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Design and Verification for Front Mirror-body Structure of On-axis Three Mirror Anastigmatic Space Camera

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Abstract—**The primary and secondary mirrors of on-axis three mirror anastigmatic (TMA) space camera are connected and supported by its front mirror-body structure, which affects both imaging performance and stability of the camera. In this paper, the carbon fiber reinforced plastics (CFRP) thin-walled cylinder and titanium alloy connecting rod have been used for the front mirror-body opto-mechanical structure of the long-focus on-axis and TMA space camera optical system. The front mirror-body component structure has then been optimized by finite element analysis (FEA) computing. Each performance of the front mirror-body structure has been tested by mechanics and vacuum experiments in order to verify the validity of such structure engineering design.**

Key words-On-axis Three Mirror Anastigmatic (TMA) Space Camera; Front Mirror-Body Structure; Structure Stability; Optical Measurement

I. INTRODUCTION

Space-borne camera of remote sensing has important scientific and military significance in the field of the ground and deep space exploration. As the resolution requirement of camera becomes higher and higher, on-axis TMA system of long focal length and large diameter is widely used. On-axis three mirror anastigmatic (TMA) optical system is a secondary imaging forming system, which image is greatly affected by the change of relative position of secondary mirror and primary mirror. For high-resolution space camera, the distance of secondary mirror and the primary mirror is large, so the rigid of connecting structure of secondary mirror is less, and the secondary mirror is a very sensitive optical component. Once the relative position of the secondary mirror and primary mirror changes, it will decline the image quality. Therefore, a reasonable design of the support structure between the primary and secondary mirror, which can meet the requirements of the optical design of the camera and adapting to the harsh mechanical environment of space is worthy of further study.

Currently, for On-axis three mirror anastigmatic (TMA) optical system, its support structure between the primary and secondary mirrors mainly has two forms like cylinder and truss rod. In recent years, cylindrical structure, because of its easy processing, easy assemblage, good structural symmetry , stable performance in the space, etc., is widely used in the front mirror-body of high-resolution camera like the United States IKONOS, WorldView-1, WorldView-2 camera, GeoEye-1 commercial satellite cameras and other high-resolution cameras; French Pleiades satellite camera, Korea satellite camera-Kompsat2, and China-Brazil resources satellites' HR camera adopt the truss rod structure.

During the research procedure of high-performance space camera, firstly design the structure of the front mirror-body of the camera from the engineering point of view. Secondly analyze and optimize the structure using the finite element analysis method. Finally process the environmental experiment and verify the correctness of the results of the engineering design. This paper introduces all the listed content including process and method.

II. DESIGN AND OPTIMIZATION OF FRONT MIRROR-BODY STRUCTURE

A. *Brief introduction of small high-performance optical camera*

For the requirement of high-resolution remote sensing data for the growing domestic demand, the small high-performance optical camera is designed and manufactured, which can be loaded in small satellites. It can achieve spatial resolution of 2.5m(Panchromatic spectrum) and 10m(Multispectral spectrum), and its swath greater than 30 km. Camera's focal length is 2.6m and the focal plane detector adopts 10 μ m / 40 μ m multicolor TDICCD. In order to meet the requirements of light weight, the structure of the primary and secondary mirrors uses the composite material.

B. *Selection of support structure between the primary and secondary mirrors*

Lens of high-performance optical camera adopts the form of on-axis three mirror anastigmatic (TMA) optical system. The optical system requirements for the secondary mirror relative to primary mirror include: its distance variation is less than 0.002 mm, its tolerance for the eccentric or inclined is 5 ", and its translation tolerance is 0.01mm, which are critical to ensure the quality of camera imaging. The requirements indicate the stability requirement for the support structure of the primary and secondary mirrors. At the same time, it requires the structure to meet the weight, structural rigidity and the optical system's assembling.

For On-axis three mirror optical systems, the commonly used support structure between primary and secondary mirrors has two types--cylindrical and rod structure. The typical for font mirror-body structure component is shown in Fig. 1.

For three-rod type, its structure component is simple and the whole front mirror-body structure component is in the open state, which is suitable for optical system's assembling and testing. But it needs strict consistency of the three rods, which includes the same coefficient of thermal expansion and the same controlled temperature environment. In addition, it needs a special cylindrical tube setting outside the front mirror-body to control temperature and suppress stray light, which causes the structure complex and increase the weight.

Comprehensively considering the camera's structure design, small high-performance optical camera doesn't adopt the rod-type support structure, but choose the cylinder-type as the main support structure between the primary and second mirrors, which can maximize reduce the weight. And it chooses the connecting rod to connect the secondary mirror and front mirror-body cylindrical tube. The cylinder type has advantage like its good rigidity, and it is also facilitate to precisely control temperature and suppress stray light for front mirror-body. Now the international similar cameras mostly adopt the cylinder-type structure as the support structure between the primary and secondary mirrors.

C. Selection of structural materials

The front mirror-body cylindrical tube needs high rigidity and very low thermal expansion coefficient. The materials suitable for cylindrical tube between the primary and secondary mirrors are titanium alloy, Invar, and carbon fiber composite materials, etc. Titanium alloy has the advantages of low density, high intensity, moderate expansion coefficient and stable processing techniques, which is widely used in the space camera. Invar has the advantages of large elastic modulus and low coefficient of linear expansion. From the point of adapting to on-orbit temperature environment's change, invar is an ideal material as the support structure material. But its density is large and causes heavy weight. Carbon fiber composite materials have the advantages of high rigidity, small linear expansion coefficient, small heat distortion and small density, and it can be designed. Its overall performance is the best among the available space mechanical materials, and it is a good space camera support structure of the material. Comprehensively considering the features of each kind of mechanical material and its sensitivity of environmental temperature, the high-intensity titanium alloy is chosen as the material of connecting rods of second mirrors.

(a)cylinder type (b) rod type

Figure 1 Structure of classic front mirror-body

The alternative structure materials of front mirror-body cylindrical tube is cyanate ester base for carbon fiber composite materials or invar material. To decide the preferred material, the two kinds of alternative materials are compared and analyzed, especially the first-order frequency and the rigid body displacement. The first option includes 12 pieces of longitudinal bar and 4 pieces of ring rib (thin-walled structures in reinforced grille), and chooses the reinforced cyanate ester base for carbon fiber materials. In order to ensure sufficient rigidity, the thickness of tube wall is 2mm. The second option chooses Invar material and adopts the thin-wall design of 0.8mm wall thickness. It adopts the structure of no-longitudinal reinforcement ribs or ring (the cavity structure of inside and outside skin), which can utmost reduce the weight of the tube.

TABLE I provides the compared result of two kinds of front mirror-body, which includes the first-order frequency and the maximum rigid body displacement.

Through the comparative analysis result, the carbon fiber of front mirror-body structure has the better dynamics and static performance and light weight because of its reinforcement within the structure (12 pieces of longitudinal reinforcement bar and 4 pieces of ring). So the carbon fiber composite material is chosen as the material of font mirror-body cylindrical tube.

D. Selection of the connecting rods of secondary mirror

The connecting rods of secondary mirror connect the secondary mirror and the front mirror-body cylindrical tube, which support the secondary mirror. Because the secondary mirror is cantilever, it requires the connecting rods has the high rigidity.

TABLE I. COMPARISON OF TWO CONNECTING CYLINDERS OF DIFFERENT MATERIAL

	Carbon fiber reinforced plastics (CFRP)	**Thin-walled invar**
Mass	2.6kg	4.7kg
First-order frequency （Free modality）	293Hz	233Hz
Maximum rigid body displacement	3.7μm	4.7μm

And because the connecting rods are in the optical light path, they will increase the block of optical system and reduce the optical system's performance, which needs to make the projective area of connecting rods along the optical axis smallest. There are two kinds of commonly used the connecting rods of secondary mirror. One is three-rod radial form, and the other is four-rod radial form. In order to improve the rigidity along the optical axis, the connecting rods are set a certain angle with the optical axis.

TABLE II shows the comparison and analysis results of two kinds of rod-type connecting rods, which include the first-order natural frequency, the rigid body displacement and torsion angles because of gravity, the axial rigidity and central block.

From TABLE II, compared to four-rod radial structure, three-rod radial structure's first-order frequency is 10% lower, and second-mirror's rigid body displacement along the direction of gravity is 2.4% larger. Second-mirror's torsion angle is 2.4% larger, and its displacement along the light axis is 4.5% larger radial 2.4%. But its area of central block is 3.7% less, which can increase system's optical transfer function about 1.8% according to the CodeV software's analysis result.

The above analysis results show that both kinds of connecting rods structure can meet the requirement of the second-mirror's rigid body displacement, torsion angle and axial displacement which affect the position relationship of the primary and secondary mirrors. From the point of area of central block, the three-pod radial structure is adopted because of its less block area, which less affects imaging performance.

E. Optimization of the connecting rods of secondary mirror

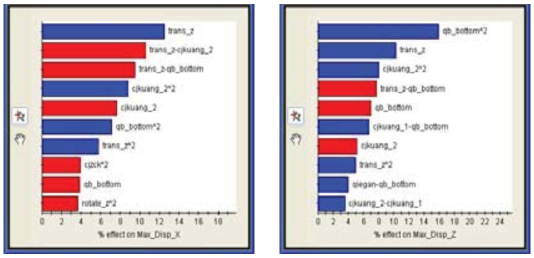
On the basis of the selected preliminary structural design, the basic structure of the connecting rods of secondary mirror is designed. Among the design results, its mass is 15.8kg, its first-order frequency is 230Hz and the axial thermal deformation is 4.9μm under the required temperature environment. Both the mass and first-order frequency cannot meet the design requirements. Thus the optimized design is done to further reduce weight, improve the first-order frequency, and lower axial thermal deformation. Optimization method is that structural parameter is adopted as design variables to change within the constrained boundary conditions and the optimal combination of parameters is selected to achieve optimal performance. For the connecting rods of second mirror, some design variables are selected as the rotation angle between connecting rod and the center frame, the center axial distance of second-mirror frame, the wall thickness of connecting rods, the shape of connecting rods, the thickness of the mounting surface of secondary-mirror components, and the thickness of central ring of second-mirror frame.

TABLE II. COMPARSION OF TWO KINDS OF ROD-TYPE STRUCTURE

	Three-rod radial form	**Four-rod radial form**	**Requirement**
First-order frequency	205Hz	227Hz	>150Hz
Rigid body displacement	4.97 μm	4.85μm	< 10μm
Torsion angle	0.43”	0.42 ”	< 5”
Axial rigidity	8.1 μm	7.7 μm	< 20 μm

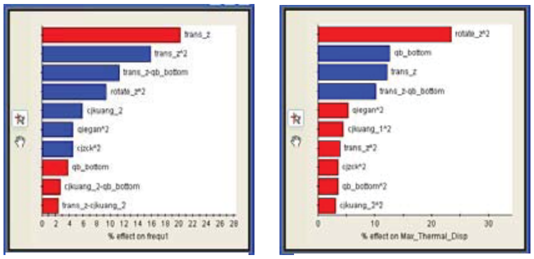
After selecting the important parameters (design space) of connecting rods of secondary mirror, the sensitivity is analyzed. From the analysis results, the effect of each design variable can be shown. Among these, the axial distance (trans_z) has lager effect on the gravitational deformation and first-order frequency, which is shown in Fig.2 and Fig.3.

Through the analysis of the sensitivity, the design-space property of the connecting rods of second-mirror is provided. Select the main design variables, and get the relationship between each design variable and the corresponding values. On the basis of this, a certain amount of sensitivity analysis samples are adopted to establish the structural optimization design model. The original simulation program is replaced by this model to carry out the structural object's optimization design. The design requires that the reduction of the weight is greater than 30%, the increase of the first-order frequency is greater than 10%, and the decreases of thermal deformation along Z axis(the direction of the optical axis)is up to 10%. By adopting the inherited optimized algorithm, the multiplicate-object optimization is carried out from the points of thermal deformation, first-order frequency and weight. The final optimized result is listed in TABLE III.



X-axis Z-axis

Figure.2 Result of designing variable's effect on second-mirror connecting rod's gravity deformation



First-order frequency sensitivity

thematic deformation sensitivity

Figure.3 Result of designing variable's effect on connecting rod's first-order frequency and thematic deformation

TABLE III OPTIMIZED RESULT OF CONNECTING RODS OF SECOND-MIRROR

	Z-axis thermal deformation （μm）	First-order frequency （Hz）	Designed mass （kg）
Before optimization	4.9	230	15.8
After optimization	3.6	263	9.0
Improvement	26.5%	14.3%	43.0%

Through optimizing design, the secondary-mirror connecting rods' weight drops 43%, the first-order frequency is increased by 14.3%, and the thermal deformation along Z axis is reduced by 26.5%. After optimization, the secondary-mirror connecting rods' performance is obviously improved, which can meet the design requirements. The performance of front mirror-body component is listed in TABLE IV.

III. ENGINEERING VERIFICATION EXPERIMENT

After optimization design, engineering verification experiment of the front mirror-body structure is needed to check whether the design results meet the use requirements of space camera, which contain two aspects. One is the structural performance of mechanics resistance. The other is the stability of structural dimension under the thermal vacuum environment.

A. *Mechanics Resistance's performance experiment*

Mechanics resistance's performance refers that the front mirror-body structure still keeps intact and is not destroyed, and the size is stable after the mechanical environment experiment. Experimental method is placing the front mirror-body structure on the platform vibrator, and conducting the vibration experiment in accordance with the provisions of the mechanical test conditions. Mechanical environment test conditions are listed in the TABLE V.

In order to quantitatively verify the mechanics resistance's performance of the front mirror-body structure, three mechanics environmental experiments have been carried out successively. After the mechanics environment experiments, both the structure and appearance of front mirror-body structure remain intact. Experiment scene is shown in Fig.4.

In order to verify the size stability after mechanical experiment, three-coordinate machine measuring method is adopted to judge the stability of support structure. Model of front mirror-body is shown in Fig.5.

TABLE IV PARAMETERS OF FRONT-MIRROR COMPONENT

Items	Parameter
Mass	11.6
Size	Φ330 ×352.7
First-order frequency	263 Hz
Rigid body displacement	4.97 μm
Torsion angle	0.43”
Axial rigidity	8.1μm
Central block	10.5%

TABLE V MECHANICAL ENVIRONMENTAL TESTING CONDITION

Frequency range(Hz)	Power spectrum density
10～95	+3dB/oct
95～120	0.22g2/Hz
120～180	-15 dB/oct
180～450	0.029g2/Hz
450～2000	-12dB/oct
Whole root-mean-square value	5.8 Grms
Loading Time	1min
Loading direction	X、Y、Z

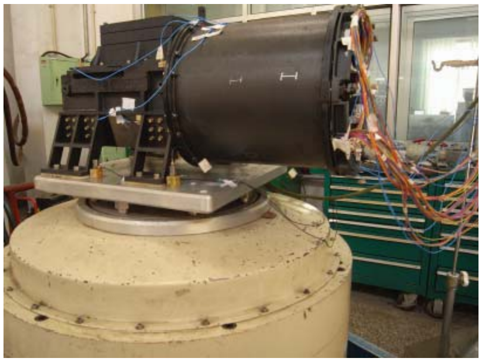


Figure 4 Mechanical experimental scene of front mirror-body

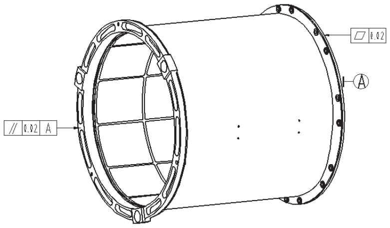


Figure 5 Model of front mirror-body

Measuring data of three-coordinate machine is listed in TABLE VI.

Through vibration experiment and experiment results, the front mirror-body supporting structure is verified to have good structural stability, which can meet requirement of the small high-performance optical camera on the front mirror-body structure.

B. *Vacuum stability Experiment*

In order to verify the vacuum stability of the front mirror-body structure, a vacuum stability experiment is conducted. Under the thermal vacuum environment, the dimensional stability of the front mirror-body composite structure component is tested. Its engineering deformation requirement is less than 0.4μm.

Experiment method is as follow: set the temperature of the front mirror-body to 20 Centigrade and keep the pressure of space environment simulation chamber below 1.3×10^{-3}Pa. After 6 hours, the temperature and pressure reach steady. Then periodically measure the length of the front mirror-body tube using optical interference measurement method. The experiment data is listed in TABLE VII and Fig.6.

The experiments show that the maximum length variation of the front mirror-body under the vacuum environment is 0.2 μm , then the variation reduces gradually, which can meet the requirements of vacuum stability.

C. *Temperature stability Experiment*

In order to verify the temperature stability of the front mirror-body structure, the temperature stability experiment has been conducted. Under the thermal vacuum environment, change the temperature of the front mirror-body cylinder, then measure its length at different temperature levels and judge its temperature stability. Its engineering deformation requirement is less than 0.4μm.

Experiment method is as follow: keep the pressure of the space environment simulation chamber below 1.3×10^{-3}Pa, measure the length of the front mirror-body structure using optical interference measurement method at different temperature levels, and monitor the relative change of the length. Set the temperature of the front mirror-body structure at 17 Centigrade, 18.5 Centigrade, 20 Centigrade, 21.5 Centigrade, and 23 Centigrade, and record the data when the temperature reaches equilibrium. The test results are shown in the following TABLE VIII.

The experiment shows that the front mirror-body of the camera has good temperature stability during the range of 17 Centigrade to 23 Centigrade. It can meet the stability requirement of mirror-body length stability.

IV. RESULTS

For the requirements of the high-Ratio of rigidity degree and the high-stability of the space camera's front mirror-body structure, the camera adopts the cylinder-type scheme as the supporting structure of the primary and secondary mirrors. Through material selection, configuration selection, and design optimization, the design results can perfectly satisfy the requirements. Three kinds of experiments have been carried out for the product, which includes the mechanical vibration experiment, vacuum stability experiment and temperature stability experiment. The experiment results show that the support structure has good structural stability, which can meet the requirements of space camera.

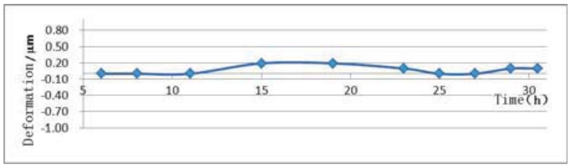


Figure 6 Front-mirror cylinder's length exchanging with time

TABLE VI MEASURING DATA OF THREE-COORDINATE MACHINE

No.	**Measuring items**	**Data before vibration （mm）**	**After 1st vibration （mm）**	**After 2nd vibration （mm）**	**After 3rd vibration （mm）**	**Maximum variation （mm）**
1	Flatness of A datum plane	0.004	0.004	0.003	0.004	0.001
2	Flatness of front-flange joint plane	0.002	0.004	0.004	0.003	0.002
3	Parallelism between front and back flanges	0.004	0.006	0.007	0.005	0.003
4	Coaxiality between the front and back flange's axes	0.164	0.154	0.166	0.158	0.012

TABLE VII DATA OF FRONT-MIRROR CYLINDER'S LENGTH EXCHANGING WITH TIME

Time（h）	6	8	11	15	19	23	25	27	29	30.5
Variation of length（μm）	0.00	0.00	0.00	0.19	0.19	0.10	0.00	0.00	0.10	0.10
Note	The temperature reaches the setting value and keeps stable after 6 hours									

TABLE VIII DATA OF FRONT MIRROR-BODY CYLINDER'S LENGTH EXCHANGING WITH TEMPERATURE

Temperature（℃）	20	17	18.5	20	21.5	23
Variation of length（μm）	0.00	-0.23	-0.13	0.02	0.11	0.19