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# Electrical Connector Ultimate Vibration Load Quantization and Application Technology

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A framework is proposed for improving electrical connector design according to ultimate vibration load based on finite element model and physics of failure model. The relationship model among environmental load, design parameters and local response is established through orthogonal experimental design, hierarchical modeling and regression analysis. Combined with the physical model of contact failure of electrical connectors, the quantization model among environmental load, design parameters and life could be established, which can help determine the ultimate vibration load based on the given life requirement. Based on this, the application technique of ultimate vibration load is given, and a case of single scheme optimization is illustrated to verify the technique above.

## 1. Introduction

Electrical connector is used for electrical connection between electronic and electrical equipment. It can realize the transmission and control of electric signal. The reliability of electrical connector has a tremendous impact on the system for it is largely and widely used in Aviation and space and other fields.

The key environmental factors affecting the life of electrical connector are temperature and vibration, and the latter is more important[7]. The main failure mode is contact failure under vibration load. The physics of failure model has been established, which gives the relationship between electrical connector's life and vibration or temperature stress.

To provide input for the contact failure physics model, it is necessary to decompose the vibration load functioning in the system or external parts of product into subsystems or components, and then quantifying the vibration response of local area. There are three methods to achieve the decomposition and quantization of vibration load: referring to standard manual[3], the actual measurement[4] and finite element modelling[1], [2],[5],[9]. Combining with the contact failure physics model, the life of electrical connector can be calculated. However, in engineering, the life is usually given while the actual environmental loads fluctuate. Therefore, new model has to be established for different electrical connectors and environmental loads.

This paper built a relationship model among vibration load, design parameters and life through orthogonal experimental design, regression analysis and combining with contact failure physics model. This model can calculate life in conditions of given environmental load, or determine ultimate vibration load in specific life requirement. It is possible to design products to improve their performances from the perspective of ultimate vibration.

## 2. Technical framework

A technical framework was presented for quantization of electrical connector's ultimate vibration load (Figure 1).The framework could support establishment of quantization relationship model among vibration load, design parameters and life based on finite element model and failure physics model.

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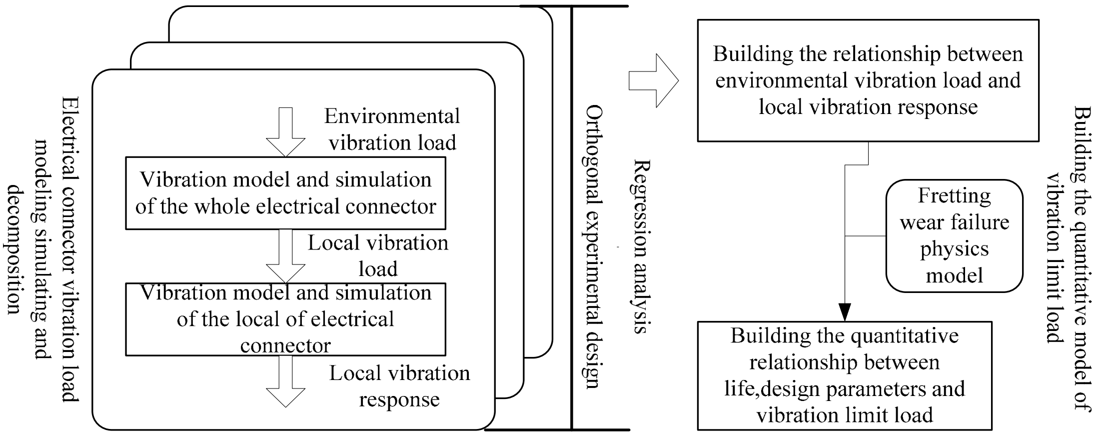

*Figure 1：Electrical connector's vibration limit load quantization technical framework*

First, multiple groups of test scheme can be obtained through orthogonal experimental design to provide original data for regression analysis. Then, the vibration response of local area can be gained by utilizing method of electrical connector vibration load hierarchical modelling and simulation. And the quantitative relationship among vibration load, design parameters and vibration response of local area can be built through regression analysis. Finally, combining with fretting wear failure physics model[8], the quantitative relationship between vibration load, design parameters and life of electrical connector can be obtained.

## 3. Establishment of quantization model for ultimate vibration load

### 3.1 Test scheme design

A large number of vibration simulation tests have to be made in the conditions of different loads and design parameters, to build the relationship model among vibration load, key design parameters and local vibration stress. Douglas (2007) introduced the orthogonal experimental design in detail, which was selected to determine test schemes for simulation.

In order to get the local vibration response of electrical connector, input factors which needed to be considered include load and design parameters. Structure size and material constant are main design parameters. When material constant and environmental load are unchanged, the change of product structural size will cause the change of internal environmental stress of product. Therefore, the structural size is a key factor that affects the local vibration response of electrical connector. Common material constants include elastic modulus, Poisson's ratio and density. The material of insulator usually chooses thermosetting plastic Bakelite, whose material constant is unchanged. The shell and contacts of electrical connector usually select metal materials, with the change of materials, the Poisson's ratio remain unchanged, while the elastic modulus and density change greatly. As a result, the local vibration response of electrical connector is influenced greatly.

Through the above analysis, this paper choose magnitude of vibration load $L_v$, elastic modulus and density of metal shell $E_1$, $\rho_1$, elastic modulus and density of contacts $E_2$, $\rho_2$, and radius of contacts $R$ as the six factors of orthogonal experimental design. Considering that the value of $L_v$ and $R$ is continuous, their levels can be equally spaced. Since the $E_1$ and $\rho_1$, $E_2$ and $\rho_2$ appear in pairs and their values depend on the material selected, they are discrete variable. Thus, their levels can not be equally spaced and the specific values rely on the materials used. The radius of contacts lies between 1.6 and 2.0.Therefore, orthogonal table of six factors and five levels were recommended (Table 1).

*Table 1: Factor-levels of orthogonal design*

| level/factor | $R$($\times10^{-3}$m) | $E_1$($G_{pa}$) | $\rho_1$($\times10^3$kg/m$^3$) | $E_2$($\times10^3$kg/m$^3$) | $\rho_2$($\times10^3$kg/m$^3$) | $L_v$($10^{-3}$ g$^2$/$H_z$) |
|---|---|---|---|---|---|---|
| 1 | 1.60 | 69 | 2.7 | 76 | 8.5 | 1 |
| 2 | 1.70 | 74 | 2.76 | 83 | 8.45 | 2 |
| 3 | 1.80 | 193 | 8.0 | 90 | 8.44 | 3 |
| 4 | 1.90 | 200 | 7.7 | 96 | 8.83 | 4 |
| 5 | 2.00 | 222 | 7.8 | 103 | 8.27 | 5 |

### 3.2 Vibration load hierarchical modelling and simulation

It will ignore the attenuation of vibration loads transferring among components if the finite element model is built directly during finite element simulation of complex products/systems. The establishment of a complete product or system structure model may cause a very expensive amount of computations and even that finite element model is unable to be generated. Building simplified model may lead to a large deviation between vibration response characteristics and true value. Therefore, the technology of hierarchical model and simulation was adopted. In order to get the local vibration response of contacts, which were the main failure part of electrical connector, vibration load of the whole was decomposed into acceleration power spectrum(PSD) of the contacts, which was taken as input for the finite element model of contacts. Then vibration response of contacts could be quantified.(Figure 2)

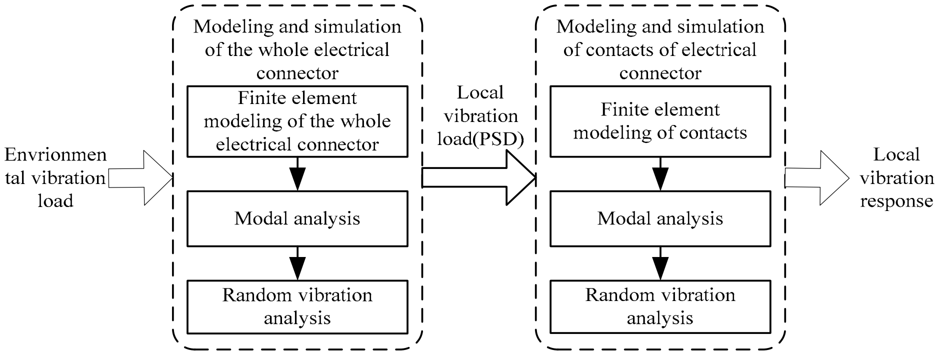

*Figure 2：The scheme of electrical connector hierarchical model and simulation*

### 3.3 Local response's algorithm based on regression analysis

Using the several series of simulation results can fit a model of equivalent stress or displacement. Since equivalent displacement would not induce influence on the life of electrical connector, regression model of equivalent stress had been analyzed only. This paper adopted liner model of regression analysis[6]. The multiple linear regression model of equivalent stress is shown as follows.

$$S = a_0 + a_1 R + a_2 E_1 + a_3 \rho_1 + a_4 E_2 + a_5 \rho_2 + a_6 L_v \tag{1}$$

The author designed 25 groups of simulation tests according to the 3.1～3.2 and obtained related data. The relationship model among environmental vibration load, design parameters and equivalent stress was obtained through fitting. The Dimensions of $a_0$, $a_1$, $a_2$, $a_3$, $a_4$, $a_5$, $a_6$ were respectively $P_a$, $P_a/m$, *1*, $P_a(kg/m^3)$ *,1*, $P_a(kg/m^3)$ and the units of all coefficients adopted international system of units.

$$S = -1.744\times10^7 - 3.2\times10^{10} R - 1.072\times10^4 E_1 + 2.856\times10^4 \rho_1 + 1.26\times10^4 E_2 + 4.551\times10^3 \rho_2 + 4.350\times10^7 L_v \tag{2}$$

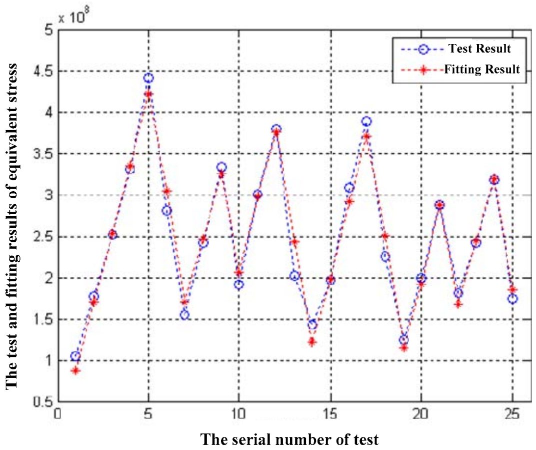

*Figure 3: The multiple linear regression fitting results of equivalent stress*

The fitting results of equivalent stress were shown in figure 3, in which the serial number of test was used as abscissa and the vibration response was used as ordinate. It could be seen that the multiple linear regression model fitted well on the equivalent stress.

The F-test is performed on the fitting result and the probability of was 1.3560 × $10^{-12}$. Therefore, regression effect is significant to electrical connector's linear regression model of equivalent stress.

### 3.4 Construction of ultimate vibration load quantitative model

The failure physics model of electrical connector is $t=\beta\times S^{-\alpha}$. The value of α and β was obtained by test. Select $\alpha$=1.18, $\beta$=12.794[8], to get:

$$t=12.794\times S^{-1.18} \tag{3}$$

Substitute the formula (2) into (3) to obtain:

$$t=12.794\times\left[a_0+a_1R+a_2E_1+a_3\rho_1+a_4E_2+a_5\rho_2+a_6L_v\right]^{-1.18} \tag{4}$$

The formula (5) is called life model of electrical connector, which describes the relationship between design parameters, vibration load and life. Life of electrical connector can be calculated when design parameters and vibration load are given. Under common conditions, however, the environmental vibration loads have high uncertainty and randomness. Thus, the design state of electrical connector can be described from the perspective of ultimate vibration load. Substitute the Eq (2) into (4) to get the quantitative formula of ultimate vibration load:

$$\begin{aligned} L &= \frac{\sqrt[\alpha]{12.794/t_d}-\left(a_0+a_1R+a_2E_1+a_3\rho_1+a_4E_2+a_5\rho_2\right)}{a_6} \\ &=\left[\sqrt[\alpha]{12.794/t_d}-\left(-1.373\times10^{-5}+0.013R-1.041\times10^{-16}E_1+1.167\times10^{-9}\rho_1+1.76\times10^{-18}E_2+8.482\times10^{-10}\rho_2\right)\right]\times\frac{10^6}{3.051} \end{aligned} \tag{5}$$

The $L$ in Eq (5) represents the ultimate vibration load electrical connector can absorb and the $t_d$ represents the design life of electrical connector. The ultimate vibration load which electrical connector can undertake in its whole life cycle can be calculated through ultimate vibration load quantization technology.

## 4. Comprehensive analysis technique based on ultimate vibration load quantization

The main content of this chapter is comprehensive analysis for ultimate vibration load of electrical connector, which is based on the relationship model among design parameters, design life and ultimate vibration load. Three contents categories are mainly included, as the figure 4 shows.

1. Improvement design of single scheme

It can be determined whether single scheme design is satisfied with the requirement based on the quantitative model of ultimate vibration load of electrical connector. If the design does not meet the requirement, sensitivity analysis can be performed to provide improving trends. If designed tolerance is enough, it can be obtained what kinds of design factors can be relaxed through sensitivity analysis to reduce cost.

2. Optimization design of single scheme

In engineering, not only the designed ultimate vibration load of electrical connector should meet the requirement, but also the weight of product should be as small as possible. Ultimate vibration load is taken as optimization objective, together with optimization objectives like weight for multi-objective optimization by using the quantitative model of ultimate vibration load. Then optimal solution which is satisfied with design requirements can be obtained.

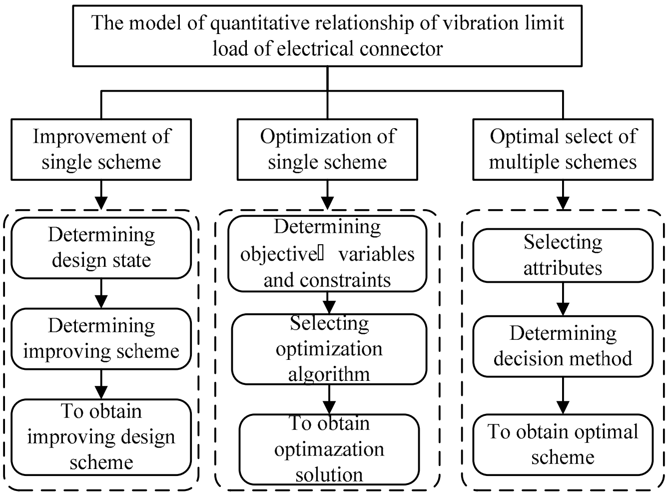

*Figure 4 : The comprehensive analysis and application idea*

3. Optimal select of multiple schemes

There are several design schemes sometimes under the condition of requirement of design life. It is possible to select a optimal project from multiple schemes by using the quantitative model of ultimate vibration load. Multiple attribute decision making method is used according to attributes of ultimate vibration load, weight and cost.

## 5. Case analysis

It is known that the dimensions of one type of electrical connector measure up to the standard of GJB5991.The external diameter of the shell is 0.0307 m, and the radius of contact pin is 0.0016 m. The material parameters of each part are shown in table 3.The lifetime is required lager than 3000 hours. By calculation, the ultimate vibration load L is equal to 0.0036 $g^2$/Hz, and the weight G is equal to 0.096kg. It is required to increase ultimate vibration load L and reduce weight G. Try to optimize the design of electrical connector.

*Table 3: Electrical connector material constant in initial state*

| Material constant | shell | insulator | contacts |
|---|---|---|---|
| | Stainless stell | Thermosetting plastic | copper |
| Elastic modulus(Gpa) | 193 | 0.013 | 103 |
| Density(kg/m3) | $8.0\times10^3$ | $1.34\times10^3$ | $8.4\times10^3$ |

The problem could be denoted as:

Minimize $J = -L = -f\left(R, E_1, \rho_1, E_2, \rho_2, t\right)$

Minimize $G = f\left(R, \rho_1, \rho_2\right)$ (6)

Subject to $t \geq 3000$

$0.0015 \leq R \leq 0.002$

The following results could be calculated according to the formula (6).

$J_{\max}=-0.002, J_{\min}=-0.0106, G_{\max}=0.1268, G_{\min}=0.0605$

The ultimate vibration load L and weight G should be standardized through substituting the above results into standardized processing formula. To obtain:

$$J' = \frac{J - J_{\min}}{J_{\max} - J_{\min}} = \frac{-L + 0.0106}{-0.002 + 0.0106} = -116.3L + 1.23$$

$$G' = \frac{G - G_{\min}}{G_{\max} - G_{\min}} = \frac{G - 0.0605}{0.1268 - 0.0605} = 15.01G - 0.91 \qquad (7)$$

So far, the multi-objective optimization problem was transformed into single-objective problem, which is:

Minimize $F = J' + G' = 15.01G - 116.3L + 0.32$ (8)

Subject to $t \geq 3000$

$0.0015 \leq R \leq 0.002$

The optimization software of iSIGHT was used to get the optimization results which were illustration on the picture 5.

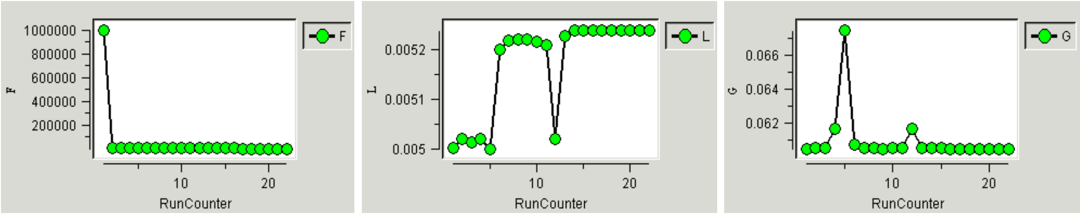

*Figure 5: The optimization result of objective function F, vibration limit load L and weight G*

Finally, the following optimization results were obtained:

$$\{R, E_1, \rho_1, E_2, \rho_2, t\} = \{0.0016, 6.9\times10^{10}, 2700, 9.6\times10^{10}, 8830, 3000\}$$

After optimization, each material of connector and contacts was aluminium alloy 1060 and ZCuSn5Pb5Zn5.

$L = 0.00525 g^2/Hz > 0.0036 g^2/Hz$ , $G = 0.06 kg < 0.096 kg$

## 6.Conclusion

The paper proposed the electrical connector's ultimate vibration load quantization technical framework. 25 groups of simulation tests were designed. Then the quantization model for a certain electrical connector, was obtained by applying hierarchical simulation, regression analysis and physics of failure model in sequence. Finally, single scheme optimization was taken as an example to verify the technical framework.

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