Research on Integrated Simulation Design Method of Performance and Reliability for Aerospace Electromechanical Products

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Abstract: This paper proposes an integrated simulation method of the performance and reliability for aerospace electromechanical products, which can obtain the reliability parameters of the product through digital simulation, so as to guide the design of the product, taking into account the factors that affect the reliability in the design stage. This method is based on a multidisciplinary performance simulation model, comprehensively considers the failure mode and failure mechanism of the product. Through the method of DESIGN OF EXPERIMENT (DOE), the key design parameters and disturbance factors are combined and designed as input, the performance response surface model, the performance and reliability integrated simulation model are constructed in turn. Taking a typical aerospace electromechanical product solar wing drive mechanism as an example, the engineering application verification is carried out, and the response surface has a high matching degree with the sampling point, which can meet the engineering application.

1. Introduction
Facing a new generation of aerospace equipment, the development of high reliability, high precision and high performance has put forward higher requirements for the design of aerospace products. At present, there are many potential dangers in the scientific research and production of aerospace mechanical and electrical products. Some products cannot work normally in complex environments. Through analysis, there are two reasons for the problem. On the one hand, the structure and composition of Aerospace Electromechanical Products are complex, involving mechanical system, control system, circuit system and many other disciplines, the product development needs to carry out more test projects, the high cost of development, long cycle characteristics and the type of high-density mission requirements between the increasingly prominent contradiction. On the other hand, the limitations of existing reliability design and analysis techniques are becoming more and more obvious. In the process of model development, the combination of performance design and reliability design is not close, and the product can not even meet the requirements of the design cycle when carrying out 1:1 test, and the time schedule of verification test lags behind the product development cycle. At present, there is no effective method for integrated simulation design and evaluation of product performance and reliability. It leads to some potential reliability problems in the design and manufacturing process of aerospace mechanical and electrical products, which may expose reliability problems in the process of product development, test, identification and use. It affects the development progress and service performance of the model products and seriously restricts the service performance of space equipment. Therefore, the reliability design work presents a serious
challenge, which is how to promote the performance and reliability of the product in a short development cycle. Aiming at the above problems, a Integrated Simulation design method of performance and reliability is proposed in this paper, which can integrate product reliability design and analysis into product design stage and effectively shorten the development cycle.

2. Design Ideas of Performance and Reliability Integrated Simulation Model
Design ideas of performance and reliability Integrated Simulation Model is shown in Figure 1. For a given Signal Factors, the product object produces a corresponding response output. Due to the existence of disturbance factors, load factors, failure factors, hazard factors and other factors, the response output may produce drift or drastic changes, thus failing to meet the expected functional/performance requirements of the product. The purpose of integrated design is to achieve stable, safe and reliable product performance by adjusting the design variable(DV) to reduce the sensitivity of the response to disturbance, stress, fault and danger within the design constraint(DC). The integrated design selection takes the performance reliability as the goal, and determines the optimal value of design variables by considering the interaction of disturbance, stress, fault and danger.

![Figure 1. Design concept of performance and reliability integration model.](image)

Performance stability is generally measured by the degree of deviation between the actual output response and the expected output response, reliability is generally expressed by the task reliability, and security can be expressed from the perspective of failure safety and probabilistic safety. The performance reliability is the probability that the performance parameters of the product meet the specified index requirements under the specified conditions and within the specified working time, starting from the functional requirements of the product. Performance reliability can be expressed as follows.

\[
R(y) = p\{y \in S\} = P\left\{\cap_{i=1}^{n} y_i \in S_i \right\}
\]

(1)

Where \( S \) represents the set of the system in normal state, and \( S_i \) represents a collection of properties \( y_i \) in a normal state.

3. Integrated Simulation Model design flow of performance and reliability
The main Integrated Simulation Model design flow of performance and reliability is shown in Figure 1.
It consists of four parts as follows.

3.1. Product information research
In this part, information investigation is carried out for aerospace mechanical and electrical products, and the functional principles and main fault modes of the products are collected to form a standardized load spectrum which is foundation of the entire design process.

3.2. Construction of performance simulation model
In this part, commercial software, such as ANSYS, ADAMS, Saber, Matlab, were used to build performance simulation models including structural performance, circuit performance and control performance based on the research in the above part. Firstly, the simulation project and simulation conditions are determined based on the main fault modes and load spectrum. Then the performance simulation results were compared with the actual test results. Finally, an accurate performance simulation model is formed.

3.3. Construction of performance response surface model
The general way to obtain product reliability is to carry out reliability test, which needs to form sample size batch test, which will consume a lot of time and economic cost. Through the means of digital simulation can also accomplish the purpose, they are similar ideas, the difference is that the latter replaces the physical object with digital. However, to form the sample size for reliability, the digital simulation method still needs thousands of working cycles, which is no less than the time of the general experiment. Therefore, this part proposes to build a performance response surface model to solve this problem. Taking the key design parameters of the product as independent variables, the accurate performance simulation model as the carrier, and the simulation output perform parameters as dependent variables, a multivariate second-order response surface model(RSM) was constructed as follows.

\[
Rs = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i x_i^2 + \sum_{i,j} \beta_{ij} x_i x_j + \epsilon
\]

Or

\[
P(FMs) = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i x_i^2 + \sum_{i,j} \beta_{ij} x_i x_j + \epsilon
\]

Or

\[
\begin{align*}
\mu_s &= \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i x_i^2 + \sum_{i,j} \beta_{ij} x_i x_j + \epsilon_1 \\
\sum x &= \gamma_0 + \sum_{i=1}^{k} \gamma_i x_i + \sum_{i=1}^{k} \gamma_i x_i^2 + \sum_{i,j} \gamma_{ij} x_i x_j + \epsilon_2
\end{align*}
\]

\[
\mathbf{x} = \{FM_1, \ldots, \mu_s, \sum_{j=1}^{i} \ldots, DDP_k, \ldots\}
\]

Where

According to the needs of the problem, a subset can be selected as an independent variable such as \(x = \{DDP_k\}\), when constructing the response surface model. Other factors such as \(x = \{FM_1, \ldots, \mu_s, \sum_{j=1}^{i} \ldots\}\) is hidden by statistical stability. In addition to response surface models, Artificial Neural Network (ANN) models, Kriging models, etc. can also be used to describe the above relationships. We can get the relationship between crucial performance parameters and indicators without enormous repetitive simulating calculations to make the whole flow simpler.
3.4. Performance and reliability joint response surface construction

The purpose of building an integrated performance and reliability model based on response surface methodology is to establish the mathematical relationship between product reliability and key design parameters, and then to support the development of related work on integrated performance and reliability design analysis. The mathematical expression of the performance and reliability integration model is:

$$R_s = f(DDP_1, \cdots, DDP_n)$$  \hspace{1cm} (5)

Where, $R_s$ is the product performance reliability, $(DDP_1, \cdots, DDP_n)$ is the key design parameter of the product.

The integrated response surface model of performance and reliability is different from the conventional reliability model. The mathematical expression of the conventional reliability model is:

$$R_s = f(R_1, \cdots, R_n)$$  \hspace{1cm} (6)

where, $R_s$ is the product reliability, and $(R_1, \cdots, R_n)$ is the lower-level product reliability.

The performance and reliability integrated model can be divided into two cases: component model and system model. The integrated model of component performance and reliability is established based on the fault physical model. Through the discretization of parameters, the mathematical relationship between the distribution of the unit's failure time and the key design parameters is established. The system performance and reliability integrated model of aerospace electromechanical equipment is established on the basis of response surface model (RSM). By establishing a system dynamics model that considers the uncertainties of internal and external factors and the effects of unit failures, the correlation between FM and VM is reflected. Through simulation and multiple statistical regression, the mathematical relationship between system reliability and key design parameters is established. Finally, the method of Residual Sum of Squares (RSS) is used to calibrate the fitting accuracy of the integrated model.
4. Application verification of typical products

The solar wing drive mechanism is a typical aerospace electromechanical product, which is mainly composed of a motor, a reducer, a drive shaft, a zero position sensor, a conductive ring, and a housing. The motor receives the driving signal from the driving circuit, outputs the speed and torque, and is amplified by the reducer to drive the solar cell array, so that it has the functions of capturing, tracking, stopping, and maintaining the orientation to the sun[1]. This paper takes the integrated simulation of the control kinematics performance and reliability of the solar wing drive mechanism as an example to carry out application verification.

Figure 2. Technical flow chart of design and analysis of aerospace electromechanical equipment performance and reliability integrated model.
4.1. Construction of the simulation model for the control motion performance of the solar wing drive mechanism

Based on the known structural composition of the solar wing drive mechanism, add material properties to each component, and build the control motion performance simulation of the product in a modeling environment based on multi-body dynamics according to the product structure design characteristics and original design data model.

4.2. Analysis and experimental design of key design parameters of solar wing drive mechanism

4.2.1. Determination of key design parameters. According to the sensitivity analysis results and the degree of influence of input parameters on the output speed of the solar wing drive mechanism, the key design parameters that affect the control characteristics of the solar wing drive mechanism are obtained, and the speed controller parameters Kp_v and the speed controller parameters in the solar wing drive mechanism line are selected. Ki_v and current controller parameter Kp_i are used as design variables. Other design parameters are used as interference factors, and their distribution rules are shown in the following table 1.

| Parameters                  | Distribution of interference factors |
|-----------------------------|--------------------------------------|
| Moment of inertia of the rotor (kg.m$^2$) | N(0.006, 0.0006)                     |
| Moment of inertia of stator (kg.m$^2$)   | N(0.005, 0.0005)                     |
| Motor mutual inductance (H)            | N(0.061, 0.0061)                     |
| Motor self-inductance (H)             | N(0.02, 0.002)                       |
| Motor damping coefficient (N.m.s/rad)  | N(0.0002, 0.00003)                   |

4.2.2. DOE of key design parameters and simulation. Orthogonal experiment method is selected for the response surface construction process[2]. If the level number of each factor in the analysis is $n$, then the orthogonal table $L_p(n^n)$ is selected, where $m$ should not be less than the number of factors required by the analysis. In the simulation, five levels of the key design parameters of the control system are selected: the speed controller P parameter Kp_v, the speed controller I parameter Ki_v, and the current controller P parameter Kp_i parameter. Therefore, the number of factors in the simulation analysis is 3, and the level of each factor is 5, so the orthogonal table $L_{25}(5^3)$ is selected. 25 experiments scheduled for key design parameters. Each set of key design parameters was simulated for 10,000 times based on the performance simulation model of the solar wing drive mechanism. According to the product reliability failure criterion, calculate the reliability of the system, and obtain the corresponding to each group of key design parameters through Logistic transformation, as shown in the table 2.

| Serial number | Kp_v | Ki_v | Kp_i | R     | Y     |
|---------------|------|------|------|-------|-------|
| 1             | 2.00 | 20   | 30   | 0.9965| 5.6616|
| 2             | 2.00 | 16   | 26   | 0.9956| 5.4217|
| ...           | ...  | ...  | ...  | ...   | ...   |
| 25            | 1.75911 | 22.2035 | 34.7404 | 0.9981| 6.1171|

4.3. Reliable response surface function construction of solar wing drive mechanism.

Through the construction of the integrated response surface model of performance and reliability, based on the simulation results of Kp_v, Ki_v, Kp_i and Y in the table, the preliminary response surface model is established as follows.
\[ \hat{Y} = 35.6544 - 30.8571Kp_v + 1.3837Ki_v - 0.9266Kp_i + 8.9131Kp_v^2 - 0.0153Ki_v^2 + 0.0158Kp_i^2 - 0.3127Kp_vKi_v \]
\[ + 0.0733Kp_vKp_i - 0.0065Ki_vKp_i \] (7)

\( \hat{Y} \) obtained from the regression model is shown in the following table:

Table 3. Comparison of simulation values and regression values.

| Serial number | Kp_v | Ki_v | Kp_i | R   | Y   | \( \hat{Y} \) |
|---------------|------|------|------|-----|-----|-------------|
| 1             | 2.00 | 20   | 30   | 0.9965 | 5.6616 | 5.6705 |
| 2             | 2.00 | 16   | 26   | 0.9956 | 5.4217 | 5.5577 |
| ...           | ...  | ...  | ...  | ...  | ...  | ...        |
| 25            | 2.25 | 22   | 32   | 0.9978 | 6.1171 | 6.2957 |

The number of \( N \) samples is 25, the number of \( p \) variables is 3. The solution formula is as follows.

\[ MSE = \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{N - p - 1} = \frac{0.1769}{25 - 3 - 1} = 0.008424 \] (8)

It can be seen from the formula that the fitting accuracy of the regression model is relatively high, and the response surface model is accurate and credible. Three factor variables, determine any one variable, we can get the response surface diagram of the other two variables with respect to reliability[3]. The following figures show the response surface of each control design variable combination and the control reliability of the solar wing drive mechanism:

Figure 3. Response surface of speed controller I parameter and speed controller P parameter to reliability.
Figure 4. Response surface of current controller P parameter and speed controller P parameter to reliability.

Figure 5. The response surface of current controller P parameter and speed controller I parameter to reliability.

The response surface model directly describes the quantitative relationship between the response variable and the key design parameters. Through its images and function formulas, the nature and strength of the impact of each key design parameter on the response variable can be quickly analyzed.

4.4. Integrated simulation design results of control performance and reliability of the solar wing drive mechanism

The design variables are taken within the range of the distribution law, and the control performance and reliability integrated simulation model are used to calculate the motion control reliability of the solar wing drive mechanism[4]. In view of the length of the report, only part of the 100 design combinations is given in this chapter. The results of the integrated simulation model for the control performance and reliability of the solar wing drive mechanism are shown in the following table 4.
Table 4. Integrated simulation results of control performance and reliability.

| Serial number | Kp_v     | Ki_v     | Kp_i     | R      |
|---------------|----------|----------|----------|--------|
| 1             | 2.3095   | 17.2231  | 28.9992  | 0.9990 |
| 2             | 1.95488  | 17.6119  | 29.8990  | 0.9961 |
| ...           | ...      | ...      | ...      | ...    |
| 100           | 1.75911  | 22.2035  | 34.7404  | 0.9981 |

5. conclusion

Based on the multidisciplinary performance simulation model of aerospace electromechanical products, this paper, comprehensively considering the product's working conditions and its own characteristics, proposes a method for building an integrated performance and reliability simulation model. The solar wing drive mechanism is used as the object to carry out the integrated simulation application verification of control performance and reliability. The matching degree between the response surface and the sampling point is relatively high, which proves that the method can meet the engineering application.

References

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