Accuracy analysis and optimization of infrared guidance test device

Zhou Wang¹, Yin Chen¹, Tao Wang² and Bo Zhang¹

Abstract
As an important modern weapon, the development of infrared-guided missile reflects comprehensive national strength of a country. Therefore, it is especially important to establish a semi-physical simulation device to test the performance of missile, and the test device requires high accuracy. Based on the above background, an infrared guidance test device is designed in this article. The accuracy of its shell and rotating mechanism are studied in detail, and the error factors are quantified to provide theoretical basis for structural optimization. The orthogonal experiment design reduces the number of sensitivity analysis experiments on key design parameters. Factors affecting the maximum deformation and overall quality of the shell were determined. The range method was used to analyze sensitivity factors, and the final optimization result that met the minimum deformation and minimum quality was determined. Experimental results show that the rotation error of the main shaft of the rotating mechanism includes axial, radial, and angular motion errors, and experimental value is basically consistent with theoretical value. After the shell optimization, the infrared target pointing error $\delta_z = 1.71$ and the infrared target position offset error $\zeta' = 0.1525$ mm meet the accuracy requirements. This method can provide new ideas for precision research and optimization of structural design of rotating mechanism.

Keywords
Infrared guidance, semi-physical simulation, accuracy analysis, error synthesis, sensitivity analysis, orthogonal experiment

Introduction
As a highly sophisticated weapon, infrared-guided missiles play an important role in modern warfare and have been proved by local wars that have occurred many times in recent years.¹ The current main method for evaluating missile guidance system performance is to simulate actual flight environment of missile or aircraft, use the simulation equipment to test and evaluate the performance indicators of guidance system on the ground, and detect the working state and tracking accuracy of the system.²

Li and Li³ developed a convenient target simulator for the overall performance test of missile in a complex environment. Gu et al.⁴ adopted field reconfigurable technology to realize the design of intelligent adapter switch network and conditioning module, which greatly improved the generalization level and test efficiency of missile test system. Li et al.⁵ designed a set of test equipments based on PXI bus and realized the overall performance test of infrared air-to-air missile with the function of post-launch interception.

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The infrared guidance test equipment is a semi-physical simulation device. The semi-physical simulation is a process of combining the mathematical model with physical model. The basic idea is to build mathematical models of simple or well-regular parts and use

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a computer to achieve them. Use complex or irregular
colorplates of the material directly.6 Fang et al.7 proposed an
X-ray pulsar navigation ground verification system that uses a semi-physical device to modulate and attenuate visible light to simulate the propagation of spatial X-rays. Tauzia et al.8 proposed a novel 0 type of diameter (OD) semi-physical model to evaluate engine exhaust NOx and soot, and reduce the cost and the time required for engine calibration. Ying et al.9 established a semi-physical brake intelligent test system to adapt to the improvement of freight train braking technology.

Due to emergence of the semi-physical simulation system, it is accompanied by the study of its error. Chinese scholar Wu10 made a detailed study on the accuracy distribution of the semi-physical simulation system and proposed that the accuracy of such simulation system consists of two parts: system sighting accuracy and dynamic accuracy. The semi-physical simulation is characterized by wide object-oriented and highly targeted, and different analysis methods must be used according to different systems. Therefore, some scholars have done a lot of research on accuracy analysis.

Zhang et al.11 established a mathematical model of missile semi-physical simulation system for self-seeking infrared imaging. The mathematical simulation experiment and statistical fitting were used to solve the problem that the sensitivity of the simulation system was difficult to calculate. Lei et al.12 analyzed the factors affecting the accuracy of the gyro based on the differential equation of the gyro motion to reduce the error of the dynamic gyro of the infrared-guided weapon seeker, and proposed a control method for the main errors of the gyro. Zhao et al.13 studied main error sources that affect the accuracy of infrared guidance semi-physical simulation, indicating that installation error of the seeker has obvious influence on simulation test results. Zhang et al.14 proposed a system compensation method to compensate the dynamic delay of the imaging system, thus improving the performance of simulation system.

After in-depth analysis of error factors to obtain quantitative indicators, it is necessary to optimize the design. In the structural design process, design parameter sensitivity analysis can quickly and effectively lock the most important design variables to optimize the design. At present, parametric sensitivity analysis methods have been widely used.15

Fu et al.16 proposed a method for analyzing design sensitivity of node displacement, element stress, and critical load factors of linear and nonlinear lattice structures. Yang and Wang17 optimized the fan blades of the aero-coil engine using multi-round numerical orthogonal test design method and obtained the Pareto optimal solution of hollow blade structure. Lin et al.18 used the orthogonal experimental design method to optimize the microporous layer and improve the performance of polymer exchange membrane fuel cell. At present, semi-physical simulation involves multiple disciplines, and there are great differences between different systems. Researchers mostly analyze the corresponding error models established by simulation systems, and there are few studies on quantitative analysis of system errors.

In this article, error sources of the accuracy of the infrared guidance testing device are analyzed. Quantitative analysis of the error factors yields specific values, and comprehensive error values are obtained using the law of error transmission. Orthogonal test method was used to optimize the structure of key parts affecting the accuracy. The sensitivity analysis of optimization results is carried out to find the optimal level. Relevant analysis and experimental results show that the experimental value of the main axis–angle error of rotating shaft is basically consistent with the theoretical value. After the structure optimization, the device accuracy is greatly improved and meets the requirements. This study may provide a new method for structural design and precision analysis of infrared guidance test device.

Infrared guidance test device accuracy analysis method

Accuracy calculation method

Let the function be

\[ y = F(x_1, x_2, \ldots, x_n) \]  

(1)

where \( x_1, x_2, \ldots, x_n \) are direct measurements and \( y \) is an indirect measurement.

If their errors are \( \delta x_1, \delta x_2, \ldots, \delta x_n \) and \( \delta y \), then equation (1) can be written as

\[ y + \delta y = F(x_1 + \delta x_1, x_2 + \delta x_2, \ldots, x_n + \delta x_n) \]  

(2)

Equation (2) is generally a nonlinear function, while \( y \) can be regarded as a continuous change with \( x \), and error \( \delta x \) is a small amount. The nonlinear function is expanded into a Taylor series, and only the first-order term is taken as an approximation to make it linearized

\[ y + \delta y = F(x_1, x_2, \ldots, x_n) + \frac{\partial F}{\partial x_1} \delta x_1 + \frac{\partial F}{\partial x_2} \delta x_2 + \cdots + \frac{\partial F}{\partial x_n} \delta x_n \]  

(3)
By simplifying equation (3), we get
\[ \delta_y = \frac{\partial F}{\partial x_1} \delta x_1 + \frac{\partial F}{\partial x_2} \delta x_2 + \cdots + \frac{\partial F}{\partial x_n} \delta x_n \]  \hspace{1cm} (4)

Equation (4) can be seen as a linear function composed of \( \delta_y = \delta x_1 + \delta x_2 \) and \( \delta_y = a_0 \delta x \). The partial differential \( \frac{\partial F}{\partial x_i} = a_i \) is a constant and can be obtained as
\[ \sigma_y = \sqrt{\sum_{i=1}^{n} \left( \frac{\partial F}{\partial x_i} \right)^2 \sigma_{x_i}} \]  \hspace{1cm} (5)

Equation (5) is the general form of the law of error transmission.19

**Infrared guidance test device kinematic chain analysis**

During the operation of the infrared guidance test device, it is necessary to have a precise positioning of the missile pose and the target pose. The transmission process of the missile pose simulation movement is as follows: slide \( O_1 \rightarrow \) rear support \( O_2 \rightarrow \) front support \( O_3 \rightarrow \) missile seeker \( O_4 \). The transmission process of the target pose simulation motion is as follows: rotation mechanism \( O_5 \rightarrow \) shell \( O_6 \rightarrow \) light pipe support \( O_7 \rightarrow \) parallel light pipe \( O_8 \). The kinematic chain is shown in Figure 1. Due to the existence of the error, the missile and the target pose cannot be in an ideal state during the motion transmission.

**Analysis of error sources**

This article mainly analyzes the target pose error of the device, which is mainly divided into two parts: infrared target pointing error and infrared target position error.

**Infrared target pointing error.** In this article, when analyzing the infrared target error, the error of the optical system is not considered. The infrared target generation system is regarded as a whole, and only the error of the mechanical structure of the infrared target motion is considered. Due to the force deformation of parts and the rotation error of the shafting, the infrared target pointing error occurs, as shown in Figure 2. The infrared target pointing error refers to the angular offset \( \delta \) between the true pointing and the ideal pointing of infrared light emitted by infrared target simulator, which affects missile seeker’s detection of the target and the reception of energy.20 From the perspective of the kinematic chain, the error sources are as follows: the deformation of shell and light pipe support, and the rotation error of shafing of rotating mechanism.

**Infrared target position offset error.** Also due to the force deformation of parts and the rotation error of shafting, the actual exit center and the ideal center point of infrared target simulation system do not completely coincide. As shown in Figure 3, the actual exit center \( (\Delta x', \Delta y', \Delta z') \) has a slight offset from the ideal center point and \( (\Delta x', \Delta y', \Delta z') \) is called the infrared target position offset error. This error is caused by the
line-of-sight angle error between missile seeker and the target, which also affects the accuracy of seeker’s detection target.

**Infrared guidance test device accuracy analysis and structure optimization**

**Device design**

The infrared guidance test device is mainly used to test a series of performances such as starting current, starting time, operating current, gyro frequency, tracking ability, command coefficient, and off-axis function of the tested missile. The specific structure is shown in Figure 4. The workflow is shown in Figure 5.

The infrared guidance test device has the following performance requirements:

1. The mass of the turntable shall not exceed 75 kg.
2. Infrared target simulation mechanism.
   (a) The angle of rotation is (–40° to 40°).
   (b) The angular velocity of rotation is adjustable from ±(0 to 18°/s).
   (c) The angular velocity accuracy is 0.2°/s.
   (d) The target pointing error not more than 2′.
   (e) The accuracy of the target position shall not exceed 0.2 mm.

**Analysis of target pose simulation accuracy**

As can be seen from the above section, the error source of the device itself is mainly caused by deformation of parts and shafting rotation error of rotating mechanism, so its accuracy is analyzed.

**Shell accuracy analysis.** The shell is the main bearing part of the whole missile test device. Taking the shell as an example, the stress state of the shell is simulated by finite element method. The target pose simulation mechanism has a mass of 30 kg, so there is 300 N of gravity. Using SolidWorks software, the distance between the center of gravity of the infrared target simulation mechanism and the center of rotation is 238 mm, and the mass of collimator and light pipe support is 6.5 kg. Therefore, the overturning moment of the shell is $M_1 = mgl = 65 \times 238 \times 10^{-3} = 15.47$ Nm.

After the simulation, the stress distributions, as shown in Figures 6 and 7, were obtained.

By observing the displacement of shell as shown in Figure 6, it can be seen that the maximum deformation of shell is 0.1554 mm, which is located at the joint with rotating mechanism. Namely, the offset error of infrared target caused by gravity in Z-direction is
\[ \zeta_{Z1} = 0.1554 \text{ mm}. \] Figure 7 shows that the position of the maximum deformation of the shell is same as that of Figure 6, and the deformation amount in Z-direction is 0.0584 mm. The radius of the circular structure at the fixed rotating mechanism of the shell is 51 mm, so the infrared target pointing error is \( \delta_{Z1} = \arcsin \left( \frac{0.0584}{51} \right) \approx 3.94^\circ \), and the distance from the target to the center of rotation is 390 mm, so the positional offset error of the infrared target in Z-direction is \( \zeta_{Z2} = \sin(\delta_{Z1}) \times 390 = 0.4472 \text{ mm}. \)

The principle of accuracy analysis of light pipe support is consistent with the shell and is not described here. After simulation, the pointing error caused by gravity is \( \delta_{Z2} = 1.23^\circ \) and the offset error \( \zeta_{Z2} = 0.1395 \text{ mm}. \) The pointing error caused by the overturning moment is \( \delta_{Z3} = 1.21^\circ \) and the offset error \( \zeta_{Z4} = 0.1373 \text{ mm}. \)

Analysis of the accuracy of the rotating mechanism. The working principle of the rotating mechanism is as follows. The motor drives spindle to rotate and parallel light pipe rotates in the azimuth direction. Due to the influence of factors such as matching clearance and elastic deformation, the rotation axis of the rotating member in shafting system cannot be kept in a certain position in space during the rotation process, and there will be slight changes. The smaller the variation, the higher the accuracy of the shafting system. Therefore, we use the change in spindle rotation axis to show the rotation accuracy of the spindle.

The actual axis of rotation and the ideal axis of rotation are unlikely to coincide. According to the relative motion’s point of view\(^{21}\), it can be considered that whenever the spindle rotates around the actual axis of revolution, it also performs axial, radial, and dip movements around the ideal axis of rotation at the same time. Therefore, the rotation error of the main shaft can be divided into three error components: axial turbulence error \( \Delta s \), radial sway error \( \Delta c \), and angular motion error \( \Delta y \), as shown in Figure 8.

**Figure 7.** Shell displacement under 16 Nm overturning moment load.

**Figure 8.** Spindle rotation error.

**Figure 9.** Measurement of axial turbulence.

Axial turbulence error \( \Delta s \). The axial turbulence of the spindle in the rotating mechanism is related to the axial clearance of the bearing. The deep groove ball bearing with inner diameters \( \phi30 \) and \( \phi50 \text{ mm} \) is used for the device, and the axial clearance is 150 and 190 \( \mu \text{m} \), respectively. Since the bearing is pre-tightened during installation to prevent its axial movement, \( \Delta s \) can be obtained by actually measuring the rotating mechanism. The measurement process is shown in Figure 9.

The measurement process is as follows. First, the pointer of the dial indicator with the accuracy of 0.01 mm fixed on the isolated ground is pressed to the axial end of the rotating mechanism, and the needle is pressed down by 0.5–1 mm, leaving a certain margin. Rotate the main shaft for one revolution at an unused angular velocity, observe the dial indicator, and record the maximum value \( M_{\text{max}} \) and minimum value \( M_{\text{min}} \) appearing during the rotation, then repeat the process four times respectively. The test results are shown in Table 1.

It can be seen from Table 1 that there is no relationship between the size of the runout of the shaft end face and the speed, and the end face runout is 0.04 mm. Therefore, the axial turbulence error \( \Delta s = 0.04 \text{ mm}. \) Furthermore, the offset error of the infrared target in Z-direction is \( \zeta_{Z5} = 0.04 \text{ mm}. \)
Radial sway error $\Delta c$. As shown in Figure 10, at any axial position of the spindle rotation, the sum of pure radial movement of actual axis of rotation of spindle $\Delta c_0$ and radial offset of spindle axis $\Delta c_i$ caused by angle swing of spindle axis is radial sway error of the spindle at this position, $\Delta c_i = l_1\Delta \gamma$, so $\Delta c$ is calculated as follows

$$\Delta c = \Delta c_0 + l_1\Delta \gamma$$

where $l_1$ is the distance from the section of the spindle in this position to the end face of the spindle at the vertex of the swing angle and $\Delta \gamma$ is the angular motion error.

Equation (6) shows that the radial sway errors of the respective vertical axis sections at different axial positions of the main shaft are different. In the same axis profile, the radial sway errors $\Delta c_1$ and $\Delta c_2$ have the following relationship on any two vertical axis sections with a distance of $l_{1-2}$

$$\Delta c_2 = \Delta c_1 + l_{1-2}\Delta \gamma$$

From which

$$\Delta \gamma = \frac{\Delta c_2 - \Delta c_1}{l_{1-2}}$$

Table 1. End face jitter test data (mm).

| Frequency (Hz) | $M_{\text{min}}$ | $M_{\text{max}}$ | $M_{\text{min}}$ | $M_{\text{max}}$ | $M_{\text{min}}$ | $M_{\text{max}}$ | $M_{\text{min}}$ | $M_{\text{max}}$ | Result |
|---------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|--------|
| 1.5           | -0.03           | 0.01            | -0.03           | 0.01            | -0.02           | 0.02            | -0.04           | 0.04            |        |
| 7.5           | -0.03           | 0.01            | 0               | 0.04            | -0.02           | 0.02            | -0.02           | 0.02            |        |
| 12            | -0.02           | 0.02            | -0.01           | 0.03            | 0               | 0.04            | -0.03           | 0.01            |        |
| 15            | 0               | 0.04            | -0.04           | 0               | -0.03           | 0.01            | -0.02           | 0.02            |        |

The radial sway of spindle of rotating mechanism of the device is related to the radial clearance of the bearing. The radial clearance of the deep groove ball bearing selected by this device is 20 and 28 $\mu$m, respectively. Radial sway error caused by the limit case is shown in Figure 11.

From the similar triangle, we get

$$\frac{e_a + e_b}{L} = \frac{\Delta c + e_b}{L + a}$$

Simplifying equation (9) we get

$$\Delta c = e_a \left(1 + \frac{a}{L}\right) + e_b \frac{a}{L}$$

where $a$ is the spindle overhang (30 mm), $L$ is the bearing span (100 mm), $e_a$ is the radial clearance of the large bearing (28 $\mu$m), and $e_b$ is the radial clearance of the small bearing (20 $\mu$m).
Since $\Delta c = 0.0424$ mm can be calculated from equation (10), the offset error of the infrared target $\xi_X = \xi_Y = 0.0424$ mm in the $X$- and $Y$-direction.

**Angular motion error $\Delta \gamma$:** Angular motion error indicates the degree of deviation of the actual axis of rotation of spindle from a given direction, namely, the orientation accuracy of shafting. In Figure 11, the spindle angular motion error $\Delta \gamma$ is

$$
\tan(\Delta \gamma) = \frac{e_a}{L_1} = \frac{e_b}{L - L_1}
$$

(11)

where $L_1$ is the distance between the intersection point of the spindle’s ideal turning axis and actual turning axis and the outer end face of the large bearing (58 mm). The calculated results show that $\Delta \gamma = 1.65^\circ$ and $\delta_{Z4} = 1.65$ mm.

**Comprehensive analysis of errors.** The infrared target pointing error can be obtained by comprehensively calculating the error of each component

$$
\delta Z = \sqrt{\delta_1^2 + \delta_2^2 + \delta_3^2 + \delta_4^2}
$$

(12)

Infrared target position offset error is

$$
\xi Z = \sqrt{\xi_1^2 + \xi_2^2 + \xi_3^2 + \xi_4^2 + \xi_5^2}
$$

(13)

According to equations (12) and (13), $\delta Z = 4.61' > 2'$ and $\xi = 0.5174 > 0.2$ mm, which do not meet the technical requirements, so the structure of the shell and the light pipe support should be optimized.

**Sensitivity analysis and structural optimization**

Sensitivity analysis is an important method of parameter study, which is used to evaluate the influence degrees of input on output. The greater the sensitivity coefficient, the greater the influence on the parameters. In the actual work, relatively accurate analysis results can be obtained while complexity of analysis model and difficulty of data analysis are reduced by adjusting weights of parameters of different sensitivity coefficients.15 Mathematical model of the sensitivity analysis is shown in equation (14)

$$
y = f(x_1, x_2, \ldots, x_n) + \epsilon
$$

(14)

where $y$ is the output variable; $x_1$, $x_2$, and $x_n$ are the input variables; $f$ is the response function, and its specific form is determined by the analysis object system; and $\epsilon$ is the system error.

Selecting a proper experimental scheme and experimental type can reduce the frequency of sensitivity experiments to obtain mathematical model and result. In this article, orthogonal experimental design method is used as the design of the experimental method. The orthogonal experimental method can select a few test factors with comprehensive representativeness among many experimental factors. After the test, the multi-objective multivariate optimal design experiment results are obtained, and the factors and levels of significant influence are found to obtain the best combination.22

Taking the shell as an example, the purpose of the shell optimization is to make the shell meet the requirements of rigidity and strength, minimize shape deformation, and make weight as light as possible. Therefore, orthogonal parameters of the key parameters are designed to obtain the best combination.

The main method is to thicken the whole structure and increase the reinforcement of the column locally. The optimized front shell model is shown in Figure 12. In Figure 13, reinforcement thickness $A$, bottom thickness $B$, total side thickness $C$, and total upper thickness $D$ are selected as the experimental factors; $t$ is the number of factor levels; and $A_j$ is the $j$th level value of factor $A$. Statistical parameters are calculated as $K_{ij}$ as shown in equation (15)

$$
K_{ij} = \frac{1}{n} \sum_{k=1}^{n} S_k - \bar{S}
$$

(15)

where $S$ is the experimental result, $i = 1, 2, \ldots$, and $j = A, B, \ldots$

Range method is used for factor sensitivity analysis. Evaluation standard is the range value $R_j$, and the computing equation is formula (16)

$$
R_j = \max\{K_{1j}, K_{2j}, \ldots\} - \min\{K_{1j}, K_{2j}, \ldots\}
$$

(16)

Figure 12. Optimized front shell model.
The larger the range value $R_j$, the greater the influence of one factor–level changes on the output, namely, the greater the sensitivity coefficient. Other conditions unchanged, changes of four parameters and their levels are shown in Table 2.

Without orthogonal experiment method, a total of $3^4 = 81$ groups of experiments need to be carried out, while orthogonal experiment only needs nine groups of experiments, which can greatly reduce the workload. By applying gravity and torque to each corresponding part of shell, the finite element simulation software was used to calculate nine groups of experimental results, and $L_9(3^4)$ orthogonal experimental table was obtained, as shown in Table 3. The shell is made of aluminum alloy. It can be seen from Table 3 that the maximum stress is much smaller than the ultimate yield strength of the material. Therefore, the experiment index of maximum stress is not considered in the following result analysis.

Table 4 lists the orthogonal experimental results of the influences of shell design parameters on the maximum deformation of the shell, where $K_1$–$K_3$ are the sums of the orthogonal test result under corresponding levels 1–3, respectively. In the case of column $A$ and row $K_1$, the sum of the test results when levels of factor $A$ are 1 is expressed. Corresponding $k$ is the average level, $k = K/4$. The range value $R$ is the difference between the maximum value and the minimum value of the statistical parameters of the factor at different levels. The larger the $R$, the higher the corresponding factor sensitivity.

According to the orthogonal analysis results of Table 4, parameter design combination for minimizing maximum deformation amount of shell is $A_3B_3C_3D_3$. According to sensitivity analysis results, the order of

![Figure 13. Shell optimization design factors.](image)

**Table 2.** Table of four parameters and their variation.

| Reinforcement thickness, A (mm) | Bottom thickness, B (mm) | Total side thickness, C (mm) | Total upper thickness, D (mm) |
|--------------------------------|--------------------------|-----------------------------|-----------------------------|
| $t$                            |                          |                             |                             |
| 1                              | 6                        | 13                          | 8                           | 13                          |
| 2                              | 7                        | 14                          | 9                           | 14                          |
| 3                              | 8                        | 15                          | 10                          | 15                          |

**Table 3.** $L_9(3^4)$ orthogonal experiment of shell design parameters on maximum deformation, maximum stress, and overall mass of the shell.

| No. | A  | B  | C  | D  | Maximum deformation (mm) | Maximum stress (MPa) | Overall mass (kg) |
|-----|----|----|----|----|--------------------------|----------------------|------------------|
| 1   | 6  | 13 | 8  | 13 | 0.0756                   | 12.2735              | 12.5518          |
| 2   | 6  | 14 | 9  | 14 | 0.0646                   | 11.2136              | 13.5069          |
| 3   | 6  | 15 | 10 | 15 | 0.0596                   | 10.7635              | 14.2034          |
| 4   | 7  | 13 | 9  | 15 | 0.0626                   | 7.7366               | 13.4100          |
| 5   | 7  | 14 | 10 | 13 | 0.0572                   | 7.7959               | 13.6512          |
| 6   | 7  | 15 | 8  | 14 | 0.0632                   | 7.3127               | 14.3623          |
| 7   | 8  | 13 | 10 | 14 | 0.0640                   | 7.1168               | 13.7392          |
| 8   | 8  | 14 | 8  | 15 | 0.0601                   | 6.8442               | 14.0321          |
| 9   | 8  | 15 | 9  | 13 | 0.0562                   | 7.1828               | 14.8202          |
range value $R$ is $B > A > C > D$, which indicates that maximum influence on the deformation of the shell is bottom thickness $B$, and then reinforcement thickness $A$, total side thickness $C$, and total upper thickness $D$. Orthogonal Table 5 shows the parameter design combination to minimize the overall mass as $A_1B_1C_1D_1$; the sequence of their influence on overall mass of shell is consistent with maximum deformation of the shell.

Analysis of the above results revealed that the optimal level of meeting minimum deformation and minimum mass indicators is inconsistent. However, maximum deformation amount of the above combination to minimize the overall mass is consistent with requirements, and the final comprehensive analysis of No. 5 test deformation and mass indicators is inconsistent. However, maximum influence on the deformation of the shell is bottom thickness $B$, and then reinforcement thickness $A$, total side thickness $C$, and total upper thickness $D$. Orthogonal Table 5 shows the parameter design combination to minimize the overall mass as $A_1B_1C_1D_1$; the sequence of their influence on overall mass of shell is consistent with maximum deformation of the shell.

Analysis of the above results revealed that the optimal level of meeting minimum deformation and minimum mass indicators is inconsistent. However, maximum deformation amount of the above combination is in accordance with requirements, and the final comprehensive analysis of No. 5 test deformation and mass is the most appropriate, which is selected as the final optimization result. Light pipe support is also optimized by orthogonal test. Due to space limitations, it will not be described here, and the performance is improved after optimization.

According to the foregoing, after optimization, $\delta'_{Z1} = 1.1''$, $\delta'_{Z2} = 10''$, $\delta'_{Z3} = 26''$, $\xi'_{Z1} = 0.0336$ mm, $\xi'_{Z2} = 0.1193$ mm, $\xi'_{Z3} = 0.0189$ mm, and $\zeta'_{Z4} = 0.0483$ mm. Bringing into equations (12) and (13), $\delta'_{Z} = 1.71'$ and $\zeta' = 0.1525$ mm are obtained. From the above results, it can be seen that after optimizing the shell, the pointing error of infrared target is reduced from 4.61 mm to 1.71' and the position deviation error is reduced from 0.5174 to 0.1525 mm, both of which meet the requirements.

### Test experiment of infrared guidance test device

#### Error experiment of spindle angle motion of rotating mechanism

The prototype of infrared guidance test device is shown in Figure 14. Front support frame and rear support frame constitute the missile position simulation mechanism to simulate the movement of missile in pitching direction. Parallel light pipe and rotating mechanism constitute the infrared target simulation mechanism to simulate the movement of target in azimuth direction.

The movement error of spindle angle of rotating mechanism affects the position accuracy of target simulation. For the experiment, an electronic level is required with the accuracy of 2", as shown in Figure 15.

![Figure 15. Laboratory equipment.](image)

The synthesis error is

$$f_i = \sqrt{f_{1i}^2 + f_{2i}^2}$$ (18)

As shown in Table 5, the measurement results and data processing are shown in equation (17). From the above results, it can be seen that after optimizing the shell, the pointing error of infrared target is reduced from 4.61 mm to 1.71' and the position deviation error is reduced from 0.5174 to 0.1525 mm, both of which meet the requirements.

### Table 5. Orthogonal experimental results of the shell design parameters to overall shell mass.

| Optimization combination | Overall mass (kg) |
|--------------------------|-------------------|
| $A_1B_1C_1D_1$          | 40.2621 39.7010 40.9462 41.0232 |
| $A_2B_1C_1D_1$          | 41.4235 41.1902 41.7371 41.6084 |
| $A_3B_1C_1D_1$          | 42.5915 43.3859 41.5938 41.6455 |
| $A_1B_2C_1D_1$          | 13.4207 40.2621 39.7010 40.9462 |
| $A_2B_2C_1D_1$          | 13.8078 41.1902 41.7371 41.6084 |
| $A_3B_2C_1D_1$          | 14.1972 42.5915 43.3859 41.5938 |
| $A_1B_1C_2D_1$          | 0.7765 0.1223 0.2637 0.2074 |
| $A_2B_1C_2D_1$          | 0.7765 0.1223 0.2637 0.2074 |
| $A_3B_1C_2D_1$          | 0.7765 0.1223 0.2637 0.2074 |

![Figure 14. Infrared guidance test equipment.](image)
Table 6 shows that the average value of the spindle angular motion error of rotating shaft is 1.79° and the mean square value error is 1.84° which is not much different from the theoretical value of 1.65°. The experimental value is basically consistent with the theoretical value. The experimental results verify that the analysis method used in this article is effective for calculating angular motion errors. In the future, it is necessary to reduce the error when designing the structure, which can better improve the accuracy level.

**PID debugging**

After the infrared target pointing error and the position error of the test device meet the requirements, the motor speed is debugged. Proportional-plus-Integral-plus-derivative control (PID) parameter debugging can make the rotation speed of the rotating mechanism meet the high-precision requirements, thereby improving the dynamic characteristics of the system. By using the debugging software of the driver, you can intuitively observe the debugging effect and improve debugging efficiency.

Through the debugging software conversion formula, the rotation speed corresponding to 250 r/min is 1.5°/s and the accuracy corresponding to 33 r/min is 0.2°/s. When the PI parameter is too small, there will be a long adjustment time and a large fluctuation of the load. In this case, PI should be increased at the same time and D should remain 0, as shown in Figure 16(a). When the PI parameter is too large, the motor will vibrate and the speed will be unstable. At this time, PI should be reduced at the same time, as shown in Figure 16(b). After adjusting PID parameters, the

![Figure 16. Rotation speed images under different PID parameters: (a) PI parameter is too small, (b) PI parameter is too large, and (c) PID with good rigidity.](image-url)
image with good rigidity will be obtained, as shown in Figure 16(c). When the motor runs at a speed of 1.5°/s, it meets the requirements of accuracy of 0.2°/s.

**Conclusion**

In this article, the structure design and accuracy analysis of the infrared guidance test device were carried out. The accuracy of the rotating mechanism was analyzed according to the viewpoint of relative motion, and the shell was optimized based on the finite element simulation software and orthogonal experiment method.

The rotation error of the main shaft of the rotating mechanism includes the axial turbulence error, the radial sway error, and the angular motion error. The theoretical calculation value of angular motion error is 1.65°, which is not much different from the test theoretical value of 1.79°. The agreement between the numerical results and the experimental data proves that the calculation method is feasible.

Quantitative analysis of the main error sources that cause infrared target simulation errors is as follows: from the shell force deformation error and the rotating mechanism rotation error, we can get the infrared target pointing error $\delta_x = 4.61'$ and the infrared target position offset error $\xi = 0.5174$ mm. Two error values did not meet the accuracy requirements of the device.

Parametric sensitivity analysis was performed from the maximum deformation and the overall mass of optimally selected shell. According to sensitivity analysis results, the maximum influence on deformation of shell and overall quality is bottom thickness $B$ and then reinforcement thickness $A$, total side thickness $C$, and total upper thickness $D$. The experimental results show that after the structure optimization, the infrared target pointing error $\delta'_x = 1.71'$, the infrared target position offset error $\xi' = 0.1525$ mm, and the accuracy meets the requirements. Finally, the comparison and analysis with test experiments verify the correctness of the method.

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