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Design and Research of Off-Axis Three-Mirror Space Remote Sensor Structure

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Abstract: On the basis of characteristics of optical system of three-mirror off-axis, with the method of topology optimization, the mirrors' support structure and the frame structure which is a truss structure of the optical system were designed and investigated, the lightweight of the support structure and the truss structure are important, the structure optimization design of the system was completed, which quality is very light, by means of the finite element analysis techniques, we know that the shape error variation RMS and PV of optical mirror which are important indexes of image quality. The modal analysis and dynamic simulation calculation were carried out and the response character of the structure under dynamic environment was solved. Finally, the correctness of the finite element analysis results and the rationality of the design are validated by environmental testing. the analysis and test results indicate that the PV and RMS meet the design indexunder the comprehensive influence of gravity and thermal load which is in the control range, the overall structure have a high enough dynamic stiffness and reasonable distribution of modal, and the dynamic response of Space Remote Sensor was within the allowable range, which meet the use requirement.

Keywords: CAE, dynamic simulation, mirror support, structure design, topology optimization, truss structure.

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1. INTRODUCTION

Off-axis three-mirror system has the characteristics of no obscuration, good image quality and compact structure can realize high resolution and high energy utilization rate. In recent years this system has been applied in space camera, imaging spectrometer, and other areas of the space of imaging observation [1-3]. Off-axis three-mirror optical system is characterized by long focal length, wide field and structural asymmetry, which makes the structure design and system adjustment very difficult. One of the key technologies to develop this kind of camera is about the high specific stiffness of the supporting structure, and the design of moderately flexible structure at the key position in the mirror support structure. Topology optimization method with the local first and the whole last is adopted to complete the design of the off-axis three-mirror optical system structure with high resolution. The main supporting structure uses the truss structure which are composed of truss rod and SiC/Al composite materials base plate, which has small quality, high specific stiffness, rational layout, high degree of lightweight; According to the sizes of the primary, secondary, tertiary mirror, the mirror support structure with moderate flexible link is designed. Using finite element analysis method, modal analysis is conducted on the whole structure. The whole machine base frequency is 305 Hz, above the system requirement of 120 Hz, and has high dynamic stiffness and the rational modal distribution. Through the calculation of dynamic response, the acceleration response magnification of the remote sensor in dynamic environment is less than 5; the camera imaging surface shape error variation in the quality of RMS and PV value, measured with the mirror component under the joint action of gravity and thermal load, can satisfy the requirements of the optical system design. The rationality and feasibility of design was verified. The final test results and simulation results are basically identical, which validates the correctness of the simulation analysis and the rationality of the structure.

2. OFF-AXIS OPTICAL SYSTEM

Off-axis three-mirror optical system in this paper consists of three pieces of aspherical mirrors and a flat mirror: the primary mirror, secondary mirror, tertiary mirror and focusing mirror. Optical system diagram is as shown in Fig. (**1**).

2.1. Mirror parameters of the mirrors

The dimensional parameters of the four reflectors of off-axis three-mirror optical system are shown in Table **1**.

2.2. Requirements of the Optical System Design

To meet the requirements of imaging, the off-axis three-mirror system has strict requirements for the three main

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mirrors' surface shape index. The PV value should be superior to λ/ 10; root mean square RMS value should be superior to λ/ 50 (λ = 632.8 nm); to ensure that the remote sensor can withstand harsh launch environment, the fundamental frequency of the remote sensor should be higher than 120 Hz and the magnification of the acceleration response in dynamic environment should be less than 5.

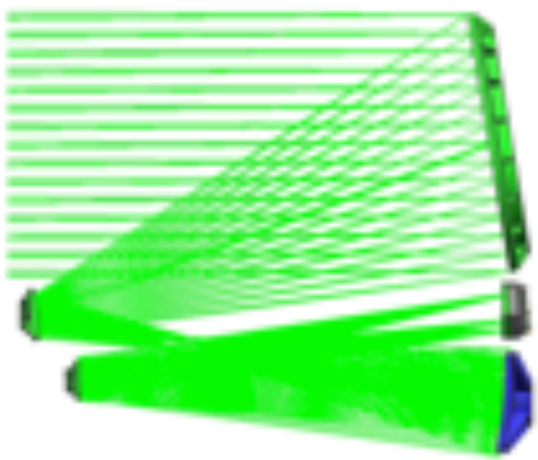

Fig. (1). Optical system of off-axis three-mirror.

Table 1. Mirrors size of optical system.

Serial Number	Mirror Components	Radius/mm	Aperture/mm
1	Primary mirror	1810	Φ392
2	Secondary mirror	521.5	92x74
3	Tertiary mirror	675	238x149
4	Focusing mirror	Flat mirror	96x58

3. THE SUPPORT STRUCTURE DESIGN OF THE OPTICAL SYSTEM

3.1. The Selection of Materials

SiC is selected for the mirrors. Used widely, SIC has characteristics of bigger rigidity, size stability, high rate of lightweight and high precision mirrors can be obtained from it; Taper sleeve is the bonding insert of the primary mirror. Its heat coefficient is adjustable so as to avoid larger thermal stress between the lens body and it when heat load exists; the connection structure of the flexible support structure and the back uses the stable titanium alloy material to eliminate the inconsistent deformation between the lens body and the triangle as temperature changes; Mirror back and front and back of the frame adopts high body of SiC/AL composite material, which has high elastic modulus, high thermal conductivity, small density, slightly lower linear expansion coefficient than that of titanium alloy. It is a new type of space application material.

3.2. The Design of Structure

The following should be considered in the design of the structure of the space remote sensor:

1. The supporting structure requires high support stiffness for resistance to mirror surface deformation caused by gravity and impact overload in the process of the emission;

2. The structure needs high stability, the size changes should be within the range of design index in the process of long use;

3. It should be able to eliminate the deformation of mirror surface due to temperature changes within a certain range.

4. The thermal deformation of the framework should be small, to guarantee that the reflector spacing under the temperature load meets the optical system imaging requirements.

In the field of mechanical optimization design, the topological optimization method [4-5] has developed rapidly and gradually mature, and more and more get the favor of mechanical engineers. On the premise of certain material usage, seeking the material optimum distribution form in which the structure has maximum stiffness in a certain measure, with the objective function of maximizing the stiffness of the structure and the volume as constraint condition, the mathematical model is as Eq.1:

$$\begin{cases} \min: f(x) = V = fV_0 = \sum_{e=1}^{N} x_e v_e \\ \text{s.t.} \quad C(x) = \boldsymbol{U}^{\mathrm{T}} \boldsymbol{K} \boldsymbol{U} = \sum_{e=1}^{N} (x_e)^p u_e^{\mathrm{T}} k_0 u_e \le C^* \\ \quad \boldsymbol{KU} = \boldsymbol{F} \\ \quad 0 \le X_{\min} \le x_e \le X_{\max} \end{cases} \tag{1}$$

The means of topology optimization is adopted to complete the design of the structure of main support of the space remote sensor.

3.2.1. TheStructure Designof the Three Mirror Support Components

The backside support, peripheral support, compound support, center support are common forms of reflector support. Considering the sizes of the three main reflectors and the overall layout in the optical system, three points back support is chosen for the primary reflector due to its big size, while the smaller secondary and tertiary reflectors, single point back support. Between the mirrors and the backplane, flexible structure are used to eliminate thermal stress and assembly stress, to ensure the accuracy of the reflector surface shape [6-8].

First of all, with the method of topology optimization and the minimum mirror surface shape error value RMS as objective function, quality as the constraint, design high specific stiffness lens bodies of the primary, secondary and tertiary mirrors; Secondly, with the objective function of maximizing the stiffness, quality as the constraint, optimize the design of the backplanes of three reflectors; Finally, with the reflection mirror form value RMS minimum, under the coupling effect of temperature load and gravity load, as objective function, optimize the flexible groove width of the flexible links between the reflectors and the backplanes. On the basis of the optimized results, considering parts processing, assembly process, design detail structures such as the reflector components' installation details, to finally obtain the reflector components that meet the design

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requirements. Structures of the primary, secondary and tertiary mirrors are shown in Figs. (**2-4**).

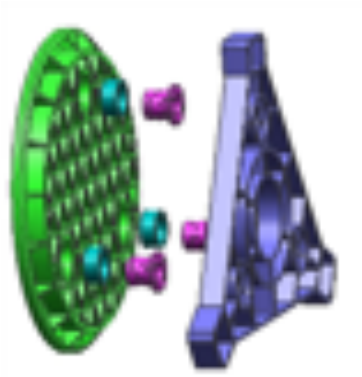

Fig. (2). The primary mirror component.

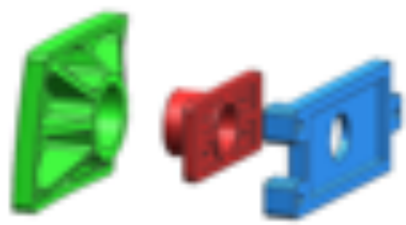

Fig. (3). The secondary mirror component

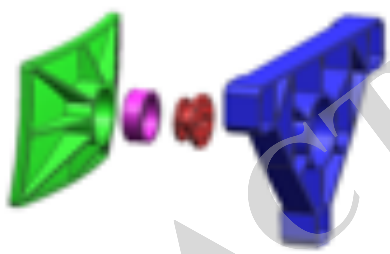

Fig. (4). The third mirror component.

3.2.2. Framework Design

Space remote sensor main support structure often adopts integral structure form, whose molding process is the use of metal casting or composite materials forming. This form is widely used in small and medium-sized space remote sensing cameras, with mature technology, manufacturability as its main characteristics; While compared with the integral structure, truss structure has better stiffness, smaller quality of the same volume, more free and concise layout. According to structure form and weight limit of the optical system, truss structure is used in the main support structure [9-11].

Remote sensor fixes the components together through the main support structure, having the function of main bearing. Main support structure has to ensure the imaging optical system, and have a high enough dynamic stiffness. Mirror components, focusing units and focal plane component of the space remote sensor obviously have a concentrated distribution at two positions: the front and the back, so the main support can be divided into two parts, namely: the front and the back frameworks, connected together using high specific stiffness of truss rod, forming the truss structure of the frame and truss rod. Similarly, topology optimization method, step by step, with the local first and the overall later, is adopted in the design of truss components. First of all, with the maximum stiffness as the optimized goal, quality as the constraint, complete the optimization design of the frames at the front and back; Secondly, install the mirror components, focal planes and focusing components on the framework, and then, with the maximum stiffness of the whole assembly as the optimized goal, quality as the constraint, inner and outer diameters and layout angle of truss are optimized and finally determine the truss structure, as is shown in Fig. (5).

To reduce the overall quality and guarantee the launch costs, SiC/Al composite materials of high stiffness is used for the main support structure at the front and back of the framework, carbon fiber composite materials for the truss rod.

Fig. (5). Framework components.

Install all the components, such the components of the primary, secondary and tertiary mirrors, on the frame components and get the whole model of the camera, as is shown in Fig. (6). The structure is simple in form and of high stiffness.

Fig. (6). The overall structure model.

4. THE ENGINEERING ANALYSIS

Before the machining and production of parts, adopting the means of the finite element analysis, verify the feasibility and the rationality of the overall structural design. The analysis of the project mainly includes the static stiffness and dynamic stiffness analysis. The finite element model is shown in Fig. (7).

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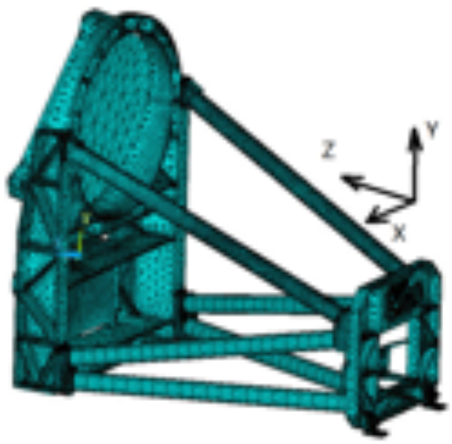

Fig. (7). The finite element model.

In view of purpose of the analysis, the finite element model is properly simplified compared with the geometric model. In the finite element model, only the components of the framework, the primary, secondary and tertiary mirrors are described in detail, using quality point instead of the focusing lens component and focal plane assembly [12].

4.1. Static Stiffness Analysis

Static stiffness analysis is to analyze the deformation of the entire model under the coupling effect of gravity load and temperature load. Based on the temperature range that can be achieved according to the space remote sensor thermal control designers for camera thermal control, temperature load is 20 ±4 ℃. Considering that the Y axis of the camera coordinate system is opposite to the gravity direction, therefore 2g gravity load and 20 ± 4 ℃ temperature load are applied in the negative direction along the Y axis, to constrain the four mounting surfaces linking the camera and satellite. Fig. (8) is the displacement cloud picture of gravity in Y direction and temperature load of 24 ℃. (reference temperature is 20 ℃). Calculated under the overall structure, the indicators of the mirror surface deformation of the primary, secondary mirror and tertiary mirrors of are shown in Table 2.

Fig. (8). The displacement cloud picture of gravity in Y direction and temperature load of 24℃.

Table 2. Mirrors surface shape accuracy under coupling load.

Mirror Components	PV/λ	RMS/λ
Primary mirror	0.072	0.011
Secondary mirror	0.060	0.008
Tertiary mirror	0.070	0.009

4.2. Modal Analysis

The first step in the dynamic analysis is usually for structural modal analysis, the calculation of the natural frequency and vibration mode of the structure. The result of the modal analysis reflects the dynamic characteristics of structure, which can predict the vibration response of the structure under the effect of various dynamic loads, so it is an important parameter of the structure vibration control. Modal analysis is an important part of the simulation analysis in the development of a camera, used to verify whether the camera meets the design requirements and whether can eventually work properly on orbit, so it is of great significance. Through modal analysis, fundamental frequency of the structure can be learnt before the processing of the structure. Through the optimization design, ensure that the camera can avoid forced vibration load in the launch process and transport process, and can avoid damage in structure caused by resonance phenomenon. Table 3 shows the natural frequency of the overall machine in the first three orders, and Fig. (9) shows the natural vibration mode for the overall machine in the first order.

Table 3. Thenatural frequency of overall structure.

Orders	Natural Frequency	Mode Shape
1	305Hz	Vibration Along Z axis
2	380Hz	Swing Around Y axis
3	450 Hz	Swing Around Z axis

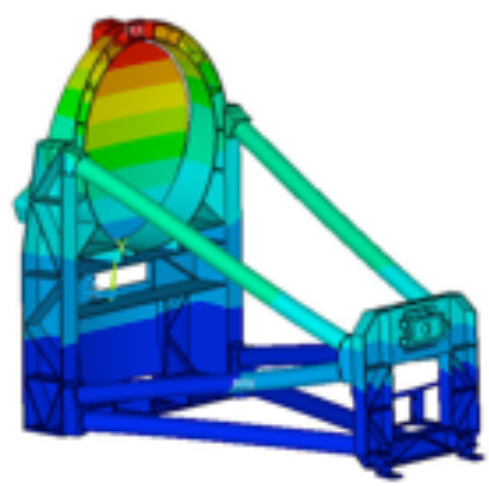

Fig. (9). The first order natural vibration mode of overall structure.

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4.3. Sine Vibration Analysis and Random Vibration Analysis

The dynamics environment the space remote sensor experiences in the launch process is mainly sine vibration and random vibration. Sine vibration results from the thrust fluctuation change caused by the instable combustion of the rocket engine and random vibration results from the acoustic vibration caused by the large amount of noise made during the launch process of the satellite vehicle. The dynamics analysis of space optical remote sensor is to calculate the mechanical response of the structure in the low frequency and random vibration environment. In the dynamics analysis of the characteristics of space optical remote sensor, incentive load is determined by dynamic environment test conditions. The specific load forms and sizes are shown in Tables 4 and 5, X, Y, Z for loading direction. In space remote sensor's dynamic environment test, it is fixed together with the mechanical test vibration table through the screws of the framework components at the front and back, and the incentive load is an acceleration load inputted through mechanical vibration table, belonging to the typical forced basic acceleration vibration. thelarge mass method is adopted in this paper to turn the forced basic acceleration vibration into incentive load to apply to the finite element model, to calculate the forced base acceleration vibration response. Connect the massive point and the space remote sensorat the position of the screw linking module which belongs to thethe front and the back frameworksby RBE2, and constrain the node of massivepoint fixed degree of freedom for all.

Table 4. Condition of sine vibration test.

Frequency Range/Hz	Amplitude
4-10	12.495mm
10-17	3.06g
17-75	7.90g
75-100	4.76g

Table 5. Condition of random vibration test.

Frequency Range/Hz	Power Spectral Density
10-250	6dB/oct
250-1000	$0.035g^2/Hz$
1000-2000	-9dB/oct
The total root mean square acceleration	6.47grms

Dynamic stiffness and strength of space optical remote sensor are the most important indicators to ensure the structural reliability, and dynamic simulation analysis can predict the acceleration and intensity responses of the structure in dynamic environment and test whether the dynamic stiffness and strength meet the requirements. In the calculation process of mechanics simulation, due to the uncertainty about the material and structural damping characteristics, accurate modal damping parameters cannot be provided, so set at 0.05 according to the experience. Select one point at the back of the triangle from the main mirror components as corresponding point, the analysis results of the response are shown in Tables 6 and 7.

Table 6. Calculation result of acceleration response under sine vibration.

Load Direction	Maximum Responses	Magnification
X	5.05g	0.64
Y	4.10g	0. 52
Z	7.20g	0.91

Table 7. Calculation result of acceleration response under random vibration.

Load Direction	Maximum Responses	Magnification
X	18.5g	2.86
Y	10.0g	1.55
Z	20.3g	3.13

Seen from the data in Table 7, the acceleration response magnification of the space optical remote sensor under sine and random vibration is less than 5; the mechanical responses in dynamic environment are within the allowable range and the dynamic stiffness and impact strength of structure meet the requirements.

5. TEST

Environmental testing is an important part of the process of structural design, which can validate the rationality of structure design and the accuracy of the simulation analysis. When the processing and assembling of the remote sensor structure is complete, the static test and dynamic test are carried out.

5.1. Statics Experiment

Statics experiment is mainly the surface shape index detection of the primary, secondary and tertiary mirrors under the coupling load of gravity load and temperature, to ensure the surface shape indicators of the three mirrors meet the design requirements under the coupling load, to guarantee the imaging stability of the remote sensor in space environment. After the mirror finishing of each of the primary, secondary and tertiary mirrors, at room temperature 20 ℃ and 0 °, the surface shape value RMS respectively is 0.015λ, 0.014λ and 0.014λ. The surface shape measuring interference figure of the primary, secondary and tertiary mirrors' components, under the state of rotating 180 degrees around the optical axis and 4 ℃ rise in temperature (room temperature 24 ℃), is shown in Figs. (10-12), the surface shape RMS value of the primary, secondary and tertiary mirror components being 0.018λ, 0.019λ and 0.019λ respectively. Analyzing the test data, the surface shape RMS value of the primary, secondary and tertiary mirrors, in the presence of residual, gravity and temperature coupling load

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cases, can all be better than 0.02λ.Therefore, the surface shape value of the primary, secondary and tertiary mirrors will surely be better than 0.02λafter the in-orbit gravitational release and meet the requirements of the optical system imaging. According to the test data got at room temperature is 20 ℃ and 0 ° loading condition and at room temperature 24 ℃ and 180 ° loading condition of the state testing data, it can be calculated that the primary, secondary, tertiary mirrors' surface shape changes, under the coupling load of 2 g gravity and 4 ℃ temperature rise, respectively, are 0.013λ, 0.01λand 0.01λ, which are basically identical with the finite element simulation calculation results.

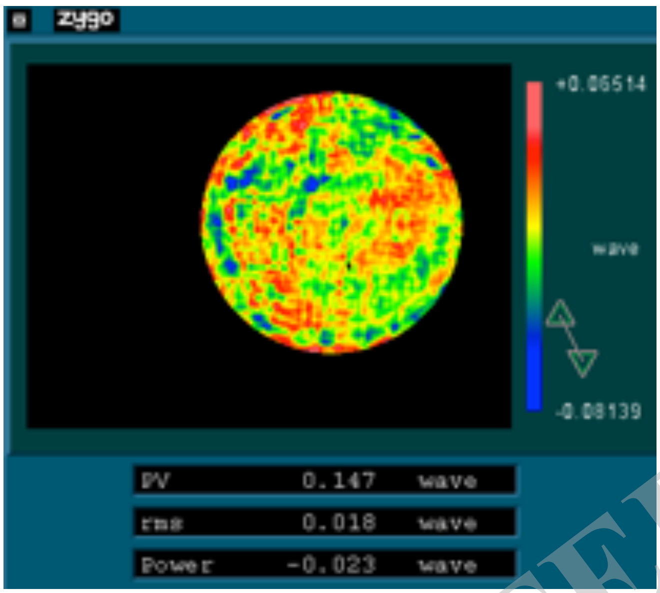

Fig. (10). The testing interferogram of the primary mirror component in the 180° condition and 24℃.

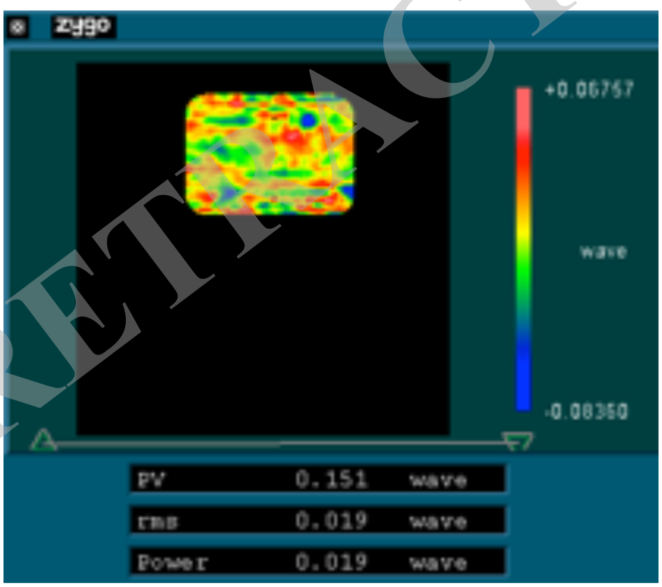

Fig. (11). The testing interferogram of the secondary mirror component in the 180° condition and 24℃.

5.2. Dynamic Test

Dynamic experiment is completed on 8 tons of mechanical vibration stage, and includes sine vibration test and random vibration test, under the same conditions as simulation analysis boundary test conditions. Through environmental test, the fundamental frequency of the structure is 293.5 Hz, consistent with the data of simulation analysis; Meanwhile, the characteristics of the response of the structure under dynamic environment are consistent with the data from the finite element analysis. The comparison between the dynamic response calculation and test results is shown in Table 8. Dynamic test verifies the structural dynamic characteristics and the validity of the mechanical characteristics simulation analysis as well.

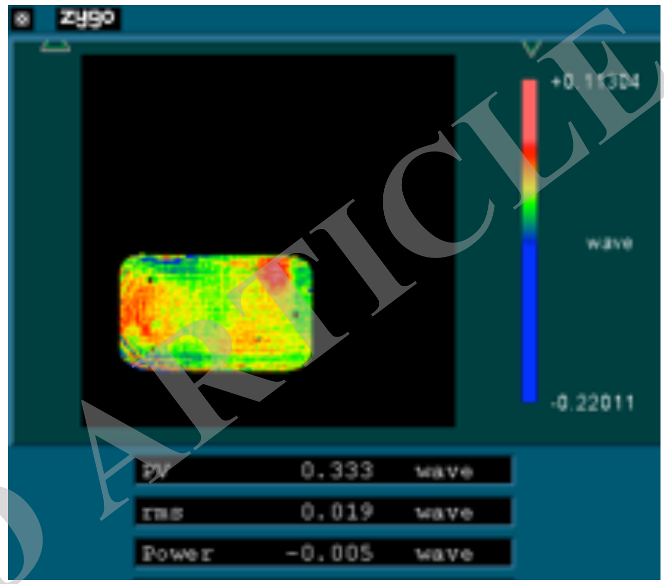

Fig. (12). The testing interferogram of the third mirror component in the 180° condition and 24℃.

To illustrate the consistency of calculation and test results, select the sensor test curve corresponding to the point in the calculation to compare with the calculation results (see Figs. 13-16). Only the simulation curve in Y direction and test response curve under all working conditions are given in this article.

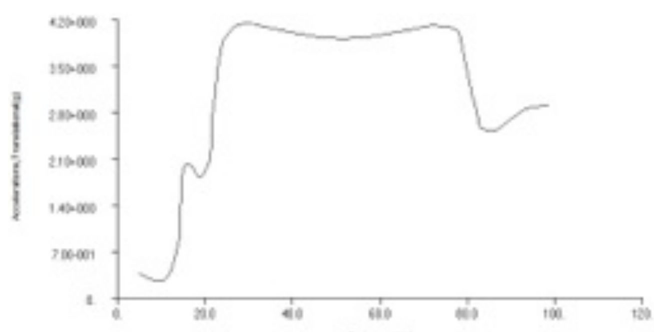

Fig. (13). Acceleration response curve of sine vibration calculation in Y direction.

CONCLUSION

In this paper, according to the layout of the off-axis three-mirror optical system, structure optimization design was carried out using topology optimization method, and static stiffness analysis is carried out on the system. The

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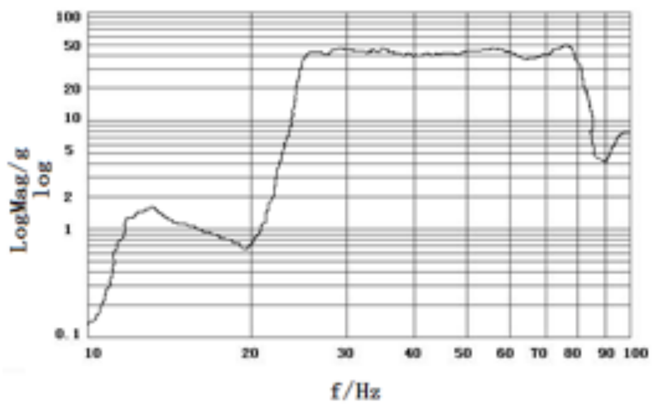

Fig. (14). Acceleration response curve of sine vibration test in Y direction.

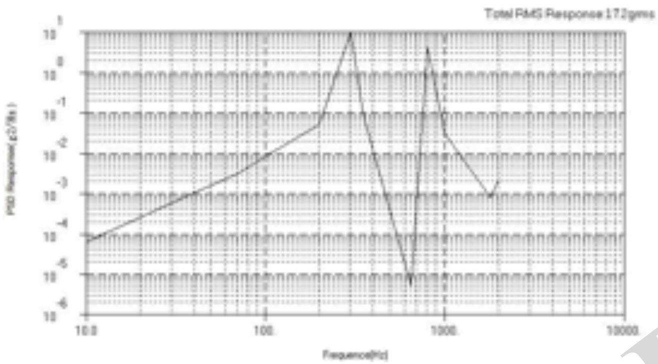

Fig. (15). Acceleration PSD response curve of random vibration calculation in Y direction.

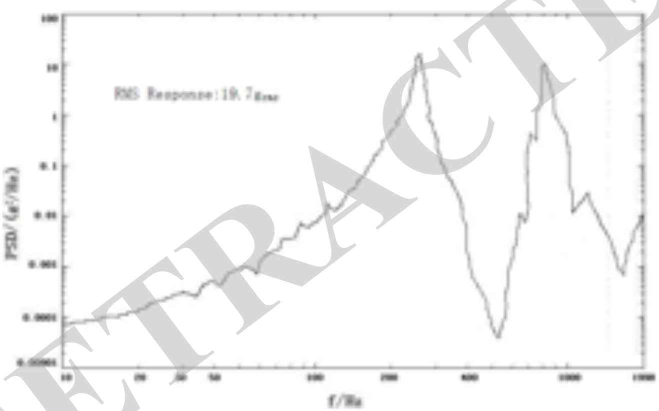

Fig. (16). Acceleration PSD response curve of random vibration test in Y direction.

results of the analysis show that, under the joint effect of the gravity and thermal control temperature range of heat load, the mirror surface shape error variation RMS and PV values which measure the imaging quality meet the design requirements of the optical system design. The modal analysis on the overall structure of the model shows the first order natural frequency of the whole machine is 305 Hz, much higher than the required 120 Hz, thus ensuring that the remote sensor can withstand severe vibration conditions in the transport and launch process, and verifying the rationality of structure design. Besides, the acceleration response magnification of the entire modal under the sine and random vibration is less than 5, which meets the requirement. Finally, after the processing of all the remote sensor components is completed, the corresponding environmental testing of statics and dynamics are carried out and the experiment results verify the rationality of the design and the reliability of analysis.

Table 8. Comparison between results of calculation and test.

Sine Vibration	Peak Frequency (Hz)	Maximum Acceleration (g)
simulation	31.0	4.10
test	29.2	4.70
Random Vibration	**Peak Frequency (Hz)**	**Maximum Acceleration (g)**
simulation	305.0	10.0
test	293.5	12.3

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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Declared none.

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