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Original research article

Lightweight design of high volume SiC/Al composite mirror for remote camera

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A R T I C L E I N F O

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Pareto front

A B S T R A C T

For the design of mirrors in the use of remote camera, high stiffness and less mass are the most critical facts. In this paper, SiC/Al composite material was selected as the material of the mirror. The precise constrains with six degree of freedom was adopted for optimizing the mirror in the diameter of Φ400mm. Traditional empirical design method was used to determine the initial shape parameters of the mirror. The RMS value of the surface shape error and mass were set as the goal of optimization. The Pareto front of the multi-objective parameters was obtained and the objective function was processed to determine the optimal design of the mirror. The results show that the mirror after optimization achieved better performance. Compared with mirror designed with experience-basedmethod, the lightweight ratio of the mirror is increased by 9.1%. The mass is reduced by 12.9% compared with the mirror in the material of SiC. The optimized design method and results of the mirror in this paper can provide a reference for the application of mirrors of the high volume fraction SiC/Al composite material.

1. Introduction

In the field of remote sensing of the earth, the design of optical-mechanical structure requires that the optical performance is guaranteed while the structure mass is reduced to save the emission cost [1]. Therefore, on the basis of meeting the design indicators, the optimization of the optical structure with lighter weight is the key to structural design. In the design of the optical-mechanical structure, the lightweight design of the mirror is a very important issue, where the higher the lightness of the mirror, the lower the design requirements for the frame bearing the mirror, and the lighter the mass of the entire camera.

The light weight design of the mirror for remote camera is a multi-variable optimization issue, on which many scholars have done systematic research [2–4]. The choice of mirror material has an effect on system performance far beyond the impact on the individual assembly [5]. In the optimization of the mirror, the material properties are a main indicator to determine the structural parameters of the mirror. SiC, Zerodur and ULE are commonly used in the design of mirrors of remote camera. These materials have advantages in terms of specific stiffness, thermal adaptability, etc.; however, these materials are relatively brittle, which are difficult to process,

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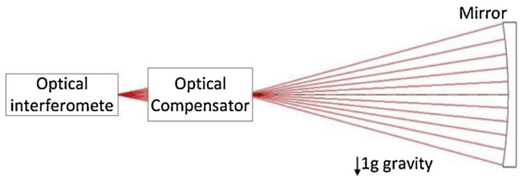


Fig. 1. Configuration for measuring mirror's surface with an optical compensator.

require glue joints, and are complex to assemble; in comparison, high volume fraction SiC/Al composite materials have better mechanical and thermal properties, while processing and installation is convenient; in addition, high volume fraction SiC/Al composite materials have similar properties to metal materials, which are suitable for the derivation of mechanical benchmarks and can bring new ideas for optical assembly and adjustment; therefore, the research on mirrors of high volume fraction SiC/Al composite material has received more and more attention.

In this paper, based on the excellent performance of high volume fraction SiC/Al composite material, a Φ400 mm mirror is optimized. A traditional empirical design is used combining with Pareto-based multi-objective optimization design in the design process. A 6-DOF(Degree of Freedom) exact constraint form is used for fixing the mirror. The design results are compared horizontally with that of traditional empirical methods and longitudinally compared to the design results of SiC. In this paper, the optimized design of mirrors of high volume fraction SiC/Al composite material can meet the needs of engineering applications.

2. Design requirements

During the entire testing process of mirror processing and adjustment, the optical axis of the mirror is horizontal, as shown in Fig.1, and the mirror should have sufficient stiffness to resist the influence of gravity. However, in the practical application of the mirror, the optical axis is theoretically perpendicular to the ground, so that the influence of gravity on the surface accuracy of the mirror will affect the practical applications, and the MTF of the optical system will deviate from the situation where the mirror is adjusted on the ground. Considering the cost and technical feasibility for mirrors of this size, in general, gravity compensation mechanism will not be applied, so the optical distortion caused by gravity should be reduced as much as possible to reduce the difference between ground test and practical optical performance. Therefore, the main objective of the optimized design of the mirror is to reduce the structural mass of the mirror as much as possible, to minimize the influence of gravity to obtain a smaller mirror surface-shape error.

Mirrors actually need to withstand various environmental tests before they can be applied. Generally,there will be a certain safe margin for the structure design. The test conditions are much harsher than the real working environment, so the mirror should have certain dynamic performance to resist vibration, shock and thermal loads. According to the decomposition of the camera specifications and the application requirements, the design and performance requirements of the mirror are shown in Table 1.

3. Exact constraint of the mirror

The back lightweight form of the mirror mainly has three types: open, semi-closed and closed. The open structure has the advantages of easy processing and high weight reduction efficiency [6], so an open design is used for the back of the mirror. Hexagonal, rectangular, sector and triangular are the commonly used shapes for lightweight holes. The stiffness of the triangular lightweight is relatively high [7], so that a triangular shape is used for the mirror lightweight hole in this paper.

According to the traditional kinematic design principle, the six DOF of the mirror should be precisely constrained. Even under-constraint or over-constraint is not permitted. The under-constraint cannot maintain exact position of the mirror, and the over-constraint will reduce the surface shape accuracy due to the influence of installation stress or thermal stress. In this paper, the mirror adopts the installation method of three points on the back, and three flexible structures are circumferentially symmetric to form the support for the mirror. As shown in Fig. 2, each flexible structure releases the rotational freedom around the three coordinate axes (θ_x, θ_y, θ_z) and the translational freedom around X-axis, and it is rigid in the vertical mirror direction (Z-direction) and the vertical mirror radial direction (Y-direction), therefore, such a combination of three flexible structures can realize precise constraint on the six DOF of the mirror. The mirror component designed by applying the exact constraint principle of mirror is shown in Fig. 2.

Table 1
Design and performance requirements of the mirror.

Components	Value
Mirror mass	< 4.5 kg
RMS Error (under 1 G gravity)	< 10 nm
Fundamental frequency	> 120 Hz
Mirror's tilt under 1 G gravity	< 20″

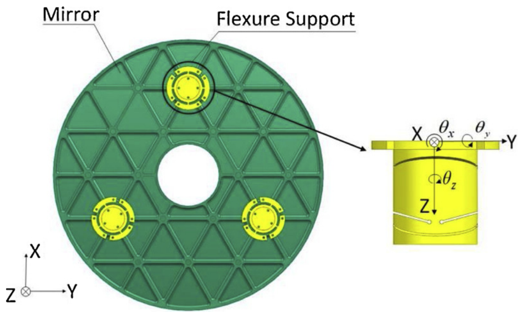


Fig. 2. Structural form of the mirror component.

4. Optimal design of the mirror

4.1. Design of initial parameters

In this paper, the research object is a Φ400 mm mirror of high volume fraction SiC/Al composite material, and the material of the back flexible support is TC4. The material parameters are shown in Table 2.

Reasonable initial parameters are necessary for structural optimization in the process of optimizing the mirror. In actual engineering design, the traditional empirical formula is often used to complete the initial parameter design of the structure.

Roberts et al. studied the relationship between the diameter-thickness ratio and self-weight deformation of disc-shaped mirrors, and gave the empirical formula

$$\delta = \frac{3\rho g r^4}{16Et^2} = \frac{3\rho g r(D/t)^2 D^2}{256E} \tag{1}$$

Where, δ is the maximum self-weight deformation (um), ρ is the material density of the disc (kg/m3), g is the acceleration of gravity, r is the radius of the disc, D is the diameter of the disc, and E is the Young's modulus of the material, and t is the thickness of the disc. According to the shape parameters and constraints of the mirror, the calculated thickness of the solid mirror is $t = 57$ mm.

For the position of the supporting structure, a empirical formula for the support radius of the disk mirror is given in the reference

$$R = \frac{\sqrt{3}}{6}D_G = 0.289D_G \tag{2}$$

Where, D_G is the diameter of the mirror. The calculated support diameter is $R = 116$ mm. In the lightweight design of the mirror, the excessive ratio of the diameter of the inner tangential circle of the lightweight hole to the thickness of the mirror surface will cause "grid effect" during processing. In order to prevent this phenomenon, combined with the engineering experience of other mirror materials, the diameter-thickness ratio of mirrors of high volume SiC/Al composite material fraction is 6–12, the initial thickness of the mirror is 4 mm, and the thickness of the back lightweight rib is 4 mm.

4.2. Definition of optimization problem

The mass and shape of the mirror are related to the lightweight structural parameters. The parameter optimization model of the mirror assembly is shown in Fig. 3. The mirror thickness and the rib thickness of the back lightweight hole depend on the manufacturing limits of mechanical and optical processing, and should have a certain safe margin, which is a constant value of 4 mm in this paper. A form of three-points support on the back is used for the mirror, and three flexible structures are mounted on the midplane of the mirror, so that the optical distortion caused by gravity is the smallest when the optical axis of the mirror is horizontally placed [8]. Based on the initial design of 4.1 mirrors and the feasibility of the process, the optimal design parameters of the mirrors and flexible supports are determined, as shown in Table 3.

In Table 3, the range of each variable and the relationship to other variables are given, and the iteration step of traversing the variable space is set.

Table 2
Mirror component material properties.

Properties	SiC/Al composites	TC4
Density(kg/m^3)	2.94	4.44
Poisson ratio	0.23	0.24
Young's modulus(GPa)	180	110
Yield stress(MPa)	235	877
Coefficient of thermal expansion(10^{-6}/K)	8	8.9

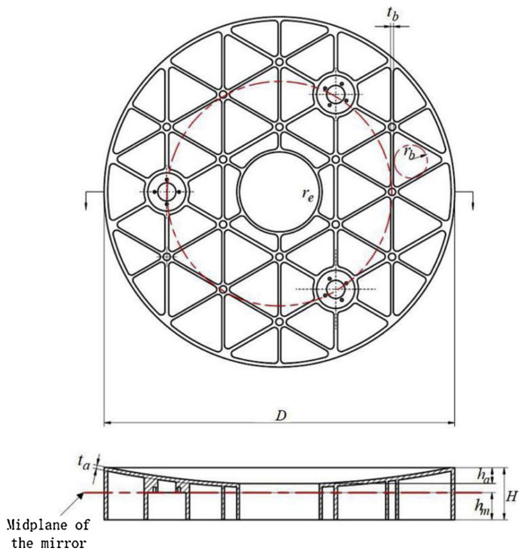


Fig. 3. Parameters optimization model of the mirror.

Table 3
Design parameters of the mirror and flexure support.

Name	Parameter	Value (mm)	Step (mm)
Mirror surface thickness	t_a	4	Const
Edge thickness	H	57 ± 5	1
Mirror diameter	D	400	Const
Radius of support	r_e	116-131	1
Web thickness	t_b	2-5	0.1
Diameter-thick ratio	k_{d-t}	6-12	0.5
Lightweight inscribed circle size	r_b	$f(k_{d-t})$	NA
Sagittal high	h_a	19	Const
Midplane position	h_m	$f(k_{d-t}, t_b, H)$	NA

The optimization of the mirror is actually to find a set of structural design parameters that can simultaneously minimize the two optimized objectives of mirror mass and the RMS value of the mirror shape error, while meeting the constraints of Table 1. H, r_e, t_b, k_{d-t} are used as the design variable for the mirror in the next section, and then the mass and the RMS value are evaluated to determine the optimal design of the mirror.

4.3. Multi-objective optimization based on Pareto

In fact, the two optimization objectives of the mass and RMS value of the mirror are conflicting, and the interests of the other objective will be lost while considering one optimization objective, therefore, there is not an optimal solution for both indicators simultaneously. The multi-objective optimization problem is actually to find a set of Pareto solutions for an optimal solution [9]. The optimized objective function in this paper is as follows

$$\min y = p(X) = (p_1(X), P_2(X)), X \in \Omega \tag{3}$$

Where, X is the optimization variable, $X = \{H, r_e, t_b, k_{d-t}\}$, Ω is a sample space, where

$$p_1(X) = mass(H, r_e, t_b, k_{d-t}$$

$$p_2(X) = rms(H, r_e, t_b, k_{d-t}) = \frac{1}{3}(rms_x + rms_y + rms_z$$

The constraint is mass $mass_i \le 4.5kg$; Surface shape error in three directions under gravity $rms_i \le 10nm$, fundamental frequency of the mirror $f_i > 120Hz$, tilt angle $\theta_i < 20''$.

The mass and RMS value of the mirror vary according to the design parameters, which are normally necessary to be calculated for 54,000 times according to the design parameters listed in Table 3, Supposing 5 min will be spent for each time, so the time cost is unbearable. Therefore, in this paper, the data set that can reflect the sample characteristics is calculated using UG, Nastran and Matlab in advance, then using the data set as the training sample to generate the neural network model, and then predict according to

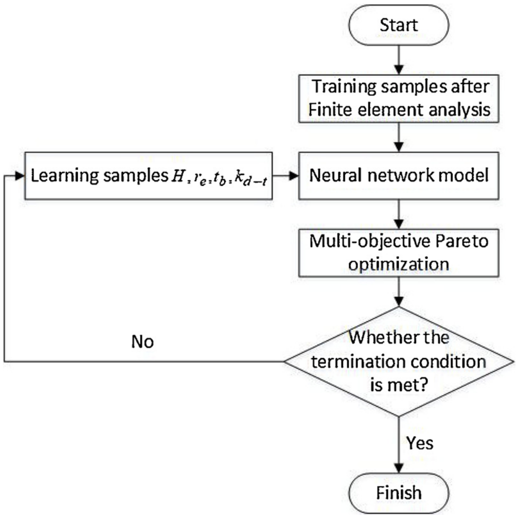


Fig. 4. Multi-objective optimization process based on Pareto.

the neural network model. It will unquestionable save a lot of time and resources using this method. The optimization process is shown in Fig. 4. Depend on the above calculation process, the feasible solution set and the pareto optimal are calculated as shown in Fig. 5.

5. Optimization results

In Section 4.3, the pareto front is obtained. In order to get the optimization result, the following objective optimization function is set

$$y = \lambda p_1(X) + (1 - \lambda)p_2(X) \tag{4}$$

Set $\lambda = 0.8$, considering the feasibility of manufacturing, set mass =4.18 kg, rms =8.2 nm. At this point, the corresponding design parameters are $H = 54mm$, $r_e = 124mm$, $t_b = 3mm$, $k_{d-t} = 10$.

Applying the above optimization results, the surface shape error in the three directions is shown in Fig. 6. The detailed calculation results are shown in Table 4. All the indications of the mirrors all meet the design requirements.

The mass of the mirror is 4.6 kg by using the traditional empirical design, while the mass of the optimized mirror is reduced by 9.1% compared to that of the experiential design method.

SiC is superior to high volume fraction SiC/Al composite material in terms of material mechanical properties, but high volume fraction SiC/Al composite material has better processability in material manufacturing. Depend on the practical application in engineering, the minimum thickness of the lightweight rib of SiC is 4 mm for this size level of the mirror, while the minimum thickness of SiC/Al composite material is 2 mm. If the mirror is designed with SiC, the design result of the mirror is 4.8 kg, which is heavier than that of high volume fraction SiC/Al composite material, which indicates that the manufacturing process limits the mechanical properties of SiC.

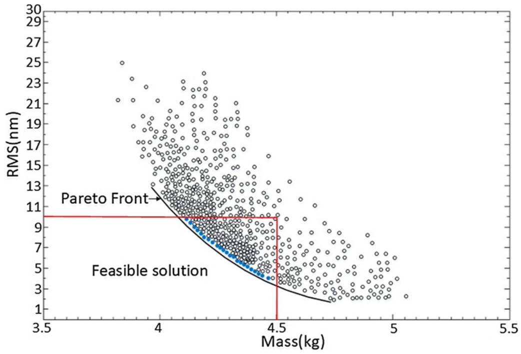
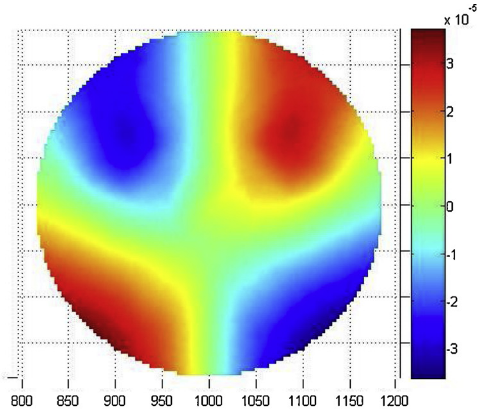
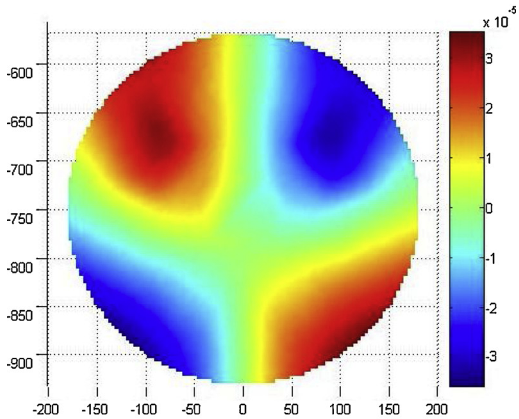


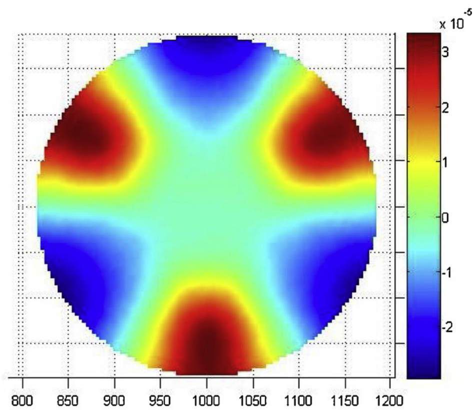
Fig. 5. The optimal design result of reflector is based on Pareto.



(a) in the X direction



(b) in the Y direction



(c) in the Z direction

Fig. 6. Surface error of the mirror due to 1 G gravity.

Table 4
Optimization results of the mirror.

Components	Value
Mirror mass	4.18 kg
Rms in the X direction (under 1 G gravity)	9.5 nm
Rms in the Y direction (under 1 G gravity)	9.5 nm
Rms in the Z direction (under 1 G gravity)	5.6 nm
Fundamental frequency	192 Hz
Mirror's tilt in the X direction under 1 G gravity	12 ″
Mirror's tilt in the Y direction under 1 G gravity	12 ″
Mirror's tilt in the Y direction under 1 G gravity	6″

6. Conclusions

Based on the good material properties of high volume fraction SiC/Al composite material, in this paper, a Φ400 mm mirror of high volume fraction SiC/Al composite material is optimized by combining the traditional empirical design method with the multi-objective optimization design method based on Pareto. The design result shows that the mass of the mirror obtained by the optimization method is 4.18 kg, the fundamental frequency of the mirror is 192 Hz, and the RMS values in the three directions under the gravity of 1 G are 9.5 nm, 9.5 nm and 5.6 nm respectively, and the rotation angles are 12″, 12″, 6″ respectively, therefore the performance of the mirror meets the requirements. Compared with the experience-based design method, the lightweight ratio of the mirror in this paper is increased by 9.1%. The weight of the mirror designed with SiC is 4.8 kg, and is 12.9% heavier than that of the mirror of high volume fraction SiC/Al composite material, which is mainly due to the limitation of SiC manufacturing process reduces the material performance advantage, therefore, improving the manufacturing process of SiC mirror is an urgent problem to be solved. The optimized design method and results of the mirrors in this paper can provide a reference for the application of mirrors of high volume fraction SiC/Al composite material.

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