Structure Optimization of Infrared Guidance Testing Device Based on Orthogonal Test

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Abstract. As an important weapon, missiles cannot be ignored in its fighting capacity. Therefore, the performance testing of the missile is particularly important. The hardware in the loop simulation test using missile test equipment on the ground can reduce the cost and improve the utilization rate; it is of great significance for the development of national defence construction. In the process of missile testing, the parts under the force of deformation will reduce the accuracy of the device, therefore the light pipe support needs sufficient strength and stiffness. In this paper, the finite element method was used to analyse the structure of the optical tube support seat, and the orthogonal test was used to optimize it. The test results were analysed by the range and variance to find out the optimal level combination and the significant influence of each factor in the result. At end, the appropriate structure of the program was determined. Comparing with the original structure, the strength and rigidity of the optical tube support seat have been greatly improved. Device accuracy has also been improved.

1. Introduction

As a sophisticated weapon, infrared guided missiles have played an important role in modern warfare and have been proved by the partial wars that have taken place in recent years [1]. As a key component of missile and aircraft, two methods are mainly used to evaluate its performance [2]. In 2010, Switzerland Acutronic Company designed a missile test device with a model of AC3355, which was utilized to tests for infrared guided missiles and seekers [3]. In 2011, Acutronic improved the AC3355 missile test device and produced the AC3355-RS model [4].

In 2012, Li Xi [5] et al aimed at the requirements of the environmental test and field test of infrared air-to-air missiles. In 2014, Jun Songxiang and Wang Zhensheng invented a folding missile test turntable and a pull-type missile test turret [6, 7]. In 2016, Huang Fang-hua [8] developed infrared guided missile test equipment including a target simulator, a swing table, and a measurement and control electrical equipment. Orthogonal experimental design is a test method based on probability theory, quantitative statistics and practical experience, and tends to optimize the experiment [9].

In the 1920s, R.A. Fisher proposed a method of analysis of variance (ANOVA) and established a theory of "experimental design" to solve the problem of non-uniform test conditions. In 1949, Taguchi Xuanyi from Japan [11] proposed an orthogonal test table to test the method which is the orthogonal test method. In 1947, the American Academy of Sciences C.R.Rao [12] first proposed the concept of
orthogonal tables. In 2003, Kwon-Hee Lee et al. [13] used two optimization methods of orthogonal test and genetic algorithm to optimize the truss structure and concept body structure respectively.

In the late 20th century, China began to introduce the field of experimental design. In 2002, Zhang Hongmei [14] et al. combined the orthogonal test method with the least square method to successfully optimize the cross-head bootless universal joint fork. In 2011, Yang Jianqiu [15] et al. optimized the P Fanotuo optimal solution of the airfoil engine by analyzing the fan blades of the airfoil engine.

In this paper, the structural design of the infrared test device and the structural optimization of the light pipe support seat based on the orthogonal test method should be performed in order to improve the precision of the device.

2. Structure design of infrared guidance test device

Infrared guidance and testing device made up consists mainly of the simulation mechanism to missile position and attitude, simulation mechanism of the infrared target, the supply component of cooling gas and the rest parts and so on. The missile poses simulation part includes a front support frame and a rear support frame. The infrared target simulation part has one rotating mechanism and a parallel light pipe. The remaining parts are mainly shell, sliding table and light tube support seat, etc. The infrared guided missile test device is shown in below figure 1.

![Infrared guidance testing device](image)

1-Rotating mechanism; 2-Cooling gas supply module; 3-Parallel light tube mechanism; 4-Black body radiator; 5-Front support frame; 6-Measured missile; 7-Rear support frame

Figure 1. Infrared guidance testing device.

The role of the missile attitude simulation mechanism is to simulate the attitude movement of the missile in the pitch direction, which is comprised of a front support frame and a rear support frame. During the test, the sliding support of the fixed support frame is pulled to the limit position, and the missile is placed on the front support frame. The fixed arm of the rear support frame can move up and down to simulate the movement of the missile. The brackets are required to be folded or disassembled, and the device is intended to be detachable.

3. Structure optimization method of the optical tube support seat based on orthogonal test

3.1. The design procedure of orthogonal test methods

The orthogonal experiment includes two parts of experimental design and data processing. The basic steps are as follows [16].

The purpose of the test will be made clear, that is to determine the test index; The operator will select the factors of the test and calculate the value of their level; The orthogonal tables will be designed; The experiment will be carried out according to the orthogonal table, and the experimental results will be generated and recorded; The results of the experiment will be analyzed statistically. It mainly includes the difference analysis and the analysis of variance; The operator will select the best test factors and analyze the results.
3.2. Analysis methods of orthogonal test results

3.2.1. The extreme difference analysis
This is a very intuitive method of analysis. The difference represents the difference between the maximum and the minimum of the results obtained by each factor. The steps are as follows [17].

(1) The main influence of each factor are Determined on the result of the test by comparing the difference of R.
(2) To The combination of the best actor level are determined.

3.2.2. Analysis of variance
The variance analysis procedure used in orthogonal experiment is to get the sum of squares of the deviations of each factor and error first, then calculate the degree of freedom, mean square and the F value, and finally carry out F test [18]. For the experiments carried out with the orthogonal table \( L_{nm} \), the value of the experimental results is \( y_i \) (i=1,2,3,…n) then the process of analysis of variance is as follows.

1) \( SS_T \) is the sum of squared sum of total deviations

\[
SS_T = \sum_{i=1}^{n} (y_i - \bar{y})^2 = \frac{1}{n} \left( \sum_{i=1}^{n} y_i \right)^2
\]  

(1)

Suppose:

\[
T = \sum_{i=1}^{n} y_i, Q = \sum_{i=1}^{n} y_i^2, P = \frac{1}{n} \left( \sum_{i=1}^{n} y_i \right)^2
\]  

(2)

Then:

\[
SS_T = Q - P
\]  

(3)

The total deviation square sum reflects the total difference of the test results. The greater the \( SS_T \), the greater the difference between the results of each test.

2) \( SS_j \) is the square sum of deviations caused by various factors. \( SS_j \) is the sum of square errors caused by the factors on the j\((j=1,2, 3, \ldots m)\) column of the orthogonal table. \( SS_T \) is the sum of \( SS_j \) and there are:

\[
SS_j = \frac{1}{n} \sum_{i=1}^{n} (k_i - \bar{k})^2 = \frac{1}{n} \left( \sum_{i=1}^{n} k_i \right)^2 - \frac{1}{n} \sum_{i=1}^{n} \left( \sum_{i=1}^{n} k_i \right)^2 - n - \frac{1}{n} \sum_{i=1}^{n} \left( \sum_{i=1}^{n} k_i \right)^2
\]  

(4)

\[
SS_T = \sum_{j=1}^{m} SS_j
\]  

(5)

3) \( SS_e \) is the sum of the deviation square of the test error.

\[
SS_e = SS_T - \sum_{j=1}^{m} SS_j
\]  

(6)

4) the degree of freedom for the sum of the totals square sum may be written in the form

\[
df_T = n - 1
\]  

(7)

The square of the deviation of any column factor of the orthogonal table and the corresponding degree of freedom becomes:

\[
df_j = df_T = r - 1
\]  

(8)

5) we can get the sum of square of the mean deviation (mean square). Divide the deviation square by the corresponding degree of freedom to get the average square, referred to as the mean square.

\[
MS_j = \frac{SS_j}{df_j}, MS_e = \frac{SS_e}{df_e}
\]  

(9)

6) we will calculate the \( F_j \) value. Divide the mean square of each factor by the mean square of error to get the \( F_j \) value.
7) $F_j$ test is used to identify the magnitude of the importance of each factor to the results of the experiment. The larger of the $F_j$, the more likely that the change of the factor level is larger than that of the test error.

3.3. Structure optimization of the optical tube support seat

The original structure of the optical tube support part is similar to the cantilever beam. After the stress, the deformation is more obvious, and the strength can be increased by increasing the thickness and strengthening the reinforcement. The original structure and the preliminary optimized structure are shown in below figure 2.

![Original structure](image1) ![Preliminary optimized structure](image2)

Figure 2. The structure of the optical tube support seat.

As showed in figure 3, the thickness of the upper panel is $x_1$, the thickness of the reinforcement is $x_2$, the height of the reinforcement is $x_3$, and the position of the reinforcing bar is $x_4$ as the design variable.

![Structure optimization design variables](image3)

Figure 3. Structure optimization design variables of the optical tube support seat

According to the structure of the support set of the original light tube, the corresponding changes are made, and the level table of each factor is listed in Table 1. The test is divided into four factors and four levels after the error column is added and the $L_{16}(4^5)$ orthogonal table is used to arrange the test. The number of tests carried out in a full experiment was $4^4 = 256$ times and 16 times after using the orthogonal test method. According to the orthogonal experiment table, the three-dimensional solid model is established, and the finite element analysis is carried out. The experimental results are given in Table 2.

| Level | Symbol | $x_1$ | $x_2$ | $x_3$ | $x_4$ |
|-------|--------|-------|-------|-------|-------|
| 1     | 1      | 7     | 6     | 18    | 1     |
| 2     | 2      | 8     | 7     | 19    | 2     |
| 3     | 3      | 9     | 8     | 20    | 3     |
| 4     | 4      | 10    | 9     | 21    | 4     |

Table 1. Optical support base orthogonal test factor level

| Level | Symbol | Upper panel thickness | The thickness of the ribs | The height of the ribs | The location of ribs |
|-------|--------|-----------------------|--------------------------|-----------------------|---------------------|
| 1     | 1      | $x_1$ | $x_2$ | $x_3$ | $x_4$ |
| 2     | 2      | $x_1$ | $x_2$ | $x_3$ | $x_4$ |
| 3     | 3      | $x_1$ | $x_2$ | $x_3$ | $x_4$ |
| 4     | 4      | $x_1$ | $x_2$ | $x_3$ | $x_4$ |

Table 2. The range of the optical tube support set of test results of the maximum deformation

| Error | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ |
|-------|-------|-------|-------|-------|-------|
| $K_1$ | 0.2229| 0.2050| 0.2026| 0.1844| 0.1848|
| $K_2$ | 0.1919| 0.1875| 0.1878| 0.1806| 0.1805|
| $K_3$ | 0.1654| 0.1716| 0.1728| 0.1803| 0.1801|
| $K_4$ | 0.1443| 0.1604| 0.1613| 0.1792| 0.1791|
| $R$   | 0.0786| 0.0446| 0.0413| 0.0052| 0.0057|
3.4. Analysis of the maximum deformation of the optical tube support seat

Based on the results obtained in Table 1 and Table 2, the impact of the level of the factors on the maximum deformation of the light pipe support is indicated by figure 4.

According to Table 2, the difference is: \( R(x_1) > R(x_2) > R(x_3) > R(x_4) \), which shows that the greatest influence on the deformation of the support base is related to the panel thickness \( x_1, x_2 \), stiffener height \( x_3 \), stiffener position \( x_4 \). The \( K \) values of the various factors in figure 4: \( (x_1), (x_2), (x_3), (x_4) \).

\[
\begin{array}{cccccc}
\text{Sources of variance} & \text{SS}_j & \text{df}_j & \text{MS}_j & \text{F value} & \text{Significance} \\
\hline
x_1 & 0.0009 & 3 & 0.0003 & 10 & ** \\
x_2 & 0.0003 & 3 & 0.0001 & 3 & [*] \\
x_3 & 0.0001 & 3 & 0.00003 & 3 & [*] \\
x_4 & 0.0001 & 3 & 0.00003 & — & — \\
\text{Error} & 0.0001 & 3 & 0.00003 & — & — \\
\Delta e & 0.0002 & 6 & 0.00003 & — & — \\
\text{Sum} & 0.0016 & 15 & — & — & — \\
\end{array}
\]

Note: \( F_{0.25}(3,6)=1.68, F_{0.1}(3,6)=3.29, F_{0.05}(3,6)=4.76, F_{0.01}(3,6)=9.78 \).

From the \( F_j \) value of Table 3, it can be seen that the influence of factor \( x_1 \) on the maximum deformation of the light pipe support seat is highly significant, while \( x_2 \) and \( x_3 \) are insignificant but influential. The change of \( x_4 \) has almost no effect on the experimental results.

4. Conclusion

In order to increase the accuracy of the device and correctly measure the performance of the infrared guided missile, the orthogonal experiment is used to optimize the structure of the light pipe support seat, which affects the accuracy of the device. The optimum structure of the test results was obtained by using the extreme analysis and variance analysis to find out the best combination of the factors. The optimal structure compares with with the original structure. The maximum deformation is reduced by 0.5317mm and the mass is only increased by 0.56kg, therefore the precision of the device is greatly improved.

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References

[1] Wu Z G 2000 Simulation technology (Chemical Industry Press, Bei Jing) p 220–256
[2] Chang Q 2003 Cruise Missile Guidance System Key Technologies (xian: Northwestern Polytechnical University) pp56068.
[3] Switzerland Acutronic Company 2011 http://rt-tech.net/uploadfile/2011/09/201109151 7054185.
[4] Switzerland Acutronic Company 2011 http://rt-tech.net/uploadfile/2011/09/2011091517.
[5] Li X and Li Y 2012 Fire Com Cont 37 p179-181
[6] Song X J, Wang Z S, Zhao F, et al 2014 The folding missile test turntable(Hebei: CN203893750U) 2014-10-22
[7] Song X J, Li W, Wang Z S, et al 2014 Pull type missile test turntable( Hebei: CN104061826A) 2014-09-24
[8] Huang H F, Li Q, Cao Y H, et al 2016 A kind of infrared guided missile tests equipment and method( Shanghai: CN105737672A) 2016-07-06.
[9] Liu R J, Zhang Y W, Wen C W, 2010 Expe Tech Mana 27 (9) p 52-56.
[10] Montgomery D C 1984 Design and Analysis of Experiment(Second Edition) (New Yock: John Wiley and Sons) p 125-136.
[11] Taguchi X C 1987 The experimental design method (Mechanical Industry Press, Bei Jing) pp 165-176.
[12] Mang J C, Wu C F 1991 J.Amer.Statist.Assoc 6 p450-456
[13] Lee K H, Yi J W, Joon S. 2003 Finite Elem Anal Des 40 p121-135
[14] Zhang H M, Wang Y H, Lu M 2002 J PLA Univ Sci Tech 3 (4) p 50-53.
[15] Yang J Q, Wang Y R 2011 J Aero Power 2 p46-54.
[16] Xu Z A, Wang T B, Li C Y, et al 2002 Sci Tech Info Deve Econ 6 p89-95.
[17] Zhang J F 1998 Mathe Stati Mana 6 p31-37.
[18] Xin Y J 2002 Analysis of variance and experimental design (China financial and economic press, Bei Jing) pp58-64