Error Analysis of the plate beamsplitter in near optical coaxial phase measurement deflectometry

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Abstract. Phase-measuring deflectometry (PMD) is a key measurement technology for specular surfaces form measurement. Compared with the phase measuring deflectometry techniques based on the conventional configuration, the near optical coaxial phase measuring deflectometry (NCPMD) can achieve compact configuration, light weight and insignificant measurement error caused by structure shadows by utilizing a plate beamsplitter. However, the introduction of the plate beamsplitter will make some influence of the measurement accuracy of the NCPMD system. In the one hand, the introduction of the plate beamsplitter can reduce the measurement accuracy of the NCPMD system due to the refractive of the ray between the two surfaces of the beamsplitter. In the other hand, due to the processing and manufacturing problems of the beamsplitter, there are inevitably certain unevenness errors on the upper and lower surfaces. In this paper, a virtual simulation system of NCPMD is established, and an error model of the NCPMD system by considering both the refraction influence and reflection influence of the plate beamsplitter is presented to analyse the shape reconstruction error caused by the plate beamsplitter.

1 Introduction

Widely used for surface slopes measurements and for three-dimensional shape reconstruction, deflectometry is a particularly powerful technique that can also be applied for defects detection on specular surfaces [1-3], such as optical elements, polished metal surfaces, automobile and aircraft painted surfaces, and solar reflectors. PMD solves for the three-dimensional shape of a mirrored object by quantifying the degree of deflection of the reflected light [4].

To improve the system compactness and efficiency, Gao et al. [5] presented a portable NCPMD by utilizing a plate beamsplitter for portable and embedded measurement of structured specular surfaces. Compared with the measurement accuracy of existing PMD technology, it also has significantly advanced portable and embedded shape measurement performance, such as small system size and light weight. However, there are several factors introduced by the beamsplitter will influence onto the measurement accuracy of the NCPMD

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system. In the above the reported research the factors of the beamsplitter that can affect the measurement accuracy of an NCPMD system, such as the flatness and refraction effects of the plate beamsplitter used has not been discussed. This paper presents an error model based on the NCPMD system. A virtual measurement system has been developed to analyze the system measurement error caused by beamsplitter.
The paper is organized as following. The principle and methods of the proposed configuration is presented in Section2. In section 3, error analysis of the beamsplitter based on the simulation experiment results, including refraction error and reflection error. The conclusion is presented in Section 4.

2 Principle

2.1 The principle of NCPMD system

A schematic of NCPMD system is shown as Fig. 1. The NCPMD system is consists of two cameras, an LCD (liquid crystal display) screen and a beamsplitter. The LCD screen is used to display two groups of orthogonal phase-shifting sinusoidal patterns. Through the reflection of the beamsplitter, the fringe patterns displayed on the LCD screen is reflected on the surface under test. The cameras are required to capture the fringe patterns displayed on the screen through the reflection of the surface under test. Then, according to the phase-shifting and phase unwrapped algorithm [6] and system calibration results, the three-dimensional (3D) information of the measured surface can be obtained.

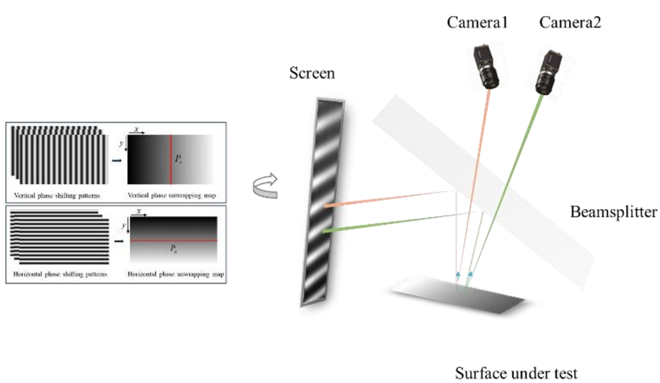

Fig. 1. Illustration of the principle of the NCPMD system configuration.

2.2 The principle of the proposed error model

According to the ray tracing algorithm, the illustration of the proposed error model is illustrated in Fig. 2. In this simulation system, the two surfaces of the beamsplitter are named BS surface1 and BS surface2 respectively. The reconstruction error of the beamsplitter can be determined by the error model that considers both refraction and reflection errors. The refraction error model is shown in Fig. 3.

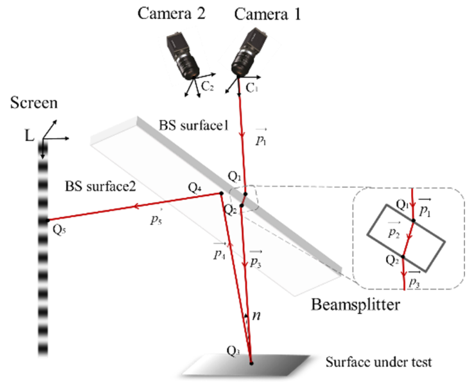

Fig. 2. The illustration of the proposed error model.

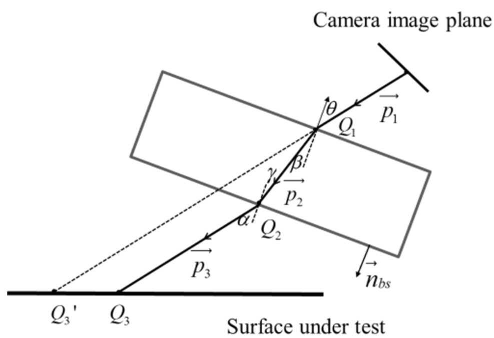

Fig. 3. The illustration of the proposed refraction error model.

The probe ray $\boldsymbol{p_1}$ intersects with surface1 at the point Q_1. The probe ray enters the beamsplitter from the air for the first refraction, and the refraction point is Q_1.

$$Q_1 = C_n + |C_n Q_1| \boldsymbol{p_1} \tag{1}$$

The incidence angle of the first refraction is denoted by θ, as seen in Fig.3. p_1 is an undetermined constant.

$$p_1 = \sqrt{n_f^{\,2} - 1 + \cos^2\theta} - \cos\theta \tag{2}$$

where $\cos\theta = \boldsymbol{p_1} \times \boldsymbol{n}$, $\boldsymbol{n}$ is the normal vector of the beamsplitter. And the refraction point $Q_1 = (Q_{1x}\ Q_{1y}\ Q_{1z})^T$, n_f is the refractive index of the beamsplitter.

$$n_f g \boldsymbol{p_2} = \boldsymbol{p_1} + p_1 g \boldsymbol{n}_{bs} \tag{3}$$

where $\cos\beta = \boldsymbol{n} g \boldsymbol{p_2}$, $\boldsymbol{n}_{bs}$ is the unit normal vector of the beamsplitter. After the first refraction, the refracted ray $\boldsymbol{p_2}$ then intersects surface2 at $Q_2\ M_2$. And Q_1Q_2 represents the straight-line distance between two refraction points.

$$Q_1Q_2 = d_f / \cos\beta \tag{4}$$

where d_f is the thickness of the beamsplitter. And p_2 is an undetermined constant.

$$p_2 = \sqrt{1 - n_f^{\,2} + n_f^{\,2}\cos^2\gamma} - \cos\gamma \tag{5}$$

where $\cos\gamma = -\boldsymbol{p_2} g \boldsymbol{n}$. In the second refraction, the refracted ray as $\boldsymbol{p}_3\ M_2$.

$$\boldsymbol{p_3} = \boldsymbol{p_2} g n_f + p_2 g \boldsymbol{n_{bs}} \tag{6}$$

$\boldsymbol{p}_3$ is then traced to surface3 and reflected at Q_3 M_3. The probe ray is first reflected at point Q_3.

$$Q_3 = Q_2 + |Q_2Q_3| \boldsymbol{p_3} \tag{7}$$

The reflected ray $\boldsymbol{p}_4$ is traced back to surface2 and reflected off M_4. The probe ray is second reflected at point Q_4.

$$\boldsymbol{p_4} = \boldsymbol{p_3} - 2\boldsymbol{n}_{sut}(\boldsymbol{n}_{sut} g \boldsymbol{p_3}) \tag{8}$$

where $\boldsymbol{n}_{sut}$ is the unit normal vector of the surface under test. The reflected ray $\boldsymbol{p}_5$ finally strikes the screen at Q_5.

$$\boldsymbol{p_5} = \boldsymbol{p_4} - 2\boldsymbol{n}_{bs}(\boldsymbol{n}_{bs} g \boldsymbol{p_4}) \tag{9}$$\

3 Error analysis of beamsplitter

3.1 Refraction error of the beamsplitter

The measurement error caused by beamsplitter refraction, the refraction error of the beamsplitter is analyzed by two physical parameters named refraction index and the angle of the beamsplitter. Under ideal conditions, the refractive index is 1 regardless of the refractive effect of the beamsplitter. The beamsplitter used in the actual experimental system is 1.1mm thick. The material of the beamsplitter used in the actual experimental system is silicon dioxide with a refractive index of 1.5. The Zernike polynomial is used as the polynomial[7,8]. Another factor affected by beamsplitter refraction is the angle of beamsplitter. When the refractive index of the beamsplitter is 1.5, the shape reconstruction error peak value (PV) and root mean square (RMS) of the beamsplitter at different angles are shown in Fig. 4. The angle of beamsplitter will not only affect the accuracy of the measurement results, but also affect the effective field of view of the measurement. Though, the angle of beamsplitter can vary from 0° to 90°, in order to ensure that the system has a certain effective field of view for measurement, only 20° to 70° angle changes can be considered. As the angle increases from 20° to 70° with a step size of 10°, the shape reconstruction error RMS considering refractive index = 1.5 of the beamsplitter is shown in Fig. 4. The errors of shape reconstruction PV and RMS are obvious at 40° to 50°.

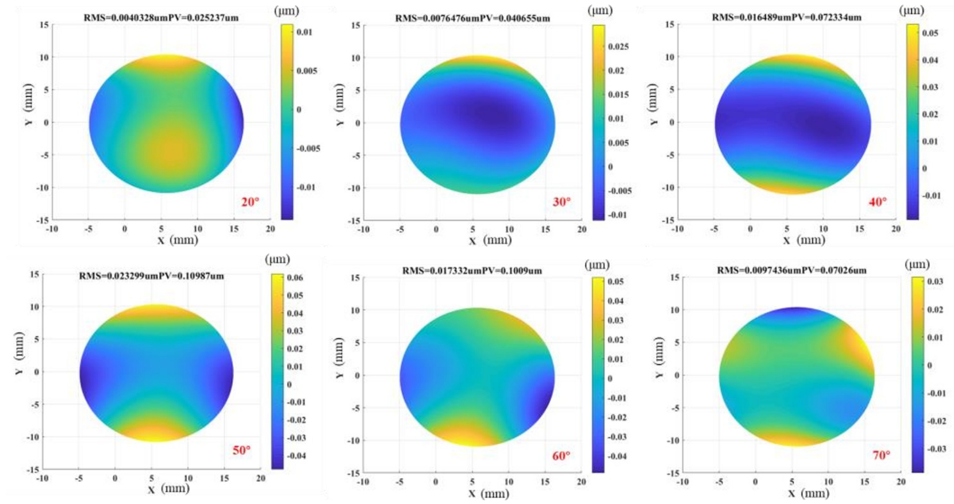

Fig. 4. Shape reconstruction error RMS of beamsplitter with refractive index=1.5 at different angles.

3.2 Reflection error of the beamsplitter

Due to the processing and manufacturing problems of the beamsplitter, there are inevitably certain unevenness errors on the upper and lower surfaces. Therefore, due to the unevenness of the upper and lower surfaces of the flat beamsplitter, the reflection effect of the flat beamsplitter will introduce certain measurement errors to the measurement results. Under ideal conditions, the value of PV is 0. But the PV of the beamsplitter used in the experiment cannot be 0. According to the characteristics of the beamsplitter used in the actual experiment and the optical detection results, the upper and lower surfaces of the beamsplitter have out-of-plane shape of PV~0.15mm respectively.

Among the influencing factors of reflection on the shape reconstruction error RMS, in addition to the influence of the PV value on the surface of beamsplitter, the angle of the beamsplitter will also have a certain influence on the measurement results. Also considering the effective field of view of the measurement system, the measurement angle is considered at 20°-70°. As the angle increases from 20° to 70° with a step size of 10°, the shape reconstruction error RMS considering reflection effects of the beamsplitter is shown in Fig. 5. The PV and RMS errors of the overall shape reconstruction at 40°-50° cannot be ignored.

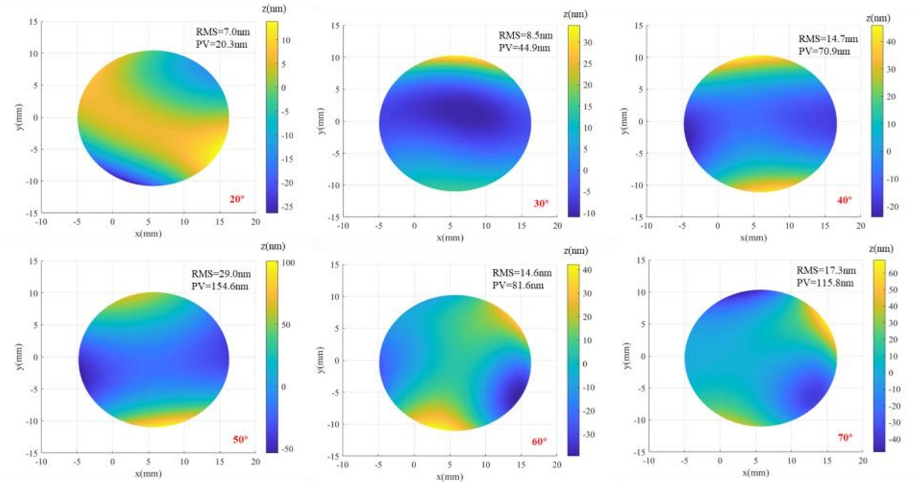

Fig. 5. Shape reconstruction results of beamsplitter with reflection error at different angles.

4 Conclusion

A virtual measurement system has been developed based on a NCPMD technique. The effects of the beamsplitter on the measurement results have been analyzed. Among them, the impact of the refraction effect and reflection effect of the beamsplitter on the measurement results is mainly analyzed and discussed comprehensively. Simulated experiments were carried out. For the refractive error of the beamsplitter, the influence of the refractive index of the beamsplitter and the angle of the beamsplitter on the measurement results are discussed. For the reflection error of the beamsplitter, the influence of the surface roughness of the beamsplitter and the angle of the beamsplitter on the measurement results are discussed respectively. Therefore, suitable system parameters can be selected for the actual NCPMD measurement system to obtain the 3D shape of a specular object with high accuracy. Moreover, according to the error analysis of the simulated system, the system with known specific beamsplitter parameters can determine the error of the system measurement, so that the measurement accuracy can be effectively improved through error compensation.

References

1. Y. Xu, F. Gao, X. Jiang, PhotoniX **1** 1-10 (2020)
2. J. Burke, A. Pak, S. Hofer, M. Ziebarth, M. Roschani, J. Beyerer, arXiv preprint, **2204.11592** 1-43(2022)
3. L. Huang, M. Idir, C. Zuo, A. Asundi, Opt. Lasers Eng. **107** 247-257 (2018)
4. L. Huang, J. Xue, B. Gao, C. McPherson, J. Beverage, M. Idir, Opt. Express **24**(21) 24649-24664 (2016)
5. F. Gao, Y. Xu, X. Jiang. Opt. Express **30**(10) 17554-17566 (2022)
6. C. E. Towers, D. P. Towers, J. D. C. Jones. Opt. Lasers Eng. **43**(7) 788-800 (2005)
7. C. Zhao, J. H. Burge, Opt. Express **15**(26) 18014-18024 (2007)
8. C. Zhao, J. H. Burge, Opt. Express **16**(9) 6586-6591(2008)