Available online at www.ijpe-online.com

International Journal of Performability Engineering

vol. 15, no. 1, January 2019, pp. 200-208
DOI: 10.23940/ijpe.19.01.p20.200208

Maintainability Test Method of Army Armored Equipment based on Small Sample Size

Chuang Li[a,*], Da Xu[a], Qinglong Jiao[a], Jieyin Huang[b], and Han Lin[c]

[a]*Department of Weapon and Control, Army Academy of Armored Force, Beijing, 100072, China*
[b]*Institute of Reliability Engineering, Military Representative Office in Four Four Seven Factory, Baotou, 014000, China*
[c]*Fujian Police Academy, Fuzhou, 350000, China*

Abstract

In view of the large manpower and financial resources required for the maintenance test of the armored equipment of the army, as well as the long acquisition period of the maintenance test data, this paper focuses on the maintenance test method based on small sample size and establishes the maintenance test verification based on the Bayes small sample theory. Assessing the model and proposing an equipment maintenance test based on this method effectively reduces the number of samples needed to validate the indicators. At the same time, it is validated with the aid of model equipment maintainability tests. The accuracy is high, and maintenance and verification are reduced. The proposed method is of great reference value for reducing the cost of equipment testing and shortening the equipment development cycle in the development of army equipment.

Keywords: small sample size; maintainability test; armored equipment; Bayes theory

(Submitted on October 10, 2018; Revised on November 17, 2018; Accepted on December 15, 2018)

1. Introduction

The army armored equipment maintenance test and assessment are an important part of the army's equipment life cycle process. At present, the verification of the army's equipment maintainability test is usually carried out at the stage of equipment design and finalization in accordance with the methods specified in the national military standard. This method is highly accurate, but the traditional method has limitations on the number of samples, especially in the verification of quantitative indicators. The evaluation method was carried out to test, and finally reached the conclusion to determine the decision-making basis of whether the maintenance of the equipment meets the needs of the users [1-2]. The existing maintenance assessment method is limited to large samples, and the required sample size is generally at least 30 [3]. With the rapid development of information technology, the complexity of armored equipment has become more sophisticated. It also involves high development costs and destructive test equipment, resulting in an increase in research and development costs, a waste of manpower and material resources, and an extension of the development cycle of equipment, making it impossible to equip troops as early as possible [4-7].

In this context, studies based on a small sample size of the equipment maintenance test and evaluation methods are of great significance. A kid-like method based on Bayes' theory gradually tries to apply in terms of equipment performance verification, the main aspects of aerospace, aircraft, missiles, etc. [8-10]. The application is more mature. Its biggest advantage is the ability to fully utilize the experience accumulated in the past and a variety of other prior information (expert information, similar equipment information, emulation information, etc.), and combine them with a small amount of field test data on equipment maintenance for checking and evaluation [11-14].

In literature [15], Jiang and other scholars effectively solved the problem of evaluating the reliability of long-life grinding spindles in the case of small samples by using the method of Bayes' theory and the analysis of virtual augmented samples. In literature [16], Zhang and other scholars found a method to effectively solve the reliability evaluation problem

* Corresponding author.
E-mail address: 15321136085@163.com

of success or failure type products under the premise of small samples by deriving the post-test probability distribution function of the reliability parameters of the success or failure type products in the Bayes pre-test distribution. In literature [17], Yin and other scholars put forward a bias verification method for the equipment testing growth model, which can be tested in the case of small sample size and different populations. The specific parameter values of the test growth model are obtained according to the historical data, which can be used to predict the equipment testability. In literature [18], Li and other scholars, in order to solve the problem of reliability verification of the wear and tear of the mechanism system under small sample sizes, extended the obtained wear data by using the small sample's virtual augmentation method and the boot-strap method to achieve the purpose of studying the wear reliability of the mechanism system in the case of small sample size. It was proven that the method is effective and of great application value. In addition, scholars have also studied the problem of small samples in the rest of the works and solved many problems that have historically required a large number of samples for verification.

In this paper, the feasibility of a small sample test method based on Bayes' theory in equipment maintainability tests is studied according to the current situation of army armored equipment tests, providing a theoretical basis for improving the equipment maintainability test method [19-20].

2. Construction of Basic Model based on Bayes' Theory Maintainability Test Method

2.1. Determine the Overall Distribution of Maintenance Time

Determining the overall distribution is the first problem to be solved in Bayesian statistical analysis. The maintenance time is a statistical distribution rather than a constant. The method of determining the overall distribution of maintenance time is to perform statistical analysis on the maintainability test data obtained through the histogram method, determine which distribution model it complies with, and then test the validity of the distribution model. This article uses the K~S test.

2.2. Pre-Inspection Information Consistency Check

Because there are many methods and equipment used during the test, equipment maintenance test information is multi-sourced, so after the historical information and field information are acquired, they must be classified, arranged, and tested for consistency. They are tested to see whether they conform to the distribution of obedience. This article uses a parametric test.

2.3. Verification of Maintainability Test based on Small Sample Size

After determining the overall distribution of the maintenance time, the following method based on Bayes' theory is used to evaluate the mean repair time, which is based on the post-survival likelihood ratio. It obtains the decision rule by calculating the post-survival likelihood ratio, and then it determines the quantity of the field test sample according to the given two types of errors.

Set $X \sim N(\theta,\sigma^2)$, where σ^2 is known, or get an estimate of its accuracy from historical data, and θ is the unknown parameter of the overall distribution. Through analysis and calculation, the θ can be determined for the pretest distribution $N(\mu,\upsilon^2)$. The party risk α and the ordering party risk β are determined by both parties, and the average repair time is verified as follows:

First make the following assumptions:

$$H_0:\ \theta=\theta_0,\ H_1:\ \theta=\theta_1=\lambda\theta_0>\theta_0,\ \lambda>1$$

Among them, λ is the detection ratio, which is determined through negotiation between the contractor and the ordering party, usually $1.2\le\lambda\le1.5$.

First, calculate the protest probability ratio of the two hypotheses:

$$P(\theta=\theta_1)=\lim_{\sigma\to0}\frac{P(\theta_1+\sigma)-P(\theta_1-\sigma)}{2\sigma} \tag{1}$$

$$P(\theta=\theta_0)=\lim_{\sigma\to 0}\frac{P(\theta_0+\sigma)-P(\theta_0-\sigma)}{2\sigma} \tag{2}$$

$$\begin{aligned}\frac{P(\theta=\theta_1)}{P(\theta=\theta_0)}&=\lim_{\sigma\to 0}\frac{P(\theta_1+\sigma)-P(\theta_1-\sigma)}{P(\theta_0+\sigma)-P(\theta_0-\sigma)}=\frac{P'(\theta_1)}{P'(\theta_0)}\\&=\frac{\exp[-\frac{1}{2\upsilon^2}(\theta_1-\mu)^2]}{\exp[-\frac{1}{2\upsilon^2}(\theta_0-\mu)^2]}=\exp\{-\frac{1}{2\upsilon^2}[(\theta_1-\mu)^2-(\theta_0-\mu)^2]\}\end{aligned} \tag{3}$$

The likelihood function:

$$L(\theta)=L(x_1,x_2,\cdots,x_n;\theta)=\prod_{i=1}^{n}f(x_i;\theta)$$

In the case where

$$L(\theta)=L(x_1,x_2,\cdots,x_n;\hat{\theta})=\max_{\theta\in\Theta}L(x_1,x_2,\cdots,x_n;\theta)$$

Then, $\hat{\theta}(x_1,x_2,\cdots,x_n)$ is the maximum likelihood estimate of θ, and $\hat{\theta}(X_1,X_2,\cdots,X_n)$ is the maximum likelihood estimator of θ.

$\hat{\theta}$ can be derived from the equation $\frac{\mathrm{d}}{\mathrm{d}\theta}L(\theta)=0$. Because $L(\theta)$ and $\ln L(\theta)$ reach extremum at the same θ, the maximum likelihood estimate of θ can also be obtained from the equation $\frac{\mathrm{d}}{\mathrm{d}\theta}\ln L(\theta)=0$.

Bayes' formula and the above equation can be used to obtain the post-likelihood ratios of the two hypotheses:

$$\begin{aligned}&\frac{P(H_1|X)}{P(H_0|X)}=\frac{L(X|\theta_1)P(\theta=\theta_1)}{L(X|\theta_0)P(\theta=\theta_0)}\\&=\exp\{\frac{1}{2\sigma^2}\sum_{i=1}^{n}[(X_i-\theta_0)^2-(X_i-\lambda\theta_0)^2]-\frac{1}{2\upsilon^2}[(\lambda\theta_0-\mu)^2-(\theta_0-\mu)^2]\}\end{aligned} \tag{4}$$

In the case where

$$\frac{P(H_1|X)}{P(H_0|X)}>1$$

It is equivalent that

$$\frac{1}{2\sigma^2}\sum_{i=1}^{n}[(X_i-\theta_0)^2-(X_i-\lambda\theta_0)^2]-\frac{1}{2\upsilon^2}[(\lambda\theta_0-\mu)^2-(\theta_0-\mu)^2]>0$$

Transfer conversion:

$$\frac{1}{\sigma^2}\sum_{i=1}^{n}[(1-\lambda^2)\theta_0{}^2+2(\lambda-1)\theta_0X_i]>\frac{1}{\upsilon^2}[(\lambda^2-1)\theta_0{}^2+2(1-\lambda)\theta_0\mu]$$

And

$$\frac{2(\lambda-1)\theta_0}{\sigma^2}\sum_{i=1}^{n}X_i > \frac{(\lambda^2-1)\theta_0{}^2}{\upsilon^2}+\frac{2(1-\lambda)\theta_0\mu}{\upsilon^2}+\frac{(\lambda^2-1)\theta_0{}^2}{\sigma^2}$$

And

$$\sum_{i=1}^{n}X_i > \frac{(\lambda+1)\theta_0\sigma^2}{2\upsilon^2}-\frac{\mu\sigma^2}{\upsilon^2}+\frac{(\lambda+1)\theta_0}{2}$$

And

$$\bar{X} > \frac{\sigma^2[(\lambda+1)\theta_0-2\mu]}{2n\upsilon^2}+\frac{\theta_0}{2}(\lambda+1) \tag{5}$$

Transform this equation to obtain an inequality:

$$\frac{\bar{X}}{\sigma/\sqrt{n}} > \frac{\sigma[(\lambda+1)\theta_0-2\mu]}{2\sqrt{n}\upsilon^2}+\frac{\sqrt{n}\theta_0}{2\sigma}(\lambda+1)=\Delta T(n,\lambda,\theta_0)=\Delta T \tag{6}$$

When this inequality is established, the assumption H_1 is accepted; otherwise, the assumption H_0 is accepted. MTTR (Mean Time To Repair) data sample obeys the normal distribution

$$\bar{X}\sim N(\theta,\sigma^2/n)$$

And

$$f(t|H_0)=\frac{1}{\sqrt{2\pi}}e^{-\frac{1}{2}(t-\frac{\sqrt{n}\theta_0}{\sigma})^2}$$

$$f(t|H_1)=\frac{1}{\sqrt{2\pi}}e^{-\frac{1}{2}(t-\frac{\lambda\sqrt{n}\theta_0}{\sigma})^2}$$

In the Equation,

$$t=\frac{\bar{X}}{\sigma/\sqrt{n}}$$

According to the definition of two types of risk:

1) Producer risk:

$$\alpha=P_0\int_T^{+\infty}f(t|H_0)\mathrm{d}t=P_0\int_T^{+\infty}\frac{1}{\sqrt{2\pi}}e^{-\frac{1}{2}(t-\frac{\sqrt{n}\theta_0}{\sigma})^2}\mathrm{d}t=P_0[1-\phi(T-\frac{\sqrt{n}\theta_0}{\sigma})]$$

2) Subscriber risk:

$$\beta=P_1\int_{-\infty}^{T}f(t|H_1)\mathrm{d}t=P_1\int_{-\infty}^{T}\frac{1}{\sqrt{2\pi}}e^{-\frac{1}{2}(t-\frac{\lambda\sqrt{n}\theta_0}{\sigma})^2}\mathrm{d}t=P_1\phi(T-\frac{\lambda\sqrt{n}\theta_0}{\sigma})$$

In the equation, P_0 and P_1 are the pretest probability of assuming H_0 and H_1, respectively. Since the previous distribution of θ is normal distribution $N(\mu,\upsilon^2)$, then

$$P_0 = \int_{-\infty}^{\theta_0} \frac{1}{\sqrt{2\pi\upsilon}} e^{-\frac{(\theta-\mu)^2}{2\upsilon^2}} \mathrm{d}\theta \tag{7}$$

$$P_1 = 1 - P_0 \tag{8}$$

From the above equation, we can get the smallest test sample:

$$n = \left(\frac{Z_{1-\frac{\alpha}{p_0}} + Z_{1-\frac{\beta}{p_1}}}{\theta_1 - \theta_0}\sigma\right)^2 \tag{9}$$

In the formula, Z is the standard point of the normal distribution.

Substitute n with Equation (5) to get the reject field:

$$\bar{X} > \frac{\sigma^2[(\lambda+1)\theta_0 - 2\mu]}{2n\upsilon^2} + \frac{\theta_0}{2}(\lambda+1)$$

In the case where

$$\bar{X} \le \frac{\sigma^2[(\lambda+1)\theta_0 - 2\mu]}{2n\upsilon^2} + \frac{\theta_0}{2}(\lambda+1)$$

The maintenance of the equipment meets the user’s requirements and is accepted.

Because of

$$\alpha < \alpha / P_0,\ \beta < \beta / P_1$$

So

$$Z_{1-\frac{\alpha}{P_0}} < Z_{1-\alpha},\ Z_{1-\frac{\beta}{P_1}} < Z_{1-\beta}$$

The following is equivalent:

$$\left(\frac{Z_{1-\frac{\alpha}{P_0}} + Z_{1-\frac{\beta}{P_1}}}{\theta_1 - \theta_0}\sigma\right)^2 < \left(\frac{Z_{1-\alpha} + Z_{1-\beta}}{\theta_1 - \theta_0}\sigma\right)^2$$

The right side of the formula is the amount of test samples required by the traditional method. Through the analysis of this, it can be seen that the small sample method based on Bayes’ theory makes full use of the pre-inspection information, which greatly reduces the number of samples in the field test. The sample size determined by this method is about 1/10 of the sample size required by the traditional method, which fully reflects the superiority of the small sample method based on Bayes’ theory.

3. Example Verification

This article will verify the method by collecting maintenance test data from a certain pilot plant of the army. In order to control the variables from other conditions, the selected data will eliminate the influence of other unfavourable factors such as the environment and obtain the test data under normal circumstances. The following are the statistics for the maintenance time of subsystems of a certain type of equipment, including historical data and field data (unit: hour):

Historical data: 0.5, 0.5, 0.4, 0.6, 1.1, 0.6, 1, 0.6, 0.3, 0.4, 1, 0.5, 0.55, 0.5, 0.8.

Field data: 0.4, 1.5, 0.5, 0.4, 0.8, 0.4, 0.6, 1, 0.8, 0.6.

3.1. Determine the Data Distribution Type

First determine the historical maintenance time data distribution mode. Assume that the historical maintenance time is *Y*, $Y=(y_1,\cdots,y_n)$, and set $X=\ln Y=(x_1,\cdots,x_n)$. As long as the check *X* obeys the normal distribution, you can determine whether *Y* obeys the lognormal distribution. Historical data is converted by the equation .

$$Y = (0.5, 0.5, 0.4, 0.6, 1.1, 0.6, 1, 0.6, 0.3, 0.4, 1, 0.5, 0.55, 0.5, 0.8)$$

$$X = (-0.6932, -0.6932, -0.9163, -0.5108, 0.0953, -0.5108, 0, -0.5108, -1.204, -0.9163, 0, -0.6932, -0.5978, -0.6932, -0.2231)$$

From the historical data, the minimum value in the data is 0.3, and the maximum value is 1.1. When the upper and lower bounds of the set histogram are set, the value of the lower limit data is 0.2, which is recorded as $a = 0.2$, and the upper limit data is 1.2, which is recorded as $b = 1.2$. According to the empirical function, the number of score groups is $K=1+3.32\ln n=10$ ($n = 15$, n is the sample capacity), so that the interval between intervals can be $\Delta=\frac{b-a}{k}=0.1$.

According to the data distribution after grouping, the maintenance time can be preliminarily determined to be lognormal distribution, and then the K~S test method is used to test the validity of the distribution model.

Testing whether X obeys normal distribution, that is, whether $X\sim N(\mu,\sigma^2)$ is valid, we can determine whether *Y* obeys the logarithmic normal distribution.

First, the unbiased estimates for μ and σ^2 are as follows:

$$\hat{\mu}=\bar{X}=\frac{1}{15}\sum_{i=1}^{15}x_i=-0.5378,\ \hat{\sigma}^2=\frac{1}{14}\sum_{i=1}^{15}(x_i-\bar{X})^2=0.1274$$

The sample values are arranged according to the order from small to large. According to the K~S test table, it can be estimated to be $\hat{D}_n=0.1367$. The significance level is $\alpha=0.2$. Check the K~S critical value table and obtain $\hat{D}_{n\alpha}=0.177$.

Therefore,

$$\hat{D}_n<\hat{D}_{n\alpha}$$

Assuming the original hypothesis, we can confirm that *X* obeys the normal distribution, that is, the maintenance time *Y* obeys the logarithmic normal distribution.

According to this method, it can be determined that the on-site maintenance time also obeys the lognormal distribution. It can be determined that the maintenance time of the equipment is generally subject to a lognormal distribution.

3.2. Pre-Inspection Information Consistency Check based on the Example

Because it has been proven that the maintenance time obeys the lognormal distribution, only the parameter verification needs to be performed. Historical data and field data are usually taken as logarithms (remembered as X_1 and X_2) for research, which translates into a normal distribution for further study. The following uses the parametric test to verify.

According to the sample data, replacing μ, σ^2 with an unbiased estimate of μ, σ^2, the following conclusions can be drawn:

$$n_1=15,\ n_2=10,\ \bar{X}_1=-0.5378,\ S_1^2=0.1274,\ \bar{X}_2=-0.4505,\ S_2^2=0.1756$$

The given level of saliency is 0.1.

First, test the variance:

$$F' = \frac{n_1(n_2-1)S_1^{\,2}}{n_2(n_1-1)S_2^{\,2}} = 0.6995$$

Given a significance level of 0.1, you can find $F_{0.05}$ and $F_{0.95}$ by consulting the distribution table:

$$F_{0.05}(14,9) = 0.333,\ F_{0.95}(14,9) = 2.65$$

We can see that $F_{0.05}(14,9) < F' < F_{0.95}(14,9)$, and there is no difference in their variance. Next, check the mean:

$$t' = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\dfrac{n_1 S_1^{\,2} + n_2 S_2^{\,2}}{n_1 + n_2 - 2}}\sqrt{\dfrac{1}{n_1} + \dfrac{1}{n_2}}} = -0.108$$

Given a significance level of 0.1, you can find that $t_{0.05}(15+10-2) = 1.7139$ by consulting the distribution table. We can see that

$$-t_{0.05}(23) < t' < t_{0.05}(23)$$

Therefore, there is no difference in their average values. Based on the above verification, it can be determined that the historical data and the field data are in good agreement.

3.3. Analysis and Verification

The repair time is Y, $X = \ln Y$, and from the above analysis we can see that X obeys the normal distribution. Set $X \sim N(\theta, \sigma^2)$, where the variance is estimated from historical data as $\tilde{\sigma}^2 = 0.1951$, θ is an unknown parameter for the overall distribution, and $\theta \sim \pi(\theta) = N(\mu, \upsilon^2) = N(-0.5342, 0.0083)$. According to the contract, the mean time to repair (MTTR) indicator value is 0.65 hours, and then θ_0 can be obtained:

$$\theta_0 = \ln 0.65 - \frac{1}{2} \times 0.1951 = -0.5283$$

In addition, giving the contractor risk $\alpha = 0.2$ and subscriber risk $\beta = 0.15$, the detection ratio is agreed by the contractor and the ordering party as $\lambda = 1.4$, which is equivalent to $\theta_1 = 1.4\theta_0$.

In the following, the average repair time is verified according to the post-survival likelihood ratio verification method.

Set: H_0: $\theta = \theta_0$, H_1: $\theta = \theta_1 = 1.4\theta_0$

First, calculate the pretest probability ratio of the two hypotheses:

$$\frac{P(\theta = \theta_1)}{P(\theta = \theta_0)} = e^{\{-\frac{1}{2\times 0.0083}[(-0.5283\times 1.4 + 0.5342)^2 - (-0.5283 + 0.5342)^2]\}} = 0.9607$$

The post-likelihood ratios of the two hypotheses can be calculated by the Bayesian formula and the above formula.

Since the pre-distribution of the θ is a normal distribution $N(\mu, \upsilon^2)$, the following conclusions are drawn according to Equation (7) and Equation (8):

$$P_0 = \int_{-\infty}^{\theta_0} \frac{1}{\sqrt{2\pi\upsilon}} e^{-\frac{(\theta-\mu)^2}{2\upsilon^2}} \mathrm{d}\theta = \int_{-\infty}^{-0.5283} \frac{1}{\sqrt{2\pi} \times \sqrt{0.0083}} e^{-\frac{(\theta+0.5342)^2}{2\times 0.0083}} \mathrm{d}\theta = 0.5832$$

$$P_1 = 1 - P_0 = 0.4168$$

The above equation can be used to calculate the minimum sample size required for the test:

$$n = \left(\frac{Z_{1-\frac{\alpha}{p_0}} + Z_{1-\frac{\beta}{p_1}}}{\theta_1 - \theta_0} \sigma\right)^2 = \left(\frac{Z_{1-\frac{0.2}{0.5832}} + Z_{1-\frac{0.15}{0.4168}}}{-0.5283 \times 0.4} \times \sqrt{0.1951}\right)^2 = 4.4315$$

n takes an integer of 5, so only five field data are needed. Substituting n into the equation:

$$\bar{X} > \frac{\sigma^2[(\lambda+1)\theta_0 - 2\mu]}{2n\upsilon^2} + \frac{\theta_0}{2}(\lambda+1)$$

The rejected field can be obtained:

$$\bar{X} > \frac{\sigma^2[(\lambda+1)\theta_0 - 2\mu]}{2n\upsilon^2} + \frac{\theta_0}{2}(\lambda+1) = 1.1026$$

If the condition $\bar{X} \le 1.1026$ is satisfied, the maintainability of the equipment is deemed to be acceptable by the user. Typically, five samples from the field data are compared with the rejection field to derive its average value.

Five samples: 0.4, 0.5, 0.8, 0.6, 0.8.

The average of these five numbers:

$$\bar{X} = (\ln 0.4 + \ln 0.5 + \ln 0.8 + \ln 0.6 + \ln 0.8)/5 = -0.5132$$

And

$$\bar{X} < 1.1026$$

Therefore, the maintainability of the equipment is tested to meet the user's requirements. If the method used in the national military standard is adopted, at least 30 field data are required. It can be seen that the sample size is greatly reduced by this method, and the superiority of the method is fully explained.

4. Conclusions

This paper analyses in detail the problems of existing assessment methods and proposes a small sample validation method based on Bayesian theory in view of the large sample size, inaccurate processing of test data, and missing data in existing assessment methods. The principle and steps of this method are mainly studied. Finally, specific examples are used to fully verify the method. Compared with the existing methods, the superiority of this method is proven. Under the condition of insufficient maintenance test data, it has important guiding significance for equipment maintainability evaluation.

References

1. J. K. Zhang, Q. Liu, and J. Feng, "Bayesian Methods in Test Analysis," National University of Defense Technology Press, Changsha, 2007
2. X. S. Zhang, K. L. Huang, P. C. Yan, G. Y. Lian, and S. G. Wang, "Evaluation of Complex Equipment Testability based on Mixed Prior Distribution," *Journal of Vibration, Measurement & Diagnosis*, Vol. 35, No. 4, pp. 697-701, 2015
3. GB/T 9414.1-2012, "Maintainability-Part 1: Application Guide," China Quality Inspection Publishing House, Beijing, 2014
4. Z. J. Chen, Q. C. Wang, and Y. X. Chen, "Determination Method of Acceleration Factor based on Life Distribution and Bayes," *Systems Engineering and Electronics*, Vol. 37, No. 5, pp. 1224-1228, 2015

5. B. C. Dong, B. W. Song, Q. W. Liang, and Z. Y. Mao, "Research on the Maintenance Test and Evaluation Method for Small Samples of Weapons and Equipment," *Acta Armamentarii*, Vol. 32, No. 3, pp. 327-330, 2011
6. M. Han, "E-Bayesian Estimation Method of Parameter and its Ap-Plications in Reliability Engineering," *Acta Armamentarii*, Vol. 33, No. 11, pp. 1473-1476, 2009
7. G. Luo, X. H. Mu, Y. T. Niu, F. P. Du, J. H. Chen, and Y. N. Wang, "Optimal Design Method for Accelerometer Step-Down-Stress Accelerated Life Testing on Condition of Small Sample," *Journal of Chinese Inertial Technology*, Vol. 23, No. 5, pp. 696-700, 2015
8. H. B. Yang, H. Cai, and S. F. Zhang, "Evaluation of Missile Guidance Precision based on Hybrid Prior Distribution," *Acta Aeronautica Et Astronautica Sinica*, Vol. 30, No. 5, pp. 855- 860, 2009
9. H. B. Yang, S. F. Zhang, and H. Cai, "Bayesian Modified Power Prior Approach for Product Reliability Assessment with Only Safe-or Failure Pattern," *Journal of Solid Rocket Technology*, Vol. 32, No. 2, pp. 131-134, 2009
10. J. J. Yang and T. Hu, "Research on System Reliability Competition Model based on Small Sample Multiple Failure Modes," *Fire Control & Command Control*, Vol. 41, No. 8, pp. 88-92, 2016
11. H. Liu and B. Guo, "Bayes Assessment for Reliability of Success or Failure Product in the Development Phases," *Electronic Product Reliability and Environmental Testing*, Vol. 24, No. 5, pp. 25- 29, 2006
12. J. Y. Miao, P. C. Yan, G. Y. Lian, R. Chen, and W. H. Qiu, "Research Status on Weapon Equipment Maintainability Verification Test Method," *Computer Measurement & Control*, Vol. 24, No. 3, pp. 122-126, 2016
13. A. W. Shen, J. L. Guo, Z. J. Wang, and Q. L. Zhang, "Sensitivity Analysis of Objective Bayesian Evaluation under Random Right Censoring and Weilbull Distribution," *Systems Engineering and Electronics*, Vol. 39, No. 8, pp. 1891-1897, 2017
14. Y. Y. Tan, C. H. Zhang, X. Chen, et al., "Bayes-Ian Analysis based on Dirichlet Prior Distribution of Dominant Failure Modes for Electromechanical Products," *Acta Armamentarii*, Vol. 33, No. 2, pp. 209- 213, 2012
15. X. Jiang, H. Z. Liu, J. J. Zi, D. N. Yuan, and L. L. Liu, "Extremely Small Sample'S Reliability of a Motorized Spindle based on Bayes Method," *Journal of Vibration and Shock*, Vol. 34, No. 4, pp. 121-127, 2015
16. W. J. Zhang, H. B. Yang, and S. F. Zhang, "Reliability Assessment for Device with Only Safe-or-Failure Pattern based on Bayesian Hybrid Prior Approach," *Acta Armamentarii*, Vol. 37, No. 3, pp. 506-511, 2016
17. Y. W. Yin, C. X. Shang, J. Y. Cai, Y. H. Ma, and G. Li, "Bayesian Verification Method based on Equipment Testability Growth," *Journal of Vibration*, *Measurement & Diagnosis*, Vol. 36, No. 3, pp. 488-491, 2016
18. W. L. Li, D. L. Yuan, H. Z. Liu, and T. Zhang, "Reliability Research on the Mechanism System Wear Simulation under the Case of the Small-Scale Sample," *Journal of Mechanical Engineering*, Vol. 51, No. 13, pp. 235-244, 2015
19. R. Q. Wang, F. Liu, D. Y. Hu, and D. Li, "Uncertainty Quantification in Low Cycle Fatigue Life Model based on Bayesian Theory," *Acta Aeronautica et Astronautica Sinica*, Vol. 38, No. 9, pp. 220832-1-220832-10, 2017
20. Y. L. Wang, Z. K. Li, B. Zhou, and M. J. Gu, "Extreme-Small-Sample Accelerated Test Method based on Segmented Section Step-Stress Experimental Principle in Life Cycle," *Journal of Huazhong University of Science and Technology* (*Natural Science Edition*), Vol. 45, No. 6, pp. 68-72, 2017

Chuang Li doctoral student, mainly engaged in equipment maintainability test and verification research.

Da Xu professor, doctoral supervisor, mainly engaged in equipment maintainability and supportability research.