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A method of sub-aperture slope stitching for testing flat element based on phase measuring deflectometry

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ABSTRACT

Phase measuring deflectometry (PMD), which is a slope measurement technique based on fringe reflection, is a contact-free, high dynamic range, full field metrological method. In this paper, the method of sub-aperture slope stitching based on PMD is proposed for testing large-size optical flat, and a two-camera stitching test system is built in our lab to verify this suggestion. We discuss in detail what aberrations are brought into the measurement result due to the errors of alignment and calibration between the reference camera and the others. In our test system, all cameras are attached around the LCD display to enable the different cameras 'see' the different areas of a test component at the same time without moving any devices or the test component. Next, based on the measurement result of multiple cameras, the full global slope data are obtained with a minimum stitching error by using our stitching model and corresponding algorithm proposed in this paper. The stitched slope data are integrated to obtain the figure of the test surface. The results of simulation experiment show this paper's stitching model is superior to traditional stitching model and algorithm in PMD. Finally, we test an optical flat with a size of 152.6 mm in diameter using our method. The final measurement result shows that our test is nearly consistent with the result measured by Fizeau interferometer. It reveals that this method has advantages in testing large-size optical flat with a high-accuracy and cost-effective.

1. Introduction

The large-size optical flat are widely used in high power laser systems [1,2] and astronomy [3]. In order to guide the processing of optical elements manufacturing and evaluate the quality of optical surface, an effective test method is essential. The common test method is interferometry [4,5]. However, the interference testing method usually requires a reference flat with the same size of test element. Generally, such a large and high-quality reference flat is obtained difficultly. Another way to test the large-size optical flat is to use small-scale interferometer instead of large-scale interferometer and sub-aperture stitching test is a popular method [6–8]. However, sub-aperture stitching test methods usually need to move the measuring devices or the test element repeatedly until covering the entire surface. Besides, interferometer is used in this method, and it means a testing need to be implemented in a qualified environment. Therefore, it is not suitable for testing large optical flats and also not applicable for on-line testing.

Apart from interferometric methods, phase measuring deflectometry (PMD), a slope measurement technique based on fringe reflection, provides a contact-free, high dynamic range, full field metrology method with easy system setup and alignment. It can be used to test free-form surface, large aperture aspheric reflector [9], discontinuous specular objects [10,11] and etc. with high-accuracy [12]. In 2010, Su et al. proposed the software configurable optical test system (SCOTS), a similar technique of PMD, as a Hartmann test in reverse to achieve optical metrology of aspheric optics [13], such as a 130 mm off-axis parabolic mirror, a 1 m solar reflector segment and the 8.4 m diameter off-axis segment for Giant Magellan Telescope (GMT) [9,13,14], but it requires a 25 m working distance for GMT. In 2014, Evelyn Olesch et al. addressed a 4 cameras measurement system with stitching method to test a 1.2 m flat-to-flat prototype mirror with radius of curvature 32 m, and the inspection accuracy was better than 10 μm. It shows that a multi-camera stitching test system can shorten the working distance, save space, and improve the lateral resolution [15]. However at present, PMD is used rarely to test large optical flats. The major challenge is the alignment and system calibration [16] when the traditional PMD is used to measure large optical flats. The large low-order aberrations are inevitably introduced during the measurement with the use of the large size LCD screen. Thus, the stitching test is needed and attractive. However, the stitching test has been applied mainly in interferometry and Hartmann test [17,18]. If traditional (piston-tilt) stitching model [7,19] and corresponding algorithm are used in PMD directly, the measurement accuracy will be difficult to

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Table 1
The difference of Zernike coefficients caused by the perturbation of each DOF.

Terms/Sensitivity		Z4(nm) (Defocus)	Z5(nm) (Oblique astigmatism)	Z6(nm) (Vertical astigmatism)	Z7(nm) (Vertical coma)	Z8(nm) (Horizontal coma)	Z9(nm) (Vertical trefoil)	Z10(nm) (Oblique trefoil)	Z11(nm) (Primary spherical)
The error of 1 mm is artificially introduced, respectively	x_c	20.94	1.73	9.74	−0.01	2.27	−0.01	−0.03	−0.01
	y_c	3.70	9.88	−1.76	2.32	−0.01	−0.03	0.01	0
	z_c	159.98	−0.62	−1.67	−0.10	−0.54	0	0	−0.05
	x_m	−41.90	−3.46	−19.54	0.02	−4.53	0.02	0.05	0.02
	y_m	−7.51	−19.75	3.58	−4.63	0.02	0.05	−0.02	0
	z_m	1.20	0	−0.01	0	0	0	0	0
	x_s	20.96	1.73	9.80	−0.01	2.26	−0.01	0.03	−0.01
	y_s	3.81	9.87	−1.82	2.31	−0.01	−0.03	0.01	0
	z_s	−158.78	0.62	1.66	0.10	0.53	0	0	0.04
The error of 1mrad is artificially introduced, respectively	screen tilt x	−0.15	0	0	0.21	0	0	0	0
	screen tilt y	−0.14	0	−0.20	0	0	0	0	0
	screen tilt z	−1.71	410.46	−0.76	−0.61	−0.17	−0.49	0.09	0
	flat tilt x	0.15	0	−0.21	0	0	0	0	0
	flat tilt y	0.14	0	0.20	0	0	0	0	0

be improved. Thus, the slope stitching method in PMD needs further study.

Different from the traditional sub-aperture stitching method based on moving the measuring devices or the test element, we propose a multi-camera sub-aperture slope stitching test method based on PMD, which can measure on-line large-size optical flat. In this case, different cameras observe different areas of the test element simultaneously to complete measurement. It has the strengths of fast measurement, space saving, and is not sensitive to the measurement environment. Under the traditional stitching model, it is generally thought of as that the errors of piston and tilt will be introduced into the measurement data during the movement of devices. Therefore, these errors should be corrected before connecting adjacent areas together. However, under the multi-camera stitching model like the PMD in our paper, the types of errors among different cameras due to inaccurate alignment and calibration are more than piston and tilt. Thus, the higher order terms should be selected to fit the slope measurement data and correct these errors. In particular, these higher order terms should be paid more attention when the size of the element is so large enough to induce a significant alignment error which cannot be neglected. It is noted that for simplicity of discussion, this paper is taking two cameras as an example.

2. Principles

Fig. 1 shows the schematic of our two-camera stitching test system based on PMD. This test system is composed of a LCD screen as a structured light source, 2 pin-hole cameras with imaging lens as optical sensing devices, a flat as a test element, and a computer as a controlling and processing unit. In this method, phase-shifting fringe patterns are displayed on the LCD screen and the two cameras observe different areas of the element and capture the deformed fringe patterns reflected by the specular reflective surface, respectively. In this paper, the principle is based on the inverse Hartmann test. It is assumed that each CCD pixel of the PMD/SCOTS cameras can be thought of as a point source emits a ray back to the test element and illuminate the corresponding screen pixel after reflection. The reflected light is analyzed to provide an accurate measurement of slope variations on the surface under test. The surface slope can be determined by triangulation using the coordinates of the illuminated screen pixel, the camera and the test surface, as described in Eq. (1), which was first described by Ritter et al. and then

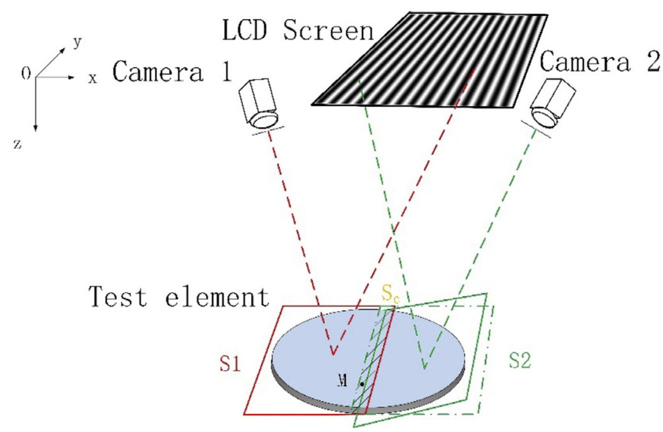

Fig. 1. Schematic of two-camera stitching test system based on PMD.

proposed in a similar manner by Su et al. in 2010. [20].

$$\tan\theta_x(x_m, y_m) = \frac{\frac{x_m - x_s}{d_{m2s}} + \frac{x_m - x_c}{d_{m2c}}}{\frac{z_{m2s}}{d_{m2s}} + \frac{z_{m2c}}{d_{m2c}}} \quad \tan\theta_y(x_m, y_m) = \frac{\frac{y_m - y_s}{d_{m2s}} + \frac{y_m - y_c}{d_{m2c}}}{\frac{z_{m2s}}{d_{m2s}} + \frac{z_{m2c}}{d_{m2c}}} \qquad (1)$$

where x_c, y_c and z_c are the coordinates of the pin-hole camera. x_m and y_m are the coordinates of the test surface that can be obtained from the calibration process. x_s and y_s are the coordinates of the illuminated pixel on the LCD screen that can be calculated by phase shifting method [21]. z_{m2s} and z_{m2c} are the z coordinates differences between the test surface and the screen and between the test surface and the camera, respectively. d_{m2s} and d_{m2c} are the distances between the test surface and the screen and between the test surface and the camera. These coordinates can be obtained from geometry measurement and calibration process [16,22].

In Fig. 1, the area within the red line block represents the sub-aperture S_1 and the area within the green represents the sub-aperture S_2, which are observed by camera 1 and camera 2, respectively. There is a common area S_c between the two adjacent sub-apertures. In the test, these separately measured slopes data cannot be directly connected together because there is a relative difference between the slopes of the two sub-apertures obtained by Eq. (1) due to the system calibration errors and alignment errors. In order to correct the relative errors, the slope data on the overlapping area S_c are used to determine the corre-