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Equivalent Conversion Method for the Reliability Evaluation Data of Aerospace Products

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Abstract—The reliability of aerospace products is evaluated and estimated using the data and information collected during the development, test, production, and use processes. Therefore, it is an important technical approach for measuring the reliability level of aerospace products and confirming the effectiveness of reliability works. Accurately evaluating the reliability of highly reliable aerospace products requires the integration of multisource reliability data at all levels and stages. This paper identifies the reliability evaluation data of various aerospace products and presents the general idea and basic principles of the equivalent conversion of reliability evaluation data from different sources and provides a data conversion method. This method can guide reliability evaluation and ensure the accuracy of aerospace products.

Keywords—aerospace, products reliability evaluation data, equivalent conversion

I. Introduction

Under appropriate conditions, reliability evaluation is achieved by obtaining sufficient test data through reliability tests or by collecting a large amount of failure data during actual use based on classical statistical methods. However, aerospace products have high reliability, and it is difficult to obtain sufficient reliability evaluation data (actual test data and on-orbit use data) before the product is used because of time limitations, conditions, funds, and other factors. Making full use of the reliability information of each development stage and product level is necessary to ensure the accuracy and credibility of the reliability evaluation results, such as reliability design information, similar product information, and test data under non-working stress.

This paper reviews the reliability evaluation data of various aerospace products to suggest the general idea of the equivalent conversion of reliability evaluation data from different sources and basic principles to be followed. The reduced use method for each reliability evaluation data is also determined.

II. Sorting Reliability Evaluation Data Types

The reliability information of aerospace products runs through the entire process of design, manufacturing, test, and use; covers different structural levels of individual products, components, and devices; and has multiple access channels. In addition to the reliability verification test data conducted for products, it includes product design information, test data under abnormal working stress, similar product data, simulation test data, on-orbit use data, etc. The specific information is shown in Fig. 1.

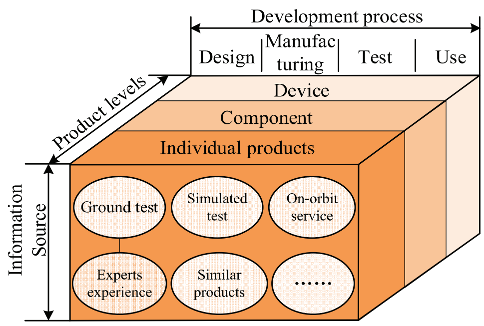

Fig. 1. Multisource reliability evaluation data.

A. Product Design Information

Reliability information reflected in aerospace product design is expressed by its reliability prediction information and failure rate information.

B. Abnormal Working Stress Test Data

All test data under abnormal working stress conditions of space products such as aging test data, accelerated life test data, etc., need to be converted into equivalent test time by a specific manner.

C. Simulation Test Data

The reliability information of products obtained by the simulation include information obtained in the process of

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digital simulation and the reliability information obtained through the data simulation.

D. Similar Product Information

The accumulated test and on-orbit use data of products with a similar technical status to the current product needs to perform a similarity and inheritance analysis using an equivalent replacement of data.

E. On-orbit Service Data

Reliability data accumulated during the on-orbit operation of the product, i.e., the on-orbit life data, includes the operation time, performance detected during operation, etc.

F. Experts' Experience Information

It has certain subjectivity and is given in the form of the confidence interval or lower confidence limit, and the statistics in practice are often different opinions of multiple experts on the same evaluation object, which is a parallel relationship.

III. General Idea of the Reliability Assessment Data Equivalent

The general idea of the equivalent conversion of the reliability evaluation data of aerospace products can be summarized as the following four steps: verification, standardization, equivalence, and synthesis.

- Verification: Specific aerospace products follow the basic principle of the equivalent replacement of reliability assessment data and carefully check the test process, test data, and service conditions of the reliability data generated by different stages, different levels, and different test methods under the premise that the technical status is consistent (or the change of technical status is not affected after assessment) and the test environmental conditions are equivalent.
- Standardization: According to different data sources, reliability requirements, and reliability criteria, the data are normalized into reliability-related characteristic parameters and given quantitative expressions.
- Equivalence: The reliability data of different types is converted into normal working conditions based on different conversion factors.
- Synthesis: Make full use of all kinds of reliability information for correlation, processing, and synthesis to obtain more complete and accurate judgment information about product reliability. Then, form the reliable estimation and prediction activities of product reliability.

The equivalent conversion of aerospace product reliability evaluation data should follow the following basic principles:

- Consistency: The technical status is consistent or the change in the technical status does not affect the final conclusion after evaluation.
- Equivalence: Relevant reliability data from other sources, after equivalent conversion, have the same effect as reliability data under normal working conditions of the product.
- Continuity: Covering the entire life cycle of product design, development, test, and use.
- Credibility: The test process and data management process are controlled to ensure that the test process is objective and the test data is true, complete, effective, and traceable.

IV. Equivalent Reduction Method of Reliability Evaluation Data

A. Overall Scheme Design

According to the characteristics of each reliability assessment data and guided by the general idea of equivalent reduction in accordance with the basic principle of equivalent reduction, study, sort out, and standardize the application methods of various types of data, as shown in the Fig. 2.

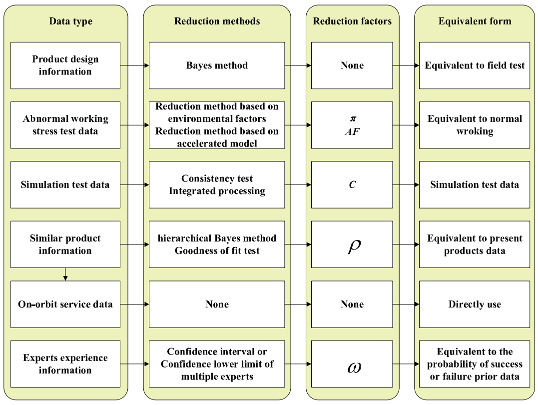

Fig. 2. Equivalent reduction schemes of reliability evaluation data.

B. Equivalent Conversion Method of Product Design Information

The reliability prediction of aerospace products is an important part of reliability work, and the predicted results reflect the reliability design level of products to some extent. In the process of product reliability evaluation, the uncertainty of the predicted results is considered, the predicted information is compressed and converted into equivalent test information under a certain degree of confidence, and as prior information, the Bayes method is used to test the compatibility of the prior information with the test information and calculation of the combined prior information and test information. Considering aerospace electronic products as an example, the equivalent reduced method of reliability predicted information is as follows:

Convert the predicted value of the failure rate into prior information, select $r_0 = 1$, calculate the equivalent test time according to (1). The calculated $(t_0,1)$ is the prior information:

$$t_0 = 2.02232 / \lambda_0 \times 10^9 . \quad (1)$$

The statistical significance test can be conducted according to the bilateral interval estimation to analyze the compatibility between the prior information (t_0,1) and field test information (T,r).

$$\left[\frac{\chi^2_{\alpha/2}(2r+1)}{2T},\frac{\chi^2_{1-\alpha/2}(2r+1)}{2T}\right], \qquad (2)$$

where α represents the significance level, ranging from 0.01 to 0.1.

The assumption of compatibility is accepted and the post information can be used for evaluation if the ratio of the prior information is 1/t0 within the interval calculated by (2). If not, the compatibility hypothesis is rejected, the prior information is discarded, and only the test information is used for evaluation.

C. Equivalent Reduction Method for Abnormal Working Stress Test Data

The reliability of the product is closely related to the environmental conditions, and it shows different levels of reliability under different working stresses. Therefore, the test data under different stress conditions should be equivalent to the working conditions when using the test data under non-working stress conditions to carry out reliability assessment. In view of this data processing problem, there are two methods: one is the reduction method based on environmental factors, and the other is the reduction method based on the accelerated model.

1) Reduction Method based on Environmental Factors

The conversion and synthesis based on environmental factors must follow the following three preconditions: a) consistency of failure mechanism, i.e., failure mechanism of products remains unchanged under different stress levels; b) homogeneity of distribution, i.e., the product life follows the same form of distribution under different stress levels; c) Nelson hypothesis, i.e., the remaining life of the product only depends on the accumulated failure and the current stress and has nothing to do with the accumulation method.

The environmental reduction coefficient (also referred to as environmental factor π) is introduced to reduce the experimental data and environmental characteristics produced in the different development stages of the product to the same test condition. There are four methods to determine the environmental reduction coefficient:

a) Score factors that affect the product reliability obviously in different environmental tests such as speed, temperature, vibration, etc., through the expert score, and compare it with the score value under the standard environment to convert the relative ratio, i.e., the environmental reduction coefficient. This method is greatly affected by subjective factors.

b) According to similar product test data using the mathematical optimization process for solving the environmental reduced coefficient, which has a wide range of engineering applications; however, it only considers the growth model test constraints and do not consider the growth trend test constraints often not found on the global optimal solution [1,2].

c) The radial basis function method is used to measure the effect of different environmental factors and their interactions on reliability for solving the environmental reduction coefficient; however, the limitation of this method is that the product life needs to obey the position-scale model [3].

d) Based on the Duane model of reliability growth, a reliability evaluation model (VE-AMSAA model) was established based on the variable environment data of the variable matrix. According to the test data of similar products, the environmental reduction coefficient was solved using the worry method that comprehensively considers the growth trend test constraints and growth model test constraints [4].

2) Reduction Method based on Acceleration Model

According to the data collected in the accelerated life test or accelerated degradation test, the specific acceleration model is selected for analysis, and the acceleration factor (*AF*) is calculated based on the test data. The test data under accelerated stress is converted into the normal working stress for reliability assessment.

Based on differences in the proposed methods of the acceleration models, they are divided into acceleration models based on failure physics (physical acceleration model), acceleration models based on engineering experience (empirical acceleration model), and acceleration models based on statistical analysis (statistical acceleration model). The physical acceleration model is proposed to explain the product failure process from the physicochemical point of view, among which the mature and common ones are the Arrhenius model and Eying model, describing the relationship between temperature stress and product life. The empirical acceleration model is proposed by reliability engineers through the long-term observation of product failure process. The more common models are an inverse power law model that describes the relationship between electrical stress and product life, and the Coffin–Manson model describing the relationship between temperature cycle stress and product life. The statistical acceleration model is proposed using a statistical analysis method for analyzing the accelerated degradation data and can be divided into parametric and nonparametric models. The parametric model needs to presuppose the life distribution type of the product, whereas the nonparametric model does not. The common nonparametric model has two types: proportional hazard and proportional advantage. The classification results of accelerated models are shown in Fig. 3.

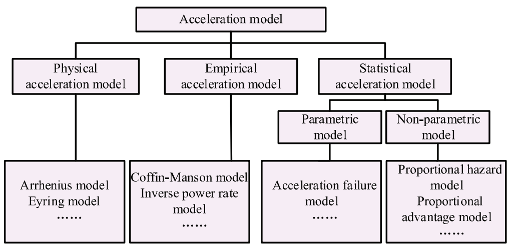

Fig. 3. Accelerated model classifications

D. *Equivalent Reduction Method of Simulation Test Data*

Considering a longer life span of aerospace products, higher cost of reliability test, and rapid development of digital design and intelligent manufacturing, the simulation technology plays an increasingly important role in reliability evaluation and life prediction. Further, for some products that cannot be tested on the ground or have insufficient test data, the reliability evaluation and life prediction can only be carried out through simulation technology. However, a problem that needs to be studied is identifying how to establish a scientific and reasonable verification method to judge whether the simulation system is accurate and reliable, whether the simulation test data is effectively available, and whether to use the simulation test data to conduct an evaluation.

The engineering selects the simulation test results under several typical conditions and actual test results under the same conditions for consistency inspection and integration processing for the equivalent replacement of simulation test data. The specific process is shown in Fig. 4.

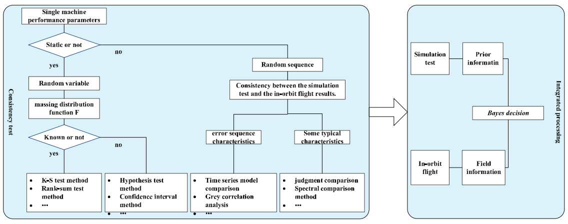

Fig. 4. Equivalent conversion process of the simulation test data.

1) *Consistency Test*

According to the characteristics of the simulation test results, the single machine performance parameters can be divided into static and dynamic, respectively, in the form of a random variable and random sequence. The rank-sum test and other methods are used to verify the consistency between the simulation test and the on-orbit flight results when the massing distribution function F is unknown. The confidence interval method or hypothesis test method in the parameter hypothesis [5-8] test is adopted when F is known. The consistency test of the random sequence is to compare and analyze the error sequence characteristics of the simulation test and on-orbit flight results by judgment comparison, grey correlation analysis, and other methods, or to compare and analyze some characteristics of simulation test and on-orbit flight results by spectral comparison method and to perform the consistency test.

2) *Integrated Processing*

The amount of data obtained by simulation is often large, whereas the amount of on-orbit flight data is generally small but its authenticity is considerably higher than that of the simulation test. A feasible integrated processing method of the simulation results is to take the simulation results with certain credibility (C) as the prior information, take the on-orbit flight results as the field information, and apply the Bayes method for decision making.

E. *Equivalent Reduction Method for Similar Product Information*

Similar product information cannot be directly used for the reliability assessment of aerospace products, and therefore, it is necessary to determine the similarity (inheritance factor ρ) between similar products and new products, to convert similar product information into the reliability data of new products according to its size, and to consider it as the prior information of reliability parameters. The Bayes method combined with the test data is used to perform the reliability evaluation of aerospace stand-alone products.

The following methods are used to determine inheritance factors:

a) This method is too subjective and less persuasive to determine the value according to the empirical knowledge.

b) Assuming that inheritance factor is a random variable, the hierarchical Bayes method is used to deal with it; however, the probability distribution and value range also need to be determined by experts' experience, and the calculation process is complex [9].

c) The influence of the historical samples and sample heterogeneous populations on reliability evaluation is analyzed, and the inheritance factor value is determined based on the χ^2 goodness of fit test of the two populations. This method is simple and easy to explain, in addition to the rationality; however, it introduces more subjective factors [10].

d) The inheritance factor value was determined based on the Kullback–Leibler (K–L) distance method [11].

e) The quantitative similarity of similar factors and the similarity of common similar factors are considered from the aspects of structure, function, and physical characteristics, and the inheritance factors are defined directly [12].

f) Considering the similarities and differences between new products and historical products, the nonequal weight coefficient method is introduced to determine the value based on the variance test of characteristic attributes [13].

g) Define the concept of sample consistency between different product data and determine the inheritance factor based on evidence theory. This method considers not only the consistency between new products and similar products, but also the influence of the consistency between different similar products on the inheritance factor determination, and it exploits the information of similar products [14].

F. *Equivalent Reduction Method for On-orbit Flight Data*

The on-orbit flight data can directly reflect the reliability level of space products, and therefore, it can be directly used in reliability evaluation. For using an on-orbit flight data, one approach is to use on-orbit life data and the other is to compare and analyze on-orbit data with ground test data. A basis for the equivalent replacement of various reliability evaluation information is provided to establish certain data equivalence criteria through the analysis results.

G. *Equivalent Conversion Method of Expert Experience Information*

Expert experience information is given in the form of the confidence interval or confidence lower limit. The equivalent reduction of such information involves assigning different weights to experts based on the degree of trust in the experts' experience. Weight factors ω are used to summarize the estimates of the confidence interval or confidence lower limit of multiple experts on evaluation objects. With the help of the interval ratio and other methods, it is equivalent to the summarized numerical expert opinion information.

V. CONCLUSIONS

From the perspective of information sources, this paper sorts out the main data types in the reliability assessment of aerospace products, analyzes the characteristics of each reliability assessment data, studies the general idea and basic principles of equivalent reduction, designs equivalent reduction schemes, and provides the application methods of reliability assessment data from different sources, which can effectively guide the development of reliability assessment of aerospace products. In addition, this effectively supports the accurate reliability evaluation of space products.

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