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Surface error modeling, evaluation and optimization of large optics in inertial confinement fusion laser system

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ABSTRACT

Surface errors of mounted large optics have significant impacts on laser performance in high power laser system. However, in SG-III inertial confinement fusion (ICF) laser system, it is really tough to realize the minimized surface error and satisfy the design criterions. In this paper, the compositions and corresponding causes of complicated surface topographies are analyzed systematically. Surface decoupling, reconstruction and fitting methods are proposed successively and constitute an integrated surface modeling methodology to visualize and evaluate both offline and online mirror surfaces. Further, we present a closed-loop "mounting – inspection – optimization" assembly process based on the combination of interferometric measuring, finite element simulation and digital reconstruction, which will lead the mounting induced surface error of the large optics to meet the wavefront criterions. Through a case study of the large aperture laser transport mirror, the proposed approach is proved to have good performance on both improving optical mounting performance and obtaining accurate surface features.

1. Introduction

Thousands of large optics are employed in the SG-III inertial confinement fusion (ICF) facility, which holds the largest high power solid-state laser system in China. In this stadium-sized facility, 48 laser beams possessing 3.75 kilojoules are transported along an 85-m beam path through hundreds of line-replaceable units (LRUs) and converged at the target capsule igniting deuterium-tritium fusion with a targeting accuracy requirement of 50 μm (Root Mean Square, RMS) [1]. Designed with favorable interchangeability, LRUs could be removed and replaced quickly, safely, and cost-effectively once the optics in it suffer serious damage [2,3]. Derived from the overall performance requirements of the laser system [4], every optical component in the LRU has extremely stringent surface accuracy requirements, and consequently, each LRU must meet many demanding requirements on mechanical precision, stability and cleanliness. However, due to the impacts from gravity, mounting and their own defects, optical surface errors can often appear on these large aperture mirrors and result in bad beam quality which will severely affect the focusability at the target point [5]. So far, it is still difficult to analyze the distorted surfaces of online optical components which are installed at varying spatial attitudes and tough to be measured. At the same time, there are still huge technical challenges in mitigating surface distortions of such large-aperture laser optics.

For realizing fusion ignition, future ICF facility will possess more beam paths and higher peak power. As the total number of optical components in next generation ICF facility will increase 6–8 times, it is urgent to have more convenient and effective method to predict, analyze and optimize the surface performance of them. Therefore, taking the laser transport mirror as an example, a surface error modeling and analysis method based on surface error decoupling and reconstruction technology is proposed to evaluate the surface topography in this paper. Furthermore, a close-loop assembly process integrating interferometric measuring, finite element simulation and digital reconstruction is presented to meet the strict specifications of mounting induced surface error. Finally, a case study is conducted to validate their performance and advantages.

2. Opto-mechanical configuration

In order to ensure the uniformity of the irradiation energy on the deuterium-tritium target capsule, SG-III requires that the incident attitudes of 48 laser beams should be evenly arranged in space [6]. As

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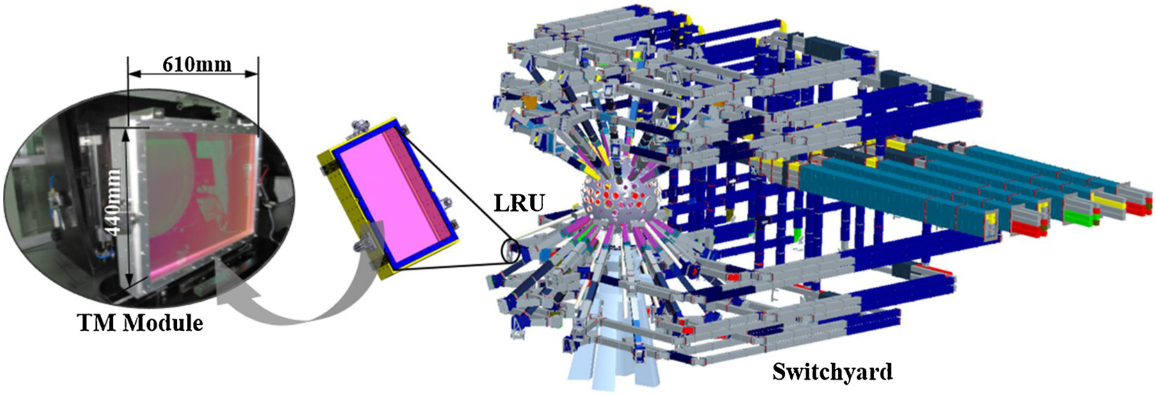

Fig. 1. Transport mirror (TM) module in the switchyard of target area.

shown in Fig. 1, the large-aperture laser transport mirror are used to change the original propagation direction of the laser beam and guide them toward the target point at the specific incident angle. With the size of 610 mm × 440 mm × 85 mm and the weight of about 60 kg, the transport mirror is the largest optical component in ICF facility [7]. Therefore, in order to firmly hold such a large component, a mechanical peripheral mounting process is applied. Firstly, the transport mirror is positioned in a high-rigidity aluminum frame and then fixed with 94 screws from four sides. Next, a hollow rectangular pressure plate is used to limit the mirror along its normal direction. After offline inspection and alignment, the transport mirror assembly is embedded into the LRU with three kinematic joints. Finally, the LRU is transported and installed into the superstructures in the switchyard [8]. It can be seen that the laser transport mirror is a typical opto-mechanical module in ICF laser system, and its mechanical assembly quality will have significant impacts on the laser optical performance. Both the surface error and positioning error can result in a performance degradation of high power laser beam.

3. Method

In order to improve the service performance of the laser transport mirror, we have conducted in-depth research on the surface errors. In this section, based on detailed analyses of the sources and characterization methods of surface errors, we introduce a decoupling method as a fundamental tool to process the optical surfaces with multi-scale textures. Moreover, a surface error reconstruction method is put forward to predict and analyze the actual surface condition of online transport mirror. Finally, a close-loop assembly process and an integrated surface error optimization method are presented.

3.1. Mirror mechanical modeling

Based on investigations of mechanical configuration and assembly process, we first make clear the static mechanic model and boundary conditions of the transport mirror module. In consideration of the efficiency of modeling and calculations, we have made some reasonable simplifications of the actual transport mirror module [9,10]. In fact, the problem of transport mirror deformation during assembly can be reduced to a rectangle block constrained by multiple loads and displacements. Therefore, components such as the aluminum frame, the pressure plate and screws can be omitted when constructing the mechanical model of the mirror. It is only necessary to retain the transport mirror and set the boundary conditions that are consistent with the actual state of the element. As shown in Fig. 2, we can assume the boundary conditions as follows.

3.1.1. Boundary conditions of loads

At the upper edges (*L*), uniform distributed linear pressure $\sigma_y = -P$;

At all sides of mirror, the preload of each screw is $P\ (i),\ i = 1, 2 \ldots, 94$

3.1.2. Boundary conditions of displacements

At the position of each screw's preload, if the preload is directed along the *X*-axis, there are: $\Delta y = 0,\ \Delta z = 0;$ If the preload is directed along the *Y*-axis, there are: $\Delta x = 0,\ \Delta z = 0.$

Because the bottom edges (*S*) are supported by the mirror frame, there is $\Delta Z_s = 0.$

Additionally, we have the differential equation for the bending of a plate [8]:

$$\begin{cases} \frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} = \frac{1}{D}\left(p_r + \sigma_x \frac{\partial^2 w}{\partial x^2} + 2\tau_{xy}\frac{\partial^2 w}{\partial x \partial y} + \sigma_y \frac{\partial^2 w}{\partial y^2}\right) \\ D = \frac{Eh^3}{12(1-\nu^2)} \end{cases} \tag{1}$$

Where σ_x is the normal stress along *X*-axis, σ_y is the normal stress along *Y*-axis, τ_{xy} is the shear stress along *X*-axis, p_r is the function of load distributed on the plate surface [9], D is the bending stiffness of the plate, and w is the normal displacement in the middle plane. E, ν and h are the modulus of elasticity, Poisson's ratio, and the thickness of plate, respectively.

3.2. Surface error analysis

Due to the special functional requirements and extreme operating environment, there are significant differences between the specifying of ICF optics and that of general optics [11]. At first, ICF optics usually have large apertures, typically 300–900 mm, which leads the scale range of geometrical feature covers almost 6 magnitudes (1000–0.001 mm). Moreover, surface errors of ICF optics can result in power related amplification of spatial inhomogeneity, which will seriously affect the high-power beam quality and even determine whether it is possible to achieve fusion ignition. Accordingly, there are more detailed classification and more stringent specification of surface errors of ICF optics. As shown in Table 1, the surface quality of large-aperture transport mirror in SG-III facility is measured by phase measuring interferometer (PMI) and specified with three parameters (roughness, waviness and figure) over four widely separated spatial frequency bands (Fig. 3). In fact, surface errors in different spatial frequency regions have different sources [12] and will cause different effects on the performance of the laser beam:

A High-frequency surface errors ($8\ \text{mm}^{-1} - 100\ \text{mm}^{-1}$) are generated by the material inhomogeneity or the cost-effective finishing technology. As the gain functions have fallen to nearly 1 [13], surface error in this region does not produce high intensity modulation and severe diffraction losses but brings about surface and bulk scattering losses. Thus, small-aperture phase measuring