Optik - International Journal for Light and Electron Optics 241 (2021) 166386

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.com/locate/ijleo

Original research article

Research and design of kinematic support flexibility for metal mirror

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ARTICLE INFO

Keywords:
Remote sensor
Kinematic support
Flexibility design

ABSTRACT

The mirror was one of the most important components of aviation remote sensors. Due to its high specific stiffness and good environmental adaptability, metal material mirror was suitable for application in airborne photoelectric load as the main optical system. In this paper, through the research on the kinematic support form of metal mirror, the flexibility of flexible joint form was optimized, and the design of aperture 190 mirror was carried out, so that the shape accuracy under the action of gravity reaches 1 / 50λ, which better meets the design requirements of aviation photoelectric load.

1. Introduction

Aerial camera imaging has been widely used in many fields, such as geographic mapping, national defense and security. Mirror was an important component of aerial camera. The assembly of the mirror directly affects the surface quality and the MTF of the camera optic system, so it was one of the most important position in the camera. With the development of aerial camera, large aperture reflective system becomes more and more important [1,2].

Due to the complex aviation environment, the temperature changes dramatically, so the traditional silicon carbide and K9 mirror materials are easy to produce temperature gradient when the temperature difference was large, resulting in the change of optical image quality, which can not meet the requirements of aerial camera [3].

With the development of materials science, the processing technology of Be-Al composite mirror has been mature and can be used in large aperture optical system. Therefore, it was necessary to design its assembling structure.

Due to the large temperature change of aviation environment, the influence of mismatch of linear expansion coefficient between different materials in optical system was increased, which requires that the support structure of mirror has a better flexibility and can adapt to the change of temperature in a wide range. At the same time, due to the vibration in the aviation environment, it was necessary to provide a stable supporting environment for the mirror assembly to ensure the imaging quality. Therefore, it was necessary to design effectively through design analysis.

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https://doi.org/10.1016/j.ijleo.2021.166386
Received 7 December 2020; Accepted 23 January 2021
Available online 29 January 2021
0030-4026/

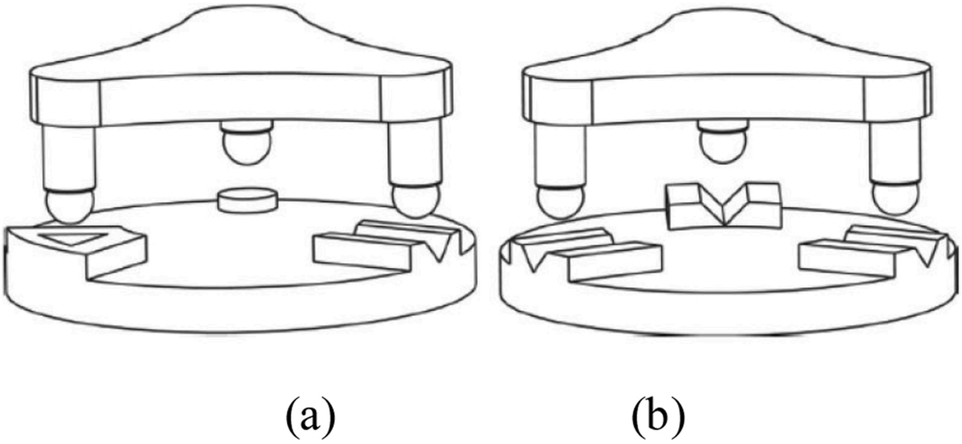


Fig. 1. Arrangements of kinematic couplings.

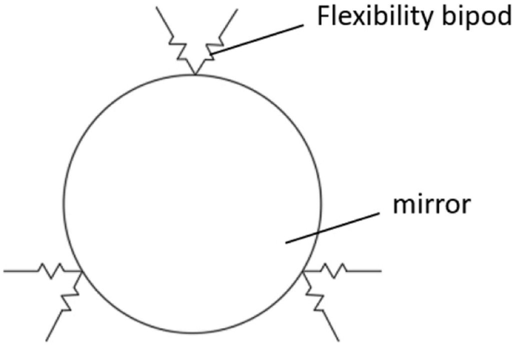


Fig. 2. Bipod support.

2. Design of the mirror kinematic support

2.1. Introduction about the kinematic support

Kinematic support can limit the six degrees of freedom in space, and avoid the problem of over positioning, so it was a good form for mirror support. The application of kinematic support the mirror can prevent the change of the mirror in the process of assembly and adjustment as well as the change of external conditions such as temperature. It can ensure that the device will not change because of the stress [4].

The principle of kinematic design was used to install two mechanisms, respectively called kinematic mounting and kinematic coupling. Instead of a kinematic mount, kinematic coupling is a kinematic design in which connections can be easily separated and reassembled. Historically, motion coupling has also been referred to as a geometric clamp, defined by Lord Kelvin in the late 19th century as "the method of applying and maintaining six mutual pressures between two objects" [5]. In addition, the use of the term "fixed position" by James Clerk Maxwell [5] explains how Lord Kelvin Uses tetrahedral-v-plane motion couplings in some of his instruments, later known as the Kelvin or Kelvin coupling. See Fig. 1.

The 2−2-2 arrangement can be changed according to the form of two legs shown in Fig. 2. As shown below, which is also called bipod [7].

As a deformation form the kinematic installation, bipod can define the stable plane of fixed point at the centroid plane of the mirror by design, which can effectively adapt to the temperature change of the mirror, and ensure that the surface shape of the mirror will not change greatly under the temperature change, which will affect the imaging quality [8].

Because the bipod kinematic support principle was flexible release principle, the flexibility design of bipod can not only provide larger flexible release capacity for mirror, but also reduce the over positioning problem caused by temperature change between support material and optical mirror. And through the improvement of the stiffness of the tripod, it can provide better stiffness for the optical mirror, ensure the rigid body displacement of the optical system does not exceed the use limit

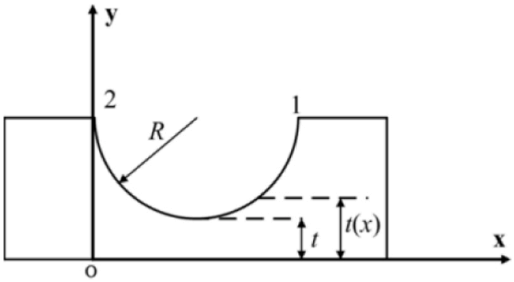


Fig. 3. Design parameters of the single-axis right circular flexure hinge.

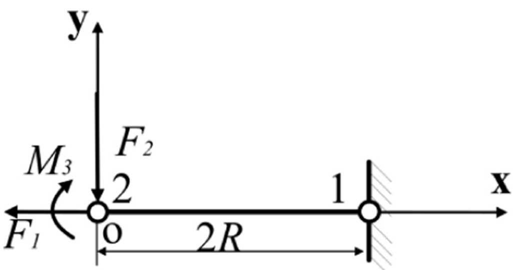


Fig. 4. Force analysis of the single-axis right circular flexure hinge.

2.2. Flexible structure design

The stress concentration method was used to release the deformation in the flexible position of the flexible structure to reduce the influence on the supporting mirror shape. At present, the commonly used flexible structure was a single side straight circular flexure hinge. The depth of the flexible groove and the minimum thickness of the hinge will have a greater impact on the flexibility of the supporting structure.

Flexibility analysis of unilateral straight circular flexure hinge [9–11].

As shown in Fig. 3, it was the unilateral straight circular flexure hinge, where R was the depth of flexible groove, t was the minimum thickness, B was the thickness of flexure hinge, t (x) was the function of minimum thickness, then the expression of T (x) was

$$t(x) = t + R - \sqrt{x(2R - x)}, x \in (0, 2R) \tag{1}$$

The unilateral straight circular flexure hinge was equivalent to a cantilever beam with small deformation, as shown in Fig. 4.

One end of the flexure hinge was fixed, and the load exerted on the other end was the load F1 and F2 along the x-axis and Y-axis and the moment m3 around the z-axis. Then the relation between displacement and load of point 2 was

$$\begin{bmatrix} \theta_z \\ y \\ x \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & 0 \\ C_{12} & C_{22} & 0 \\ 0 & 0 & C_{33} \end{bmatrix} \begin{bmatrix} M_{z1} \\ F_{y1} \\ F_{x1} \end{bmatrix} \tag{2}$$

Where θ Z was the angle around the Z axis, y was the displacement along the Y axis, X was the displacement along the X axis, and C_{ij} was the flexibility.

The denaturation energy of one side straight circular flexure hinge is

$$U = \frac{1}{2}\left(\int_t \frac{F_x^2}{EA(x)} + \int_t \frac{M_z^2}{EI_z(x)}\right) dx \tag{3}$$

Where E was the modulus of elasticity and I was the moment of inertia.

$$\begin{aligned} &A(x) = bt(x), I(x) = \frac{bt(x)^3}{12}, \\ &F_x = F_1, M_z = M_3 - F_2 x \end{aligned} \tag{4}$$

By deriving the equation, the following relation was obtained

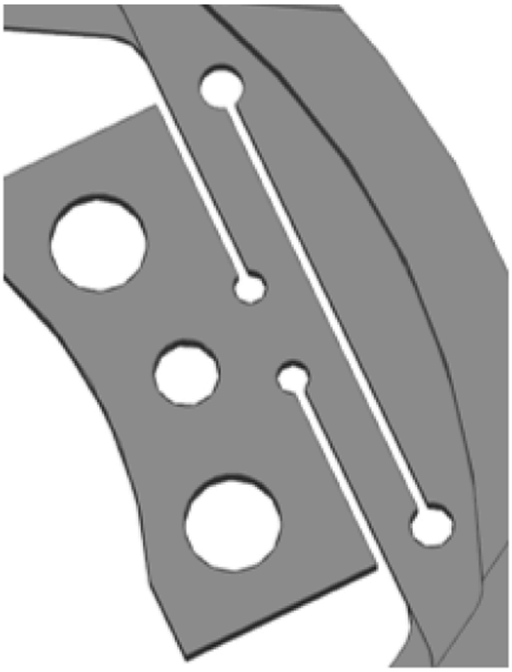


Fig. 5. flexure hinge design model.

$$\begin{cases} \theta_z = \dfrac{\partial U}{\partial M_{z1}} = \dfrac{12}{Eb}\left(M_{z1}I_1 - F_{y1}I_2\right) \\ y = \dfrac{\partial U}{\partial F_{y1}} = \dfrac{12}{Eb}\left(-M_{z1}I_2 + F_{y1}I_3\right) \\ x = \dfrac{\partial U}{\partial F_{x1}} = \dfrac{F_{x1}I_4}{Eb} \end{cases} \tag{5}$$

According to Eqs. (2) and (5), the flexibility of a single-sided straight circular flexure hinge was

$$\begin{cases} C_{11} = \dfrac{12}{Eb}I_1 \\ C_{12} = -\dfrac{12}{Eb}I_2 \\ C_{22} = \dfrac{12}{Eb}I_3 \\ C_{33} = \dfrac{1}{Eb}I_4 \end{cases} \tag{6}$$

Where the integral variables are

$$\begin{aligned} I_1 &= \int_0^{2R} \frac{1}{t(x)^3}dx \\ I_2 &= \int_0^{2R} \frac{x}{t(x)^3}dx \\ I_3 &= \int_0^{2R} \frac{x^2}{t(x)^3}dx \\ I_4 &= \int_0^{2R} \frac{1}{t(x)}dx \end{aligned} \tag{7}$$

According to Eqs. (1) and (7), the flexibility of a single side straight circular flexure hinge was obtained

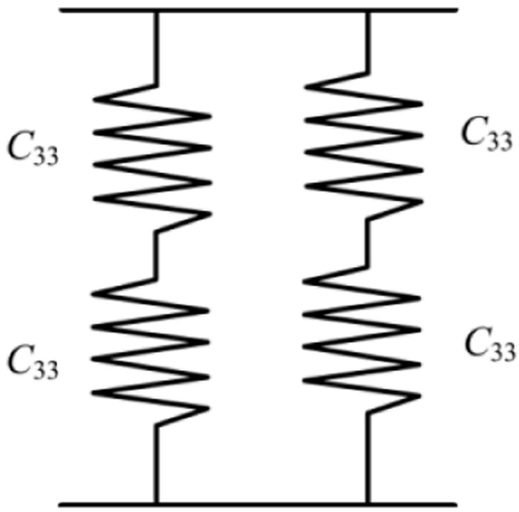


Fig. 6. The flexible structure of the simplified model.

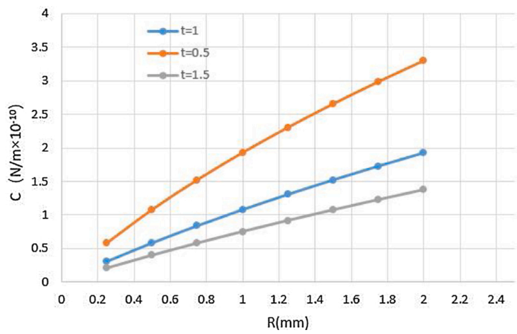


Fig. 7. The changes between t, R and C.

$$\begin{cases} C_{11} = \dfrac{12}{Eb}\displaystyle\int_0^{2R} \dfrac{1}{\left[t+R-\sqrt{x(2R-x)}\right]^3}dx \\ C_{12} = -\dfrac{12}{Eb}\displaystyle\int_0^{2R} \dfrac{x}{\left[t+R-\sqrt{x(2R-x)}\right]^3}dx \\ C_{22} = \dfrac{12}{Eb}\displaystyle\int_0^{2R} \dfrac{x^2}{\left[t+R-\sqrt{x(2R-x)}\right]^3}dx \\ C_{33} = \dfrac{1}{Eb}\displaystyle\int_0^{2R} \dfrac{1}{t+R-\sqrt{x(2R-x)}}dx \end{cases} \tag{8}$$

2.3. Flexibility design of flexible structures

According to the design method of unilateral hinge, the structure of flexure hinge was analyzed. Design the structural model as shown in Fig. 5.

Simplify the flexible structure to get the simplified model as shown in the Fig. 6.

According to the calculation principle of series parallel spring, the total flexibility of bipod in x-axis direction was

$$C_1 = 2C_{33} \tag{9}$$

$$C_x = \frac{1}{\frac{1}{C_1}+\frac{1}{C_1}} = C_{33} \tag{10}$$

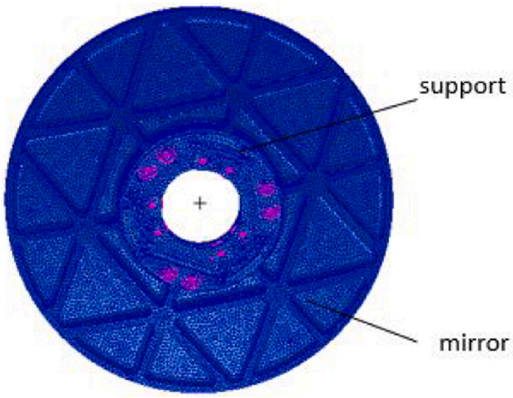


Fig. 8. The FEA model of the mirror.

Table 1
The three of the order frequency about the mirror FEA analysis.

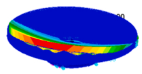
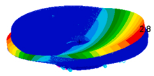
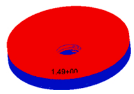
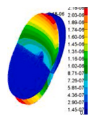
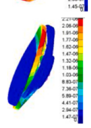
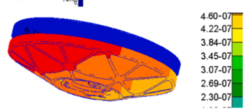
	Frequency (Hz)	Direction	Cloud chart
First-order	294	X-Axial	
Second-order	297	Y-Axial	
Third-order	694	Z- Axial	

Table 2
the gravity deformation analysis of the mirror.

Gravity Direction	MAX displacement(um)	Cloud chart
X-Axial	2.18	
Y-Axial	2.21	
Z- Axial	0.57	

C1 was the flexibility of the outrigger in the x-axis direction.

According to the formula, the model stiffness with different thickness was calculated according to the formula, as shown in the Fig. 7.

The conclusions are as follows

1) The flexibility of single fillet was directly proportional to the depth of flexible groove R and inversely proportional to the minimum thickness t.
2) When the minimum thickness t was fixed, the change rate of the bipod flexibility decreases with the increase of the design parameter R.

Therefore, in the design of bipedal structure, the design value of parameters R and t should be reasonably selected according to different design objectives, which was conducive to the design of ideal kinematic support structure.

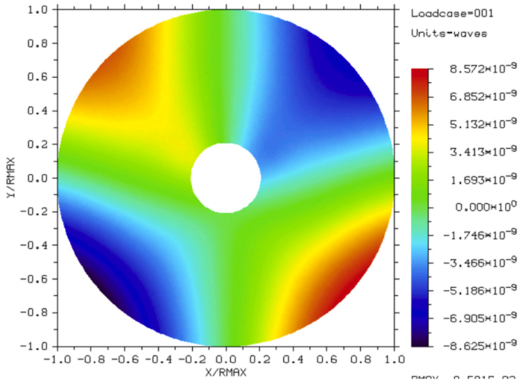


Fig. 9. The RMS analysis of X-direction gravity.

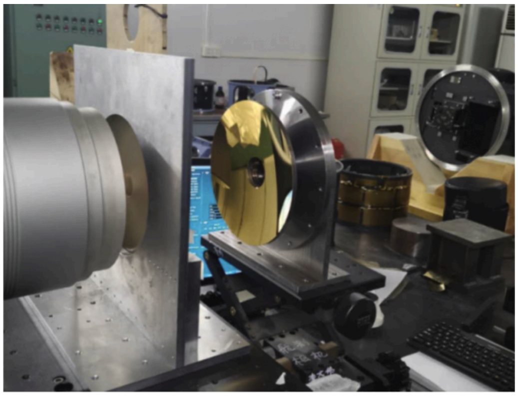


Fig. 10. The test of the mirror.

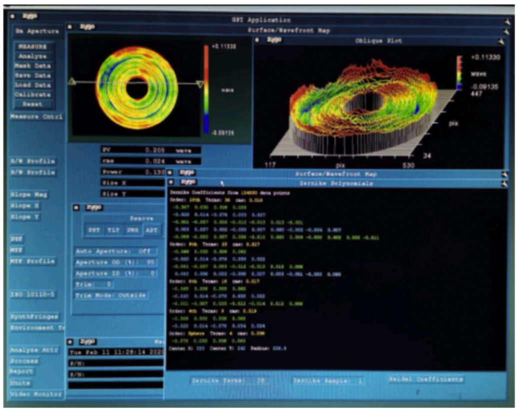


Fig. 11. The result of the test.

2.4. Simulation analysis

The mirror structure was simulated and analyzed. The finite element model was shown in the Fig. 8. Through static analysis, the gravity deformation and temperature deformation of the mirror were obtained.

The three of the order frequency analysis of the mirror was shown in the Table 1:

The Gravity deformation analysis of the mirror was shown in the Table 2:

The surface fitting result obtained by calculating the surface shape. There are many methods used in surface fitting analysis, including Least Square polynomial fitting and Standard Zeniko Polynomial fitting. In the paper, the Standard Zeniko Polynomial fitting was used to analysis the change of the surface shape under the gravity effect in the X-axis direction. The RMS value of X-direction gravity was shown in the Fig. 9, and the value was 12.286 nm.

2.5. Test

The measured value of the surface shape change of the mirror was obtaind by detecting the surface shape of the mirror through the interferometer, the test was shown in Fig. 10. Under the action of gravity, the surface shape change of the mirror was 0.021λ. The result of the test was shown in Fig. 11.Compared with the simulation result, the different of the two result was very small. That can proved that the design stiffness of the mirror flexible structure was reasonable.

3. Conclusion

In this paper, based on BeAl metal mirror, the support structure of 190 mm mirror was optimized and tested. The final gravity deformation of the mirror was 0.021λ. The simulation results match the experimental results. The results show that the flexible structure design can ensure the support stiffness of the mirror, and solve the problem of the mismatch of the linear expansion coefficient between the metal mirror and the frame structure, and provide a design method for the metal mirror applied in aviation load.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank for the support from the Key Laboratory of Airborne Optical Imaging and Measurement, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences.

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