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Effect of the particular temperature field on a National Ignition Facility deformable mirror

Qi Bian, Lei Huang*, Xingkun Ma, Qiao Xue, Mali Gong

Center for Photonics and Electronics, Department of Precision Instruments, Tsinghua University, Beijing 100084, China

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ABSTRACT

The changes caused by temperature in the surface shape of a deformable mirror used at the National Ignition Facility has been investigated previously. In this paper the temperature induced surface shape under different temperature fields is further studied. We find that the changes of the peak and valley (PV) or root-mean-square (RMS) value rely on the temperature gradient as well as the difference between the mirror and the environment with a certain rule. This work analyzes these quantitative relationship, using the finite element method. Some experiments were carried out to verify the analysis results. The conclusion provides guidance to minimize the effect of the temperature field on the surface shape. Considerations about how to improve the temperature induced faceplate in actual work are suggested finally.

1. Introduction

Adaptive optics is a technology that can reduce optical aberrations actively to improve the performance of optical systems. A typical adaptive optics system mainly consists of wavefront sensor, wavefront corrector and arithmetic processor, among which a deformable mirror is the most important component. Generally speaking, the distorted wavefront is detected by the wavefront sensor and then corrected by a deformable mirror. Adaptive optics is widely used in optical systems to correct wavefront aberrations, in National Ignition Facility (NIF) for instance [1–3].

The complex system structure of NIF comprises variety of modules, each of them can introduce aberrations by many mechanisms in the whole optical path, such as pump-induced distortions, thermal distortion, beam off-axis effects etc. The NIF deformable mirror plays an important role to correct optical aberrations [1,3]. Therefore the NIF deformable mirror, as a wavefront corrector, must have a good surface shape so that it cannot introduce additional aberrations to the non-corrected wavefront. Whereas in the process of fabrication, mounting and debugging of the NIF deformable mirror even during its performance, it works in different environment where multiple temperature field caused by heat conduction, convection and radiation exists. All of mirrors may be influenced by temperature [4–7]. The temperature distribution certainly causes the change to the surface shape of the NIF deformable mirror, thereby causes additional distortion. In previous study, some researchers analyzed the relationship between deformable mirrors and temperature distribution [4,5,8,10] but they merely presumed that the deformable mirror worked under different uniform temperature conditions [11]. The uniform temperature field is a relatively ideal condition. There is still a gap with the actual situation so this paper aims at further research on the influence of relatively complex temperature distribution.

In this paper, the structure of the NIF deformable mirror is firstly introduced as well as the theoretical principle. The finite element method is used to simulate and analyze the surface shape of the NIF deformable mirror induced by temperature field. Then a particular deformable mirror of similar structure with NIF is manufactured. The changes of the surface shape in diverse temperature fields are measured by an interferometer. Finally the significance of this research and the practical application is discussed. On the basis of this article, we can take effective measures to reduce the influence of the temperature fields. We are able to foresee the changes of the temperature induced surface shape. It will be of great help and convenience for our actual work.

2. Structure of the NIF deformable mirror and analysis of temperature response of surface shape

In NIF the deformable mirror with a large caliber of 400mm or so is widely used [1–3]. As shown in Fig. 1, the structure of the NIF deformable mirror mainly consists of the mirror and the base

* Corresponding author.
E-mail address: hl@mail.tsinghua.edu.cn (L. Huang).

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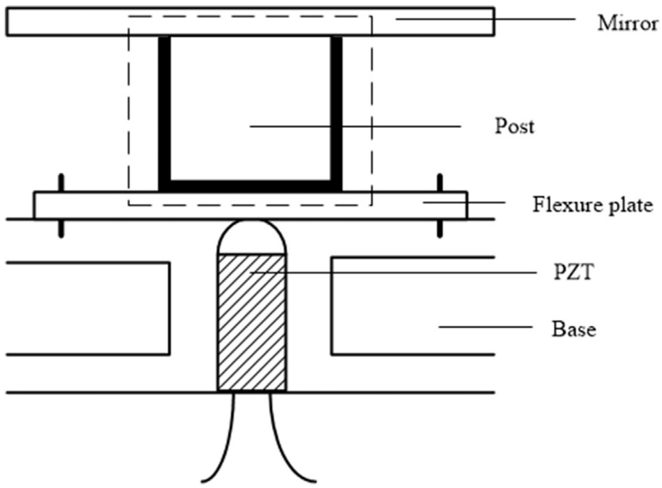

Fig. 1. Structure sketch of the NIF deformable mirror.

[9,11]. The mirror is about 10 to 15 mm thick. A post with the transition layer and a metal layer is located on the back of the mirror. The flexure plate is fixed on the base by screw nails. The metal layer is used to connect the transition layer with the flexure plate through the shear joint and butt joint with structural adhesive separately. Thirty-nine lead magnesium niobate (PMN) actuators of hexagonal layout are used to pull or push the faceplate of the mirror via the preloaded flexure plate.

Such a deformable mirror is assembled in a certain surrounding defined as the mounting environment. However the assembled mirror exchanges the heat with the environment when placed in the working condition different from the mounting one. After a period of heat exchange, the deformable mirror achieves a balance with surroundings and a new temperature field has been established inside the deformable mirror, which can be solved by Eq. (1)

$$\frac{\partial T}{\partial \tau} = a\nabla^2 T \tag{1}$$

where T is the temperature field inside the mirror, τ represents the time, a is the thermal diffusivity of the material and ∇^2 is the Laplacian operator. During the establishment of the inside temperature field each part of the mirror is heated and expanded. The thermal expansion of each part is different due to the difference of the material properties as well as the structure. Then the thermal stress is induced with the thermal strain, shown as follows,

$$\begin{aligned}\varepsilon_x &= \frac{1}{E}\left[\sigma_x - \mu\left(\sigma_y + \sigma_z\right)\right] + \alpha T\\ \varepsilon_y &= \frac{1}{E}\left[\sigma_y - \mu\left(\sigma_z + \sigma_x\right)\right] + \alpha T\\ \varepsilon_z &= \frac{1}{E}\left[\sigma_z - \mu\left(\sigma_x + \sigma_y\right)\right] + \alpha T\end{aligned} \tag{2}$$

$$\begin{aligned}\gamma_{yz} &= \frac{2(1+\mu)}{E}\tau_{yz}\\ \gamma_{zx} &= \frac{2(1+\mu)}{E}\tau_{zx}\\ \gamma_{xy} &= \frac{2(1+\mu)}{E}\tau_{xy}\end{aligned} \tag{3}$$

where ε is the normal strain, γ is the shear strain, σ is the normal stress, τ is the shear stress, E is the Young's modulus, α is the thermal expansion coefficient and μ is the Poisson's ratio. Then the thermal strain causes the deformation of the surface shape shown as Eq. (4), in which ω is the surface shape of the mirror.

$$\varepsilon_z = \left.\frac{\partial\omega(x, y, z)}{\partial z}\right|_{z=surface} \tag{4}$$

The normal strain in the direction of x and y is always ignored and the normal strain in the direction of z can be erased by pushing or pulling of actuators for common deformable mirror of NIF. Nevertheless the shear strain or the shear stress brings about torque, which cannot be revised by vertical drive force of actuators and produces residual deformation after correction.

As mentioned above, the temperature field can make the faceplate deformed. The deformation of the surface shape is affected by many factors, such as the temperature gradient, the temperature difference, different material parameters and so on. Therefore we take advantage of the finite element method to obtain the simulation solution.

3. Finite element method simulation

In order to simplify calculations, the finite element model consists of a continuous plate mirror and a metal base connected rigidly by several discrete glass posts. The deformation induced by temperature is embodied in a piston to the surface shape [9,11]. The stress caused by the different thermal expansion of mirror and base, provides deformations on the faceplate. The main parameters taken to be constants in small temperature variation range, are stated in Table 1.

The mirror with a dimension of 390 mm × 390 mm × 10 mm is united to 39 hexagonal distributed posts, each with a diameter of 20 mm and a height of 20 mm. The clear aperture of the mirror is 360 mm × 360 mm, only in which the surface shape will be analyzed below if no special instructions. The mirror and the posts are bonded onto the base with a dimension of 410 mm × 410 mm × 50 mm. The whole model is built with structural tetrahedron solid elements, each having 10 nodes. In the simulation process, due to symmetry, only the temperature rise is taken into account. The surface shape is totally opposite in the process of temperature drop with the same extent as temperature rise.

In the whole simulation it is assumed that the original surface shape of the deformable mirror is plane without any deformation, which is set as the reference, so the surface of the mirror deforms from the planar. If no special instructions, when the mirror achieves a balance with the environment the deformed mirror is defined as the initial surface shape. The deformable mirror can correct the low-order aberration by the pulling and pushing of the

Table 1
Parameters in finite element simulation.

Material	Young's modulus/GPa	Poisson's ratio	Density/kg m^{-3}	Thermal expansion coefficient/K^{-1}	Thermal diffusivity/m^2 s^{-1}
K9	81	0.17	2400	7.1e−6	0.5e−6
Steel	200	0.3	7800	11.2e−6	4.1e−6