed as

$$\begin{aligned} L(\varphi) &= \prod_{i=1}^{l} g(y_{i,1}, y_{i,2}, \cdots, y_{i,m_i}) \\ &= \prod_{i=1}^{l}\prod_{j=1}^{n_i} g[y_{i,k}, \varphi(t_{i,k})] \Big/ \prod_{i=1}^{l} B_i \end{aligned} \qquad (10)$$

The maximum likelihood estimates for the model parameters $(\hat{\alpha}, \hat{\beta}, \hat{\sigma}_x)$ can be obtained by maximizing $\ln L(\varphi)$. Therefore, the estimate of the contact failure probability $\hat{F}_e(t)$ at use stress can be obtained, and the failure probability of electrical connector can be obtained from $\hat{F}(t) = 1 - [1 - \hat{F}_e(t)]^N$, and the least square estimations of the distribution parameters $\hat{m}$ and $\hat{\eta}$ for electrical connector can be obtained by fitting $(t, \hat{F}(t))$.

5 Test Data Statistical Analysis

To verify the correctness of the model as well as the statistical analysis method, all of the data in this paper originate from the performance degradation data measured in accelerated life test in literature[17], in which Y11X-1419-type of circular electrical connector is taken as the object, and the experiment is carried out at three elevated but constant levels of stress 105℃、120℃and 158℃, with 20, 5 and 5 specimens allocated at each stress level respectively. As the degradation rate of product performance varies with temperature, the inspecting intervals are chosen to be 80, 20 and 3 h respectively, and each specimen is observed for ten times. The total test time is 1030 h. The log means of the increments for contact resistance for each inspecting time at different test temperature are shown in table 1.

Table 1. The log means of the increments for contact resistance

θ_1 =105℃		θ_2 =120℃		θ_3 =158℃	
$t_{1,j}$ (h)	$\hat{\mu}_{1,j}$	$t_{2,j}$ (h)	$\hat{\mu}_{2,j}$	$t_{3,j}$ (h)	$\hat{\mu}_{3,j}$
80	-2.013 9	20	-2.264 4	3	-2.483 0
160	-2.013 5	40	-1.777 3	6	-1.930 2
240	-1.740 0	60	-1.255 3	9	-1.701 4
320	-1.670 0	80	-1.229 4	12	-1.591 9
400	-1.593 3	100	-1.278 6	15	-1.574 7
480	-1.441 9	120	-0.716 1	18	-0.921 3
560	-1.410 9	140	-0.448 1	21	-0.860 4
640	-1.300 8	160	-0.407 7	24	-0.625 6
720	-1.219 8	180	-0.139 6	27	-0.566 9
800	-1.118 6	200	0.123 3	30	-0.112 5

It is known that the normal use temperature for electrical connector is 45℃, and the failure threshold is R_f =5 mΩ and the initial value for contact resistance is R_0= 2.8 mΩ respectively. Through statistical analysis of the data in table 1 with the analysis method mentioned above, the estimations of the parameters for the degradation model can be obtained as $(\hat{\alpha}, \hat{\beta}, \hat{\sigma}_x)$= (-2.658, -473, 0.0804), and the estimations for shape parameter and the character life at normal stress could be obtained respectively as $\hat{m} = 2.99$ and $\hat{\eta}_0$ =310047 h, that is about 35.39 years.

In literature [17], the estimation of the character life at normal stress based on failure data is $\hat{\eta}_0$ =285180 h, which is about 32.55 years and the total test time is 1986 h. Thus it can be seen that the estimation of the product's character life obtained from degradation data is basically consistent with that obtained in literature[17] with a difference of 8.7% only, but the test time shortens about a half.

6 Conclusions

(1) Through analyzing the failure mechanism of aerospace electrical connector, the law of the performance degradation was researched and the statistical model for

degradation failure was set up.

(2) The improved time series analysis method based on degradation data was presented according to the characteristic of the degradation data, and accelerated life test theory and method for aerospace electrical connector based on performance degradation was proposed.

(3) The storage reliability for Y11X series of aerospace electrical connector was assessed using the degradation data obtained from ADT. Compared with the results obtained from accelerated life test based on failure data, the two estimates of product's characteristic life only have a difference of 8.7%, but the test time shortened about a half.

(4) The conclusions above show that, as it takes full advantage of degradation information of performance parameter in test, the approach based on performance degradation provides a comparatively objective and credible assessment for products reliability even without failure data during a rather short period of time, and it is more applicable for engineering field.

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