Study on Testability Evaluation of Complex Equipment Based on Fault Injection Test Data

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Abstract. Classic statistic method can not make use of the history test information and produce the evaluation conclusion with low confidence level and high risk under the condition of small sample, a new testability evaluation method based on test data in development stages is proposed in this paper. The result shows that this method can produce the evaluation conclusion with high confidence level in the same test condition and it is more rational with this new method than with classical statistical method and the traditional Bayes method.

Introduction

Testability is an important design feature of equipment. It describes the equipment's ability to detect and isolate faults. It can reduce cycle costs of equipment life and increase mission reliability, and enhance the comprehensive protection of equipment capability which has a good testability. In recent years, testability is becoming one of comprehensive security indicators as reliability and maintainability.

The main indicators of testability is including fault detection rate (FDR), fault isolation rate (FIR), the false alarm rate (FAR), the fault detection time (FDT), fault isolation time (FIT) and re-test OK rate (RTOKR), etc. The first three indicators are the most important among them. Therefore, assessment of testing complex equipment is actually assessing FDR, FIR and FAR.

Complex equipment testability experiments

In testing experiment, choose the pre-selected fault to be injected, and inject it into the unit of system or equipment, and detect its fault and implementation procedures for fault isolation and fault indication. Its corresponding results can only be two kinds of forms: success or failure; failure to be detected (detection success) or not detected (detection failure); fault is isolated to a specific unit (isolated success), or did not complete isolation (isolation failure); when indicates, test (or use) a failure instructions may be true (indicating success), or there is no actual fault (indicating failure), a false alarm.

Testability Bayes evaluation of the complex equipment

It's the key of Bayes assessment that using a priori information to determine the prior distribution. To the overall test for complex equipment of success or failure type (binomial distribution), it commonly used conjugate prior distribution to determine the prior distribution in engineering, the parameter, FDR, conjugate prior is the Beta distribution. To facilitate the calculation, set the FDR for P, the experiment is divided into N stages and achieve prior distribution $I\ Be(P|a_i, b_i)$. Its density function is

$$\pi_i(P) = \frac{\Gamma(a_i + b_i)}{\Gamma(a_i)\Gamma(b_i)} P^{a_i - 1}(1-P)^{b_i - 1} = \frac{P^{a_i - 1}(1-P)^{b_i - 1}}{\beta(a_i, b_i)} \quad (1)$$

$$0 \le P \le 1,\ i = 1, 2, \cdots, N$$

Where $a_i > 0, b_i > 0$ are the ultrasonic parameters in development stage of prior distribution *i*. In the case of knowing the prior distribution, the value of a_i and b_i are keys of determining the prior distribution. Their value can be calculated used the method provided in literature [6].

When determine a_i and b_i, then achieve prior distribution of I, $Be(P|a_i,b_i)$. Development phase has been determined after is. kWith the prior distribution, combined with field testing experimental information (set the number of field test n, the number of fault detection failure f), and use Bayes Theorem to export the posterior distribution ,Its density function:

$$\pi(P|D)=\frac{P^{\sum_i^N a_i+n-f-1}(1-P)^{\sum_i^N b_i+f-1}}{\beta(\sum_i^N a_i+n-f,\sum_i^N b_i+f)} \quad (2)$$

In the equation, $D=(n,f)$ means the field test information.

Typically, when calculate fault detection rate FDR, the bigger of its confidence interval upper limit, the better it is. So it can not consider the confidence interval upper limit; most concerned about is their confidence interval lower limit is too low or not. For this reason, when given the confidence level $\gamma(0<\gamma<1)$, thenFDR confidence interval lower limit solved by equation (3)

$$\int_{P_L}^1 \pi(P|D)dP=\gamma \quad (3)$$

As the growth process of testing, the distribution parameters of FDR are not fixed after the test at every stage. So the field test samples and the history are from different totality. The equation (2) directly uses historical information. It actually considers the field test information and each phase of the trial from the same information as a whole.

Trials Information Fusion in Development Phase

Mixed Beta distribution

In order to effectively use both the historical information in development phase, and describe the different totality between historical information and field information, and reduce affection of two types of information to the test assessment, the literature [7-8] introduce a hybrid Beta prior distribution. Now the paper extended it to the multiple testing experimental stages. After getting the prior distribution in various stages, structuring mixture prior test:

$$\pi(P)=\sum_{i=1}^N\left[\rho_i\frac{P^{a_i-1}(1-P)^{b_i-1}}{\beta(a_i,b_i)}\right]+(1-\rho),\ \rho=\sum_i^N\rho_i,\quad 0\le P\le 1,\quad 0\le\rho\le 1 \quad (4)$$

In the equation, ρ and ρ_i are called inherited factors, ($1-\rho$) is called updating factor. Among them, ρ reflects the inheritance of historical experimental information of the researching equipment in aspect of testability. It can be given by trial information or experts; ρ_i reflects entire similar degree that from the test and field test information during development phase i ;($1-\rho$)reflects the unique features of new research equipment in the way of testability. Actually, this mixture distribution is a combination. It comminutes classical assessment methods and the traditional Bayes assessment methods which directly using historical information. So the mixed distribution is more reasonable, and results are more accurate.

Based on Bayes theorem, after the prior distribution determine, and field test information substitution, getting posterior density:

$$\pi_\rho(P|D)=\frac{(1-\rho)P^{n-f}(1-P)^f+\sum_{i=1}^N\rho_i\frac{P^{n-f+a_i-1}(1-P)^{f+b_i-1}}{\beta(a_i,b_i)}}{(1-\rho)\beta(n-f+1,f+1)+\sum_i^N\rho_i\frac{\beta(n-f+a_i,f+b_i)}{\beta(a_i,b_i)}} \quad (5)$$

For the testing assessment, after giving the confidence level $\gamma(0<\gamma<1)$,the lower confidence limit P_L of FDR can been solved by equation (6):

$$\int_{P_L}^1 \pi_\rho(P|D)dP=\gamma \quad (6)$$

Inheritance Factor ρ and ρ_i

From the above analysis, the values the inheritance factor ρ and ρ_i are very important for testing equipment, so they must be chosen carefully to assess the General, ρ can be given by experts who research new types based on equipment. They can use hierarchical Bayes method deal with when ρ is different to calculate, and ρ is a random variable. But the range and probability distribution both need the same expertise to decide. This method has a strong subjective, and when extended to multiple stages, due to each probability distribution and integral transformation of inherited factors ρ_i should be given, so the calculation is more complicated. To this end, literature [9] gives the way to determine value by using historical test sample and field test sample from the overall goodness of fit test. The method is simple. It can be used in multi-stage test situation after improving.

Before ρ determination, First needs to integrate test development information of various stages, calculate the number of successes and failures of equivalent experiment of historical testing information after post-synthesis test (fault detection or alarm indication). So comprehensive testing equivalent pre-test successful number S and failures F can be determined by equation (7):

$$\begin{cases} S+F=\dfrac{N-1}{N}\left(\dfrac{N\sum_{i=1}^{N}\overline{P_i}-\left(\sum_{i}^{N}\overline{P_i}\right)^2}{N\sum_{i}^{N}\overline{P_i}^2-\left(\sum_{i}^{N}\overline{P_i}\right)^2}\right)-1 \\ S=(S+F)\overline{P} \end{cases} \tag{7}$$

Where, $\overline{P_i}$ is point estimate in phase *i* trial, $\overline{P}=\dfrac{\sum_{i=1}^{N}\overline{P_i}}{N}$.

Set comprehensive pre-test test sample (S, F) from the overall Y, field sample (nf, f) from the overall X. Constructed general contingency table as shown in Table 1:

TABLE 1 X, Y TWO GENERAL CONTINGENCY TABLE

Overall	Testability experiment data		
	Number of detected faults	***number of undetected faults***	***Sum***
X	*n-f*	*f*	*n*
Y	*S*	*F*	*S+F*
Sum	*S+(n-f)*	*f +F*	*n+(S+F)*

Make: $$K=\frac{\left[(n-f)F-Sf\right]^2\left(n+(S+F)\right)}{n\left(S+(n-f)\right)(f+F)(S+F)} \tag{8}$$

In the equation (8), K is a person statistic measure, which converges 1 degree of freedom depend on χ^2 distribution, and requires the number of detected and undetected failure of two samples in the experiment must be both greater than 5. So it needs to be amended as follows:

$$K=\frac{\left[\left|(n-f)F-Sf\right|-\frac{1}{2}\left(n+(S+F)\right)\right]^2\left(n+(S+F)\right)}{n\left(S+(n-f)\right)(f+F)(S+F)} \tag{9}$$

In equation (9), K is also similar to the χ^2 distribution of 1 degree of freedom. In a given test level α, the available K as a test statistic can test whether X and Y are from the same overall total. Even if they pass the test, nor can mix the two parts of the trial information together simply, so still need to determine the similarity measure value of the trial information and field test information in the development phase.

Here, $Q=P(\chi_1^2>K)$ is called Goodness of fit for this test. In fact, Q expresses probability of X and Y. It directly relates to part of the similarity ρ of the two values, and it is very difficult to accurately describe the relation between Q and ρ, so usually $\rho=Q^{1/2}$ in practical engineering.

Development stage i have m_i batches of test information, l_{ij} and f_{ij} (j=1,2,…, m_i)are the numbers of tests and fails. Set the test sample ($\sum_{j=1}^{m_i}(l_{ij}-f_{ij})$, $\sum_{j=1}^{m_i}l_{ij}$)of phase i from the overall Y, on-site sample(n-f, f)from the overall X. By constructing X, Y general contingency table, take the following test statistic:

$$K_i=\frac{\left[\left|\left(\sum_{j=1}^{m_i}f(l_{ij}-f_{ij})-\left(\sum_{j=1}^{m_i}(n-f)f_{ij}\right)\right)\right|-\frac{1}{2}\left(n+\sum_{j=1}^{m_i}l_{ij}\right)\right]^2\left(n+\sum_{j=1}^{m_i}l_{ij}\right)}{n\sum_{j=1}^{m_i}l_{ij}\left[(n-f)+\sum_{j=1}^{m_i}(l_{ij}-f_{ij})\right]\left(f+\sum_{j=1}^{m_i}f_{ij}\right)} \tag{10}$$

According to K_i ,by using the same contingency table of ρ (goodness of fit test methods), obtain similar levels measure value of various stages trials information and field trials information $T_i=Q_i^{1/2}$. Here, $Q_i=P(\chi_1^2>K_i)$. After obtaining T_i , the ρ_i can be got by the equation (11):

$$\rho_i=\rho\frac{T_i}{T_1+T_2+\cdots+T_N},\ \text{i=1,2,…,N} \tag{11}$$

Conclusions

This paper uses testing data of development phase, combined with the field test information, and uses Bayes data fusion method of that mixed Beta distribution for the prior distribution. This way can analyses and evaluate FDR of some large missile complex equipment. Comparing with the classical assessment methods and traditional Bayes assessment methods, its findings are more reliable. It has more advantages especially for complex equipment testability assessment in small sample.

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