Research on the Optimization Design Method of Reliability Enhancement Test of Fiber Optic Acousto-optic Modulator Based on Fuzzy Theory

Xi Yuan¹, Guicui Fu¹, Zhongqing Zhang¹ and Bo Wan¹

¹ School of Reliability and System Engineering, Beihang University, Beijing, CN

E-mail:yuanx@buaa.edu.cn

Abstract. The main purpose of the reliability enhancement test is to expose the weakness of the components in order to improve the process structure design. The current domestic test standards are Accelerated stress test procedures for electric and electronic products, Guidance on the definition and application of high-acceleration tests for avionics and so on. However, these standards have relatively broad provisions on test conditions. The feasible test schemes are not unique that lead to different required test conditions and test costs. The emerging device fiber optical acousto-optic modulator is expensive and the test cost is high. How to choose an efficient enhanced test program is particularly important. Based on the fuzzy theory, an optimization design method for the enhancement test of the fiber-optic acousto-optic modulator is established in this paper. This paper takes the test cost-efficiency ratio as the optimization target, and uses the reliability estimation deviation and cost as the fuzzy evaluation index for optimizing and designing of the enhancement test plan. Finally, the feasibility of the method is verified by case analysis.

1. Introduction
Reliability enhancement test finds and exposes the weak links of the design mainly by means of enhancement test. By taking improvement measures, the reliability of the product can be greatly improved. At present, reliability enhancement test stimulates product defects by artificially applying stepped environmental stress. The design of test profile of reliability enhancement test is mainly based on the product specifications and relevant standards of the enhancement test. So the test conditions are relatively broad. Test stress level, test and inspection time and cost are uncertain which leads to low strengthening efficiency of the device. Jan Snook thought that the method of failure physics could be used in the design of reliability enhancement tests. By establishing the failure model of the product, the conditions required to trigger the relevant faults can be further determined, and the reasonable test stress can be determined which can help avoid excessive stress and improve test efficiency[1][2][3]. This method requires a lot of simulation work for the device and the time and cost of testing cannot be determined. So the test conditions are still relatively broad and the test efficiency is not high. This paper converts the process of analysis using the failure physics method to the method of using fuzzy theory combined with Monte Carlo method for verification in the design of the fiber optic acousto-optic modulator reliability enhancement test and greatly reduces the workload. And this article takes the cost-effective ratio as the optimization goal to design the test plan which realizes a reasonable arrangement of test conditions and increases test efficiency at the same time.
Based on the fuzzy theory, this paper takes the cost-efficiency ratio of the fiber optic acousto-optic modulator reliability enhancement test as the optimization target and introduces the reliability estimation deviation and cost as evaluation indicators for fuzzy evaluation to obtain the optimal test plan. The article first introduces the fuzzy comprehensive evaluation model, the optimization objective of reliability enhancement test and the definition of the membership function of the optimization index. Then it describes the specific steps of the optimization design of the reliability enhancement test of the fiber optic acousto-optic modulator. Finally, it uses a typical device as an example for case analysis to verify the feasibility of the method.

2. Optimization design method of reliability enhancement test based on fuzzy theory

According to product specifications and relevant standards for enhancement test there are a large number of fiber optic acousto-optic modulator reliability enhancement test plans can be selected. However, the exposure degree and time of the weak links of products under different test schemes are different, which affects the cost and efficiency of the test. Therefore, this paper takes the test cost-efficiency ratio as the optimization goal, and uses the fuzzy comprehensive evaluation model to optimize the test plan.

2.1. Fuzzy comprehensive evaluation model

The steps of fuzzy comprehensive evaluation are as follows:

- The comprehensive evaluation is as follows: Determine evaluation factor sets and evaluation sets. It is assumed that there are n factors that affect the test efficiency, and there are k possible evaluations. Evaluation factor set $U = \{u_1, u_2, \ldots, u_n\}$ and evaluation sets $V = \{v_1, v_2, \ldots, v_k\}$.

- Evaluation matrix. There are m test programs. According to the mapping relationship between the evaluation factors of each program and the test efficiency and the principle of maximum membership, the comment of the $j$th factor of the $i$th plan is $r_{ij}$. The fuzzy evaluation judgment matrix is:

$$ R = \begin{bmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix} \quad (1) $$

Among them, comments can be determined by expert statistical methods, maximum membership methods and other methods. This article uses quantitative analysis of maximum membership.

- Determine weight. Various factors have different influences on the evaluation results, and it is necessary to determine appropriate weights. The weight matrix is $c = \{c_1, c_2, \ldots, c_n\}$ . Methods commonly used are expert estimation method, analytic hierarchy process, coefficient of variation method, gray correlation method, entropy value method, neural network method and so on.

- Comprehensive evaluate. According to the fuzzy operation, the comprehensive evaluation matrix is:

$$ B = c \cdot R \quad (2) $$

2.2. Optimization goals and evaluation indicators

This paper takes the test efficiency ratio as the optimization goal and integrates the effects of device enhancement efficiency and test cost on different test programs for optimized design of the reliability enhancement test. The evaluation indicators it introduces include reliability estimation deviation and test cost.

2.2.1. Reliability estimation deviation and its membership function

In this paper, the Monte Carlo method is used to determine the stress level replace the failure physical method. At the same time, it introduces reliability estimation deviation as an evaluation indicator considering the influence of the changes of different reliability strengthening test schemes on the device
strengthening efficiency. This paper transforms the traditional finite element simulation analysis process into Monte Carlo simulation, the formula of the reliability estimate is as follows:

\[ R_Q(t) = \frac{N_{MC} - F_Q(t)}{N_{MC}} \]  

(3)

Here the fuzzy distribution[4][5] method is used to define the membership function of the reliability estimation deviation \( \mu_R \):

\[ \mu_R = \left| R_r - R_Q(t) \right| \]  

(4)

Among them: \( R_r \) is the specified threshold of device parameters; \( R_Q(t) \) is the estimated value of device reliability under \( Q \) enhanced test plans; \( N_{MC} \) is the number of Monte Carlo simulations; \( F_Q(t) \) is the number of device degradation parameter models exceeding \( R_r \) during the \( N_{MC} \) simulation for each enhanced test method.

2.2.2. Test cost and its membership function.

The cost of the test is one of the key factors directly restricting the progress of the test, so the test cost is used as the evaluation index. For the component of the total cost of the test, in addition to some of the fixed variable \( C_0 \), the two most important costs are the cost \( C_t \) related to time \( t \) and the total sample size \( n \) used in the sample \( C_n \). The fixed cost \( C_0 \) as a constant term can be deducted from the total cost \( C_{total} \), so the experimental cost of this study is:

\[ C_{total} = C_t + C_n \]  

(5)

The triangular membership distribution[4][5] is used here and the membership function of the test cost \( \mu_C(x) \) is:

\[ \mu_C(x) = \begin{cases} 
\frac{x - C_1}{C_2 - C_1} & (C_1 \leq x \leq C_2) \\
\frac{C_3 - x}{C_3 - C_2} & (C_2 \leq x \leq C_3) \\
0 & Others 
\end{cases} \]  

(6)

Among them \( C_1 < C_2 < C_3 \).

3. Optimized design method for reliability enhancement test of fiber optic acousto-optic modulator

According to the above theory, the reliability enhancement test optimization method of fiber optic acousto-optic modulator can be established as follows:
3.1. Reliability enhancement test program set
Fiber optic acousto-optic modulator can realize the time control and spatial switching of light beam through optical modulation, optical frequency shift, etc. It is the core device of various optical communication systems [6][7]. According to the environmental factors of the fiber optic acousto-optic modulator and the main stresses in its life cycle, the sensitive stress analysis was conducted to obtain the sensitive stress of the fiber optic acousto-optic modulator.

Taking the sensitive stress to determine the stress applied in the strengthening test project and the stress limit required by the technical specifications as the initial test conditions, a set of high temperature stepping, low temperature stepping, rapid temperature change, vibration stepping and comprehensive stress strengthening test programs can be established separately [8].

3.2. Membership function of fuzzy evaluation index
According to the characteristics and test conditions of the device, the reliability estimation deviation and test cost are introduced as evaluation indicators. According to the historical test data of the device, the linear degradation method is used to establish the parameter degradation models of extinction ratio and insertion loss. The parameter degradation model is as follows:

$$y(t) = a_i + a_t t + \varepsilon$$  \hspace{1cm} (7)

Reliability estimation deviation is:

$$R_Q(t) = \frac{N_{MC} - Q(t)}{N_{MC}}$$  \hspace{1cm} (8)

Then the membership function is:

$$\mu_R = \left| R - R_Q(t) \right|$$  \hspace{1cm} (9)

Among them $t$ is the ambient temperature, $Q(t)$ is the number of devices whose extinction ratio parameter is lower than the specified value and the insertion loss is higher than the specified value, $N_{MC}$ is the number of Monte Carlo simulations, $R$ is specified threshold of device parameters, $\varepsilon$ is errors.

The hourly test cost is 400 yuan, the cost of each device is about 30,000 yuan, and the total budget of the test is 430,000 yuan. This project sets up 6 test projects which uses two devices and uses a total of 12 fiber optic acousto-optic modulators about 360,000 yuan. The remaining test cost is about 70,000 yuan which is evenly distributed to each test project. The test cost constraint for each test project is $C_{total} = 10,000$ yuan fuzzy processing and the membership function $\mu_C(x)$ is:
1 \begin{align*}
\mu_C(x) &= \begin{cases} 
\frac{x-C_1}{C_2-C_1} & (C_1 \leq x \leq C_2) \\
\frac{C_3-x}{C_3-C_2} & (C_2 \leq x \leq C_3) \\
0 & \text{Others}
\end{cases} 
\tag{10}
\end{align*}

Among them, $C_1=6,000$ yuan, $C_2=10,000$ yuan, $C_3=14,000$ yuan.

3.3. Membership degree table and comprehensive evaluation
Combining the reliability enhancement test plan set and Monte Carlo method, the membership table of the enhancement test plan is calculated. And the fuzzy comprehensive evaluation of the plan is carried out to obtain the optimal enhancement test plan.

4. Case study
Finally, the optimized design of the reliability enhancement test of the typical device of the fiber optic acousto-optic modulator is carried out taking the optimized design of the high-temperature stepped reliability test as an example.

According to the sensitive stress analysis and the technical specifications of the device, the set of high temperature step reliability enhancement test options is shown in Table 1 and take the deviation of reliability estimate and test cost as evaluation indicators.

Table 1. High temperature step reliability enhancement test alternative program set.

| Number | Starting temperature | Termination temperature | Step | Temperature change rate | Hold time |
|--------|----------------------|-------------------------|------|-------------------------|-----------|
| 1      | 60°C                 | 95°C                    | 2°C  | 2°C/min                 | 60min     |
| 2      | 60°C                 | 115°C                   | 3°C  | 2°C/min                 | 60min     |
| 3      | 60°C                 | 135°C                   | 5°C  | 2°C/min                 | 60min     |
| 4      | 60°C                 | 155°C                   | 5°C  | 2°C/min                 | 60min     |

Taking Scheme 4 as an example to calculate the index membership degree. According to the historical high temperature test data of the device, the parameter degradation models of extinction ratio and insertion loss at high temperature were established by linear fitting method.

The degradation model of high temperature extinction ratio parameters is as follows:

\[ y_X(t) = -0.0797t + 68.3242 + \varepsilon_X \tag{11} \]

The high temperature insertion loss parameter degradation model is as follows:

\[ y_C(t) = 0.011t + 0.9918 + \varepsilon_C \tag{12} \]

Among them: $t=155$, $R_e=0.9$, the minimum threshold of high temperature extinction ratio is 40 and the maximum threshold of high temperature insertion loss is 0.4, $\varepsilon_X \sim N\left(0, 0.46^2\right)$, $\varepsilon_C \sim N\left(0, 0.4921^2\right)$.

Through 5000 Monte Carlo sampling $R_d(t) = 0.9932$, so $\mu_r = 0.0932$.

The total test time of Scheme 4 is 19.8h, and the test and test cost per hour is 500 yuan. According to the test cost membership function $\mu_c = 0.026$.

Perform the above Monte Carlo simulation and calculation on the four schemes to obtain the membership degree table of the high temperature stepping reliability enhancement test scheme shown in Table 2.
Table 2. Membership Degree Table of High Temperature Step Reliability Strengthening Test Plan.

| Number | Fuzzy parameters | Plan 1 | Plan 2 | Plan 3 | Plan 4 |
|--------|------------------|--------|--------|--------|--------|
|        | \( \mu_R \)     | 0.1002 | 0.0998 | 0.0976 | 0.0932 |
|        | \( \mu_C \)     | 0.2760 | 0.1510 | 0.5469 | 0.0260 |

Then there are two main factors that affect the test efficiency, the evaluation factor set \( U = \{u_1, u_2 \} \). Suppose there are four possible evaluations, there are evaluation sets \( V = \{v_1, v_2, v_3, v_4 \} \).

The comprehensive evaluation process is as follows:

- According to the membership table of the high temperature step reliability enhancement test plan, the evaluation matrix is:

  \[
  R = \begin{bmatrix}
  0.1002 & 0.0998 & 0.0976 & 0.0932 \\
  0.2760 & 0.1510 & 0.5469 & 0.0260
  \end{bmatrix}
  \]  

  (13)

- Set the weight set to \( c = [0.7, 0.3] \).

- The comprehensive evaluation is as follows:

  \[
  B = c \cdot R = \begin{bmatrix}
  0.5130 & 0.1152 & 0.2324 & 0.0731 \\
  \end{bmatrix}
  \]  

  (14)

According to the evaluation results, the plan3 with the highest is selected as the most optimal profile of the high-temperature step reliability enhancement test. The optimal high-temperature step strengthening test plan is shown in Table 3.

Table 3. High temperature stepping strengthening test plan.

|                          |               |
|--------------------------|---------------|
| Starting temperature     | 60°C          |
| Termination temperature  | 135°C         |
| Step                     | 5°C           |
| Temperature change rate  | 2°C/min       |
| Hold time                | 60min         |

5. Conclusion

Aiming at the problem of low efficiency of fiber optic acousto-optic modulator reliability enhancement test, this paper introduces fuzzy evaluation indicators to comprehensively evaluate the test plan and obtains the optimal enhancement test plan of the fiber-optic acousto-optic modulator which improves the device enhancement efficiency based on fuzzy theory. At the same time, the method uses Monte Carlo analysis instead of device simulation analysis and reduces the workload of experimental design. This method is simple in procedure and easy to implement which can provide a reference for failure mode and failure mechanism verification for subsequent device improvement.

Acknowledgments

Upon the completion of the thesis, I would like to take this opportunity to express my sincere gratitude to my supervisor Professor Fu Guicui and Professor Wan Bo who have given me important guidance on the thesis. Without their help and encouragement, my thesis would have been impossible. Besides their help with my thesis, they have also given me much advice on the methods of doing research, which is of great value to my future academic life. All in all, I would like to express my gratitude to all the friends and family members who have offered me help. Without their help, I could not have finished my study and this thesis.
References

[1] Huibin Hu, Lijun Cao, Shuxiao Chen and Ji-Sheng Ma 2015 Simulation on reliability enhancement testing technology of ramming system *Journal of Shanghai Jiaotong University (Science)*** 20(4) 477-81

[2] Yu I T and Chang C L 2012 Applying Bayesian model averaging for quantile estimation in accelerated life test *IEEE Transactions on Reliability* **61**(1) 74-83

[3] Kearney M, Marshall J and Newman B 2003 Comparison of reliability enhancement tests for electronic equipment *Reliability & Maintainability Symposium*. Tampa FL USA 435-40

[4] Said Z, Abdelkareem M, Rezk H and Nassef A 2019 Dataset on fuzzy logic based-modelling and optimization of thermophysical properties of nanofluid mixture *Data in brief*. 26 104547

[5] Xiaodong Pan and Yang Xu 2015 Semantics of Propositional Fuzzy Modal Logic with Evaluated Syntax and its Application to Fuzzy Decision Implications *International Journal of Computational Intelligence Systems*. 8(sup1) 85-93

[6] D Y Wang, Y M Wang, J M Gong and A Wang 2011 Fully distributed fiber-optic temperature sensing using acoustically-induced rocking grating *Optics Letters*. 36(17) 3392-4

[7] Lee K J, Hwang I K, Park C H and Kim B Y 2010 (1-7) *Optics Express*. 12(18) 12059-64

[8] SJ 21103-2016 *General specification for fibre-coupled acousto-optic device*