Optik - International Journal for Light and Electron Optics 193 (2019) 162966

Contents lists available at ScienceDirect

Optik

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

Original research article

Design and analysis for the multi-point flexible support structure of large and precision lens

Linmin Zhang*, Wenpan Wang, Jianli Wang, Peng Guo, Liang Hao

Changchun Institute of Optics, Fine Mechanics and Physic, Chinese Academy of Sciences, Changchun, 130033, China

ARTICLE INFO

Keywords:
Ground-based telescope system
Large aperture lens
Rigidity of the support structure
Wave-front aberration

ABSTRACT

In order to achieve accurate surface figure and optical axis stability of a large aperture lens in the ground-based telescope system which subject to various load case, a novel lens support with multi-point flexible support structure is proposed. Then, the parameters of the support structure are optimized based on low-order modal and system accuracy, and the sensitivity of the flexure element's parameters, the impact on the optical axis inducted by assembly and machining error of the support structure and the stability of the lens under different load cases are analyzed, meanwhile the rigidity of the support structure is tested. The result show that: the support rigidity of the system is higher, the optical axis offset causing by gravity is less than 2 μm when the lens is mounted horizontally; lens wave-front aberration (RMS) is 11.07nm when thermal load is altered from reference temperature(+ 20 °C) to − 20 °C. The results and practice indicate that the multi-point flexible support structure can improve lens surface figure, and the assembly design is practicable and extensible.

1. Introduction

Lens is the fundamental optics of the refractive optical system. By properly combing different forms of lens, optical systems with diversity of functions, such as typical telescopes, microscopic systems and cameras, can be constructed. Taking the ground-based large aperture telescope as an example, as the enlargement of the field of view and the improvement of the resolution and imaging quality, it has to amplify the aperture of optics; the requirements of optical elements' surface figure and relative position error are also getting higher and higher. So under the change of the temperature and external load, thickness, surface figure and spatial position of the large aperture lens are altered, which cannot be ignored to the imaging quality of the system [1]. So it is necessary to design the lens support structure reasonably for the better overall performance of the optical system。

Common single precise lens is supported by rigid frames, elastic structures or flexure elements. Rigid supports are applied by means of mechanical clamping directly, for example imposing axial load by rotating a threaded compression ring to push the lens against the mechanical base surface. It is convenient to assemble and disassemble, but the environmental adaptability is poor, and the initial assembly state will be destroyed by external temperature changes and vibration. Elastic assembly is to place resilient ring constraining lens in the lens holder, thereby effectively improving the position accuracy, but the eccentricity become greater under the impact and vibration, which is adverse for the optical path stabilization. In order to ensure the fine surface figure of optical unit, flexible support is the most widely used, which can provide flexible elements to connect the optical element and cell. Flexure elements can supply controllable and relative motion for the optical element by their bending deformation so as to unload the local

* Corresponding author.
E-mail addresses: zhangtqx@163.com (L. Zhang), wangwenpan281@163.com (W. Wang), wangjianli@ciomp.ac.cn (J. Wang), guopenghust@hotmail.com (P. Guo), 24133412@qq.com (L. Hao).

https://doi.org/10.1016/j.ijleo.2019.162966
Received 2 April 2019; Accepted 14 June 2019

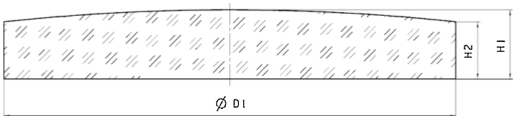


Fig. 1. Parameters of lens.

acting force on the optical element and reduce the external impact on the surface figure [2]. Flexible support has two functions: locating optical elements and coordinating deformation. But the former requires high rigidity to keep the optical element stable, another needs certain flexibility in the given degree of freedom. Therefore, high requirements are put forward to the support structure of optical elements. Many scholars such as Wang Ping, Ma Lei, Zhao Lei, Gao Yan and Stephen have researched the flexible support of optical components [3–7]. Uniform radial flexible frame with multi-point support can enhance the capability to withstand temperature change, impact and vibration, yet at the same time higher requirements are put forward to machining the flexible holder.

Therefore, a novel lens support structure with multi-point flexible units is proposed in order to provide design reference for high accuracy single lens assembly. Then Minimum surface figure value is considered as the design objective under the large temperature excursions environment, and low-order support frequency is the constraint condition. Finally the influence of temperature and gravity on surface figure of the lens under this support structure is analyzed.

2. Design of the support structure

In this paper a plano-convex lens made of K9 is used. The shape and dimension parameters are shown in Fig. 1, where: spherical radius:1570.1 mm, H1 = 50 mm, H2 = 41.31 mm, D1 = 330 mm.

In order to ensure the high-precision surface figure, multi-point flexible support is one of the most widely used structure form of the frame modes. The number and layout of lens supports not only have an important influence on the wave-front aberration of the lens, but also play a significant role in the support stiffness of the optical element.

For large aperture lens, firstly it is necessary to determine the number of support points, then the surface figure of the upper and lower surface is analyzed through FEA under 3 load cases: full restricted circumferentially, supported evenly through 3 points and 6 points respectively(the layout of support points is shown in Fig. 2) when the optical axis is vertical. The surface figure results are shown in Table1.

According to the analysis results, in the case of 3-points support, the lens has to undergo a complicated refining process to remove the trefoil aberration introduced by self-weight, but the above aberration will be introduced when the lens subjected to a temperature load. After altering to 6-points support, the value shows some improvement, and the 6 points even distribution is the best. Therefore increasing the number of supporting points is an effective measure to ensure the surface figure accuracy of the large aperture lens [8,9]. Fig. 3 illustrates the basic design for a large aperture lens assembly adopting a novel support structures. Here 6 bonding pads are evenly distributed along the circumference, integrated to the lens mount by epoxy, and three sets of flexible support structures divide the bonding pads into three groups, finally they are mounted on the lens holder.

3. Rigidity analysis of the flexure support structure

The flexible support unit can be equivalent to a restricted cantilever beam with rectangular cross-section, whose boundary condition is: the terminal deflection angle $\theta = 0$. In the model, because of $t \ll b$, $t \ll L$, the rigidity s in the radial direction is far smaller

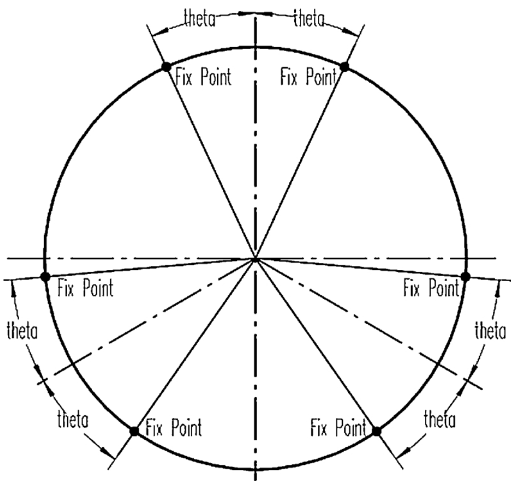


Fig. 2. Support point layout.

Table 1
The surface figure value of the lens.

Constraint state		Upper surface RMS/nm	Lower surface RMS/nm
Full Circumferential constraint		1.36	15.18
3 points		12.8	18.1
6 points	theta = 18	6.65	15.4
	theta = 24	3.72	15.02
	theta = 30	2.02	14.97

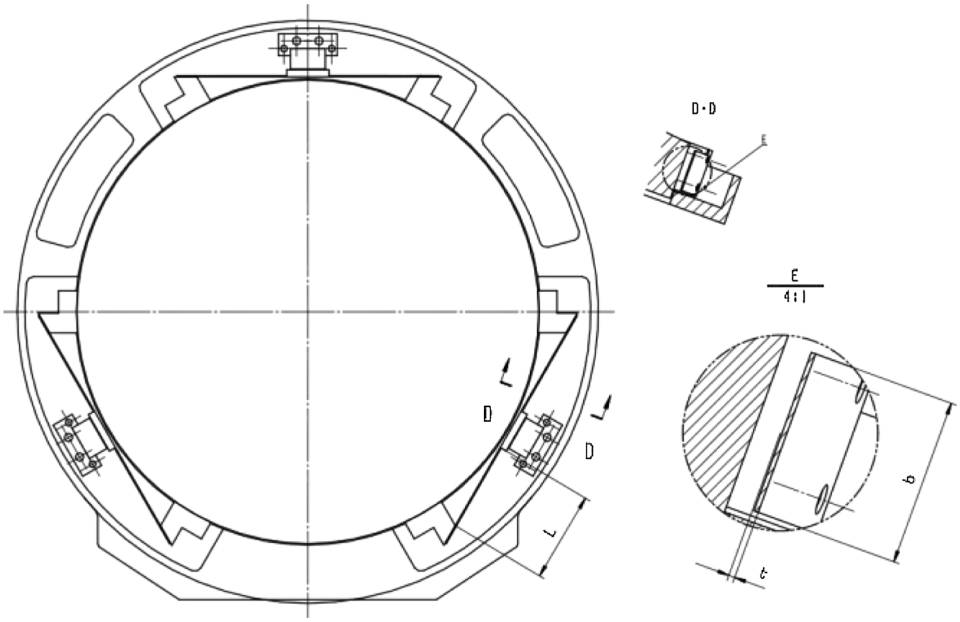


Fig. 3. Flexible support assembly of the lens.

than that in other directions. As a result, only the bending of cantilever beam is considered to indicate approximately the mechanical properties of flexible support structure. An equivalent model is established, as shown in Fig.4(a), where i= 1,2, ⋯n, n≥ 3, is the number of flexible units group, the number of flexible units is taken into account, but their damping is ignored, and the optics component is assumed to be rigid body. According to the theory of material mechanics, the single-strip flexure is used to guide translation. The relationship between the load P required translating the flexure and the translation deflection is given by $f_B = -\frac{PL^3}{3EI}$. By constraining the flexure against rotation, $f_{BL} = -\frac{PL^3}{12EI}$,so the stiffness $K_r = \frac{12EI}{L^3}$ [10,11]. And the tangential stiffness K_t is given by

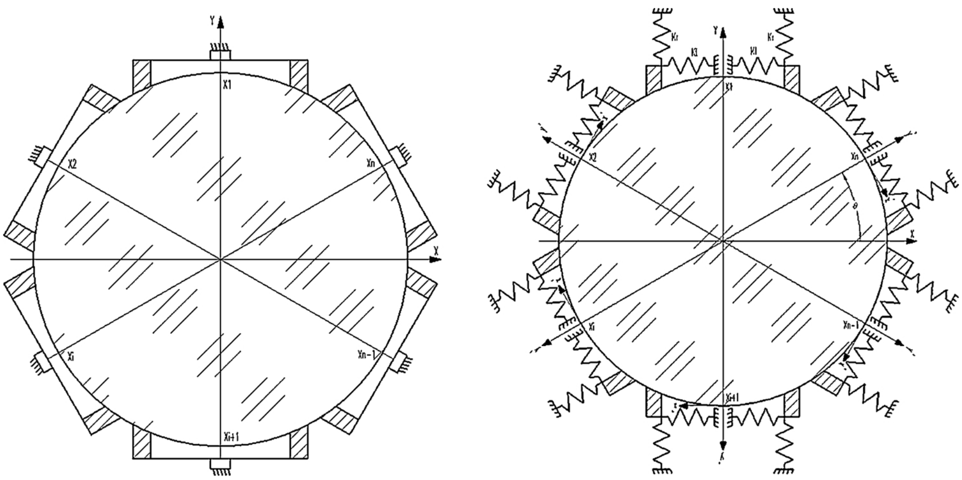


Fig. 4. (a) Simplified diagram of flexible support structures. (b) Spring model of flexible support structures.

$K_t = \frac{EA}{L}$. Each set of flexible elements is composed of tangential stiffness K_t and radial stiffness K_r. It is simplified to spring combinations as shown in Fig. 4(b), where x_i' and y_i' are local coordinate system, respectively for tangential and radial direction of flexible support, the conversion relationship with global coordinate system is shown as following:

$$\begin{bmatrix} x_i' \\ y_i' \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}, \ \theta=(i-1)\frac{2\pi}{n}$$

The dynamics equation is formulated according to the Lagrange equation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = 0(i = 1 \dots n)$$

Kinetic energy: T= $\frac{1}{2}M(\dot{x}^2 + \dot{y}^2)$,M is the total mass of the lens and bonding parts.
Potential energy:

$$\begin{aligned} V= \sum_{i=1}^{n}(K_t x_i^2 + K_r y_i^2) &= \sum_{i=1}^{n}\left[K_t\left(x\cos\left((i-1)\frac{2\pi}{n}\right) + y\sin\left((i-1)\frac{2\pi}{n}\right)\right)^2 + K_r\left(-x\sin\left((i-1)\frac{2\pi}{n}\right) + y\cos\left((i-1)\frac{2\pi}{n}\right)\right)^2\right] \\ &= \sum_{i=1}^{n}\left[x^2\left(K_t\cos^2\left((i-1)\frac{2\pi}{n}\right) + K_r\sin^2\left((i-1)\frac{2\pi}{n}\right)\right) + y^2\left(K_t\sin^2\left((i-1)\frac{2\pi}{n}\right) + K_r\cos^2\left((i-1)\frac{2\pi}{n}\right)\right)\right. \\ &\quad \left. + 2xy(K_t - K_r)\sin\left((i-1)\frac{2\pi}{n}\right)\cos\left((i-1)\frac{2\pi}{n}\right)\right] \end{aligned}$$

Assuming the flexible units are distributed equal space circumferentially, so $\sum_{i=1}^{n}\sin\left((i-1)\frac{2\pi}{n}\right)\cos\left((i-1)\frac{2\pi}{n}\right) = 0$, where:
A= $\sum_{i=1}^{n} K_t\cos^2\left((i-1)\frac{2\pi}{n}\right) + K_r\sin^2\left((i-1)\frac{2\pi}{n}\right)$,
B= $\sum_{i=1}^{n} K_t\sin^2\left((i-1)\frac{2\pi}{n}\right) + K_r\cos^2\left((i-1)\frac{2\pi}{n}\right)$,
Finally, the equation is expressed as

$$\begin{bmatrix} M & \\ & M \end{bmatrix}\begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} + \begin{bmatrix} A & \\ & B \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix} = 0$$

4. Accuracy analysis of the flexible support assembly

4.1. Sensitivity analysis

The effect of flexible support on the system modal is analyzed by taking parameters b and t as variables and ignoring the influence of the lens cell. According to the actual structure, b ranges from 25 mm to 30 mm, and t from 0.6 mm to 1 mm. the first five modal values are shown in Fig. 5. According to the analysis data, a modal function with t and b as parameters is fitted, expressed as

$$M(b, t) = a_1 \times b^3 + a_2 \times t^3 + a_3 \times b^2 t + a_4 \times bt^2 + a_5 \times b^2 + a_6 \times t^2 + a_7 \times bt + a_8 \times b + a_9 \times t + a_{10}$$

The fitting coefficients of each order are shown in Table 2.

By analyzing the above coefficients, it can be obtained that 1) parameter b has a greater impact on the torsion of flexible support than t; 2) with the increase of parameter t, the influence on the modal is enhanced obviously. In addition, in order to meet the requirements of thermal characteristics and reduce the position accuracy of optical component assembly, it is necessary to decrease the radial stiffness. Therefore increasing b while decreasing t is an effective method to improve performance of lens assembly.

A flexure support structure is designed by taking b = 30 mm and t = 0.6 mm.The lens assembly is installed on the optical platform according to the state of usage, and its low-order modals are tested by a modal analyzer (see Fig. 6).Test is run several times through

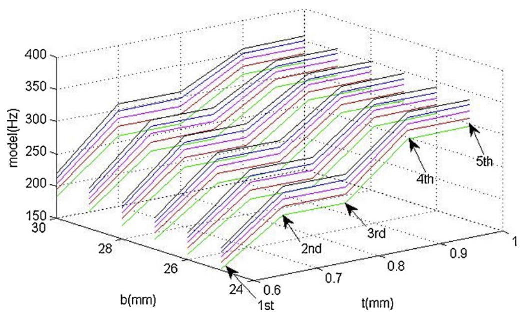


Fig. 5. Change of modal values of the first five orders. The 1st mode is a translation along the optical axis, the 2nd and 3rd mode are rotations around the X and Y axis, and the 4th and 5th are translations along the X and Y axis.

Table 2
Fitting coefficients.

	1st	2nd	3rd	4th	5th
a1	−0.0254	−0.0320	−0.0319	0.0006	0.0001
a2	33.3333	45.5556	47.361	62.0833	70.8333
a3	−0.0398	−0.0493	−0.0498	−0.0714	−0.0450
a4	−1.9245	−2.5612	−2.7612	0.2510	−0.4082
a5	1.9818	2.4795	2.4761	−0.0661	−0.0491
a6	75.7313	−107.4354	−106.5068	−236.6054	−240.6088
a7	7.1382	9.1324	9.4887	3.0724	2.7372
a8	−47.3493	−57.8279	−57.6918	6.7414	6.4556
a9	60.2860	99.0353	93.4394	317.7807	325.6644
a10	403.2750	486.5925	487.3294	19.2346	19.4360

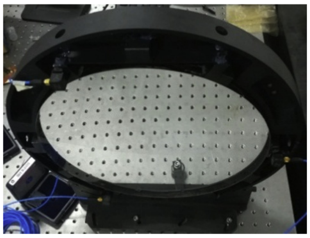


Fig. 6. Modal test.

adjusting repeatedly the location of the flexible support structure. The experimental results show that the deviation of each order resonant frequency was less than 9% compared with the simulation result of the overall model. After analysis and research, the error source includes mainly 3 parts: the reduction of connection stiffness cause by epoxy, machining error and installation error.

4.2. Assembly error analysis

Fig. 7 shows the equivalent mechanical model relating lens to flexure support that is founded on Fig. 4. After considering the assembly error of three groups of bonding pads, the gravity direction is set at a certain angle with the X axis, and the outer circle represents the location of 3 groups of fixed points. Assuming that in the initial state, the lens is concentric with the outer circle, the center of the lens is translated from the location of O under the condition of assembly process and gravity load, yielding the offset (Δx, Δy). As a result, the lens is applied more or less amount of force by various springs.In the absolute coordinate system, XOY the initial coordinates of each connection point is: $\begin{bmatrix} X_i \\ Y_i \end{bmatrix} = \begin{bmatrix} r\cos\alpha_i \\ r\sin\alpha_i \end{bmatrix}$. After the local coordinate system same as above is moved to the new

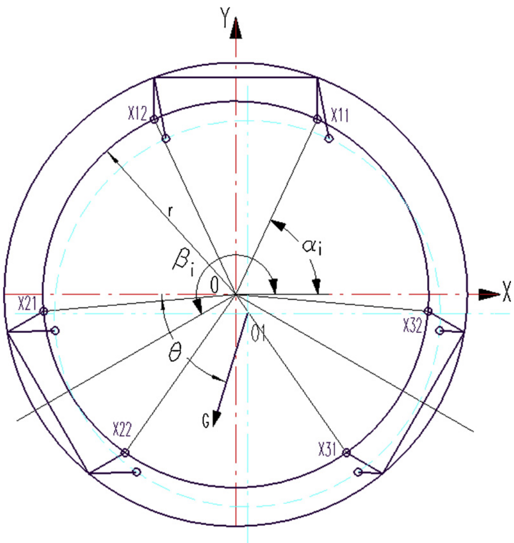


Fig. 7. Equivalent mechanical model of flexure support.

position, the coordinates of each point in it are as follows:

$$\begin{bmatrix} x_i^{''} \\ y_i^{''} \end{bmatrix} = \begin{bmatrix} cos\beta_i & sin\beta_i \\ -sin\beta_i & cos\beta_i \end{bmatrix} \begin{bmatrix} X_i - \Delta x \\ Y_i - \Delta y \end{bmatrix} \text{ where } \beta_1 = \beta_2 \ \beta_3 = \beta_4 \ , \ \beta_5 = \beta_6$$

Therefore, the deformations of six groups of springs are

$$\begin{bmatrix} \Delta x_i \\ \Delta y_i \end{bmatrix} = \begin{bmatrix} x_i^{''} - x_i^{'} \\ y_i^{''} - y_i^{'} \end{bmatrix}$$

The mechanical equilibrium equation is constructed as following:

$$k_t(\Delta x_1 + \Delta x_2) + (-k_t sin\beta_3 - k_r cos\beta_3)(\Delta x_3 + \Delta x_4) \ + (-k_t sin\beta_{53ns} + k_r \cos\beta_5)(\Delta x_5 + \Delta x_6) - Gcos\theta = 0$$

$$k_r(\Delta y_1 + \Delta y_2) + (-k_t cos\beta_3 - k_r sin\beta_3)(\Delta y_3 + \Delta y_4) \ + (k_t cos\beta_5 - k_r sin\beta_5)(\Delta y_5 + \Delta y_6) - Gsin\theta = 0$$

Compared with the rigidity among lens, mount and flexible support structure, the latter is much smaller, after ignoring the stiffness difference of all springs, the above formula can be simplified as follows:

$$2k_t\Delta x(1 - sin\beta_3 - sin\beta_5) + 2k_r\Delta x(-cos\beta_3 + cos\beta_5) = Gcos\theta$$

$$2k_t\Delta y(-cos\beta_3 + cos\beta_5) + 2k_r\Delta y(1 - sin\beta_3 - sin\beta_5) = Gsin\theta$$

Therefore, the relationship among installation errors is obtained when the optical axis of the lens is horizontal. According to the above formulas, it can be achieved that the deviation trajectory of the lens center is an ellipse.

4.3. stability analysis of the optical axis

The eccentricity and tilt of the optical axis of the lens have a neglectable influence on the optical system, and the usage of flexible support structure makes this feature more prominent. Therefore it is essential to analyze the relative position relationship between lens and mount under different loading case. Fig. 8 shows the eccentricity trajectory of the optical center when three sets of support points are evenly distributed along the circumference and θ varies from 0° to 90°. When the optical axis is horizontal, the relative position relationship between the lens and the mount is changed. As a result, the offset of the center is less than 2 μm, and the stress at each connect point is also changed with θ which affects the wave-front aberration of the lens. Fig. 9 illustrates the relationship between the maximum stress at each point and θ.

4.4. Analysis of thermal stability

Because the thermal expansion coefficient of lens material is relatively large, both the incident surface and exit surface have a deformation with respect to the ideal surface with the change of ambient temperature, which will cause system aberrations such as defocus. Moreover, the mismatch of materials between the lens and the lens cell will introduce additional aberrations. The relationship between wave-front error of the lens and the variation of the optical surface is as following [12]:

W= (n− 1)Δd(x, y), where, W is the wave-front error caused by the deformation of lens along in the direction of optical axis; n is the refractive index of the lens material, Δd(x, y) is the axial geometric variation of the lens.

The usage of flexible support structures reduces the coupling rigidity between the lens and the holder, which cause the stress on the lens to change with temperature variation. The process can be regarded as a preload of the spring applied to the lens. The material

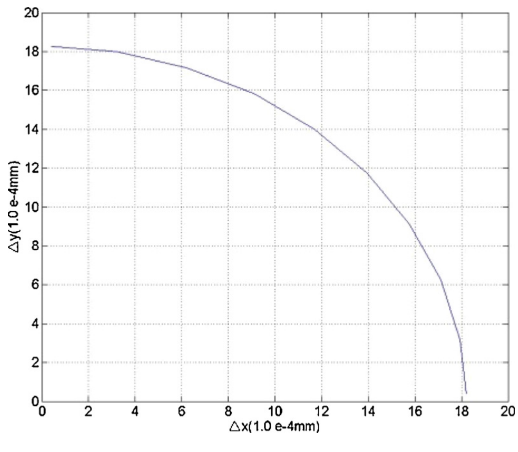


Fig. 8. Center eccentric of the lens.

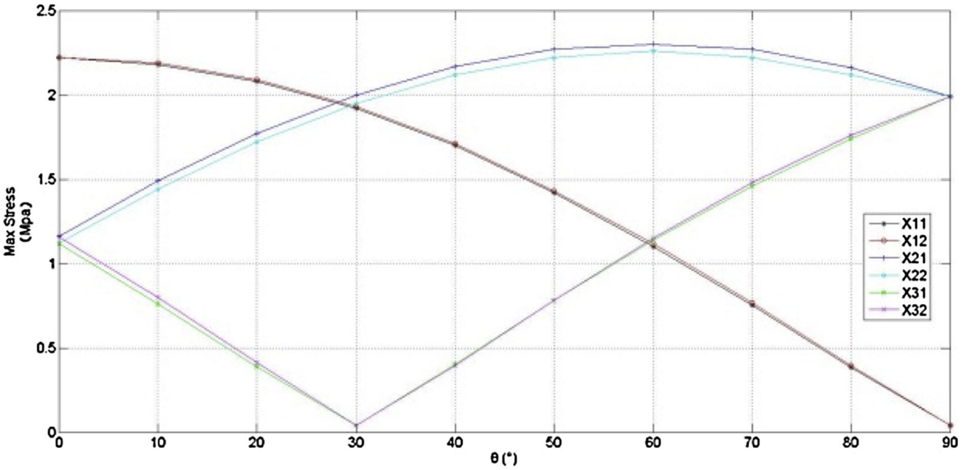


Fig. 9. Changes of the coupling points.

parameters(reference temperature 20 °C) used are shown in Table 3. Fig. 10 shows the deformation nephogram of the upper and lower surface when the lens is analyzed by FEA at −20 °C.

Zernike polynomial is a commonly tool for optomechanical integration analysis. It is an effective method to selectively analyze variation characteristic of each aberration, process various aberration coefficient and optimize the performance of optical system. The type and size of the wave-front error of the lens can be definited under the temperature load by analyzing the Zernike coefficient and the aberration forms, which is taken as one of the criteria whether the parameters of the flexible support structure is reasonable or not [13].Through the Zernike fitting coefficients of the upper and lower surface, the RMS of geometric deformation $\Delta d(x, y)$ in the optical axis direction $\Delta d(x, y)$ is calculated to be 21.5 nm [14]. So the RMS of the wave-front error is 11.07 nm (wavelength 632.8 nm), the nephogram is shown in Fig. 11.

According to the above analysis results, the trefoil aberration is the main wave-front error source under temperature load case, and it becomes more prominent with the increase of the aperture of lens. Therefore, adjusting the suitable number of the support structure is one of the effective ways to reduce the wave-front error of the lens.

5. Conclusion

This paper introduces a new multi-point flexible support structure for large aperture lens. According to the results of FEA and the experiment, each index meets the optical design requirements. The detailed conclusions are shown as follows:

1) magnifying the parameter b whiling decreasing t of the flexible support structure can harmonize the contradiction between support rigidity and temperature adaptability of the lens;
2) The center deviation of the lens is less than 2 μm when the positions of the support structures are altered along the circumference with horizontal optical axis.
3) The temperature adaptability of the lens could be enhanced by setting properly the number of support points.
4) The flexible support structure is compact, and can be combined neatly in application.

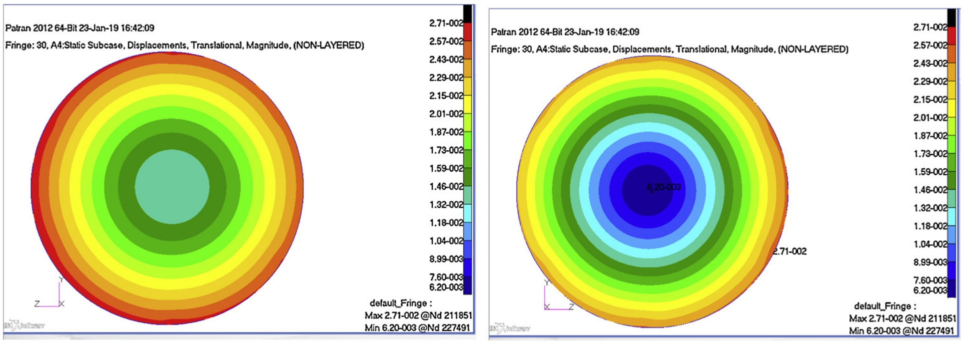
Through the above design and analysis, the wave-front aberration and optical axis stability of the large aperture lens is optimized, which is beneficial to the later adjustment and alignment of the optical system.

Funding

The work of this paper was supported by the National Key R&D Program of China through grant (Project Number: 2017 YFE0102900).

Table 3
Materials performance.

material	E/MPa	υ	ρ/t/mm3	α/E-6/°C
K9	617000	0.2	2.53E-9	3.5
TC4	109000	0.34	4.44E-9	9.1



(a) The upper surface (b) The lower surface

Fig. 10. Deformation nephogram of the lens.

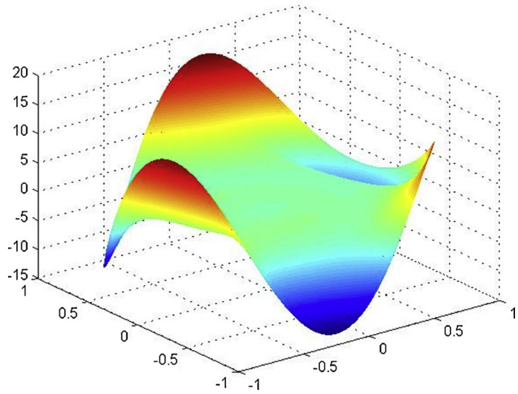


Fig. 11. Nephogram of the WFS.

Acknowledgement

The work of this paper was supported by the National Key R&D Program of China through grant (Project Number: 2017 YFE0102900) and the 4 m large aperture telescope project of CIOMP. We thank Guo Peng for his excellent work on the calculate of the Zernike and Wang Wenpan and Hao Liang for his careful test of lens mounts. Wang Jianli, the project director for the 4 m telescope project, was involved in all stages of the design of the flexible support structure of the lens.

References

[1] Zhou Yi, Liao Jing, Guo Rui, et al., Study on low-stress supporting structure for large-aperture precision optical element, Laser Infrared 44 (5) (2014) 554–558.
[2] P.R. Yoder, Opto-Mechanical Systems Design, China Machine Press, Beijing, 2008, pp. 189–196.
[3] Wang Jianguo, Ren Jiangang, Design and analysis of large diameter precision optics flexible supporting structure, Coal Technol. 37 (7) (2018) 314–316.
[4] Stephen A. Smee, A precision lens mount for large temperature excursions, SPIE 7739 (2010) 7739 3O-1-3O-13.
[5] Gao Yan, Zhang Bao, Design and analysis for the flexible support structure of high precision lens assembly, Optik 175 (2018) 228–236.
[6] Wang Ping, Wang Rudong, Wang Lipeng, et al., Optimized design of high precision flexure-support barrel for reference sphere, Chin. Opt. 4 (4) (2011) 380–387.
[7] Ma Lei, Cao Diansheng, Liu Chengzhi, Design and analysis on multi-points flexible supporting structure of large-aperture lens, Opto-Electron. Eng. 42 (5) (2015) 88–94.
[8] Zhao Lei, Peng Haifeng, Yu Xinfeng, et al., Lens support structure of multi point equal supporting with wholly radical freedom, Opto-Electron. Eng. 42 (10) (2015) 43–48.
[9] Wang Ping, Tian Wei, Wang Rudong, et al., Influence of mounting stress on wavefront distortion of lithographic object lens, Chin. Opt. 6 (1) (2013) 57–63.
[10] Daniel Vukobratovich, Ralph M. Richard, Flexure mounts for high-resolution optical elements, SPIE 959 (1988) 17–36.
[11] Cao Yuyan, Wang Zhichen, Zhou Chao, et al., General modeling and optimal design of flexure supporting structure for optical components, Opt. Precis. Eng. 24 (11) (2016) 2794–2803.
[12] Zhang Dejiang, Liu Liren, Xu Rongwei, et al., Finite element analysis for wavefront error of lens induced by gravity, Acta Opt. Sin. 25 (4) (2005) 538–541.
[13] Zhou Lei, Luo Xin, Liu Yuan, Influence of mounting method & pre-load on lens aberration, Semicond. Optoelectron. 34 (3) (2013) 498–502.
[14] Zhu Xingshen, Gong Xuefei, Optimization on supporting method of large-aperture aspheric lens, Laser Optoelectron. Prog. 54 (2017) 225–231.