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Key technologies and engineering applications of digital simulation for reliability of aerospace products

Xinggao Zhu, Pengfei Liu*, Jiahui Luan, Haibo Mi, Hao Dong, Hao Chen, Zhaopeng Xue, Haipeng Wen and Yongde Dai

China Astronautics Standards Institute, Beijing 100071, People's Republic of China

E-mail: liupengfei708@spacechina.com

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Abstract

A theoretical system for digital modeling, decoupling, and prediction of the reliability for aerospace products is proposed in order to solve the problem of the reliability issues of aerospace 'small sample' products facing high-density launch missions under multi stress coupling. Key technologies such as digital modeling of the reliability of aerospace electromechanical products based on response surfaces, and digital decoupling analysis of reliability under multi stress coupling, and life reliability analysis of aerospace products under multi stress coupling have been overcome. Engineering applications have been carried out in aerospace machinery, electromechanical, and electronic products, achieving comprehensive level improvement of aerospace product support for aerospace equipment with 'long life, high reliability, high precision, and high performance'.

Keywords: aerospace products, performance and reliability, digital simulation, modeling, decoupling, prediction

1. Introduction

The 'small sample' products in aerospace have numerous internal and external influencing factors, various failure modes, complex failure mechanisms under multi stress coupling. Traditional physical verification under high-density launch missions is costly and inefficient, and the test stress under multi stress coupling is difficult to quantify, resulting in insufficient ground verification. The accuracy of reliability evaluation under limited test data is difficult to guarantee, and reliability design lags behind performance design. The difficulty in predicting reliability indicators in the early stage of design has become a bottleneck in reliability modeling analysis and verification. It is urgent to develop digital verification theory with lower cost, higher efficiency and multidisciplinary collaboration [1] to improve the overall level of 'long life, high reliability, high precision, and high performance' of aerospace products.

The reliability is a comprehensive fundamental science, and the research in the development of disciplines has the characteristics of foundation and continuity. The reliability model is a qualitative and quantitative mathematical and physical model established to predict or evaluate the reliability level of a product. It is divided into two levels: the low-level unit failure mechanism model and the top-level system reliability model. The failure mechanism reveals the physical and chemical essence and processes behind the fault phenomena below the unit level, which is described using quantitative models.

* Author to whom any correspondence should be addressed.

The failure mechanism model is the core of physics of failure (PoF) research. Currently, extensive research has been conducted on reliability theory, fault physics, reliability simulation prediction, and interdisciplinary reliability joint simulation.

Griffith [2] proposed a fracture theory by studying the strength of elastic brittle materials, which solved the PoF research in the field of structural reliability. Meanwhile, Dasgupta and Pecht [3] studied the failure mechanism and damage model of materials. Weibull [4] explored the issue of establishing mechanism models by using fatigue and creep failure data. Angadi *et al* [5] established a multi physics field model of the hydraulic solenoid valves of automotive transmissions involving thermodynamics, mechanics, electromagnetics, and mechanical characteristics. They obtained a failure mechanism model for mechanical, electrical and thermal coupling, and analyzed the reliability and lifespan of solenoid values. Wang *et al* [6] established a multi physics field model of mechanical, electrical, and thermal coupling for microelectromechanical switches and conducted multi mechanism coupling analysis. As researcher realizes that PoF cannot express uncertainty and gradually move towards probabilistic approaches, a phenomenon has emerged Probabilistic PoF [7, 8]. The main models in reliability modeling include reliability block diagram, fault tree analysis (FTA), etc. Among them, FTA is the most representative. FTA usually combines failure mode and effect analysis to construct system reliability models [9–11]. Yeh *et al* [12] studied the reliability modeling method of Monte Carlo systems based on cellular automata. A comprehensive reliability modeling method has been developed by combining Monte Carlo method with various analytical modeling methods [13–19]. Ejlali and Miremadi [13] proposed a time-dependent system reliability FTA model and described the relationship between time and the number of system and component failures through Monte Carlo simulation. Bouissou and Bon [14] presented a system reliability model based on Boolean motion logic driven Markov processes. Transforming the logical diagram of the analytical method into a Belief Bayesian Network model, and using Bayesian inference to calculate the failure probability of system unit, which can analyze system reliability and identify weak links [1, 15–18, 20]. In order to obtain as much failure data as possible and evaluate system reliability under limited time and condition, the accelerated testing method have been studied and applied [21]. In terms of reliability assessment, Zio [22] studied the progress of reliability analysis and risk assessment for security enhancement. Huang *et al* [23] reviewed the basic theoretical methods for reliability assessment under cognitive uncertainty. Liu *et al* [24] studied the method of life and reliability assessment of solar array drive assembly. Zhao *et al* [25] evaluated the reliability of urban rail transit network systems by using passenger flow as the network node attribute. Yang *et al* [26] conducted the reliability assessment of multi state systems with relevant components and imprecise parameters. Diamantidis *et al* [27] explored the reliability assessment methods and processes for existing structures. Zhu *et al* [28] conducted a joint simulation study of performance and reliability, and applying in the evaluation of aerospace electromechanical product. Papaioannou and Straub [29] conducted the form-based global reliability sensitivity analysis of systems with multiple failure models, which improves the accuracy of reliability assessment.

Based on existing research, the aerospace products face two core challenges: one is multi stress coupling, which refers to the interaction of multiple stresses such as mechanical, thermal, and electrical, resulting in complex fault mechanisms. The other is small sample testing, which means high product costs, long testing cycles, and difficulty in obtaining sufficient fault data. Digital methods provide targeted solutions to these two challenges by constructing accurate digital models (to solve the problem of insufficient small sample data), quantitatively decoupling multi stress effects (to solve the problem of complex coupling mechanisms), and predicting life based on fault mechanisms (to solve the problem of reliability assessment), providing support for the high reliability development of aerospace products.

This paper focuses on the significant demand for aerospace products, and breaks through multiple key technologies in the digital simulation of aerospace product reliability. Digital simulation modeling technology has revealed the quantitative relationship between reliability parameters and key performance design parameters of mechanical structures, motion control, and signal circuits. Three types of digital models for aerospace products have been constructed, which solve the problem of integrated design and simulation of reliability and performance, and realizing that reliability is designed. The digital simulation decoupling technology proposes a decoupling method based on coupling matrix, coupling coefficient, and coupling degree function, which realizes the conversion of three typical stress coupling effects of force, heat, and electricity into two stress coupling effects, as well as the equivalent conversion of single stress effects. It solves the problems of difficult quantification of multiple test stresses, small sample size, and insufficient ground verification in reliability testing. The digital simulation prediction technology has formed methods for evaluating the life and reliability of active components considering spatial factors, which solve the problem of accurate evaluation in the engineering development of aerospace products.

The key technologies proposed in this article are used in the aerospace product design stage in order to optimize design parameters, and identify weak links in product design, and evaluate reliability levels. In the stage of product finalization, they are used to supplement or replace some experimental verification, and enrich existing experimental verification methods, and improve the effectiveness of experimental verification. The data support is provided for failure analysis during the product application stage in order to validate the experimental results. In this paper, the reliability digital simulation modeling technology, reliability digital simulation decoupling technology, and reliability digital simulation prediction technology are proposed in Section. The engineering applications of response surface based digital modeling technology for the reliability of aerospace electromechanical products, the engineering applications of digital decoupling analysis technology for reliability under multi stress coupling, and the engineering applications of life and reliability analysis and evaluation

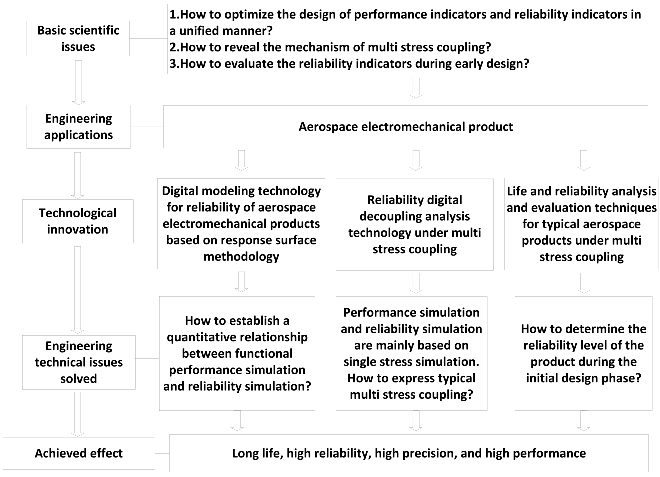

Figure 1. Overall research idea.

technology for aerospace electromechanical products under multi stress coupling are introduced in section 3; The Section is the conclusion.

2. Key technologies

The key technologies such as digital modeling, decoupling, and prediction of the reliability of aerospace products have been broken through. It solves the problem of how to establish a quantitative relationship between functional performance simulation and reliability simulation, how to express typical composite stress coupling, and how to determine the reliability level of products in the initial design stage. The key technologies have been promoted in aerospace products, which achieving the service requirement of 'long life, high reliability, high precision, and high performance' of aerospace equipment supported by aerospace products.

The overall research approach of this article is shown in figure 1. The theoretical system of reliability digital verification for aerospace products provides a practical method for reliability digital design, verification, and evaluation of aerospace equipment, improving the current level of digitalization of aerospace equipment, and meeting the technical requirements of reliability engineering for new aerospace equipment. Mechanical, electronic, and electromechanical standalone products in aerospace products are important components of aerospace equipment, which can ensure the realization of 'long life, high reliability, high precision, and high performance' of aerospace equipment and meet the service requirements of aerospace equipment.

The key technologies for reliability digital simulation proposed in this paper can handle stress types including mechanical (vibration, impact, constant stress), thermal (high temperature, low temperature, temperature alternating), electrical (current, voltage, power), irradiation (total dose effect), etc. The product types that can be analyzed by this method include aerospace machinery, electromechanical, and electronic products. The functions that this method can achieve include reliability modeling, multi stress decoupling, life prediction, and weak link identification. The method proposed in this paper is applicable to the reliability parameters of mechanical structures, motion control, and signal circuits. However, its accuracy in handling extremely complex coupling effects is limited. For new products without clear fault mechanism models, a basic mechanism model needs to be established before it can be applied. The reliability digital simulation technology includes three core modules. Firstly, a digital model that correlates performance and reliability is constructed to obtain basic simulation data through digital modeling technology. Secondly, the coupling effect of multiple stresses is quantified and transformed into equivalent stresses that can be analyzed separately through digital decoupling technology. Finally, the accurate assessment of lifespan and reliability is achieved based on fault mechanism model through digital prediction technology.

2.1. Reliability digital simulation modeling technology

A digital modeling technology for the reliability of aerospace electromechanical products based on response surfaces is proposed, revealing the quantitative relationship between mechanical structure, motion control, and signal circuit reliability parameters and key performance design parameters. Three types of digital models for aerospace products are constructed, solving the problem of integrated design and simulation of reliability and performance. The specific contents are as follow. The construction of performance digital mo the validation of performance digital mo the sensitivity analysis and value matrix acquisition of key design parameters; the iterative simulation calculation and construction of reliability response surface; and the reliability analysis and evaluation.

2.1.1. Construction of performance digital model. Based on the structural composition of aerospace products and related design inputs, the performance digital models are established. The digital models of mechanical structure performance, motion control performance, and signal circuit performance for aerospace products are constructed, which considers account key design variables and environmental loads that affect their performance and reliability (including material characteristics, control parameters, device parameters, etc).

2.1.2. Validation of performance digital model. In the process of benchmarking verification, different performance digital models are combined to select different performance parameters for benchmarking verification based on experimental data. If the closed-loop verification accuracy of the model can meet the relevant technical requirements, the subsequent implementation process is carried out. If the accuracy of the benchmark model does not meet the relevant technical requirements, the model needs to be modified and improved again until it meets the target requirements.

2.1.3. Sensitivity analysis and value matrix acquisition of key design parameters. The sensitivity of design parameters of aerospace agency products to their important performance indicators is analyzed. The design parameters with sensitivity values exceeding the set threshold are selected, and which is recorded as key design parameters. The range of each key design parameter value is determined, and the value matrix of key design parameters is obtained by using orthogonal experimental design method.

2.1.4. Iterative simulation calculation and reliability response surface construction. The performance response indicators of aerospace agency products under multiple sets of different key design parameter values are obtained by inputting the key design parameter value matrix into the performance digital model for iterative simulation calculation. The reliability R is obtained by combining the failure domain of performance response indicators. Based on the R and effective key design parameters, the reliability response surface function of the design variables is fitted to obtain the reliability digital model, including mechanical structure reliability digital model, motion control reliability digital model, and signal circuit reliability digital model. The reliability response surface was generated by polynomial regression fitting. Firstly, the matrix of key design parameter values is obtained based on orthogonal experimental design; secondly, the multiple sets of performance response indicators and reliability data are obtained by substituting the performance digital model for iterative simulation calculations. Then, a quadratic polynomial regression is used to fit the relationship between reliability and key design parameters, and the response surface function is obtained; finally, the fitting effect is verified.

2.1.5. Reliability analysis and evaluation. The reliability of products under different key design parameters is obtained based on the different values of key design parameters for aerospace products, combined with the reliability response surface function, which achieves the quantitative evaluation of the reliability of aerospace products.

2.2. Reliability digital simulation decoupling technology

A decoupling method based on coupling matrix, coupling coefficient, and coupling degree function is proposed according to the reliability digital decoupling analysis technology under multi stress coupling, which realizes the equivalent transformation of three typical stress coupling effects into two stress pairwise coupling effects and single stress effects.

2.2.1. Coupling matrix. The stress coupling matrix is constructed considering three types of stresses based on the multiple stress factors of aerospace products, where stress 1 is represented by M, stress 2 is represented by T, stress 3 is represented by W [30].

Assuming stress vector is $[M\,T\,W]$ or $[M\,T\,W]^2$, and the relationship between the stresses is represented by the cross product of the vectors, the generalized coupling matrix of the dual stresses is shown as follows:

$$\begin{bmatrix} M \\ T \\ W \end{bmatrix} \times \begin{bmatrix} M & T & W \end{bmatrix} = \begin{bmatrix} M\times M & M\times T & M\times W \\ T\times M & T\times T & T\times W \\ W\times M & W\times T & W\times W \end{bmatrix}. \tag{1}$$

In the formula, $M\times T$ or $T\times M$ represents the coupling relationship between stress 1 and stress 2, including size and direction. $M\times M$ represents the action relationship of a single stress 1 without coupling, and other stress factors are similar, which can be inferred successively.

The coupling matrix quantifies the strength and direction of the interaction between different stresses. The larger the values of the matrix elements, the stronger the coupling effect of the stresses. The cross-product symbol is used to represent the directional characteristics of stress interaction. Its positive and negative signs indicate the promotion (positive) or suppression (negative) of coupling effect on product failure, and the numerical value represents the strength level of coupling effect. This representation method conforms to the vector expression logic of stress interaction in multi physics field coupling analysis and can accurately reflect the true stress coupling relationship.

According to the importance of stress factors in different stages of different tasks, it can be assumed that a third stress type is added under two stress coupling. For example, $M\times T$ indicates the coupling relationship between stress 1 and stress 2. When the W of stress 3 is added, the three stress coupling matrix is shown as follows:

$$\begin{bmatrix} M\times T \\ W \end{bmatrix} \times \begin{bmatrix} M\times T & W \end{bmatrix} = \begin{bmatrix} M\times T & M\times T\times W \\ W\times M\times T & W\times W \end{bmatrix}. \tag{2}$$

In formula, $M\times T\times W$ represents coupling relationship between stress 1, stress 2 and stress 3, including the size and direction of coupling.

2.2.2. Coupling coefficient. Assuming $f_i\,(i=1,2,\ldots,n)$ is the typical stress characteristics of a product under multi-stress coupling, S represents the impact of each stress coupling on the product's functional performance and reliability. S_{f_1} indicates the effects of f_1 on the product's functional performance and reliability. Similarly, S_{f_n} represents the effects of f_n on the product's functional performance and reliability. Thus, the equation for the effects of multiple stress factors on the product's functional performance and reliability is established as follows:

$$S = F\left(S_{f_1}, S_{f_2}, \ldots, S_{f_n}\right). \tag{3}$$

The exact differential equation can be obtained as follows:

$$\mathrm{d}S = \frac{\mathrm{d}F\left(S_{f_1}, S_{f_2}, \ldots, S_{f_n}\right)}{\mathrm{d}S_{f_1}}\mathrm{d}S_{f_1} + \frac{\mathrm{d}F\left(S_{f_1}, S_{f_2}, \ldots, S_{f_n}\right)}{\mathrm{d}S_{f_2}}\mathrm{d}S_{f_2} + \cdots + \frac{\mathrm{d}F\left(S_{f_i}, S_{f_j}, \ldots, S_{f_n}\right)}{\mathrm{d}S_{f_n}}\mathrm{d}S_{f_n} \tag{4}$$

$$\frac{\mathrm{d}S}{S}=\frac{S_{f_1}}{S}\frac{\mathrm{d}F(S_{f_1},S_{f_2},\ldots,S_{f_n})}{\mathrm{d}S_{f_1}}\frac{\mathrm{d}S_{f_1}}{S_{f_1}}+\frac{\mathrm{d}F(S_{f_1},S_{f_2},\ldots,S_{f_n})}{\mathrm{d}S_{f_2}}\cdot\frac{S_{f_2}}{S}\cdot\frac{\mathrm{d}S_{f_2}}{S_{f_2}}+\cdots+\frac{S_{f_n}}{S}\frac{\mathrm{d}F(S_{f_1},S_{f_2},\ldots,S_{f_n})}{\mathrm{d}S_{f_n}}\frac{\mathrm{d}S_{f_n}}{S_{f_n}}. \quad (5)$$

Assume that $L_1=\frac{S_{f_1}}{S}\frac{\mathrm{d}F(S_{f_1},S_{f_2},\ldots,S_{f_n})}{\mathrm{d}S_{f_1}}$ represents the influence factor of stress f_1 on product functional performance and reliability characteristic quantity. $L_2=\frac{S_{f_2}}{S}\frac{\mathrm{d}F(S_{f_1},S_{f_2},\ldots,S_{f_n})}{\mathrm{d}S_{f_2}}$ represents the influence factor of stress f_2 on product functional performance and reliability characteristic quantity. $L_n=\frac{S_{f_n}}{S}\frac{\mathrm{d}F(S_{f_1},S_{f_2},\ldots,S_{f_n})}{\mathrm{d}S_{f_n}}$ is the effect factor of stress f_n on product functional performance and reliability characteristic quantity.

In the case of $\ln S=\mathrm{d}S/S$, the weight coefficient (i.e. coupling coefficient) of each stress on product functional performance and reliability characteristics can be calculated by formula.

$$\mathrm{In}\,S=L_0+L_1\mathrm{In}\,(S_{f1})+L_2\mathrm{In}\,(S_{f2})+\cdots+L_n\mathrm{In}\,(S_{fn}) \quad (6)$$

where, L_0 is a constant, L_1, L_2 and L_n are the coupling coefficients between the stresses.

The coupling coefficient indicates the contribution degree of each stress factor to the functional performance and reliability characteristics of aerospace products.

2.2.3. Coupling degree function. Based on the coupling degree and correlation degree of the three types of stresses, the influence degree of each stress on the functional performance and reliability of aerospace products, and constructs a coupling degree function is investigated. The hypothetical variable u_i is the ordinal parameter of the internal stress in the mission profile of the aerospace product, and u_ij is the jth index of the ith ordinal parameter, whose value is $X_{ij}\,(i,j=1,2,\cdots,n)$. α_{ij} and β_{ij} are the upper and lower limits of the ordinal parameters at the critical point of functional performance and reliability stability of the aerospace product. The ordered effectiveness coefficients of the stress sequence parameters on performance, function, and reliability can be expressed as: $u_{ij}=(X_{ij}-\beta_{ij})/(\alpha_{ij}-\beta_{ij})$ when u_ij has the same directional coupling effect, $u_{ij}=(\alpha_{ij}-\beta_{ij})/(X_{ij}-\beta_{ij})$ when u_ij has the anomalous coupling effect.

In the formula, u_ij has a coupling effect, which is expressed as the functional contribution of variable X_ij to the functional performance and reliability of aerospace products. u_ij reflects the satisfaction degree of each index to reach the target, $u_{ij}>0$ indicates the co-directional coupling of each stress factor, and $u_{ij}<0$ indicates the cross-directional coupling of each stress factor. Therefore, $-1\leqslant u_{ij}\leqslant 1$.

Through the above analysis, the coupling degree function of the three types of stress is obtained, which is expressed as:

$$C=3\{(u_1\cdot u_2\cdot u_3)/[(u_1+u_2)(u_1+u_3)(u_2+u_3)]\}^{1/3}. \quad (7)$$

Obviously, the coupling degree value $C\in[-1,1]$. The coupling degree is maximum when $C=1$, which is called the same direction coupling. The coupling degree is minimum when $C=-1$, which is called the opposite direction coupling.

Therefore, different coupling mechanisms of each stress factor are quantified by studying the 'coupling matrix, coupling coefficient and coupling degree function'. A coupled system of mechanical stress, temperature stress and working stress is formed in the mission profile of space products, which provides theoretical support for reliability digital modeling, decoupling and prediction.

2.3. Reliability digital simulation prediction technology

The life and reliability analysis and evaluation of aerospace products under multi-stress coupling is proposed, forming a life and reliability evaluation method for moving parts considering space factors and a life prediction method for on-board electronic products under comprehensive stress, which solves the problem of accurate evaluation of engineering development of aerospace products.

2.3.1. Multi-stress characteristics. The stress in aerospace products is characterized by the interaction of multiple stresses, primarily environmental and operational stresses. Environmental stresses include mechanical, thermal, and radiation-induced stresses. Mechanical environmental stresses encompass vibration, impact, and constant stress. Thermal environmental stresses involve high temperatures, low temperatures, and temperature cycling. Operational stresses consist of electrical and mechanical components. Electrical stresses include current, voltage, and power, while mechanical operational stresses include torque, speed, and rotational force. The impact of different stress conditions on the performance and reliability of equipment, components, and parts is different, and the coupling relationships among these stress factors are complex.

2.3.2. Failure modes under multi-stress coupling. The failure modes of electronic products include: short circuits, open circuits, broken circuits, drift in electrical parameters, decreased capacitance, fluctuations in the current density of thermistors, abnormal internal leakage currents in components, reduced insulation performance, open normally closed contacts, open coils, increased contact resistance at points, decreased insulation resistance between coils and enclosures, electrical contact failures, electrical insulation failures, mechanical failures, failure to start oscillation, cessation of oscillation, frequency deviations, increased resistance, cracks, and 20 other types. The failure modes of mechanical-electrical products include: fatigue spalling, permanent deformation, wear, electrochemical corrosion, degradation of characteristics, delamination at adhesive joint, decreased rotational accuracy, motion jamming, structural component fracture, gap jamming, signal transmission failures, and thermal effect failures, among 12 others.

The dominant failure modes under specific stress scenarios are shown as follows.

(1) Vibration stress dominant scenario: the dominant failure modes for mechanical products are fatigue peeling and structural component fracture, while the dominant failure modes for electronic products are solder joint cracking and pin disconnection.
(2) Temperature stress dominant scenario: The dominant failure mode of mechanical products is adhesive surface cracking and permanent deformation, while the dominant failure mode of electronic products is interconnect welding thermal fatigue and insulation performance degradation.
(3) Scenario dominated by electrical stress: The dominant failure modes of electronic products are electromigration and hot carrier failure, while the dominant failure modes of mechanical products are erosion and characteristic degradation. Establish the correlation between failure modes and stress scenarios.

2.3.3. Fault mechanism under multi-stress coupling. The failure mechanism models of electronic products include: random vibration fatigue, interconnect welding thermal fatigue, chip electromigration, hot carrier physics, hole-induced breakdown, thermal chemical degradation, and quartz glass transmission rate degradation. For mechanical (mechatronic) products, there are ten types of failure mechanism models: stress intensity, cumulative degradation rate, stress impact, thermal deformation, cutting wear, indentation wear, fatigue wear, adhesive wear, electrical wear, and current-carrying wear. Among these, random vibration fatigue, interconnect welding thermal fatigue, cutting wear, indentation wear, fatigue wear, adhesive wear, electrical wear, and current-carrying wear are categorized as loss-type failure mechanisms.

This technology introduces for the first time the integration of electric field influence factors into the life prediction of electronic products. It comprehensively considers the impact of vibration, thermal, and electrical stress conditions on the weak points, failure modes, and mechanisms of packaged and high-power device electronic products, achieving the calculation of life characteristics and reliability indicators for aerospace electronic products based on digital models.

3. Engineering applications

3.1. The engineering application of digital modeling for reliability of aerospace electromechanical products based on response surface

This section focuses on the digital modeling of the overall reliability of aerospace electromechanical products, with a particular emphasis on the integrated modeling of overall reliability. An aerospace electromechanical product was selected as the application object. Considering the actual conditions, the environmental stress for electromechanical product is vibration and temperature, while the working stress is rotational speed. A digital model of the mechanical thermal performance and electromechanical performance of the electromechanical product is constructed. The reliability of the product is calculated by integrating functional functions and using the Monte Carlo analysis method.

3.1.1. Digital model of machine thermal reliability. The digital model of machine thermal reliability is constructed as follows. $Y_{\mathrm{P(mt)}}$ is a mechanical thermal performance indicator, representing the stress value of the mechanical thermal structure. $T_{\max}$ represents the maximum allowable stress of the material, which is 450 MPa. $p_{(\mathrm{F})}$ is the external load force. $p_{(\mathrm{E})}$ is the elastic modulus of the material, and $p_{(\mathrm{a})}$ is the thermal expansion coefficient (CTE) of the material, all of which follow a normal distribution. When the simulated number of times is 10^6, the failure number calculated by this method is 1961 times, the failure probability is 0.001 961, and the mechanical thermal reliability is 0.997 039

$$\begin{cases} Y_{p(\mathrm{mt})} = -91.6828 - 0.4635 p_{(\mathrm{F})} + 903.1556 p_{(\mathrm{E})} + 16.2539 p_{(\mathrm{a})} \\ -0.0038 p_{(\mathrm{F})}^2 - 1128.254 p_{(\mathrm{E})}^2 - 0.1564 p_{(\mathrm{a})}^2 - 4.0124 p_{(\mathrm{F})} p_{(\mathrm{E})} \\ -0.0492 p_{(\mathrm{F})} p_{(\mathrm{a})} - 0.0001 p_{(\mathrm{E})} p_{(\mathrm{a})} \\ C_P = T_{\max} - Y_{p(\mathrm{mt})} = 450 - Y_{p(\mathrm{mt})} \\ \breve{p}_f = 1961/10^6 = 0.001\,961 \\ R_{(\mathrm{mt})} = 1 - 0.001\,961 = 0.997\,039 \end{cases} \tag{8}$$

3.1.2. Digital model of electromechanical reliability. The digital model of electromechanical reliability is constructed as follows. $Y_{P(\mathrm{me})}$ is the displacement value of the ball screw nut. $T_{\max}$ is 125 mm, which is the maximum displacement under actual operating conditions. The *P, I*, and *D* parameters of the PID controller significantly influence the maximum displacement of the ball screw nut. These parameters are denoted as $p_{(P)}$, $p_{(I)}$, and $p_{(D)}$, respectively, and all follow a normal distribution. When the simulated number is 10^6 times, the failure number calculated by this method is 1565 times, the failure probability is 0.001 564, and the electromechanical reliability is 0.998 435.

$$\begin{cases} Y_{p(\mathrm{me})} = -1.4686 + 750\,857 p_{(P)} + 171.6952 p_{(I)} + 27.781 p_{(D)} \\ -14.2857 p_{(P)}^2 - 9.5238 p_{(I)}^2 - 3.3333 p_{(D)}^2 - 9.5238 p_{(P)} p_{(I)} \\ +10.4762 p_{(P)} p_{(D)} - 0.0001 p_{(I)} p_{(D)} \\ C_P = T_{\max} - Y_{p(\mathrm{me})} = 125 - Y_{p(\mathrm{me})} \\ \breve{p}_f = 1565/10^6 = 0.001\,565 \\ R_{(\mathrm{me})} = 1 - 0.001\,565 = 0.998\,435 \end{cases} \tag{9}$$

Any problem in the structure and control of the electromechanical product will cause the whole machine failure. Therefore, the reliability of the electromechanical product is calculated as follow.

$$R = R_{(\mathrm{mt})} \cdot R_{(\mathrm{me})} = 0.997\,039 \ \cdot \ 0.998\,435 = 0.995\,479. \tag{10}$$

3.2. Engineering application of digital decoupling analysis technology for reliability under multi-stress coupling

As the main component of aerospace electromechanical products, aerospace electronic products are subject to reliability digital decoupling in this section, with a focus on multi stress decoupling analysis of components. The engineering application of digital decoupling reliability analysis technology under multi-stress coupling is selected for the aerospace electronic products.

3.2.1. Accelerated test stress type. According to the design structural parameters of aerospace electronic products and various environmental and payload conditions during the in-orbit process, the parameter values of vibration, thermal stress and electrical stress of aerospace electronic products are obtained, and it is clear that heat, electricity and radiation are the main accelerated stress types of aerospace products. The aerospace products will periodically experience sunshine area and shadow area, and be periodically heated and cooled, so that the onboard products often undergo a large range of high and low temperature changes, generally from-160 °C to +120 °C. The Spaceborne products with a service life of about three years will undergo about 1750 thermal cycles during orbital operations. The extreme environment of a product includes external environmental factors (temperature), its own performance limit factors (voltage and current), and the combination of these factors, namely composite environmental factors. The extreme input voltage range is the extreme high and low voltages that may occur in aerospace products power supply distribution system. Extreme load jump is the variation between no-load and 100% load points. The range of extreme temperature is from-35 °C to +85 °C. The product is subjected to a thermal cycling test not less than the identification grade, and then further probing test is carried out with a 5 °C gradient expansion, and the overcurrent protection characteristics are verified at the high end.

The space particle radiation sources primarily consist of three components: the Earth's radiation belts, solar cosmic rays, and galactic cosmic rays. The effects of various particle radiation on aerospace products are mainly the total dose effect and single particle effect. The single particle effect mainly affects the logical fault failure of the control software of each onboard system, and the radiation stress in this paper only considers the total dose effect. The total dose effect includes the ionizing total dose effect and the displacement total dose effect. The space environment that causes the total dose effect includes earth's capture of electrons and protons, solar flare protons, cosmic ray protons, etc.

3.2.2. Accelerated life test model. The selected traditional unidimensional or two-dimensional stress accelerated test models include the Arrhenius model related to thermal stress, the exponential model related to electrical stress, the generalized Ayring model related to thermal and electrical stress, and the dual stress accelerated test model related to temperature and irradiation stress.

(1) Arrhenius model related to thermal stress
It is common to use temperature as the accelerated stress in accelerated life tests, because high temperatures can accelerate chemical reactions inside products (such as electronic components, insulating materials, etc) and cause premature failure of products. The accelerated model is shown as follow.

$$\xi = A\mathrm{e}^{E_{\mathrm{a}}/kT} \tag{11}$$

where, ξ indicates the characteristic quantity of the lifetime. A is a constant, and $A > 0$. E_{a} is the activation energy, which is material-dependent and measured in electron volts (eV). k is the Boltzmann constant. E/k is the activation temperature. T is the absolute temperature.

According to the Arrhenius model, the life characteristics decrease exponentially with increasing temperature. Taking logarithms on both sides of this model.

$$\ln\xi = a + b/T \tag{12}$$

where, $a = \ln A$, $b = E_{\mathrm{a}}/k$, they are all undetermined parameters. So, the Arrhenius model shows that the logarithm of the life characteristic is a linear function of the inverse of the temperature.

(2) Exponential model related to electrical stress
In accelerated tests, electrical stress (such as voltage, current, power, etc) is also commonly used as accelerated stress. For example, increasing the voltage can also cause products to fail prematurely. In physics, many experimental data have been confirmed that some life characteristics of products are related to stress as follows.

$$\xi = AV^{-c} \tag{13}$$

where, c is a normal number related to the activation energy, V is the stress and usually taken as the voltage.

If the logarithm of both sides of the above relationship is taken, the inverse power law model can be linearized, that is

$$\ln\xi = a + b\ln V \tag{14}$$

here, $a = \ln A$, $b = -c$, they are all parameters be determined.

(3) Double stress acceleration test model related to temperature stress and irradiation stress
In the accelerated test, the attenuation caused by irradiation is represented by λ, and the cumulative total dose of irradiation is

represented by R. Under the condition that the irradiation dose rate is constant, the calculation formula of λ under the combined action of temperature and irradiation stress is expressed as follow.

$$\lambda = C^{*}\hat{R}^{1-a+\frac{kT}{E_0}}R^{a-\frac{kT}{E_0}} = C^{*}R^{a}\hat{R}^{1-a\left(\frac{\hat{R}}{R}\right)^{\frac{kT}{E_0}}} = C^{*}\hat{R}\left(\frac{\hat{R}}{R}\right)^{a-\frac{kT}{E_0}}. \tag{15}$$

Combined with dimensional analysis, both sides of the formula are dimensionless, and further simplified as follow.

$$\lambda = C^{*}R^{a}\hat{R}\left(\beta\hat{R}/R\right)^{\frac{kT}{E_0}} \tag{16}$$

where, β is the parameter related to the irradiation dose. a and C^{*} are constants. E_0 is the estimated parameter related to the activation energy. k is the Boltzmann constant, and T is the absolute temperature.

The temperature and total dose of irradiation are used as the stress of accelerated test. In the test, and the irradiation dose rate is constant, that is $\hat{R} = R/t$. The life of electronic products under the temperature and irradiation stress is obtained as follow.

$$t = \beta\left(\frac{\lambda}{C^{*}R^{a}}\right)^{-\frac{E_0}{kT}}. \tag{17}$$

The accelerated life test model under typical stress is selected, and the key technical theories and methods are utilized to construct the model. The model includes thermal, electrical, and irradiation stress parameters, which can clearly quantify the coupling effects among these stresses. The models for electrical stress and the combined models for temperature and irradiation stress are chosen. Multiplying these two models results in a total accelerated life test model, which is based on the coupling of multiple stresses.

$$\xi_{\text{couple}} = \left(AV^{-c}\right)\beta\left(\frac{\lambda}{C^{*}R^{a}}\right)^{-\frac{E_0}{kT}}. \tag{18}$$

If the logarithm of both sides of the above relationship is taken, the inverse power law model can be linearized, that is

$$\ln\xi_{\text{couple}} = \frac{\ln R}{T}\left(\frac{aE_0}{k}\right) - c\ln V + \ln(A\beta) - \frac{1}{T}\left(\frac{E_0}{k}\right)\ln\left(\frac{\lambda}{C^{*}}\right) \tag{19}$$

herein, $\phi_1(T) = 1/T$, $\phi_2(V) = \ln V$, $\phi_3(R) = \ln R$, $A = a$, $B = \frac{E_0}{k}$, $C = -c$, $D = -\ln\left(\frac{\lambda}{C^{*}}\right)$ and $E = \ln(A\beta)$.

The above formula can be simplified as follow.

$$\ln\xi_{\text{couple}} = AB\varphi_1(T)\varphi_3(R) + C\varphi_2(V) + BD\varphi_1(T) + E. \tag{20}$$

The coupling of temperature stress, electric stress and irradiation stress is transformed into the equivalent transformation of two stresses acting on each other, and the action of a single stress.

3.3. Engineering application of life and reliability analysis and evaluation technology for aerospace products under multi-stress coupling action

This technology focuses on spatial electronic products, taking into account the multi-stress integrated usage environment, failure modes, and the cumulative and competitive relationships of failure mechanisms. The lifespan of electronic products is predicted combined with theoretical models and simulation results by constructing a single-stress damage simulation analysis and a multi-stress cumulative damage analysis.

3.3.1. The life of components of electronic product packaging structures. The vibration fatigue model and thermal fatigue model are applied to determine the stress cycle times before structural vibration and thermal fatigue failures by using the results from random vibration and thermal simulation analyses. A cumulative damage model under the combined effects of thermal and vibration is proposed, and the life calculation of the packaging structure is conducted.

(1) Vibration fatigue model

A large number of finite element analyses and vibration tests have shown that the fatigue life of various electronic components is often related to the dynamic displacement experienced by the printed circuit board (PCB) supporting these components. The board structure is forced to bend back and forth when the PCB's resonant frequency is excited. The relative motion between the component and the PCB is substantial when the displacement amplitude is significant, which leads to solder joint damage or electrical lead breakage.

The random vibration fatigue model is shown in the following formula.

$$N_{\mathrm{f}} = C\left[\frac{z_1}{z_2\sin(\pi x)\sin\pi y}\right]^{\frac{1}{b}} \tag{21}$$

where, N_{f} is the number of stress cycles before the vibration fatigue failure of the device. x and y is the position coordinate of the device on the circuit board. C is a constant determined according to the standard test. For random vibration, $C = 2 \times 10^{6}$, b indicates the fatigue strength index, z_1 and z_2 are determined by equation (22).

$$\begin{cases} z_1 = \dfrac{0.000\,22B}{ct\sqrt{L}} \\ z_2 = \dfrac{36.85\sqrt{\mathrm{PSD}_{\max}}}{f_{\mathrm{n}}^{1.25}} \end{cases} \tag{22}$$

herein, $\mathrm{PSD}_{\max}$ represents the maximum power spectral density of random vibration. f_{n} is the minimum natural frequency of random vibration. B is the maximum distance between the four edges of the device and the four edges of the circuit board. L is the length of the device. t is the thickness of the circuit board. c is a coefficient. This formula applies to two-row pin devices as $c = 1$, four-row pin devices as $c = 1.26$, and pinless devices (such as chip resistors and capacitors) as $c = 2.25$.

(2) Thermal fatigue model
A primary cause of failure in surface mount electronic devices is the mechanism of solder joint failure due to temperature cycling. This failure occurs because the CTE of the electronic device and the circuit board do not match. The periodic on-off cycles of the circuit and the cyclical changes in environmental temperature subject the solder joints to temperature cycling. The expansion differences between the electronic device and the printed circuit board cause periodic stress-strain on the solder joints when temperatures fluctuate. The fatigue damage first occurs in the stress concentration areas of the solder joints when plastic strain accumulates to a certain level, which leads to thermal fatigue ultimately. In the aerospace industry, the fatigue creep damage of solder joints becomes an internal hazard for product failure where products are exposed to the conditions of alternating hot and cold.

Moreover, the overall reliability of PCBs is impacted by the failure of plated-through holes (PTH) significantly. This failure is primarily due to the mismatch in CTE between the plating material and the substrate material. The structural micro-analysis of numerous PTH failure samples reveals that the primary failure modes include the fracture of the plating layer at the center of the hole wall, the separation of the plating layer from the internal pad, and the fracture at the corners of the external pad.

The Coffin-Mason model is commonly used to describe the thermal fatigue of electronic interconnection welding.

$$N_{\mathrm{f}} = \frac{1}{2}\left(\frac{\Delta\gamma_{\mathrm{P}}}{2\varepsilon_{\mathrm{f}}}\right)^{\frac{1}{c}} \tag{23}$$

here, $c = -0.442 - 0.0006T_{sj} + 0.0174\ln\left(1 + \frac{360}{t_D}\right)$, $\varepsilon_{\mathrm{f}} = 0.325$. N_{f} is the number of stress cycles before thermal fatigue of the device. T_{sj} is the average cycle temperature of the solder. t_D is the holding time of the highest temperature.

In terms of vibration stress damage, the vibration fatigue model considering temperature is used to calculate the number of stress cycles before vibration fatigue failure at different temperatures, and the damage amount under vibration stress is obtained.

$$D_{v(\mathrm{total})} = \sum_{T} D_v(T) f_j = \sum_{T} \frac{f_j}{N_{\mathrm{f}(T)}} \tag{24}$$

where, $D_{v(\mathrm{total})}$ is the total loss caused by vibration. $D_v(T)$ is the vibration damage at different temperatures, and f_j is the percentage of total time occupied by different temperatures.

In terms of thermal stress damage, the number of stress cycles before thermal fatigue failure N_{f1} is calculated by using the thermal fatigue model, and the amount of damage under thermal stress D_{th} is obtained.

$$D_{\mathrm{th}} = \frac{1}{N_{\mathrm{f1}}}. \tag{25}$$

The total damage is obtained by summing the structural vibration stress damage and thermal stress damage. The inverse of the total damage is the fatigue life of the packaging structure. The total damage is shown as follow.

$$D_{\mathrm{total}} = D_{v(\mathrm{total})} + D_{\mathrm{th}}. \tag{26}$$

The fatigue life of electronic product packaging structure is obtained as follow.

$$N_{\mathrm{f}} = \frac{1}{D_{\mathrm{total}}}. \tag{27}$$

3.3.2. The life of power devices of electronic products. The weak links of the circuit are determined according to the results of electrical stress simulation. The device life is calculated by using the mechanism model related to electrical stress, and the principle of competitive failure is adopted to deal with it, that is, the shortest pre-fault time is regarded as the life of the device.

(1) Electric migration model
The electrical migration of wires in a chip is commonly described by the Black model.

$$\mathrm{TTF} = \frac{w \cdot t}{c} \cdot J^{-2} \cdot \exp\left(\frac{E_{\mathrm{a}}}{kT}\right) \tag{28}$$

here, w represents the width of the chip's metallization layer (cm). t is the thickness of the metallization layer (cm). J denotes the current density of the metallization layer (A cm^2). E_{a} is the activation energy (eV). T is the temperature at which the chip operates (K). k is the Boltzmann constant, set at 8.62×10^{-5} eV (atom·K^{-1}). c is a parameter related to the geometric dimensions and temperature of the metal, indicating the values of c and E_{a} for different cross-sectional areas of the chip's metal wires.

(2) Hot current model
The mechanism of hot current is $I_{\mathrm{sub}}/I_{\mathrm{d}}$ model.

$$\frac{tI_{\mathrm{d}}}{W} = H\left(\frac{I_{\mathrm{sub}}}{I_{\mathrm{d}}}\right)^{-m}. \tag{29}$$

Taking logarithms on both sides.

$$\lg\left(\frac{tI_{\mathrm{d}}}{W}\right) = \lg H - m \cdot \log\left(\frac{I_{\mathrm{sub}}}{I_{\mathrm{d}}}\right) \tag{30}$$

where, t is the device life, I_{d} is the leakage current, W is the channel width, and I_{sub} is the substrate current, H and m are two fitted parameters. $M = \Phi_{\mathrm{i}t}/\Phi_{\mathrm{i}}$, where $\Phi_{\mathrm{i}t} = 3.7$ eV and $\Phi_{\mathrm{i}} = 1.3$ eV. m is typically set to 2.9. Φ_{i} denotes the activation energy for shock ionization, while $\Phi_{\mathrm{i}t}$ represents the activation energy for interface thermal carrier damage or degradation. H is a proportionality constant influenced by the manufacturing technology of the dielectric between the oxide layer and the interface, with a value of 100.

3.3.3. The life prediction of electronic products. The life of the electronic product is determined by the competition between the fatigue damage caused by vibration and thermal stress, and the failure caused by electrical stress. The life of the weak link is the whole life of the electronic product, and the life prediction of the electronic product is completed.

Taking a specific circuit board of an aerospace products as the subject, the typical case application is conducted in this study. The circuit board is subjected to combined stress from random vibrations and temperature cycling during the power-on process. The root mean square vibration acceleration is 6.65 g, and the temperature cycling range is from −40 °C to 60 °C. Under these conditions, the failure mechanisms for the circuit board's packaging structure are vibration fatigue and thermal fatigue, while for the power devices, they are electromigration and hot carriers. The life prediction results for circuit board components under vibration, temperature, and electrical stress are calculated based on these failure mechanisms.

4. Conclusions

This paper focuses on the reliability issues of aerospace products. A digital modeling technology for the reliability of aerospace electromechanical products based on response surface is proposed by solving key technological challenges for integrated design and simulation of reliability and performance. Meanwhile, a digital decoupling analysis technique for reliability under multi-stress coupling is presented, which effectively converts three typical stress couplings into two pairs of stress coupling and single stress effects. Furthermore, an analysis and evaluation method for the life and reliability of aerospace products under multi-stress coupling is proposed, which solves the challenge of precise assessment in the engineering development of products. The technologies have been successfully applied to several aerospace models, providing effective support for the development of aerospace models with long life, high reliability, high precision, and high performance. The model is suitable for the special scenario of 'small sample, high reliability, and multi stress coupling' in aerospace. This method can be extended to complex equipment fields such as aviation, weapons, and ships with multi stress effects, small sample testing, and high reliability requirements.

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Xinggao Zhu is the first author of this paper. He received a PhD from the Beijing Institute of Technology, Beijing, China. He is currently a senior engineer at the China Astronautics Standards Institute. His research interest is mechanical reliability engineering.

Pengfei Liu is the corresponding author of this paper. He received a PhD from the Tiangong University, Tianjin, China. He is currently an engineer at the China Astronautics Standards Institute. His research interest is mechanical system dynamics.

Jiahui Luan is currently a researcher at the China Astronautics Standards Institute. His research interest is mechanical reliability engineering.

Haibo Mi is currently a senior engineer at the China Astronautics Standards Institute. His research interest is reliability testing technology.

Hao Dong graduated from Yanshan University. He is currently an engineer at the China Astronautics Standards Institute. His research interest is fault diagnosis and health management of intelligent devices.

Hao Chen is currently a senior engineer at the China Astronautics Standards Institute. His research interest is reliability and EMC test simulation.

Zhaopeng Xue received Master's degree in Nanjing University of Aeronautics and Astronautics, Nanjing, China. He is currently an engineer at the China Astronautics Standards Institute. His research interest is mechanical reliability engineering.

Haipeng Wen graduated from the University of Science and Technology Beijing, China. He is currently employed as an engineer at the China Astronautics Standards Institute. His research focuses on the field of multiphysics coupling simulation.

Yongde Dai received his Master's degree from the China University of Geosciences, Beijing, China. He is currently an engineer at the China Astronautics Standards Institute. His research interest is mechanical reliability engineering.