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600-mm aperture simultaneous phase-shifting Fizeau interferometer

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ABSTRACT

In this study, a 600-mm aperture simultaneous phase-shifting Fizeau interferometer is presented. This interferometer has a special light source configuration produced by an arrangement of four identical point sources diffracted by a phase grating. With this configuration, the phase shifts are introduced between each pair of coherent beams. A 2×2 image lens array is designed such that four conjugated interferograms with a phase step of $\pi/2$ can be captured in a single shot using one detector, thereby realizing dynamic measurement. The experiment was carried out using the proposed interferometer with a pair of 600 mm aperture transmission flat and reference flat placed on a platform with no vibration resistance facility. The results depict a peak-valley value of $\lambda/10$ and present a real-time phase variation caused by environmental factors, which indicates that the instantaneous measurement of the phase by the proposed large-aperture interferometer provides robust results despite the presence of environmental factors such as vibration and airflow.

1. Introduction

With the increasing aperture size, the measurements of optical instruments has become proportionally more difficult. The commonly used instrument for surface measurement is Fizeau interferometer because of its common-path configuration that can reduce or eliminate the error influence of the optical system of an interferometer. At present, the type of laser interferometer with an aperture of 600 mm or larger is Fizeau interferometer, such as the wavelength phase-shifting interferometer [1] and the piezoelectric ceramic transducer (PZT) phase-shifting interferometer [2], which are the mainstream instruments for surface measurement. The phase shifting accuracy of these interferometers in the data acquisition process is compromised by environmental disturbance, resulting in measurement errors in the following major aspects. (1) The test mirror and interferometer usually cannot be placed on the same vibration isolation platform, causing deflection and jitter of interference fringes; (2) a large-aperture test mirror is vulnerable to acoustic shock, which cannot be blocked by the vibration isolation platform; (3) cavity temperature difference leads to fringe twist; and (4) air turbulence causes fringe drift. These environmental disturbances are difficult to control during testing, and the best solution to reduce their influence is the dynamic interferometer, which can measure the transient wavefront and calculate the average of a large statistical sample.

At present, the commonly used dynamic interferometers are mainly based on polarizing interferometric methods. Kimbrough et al. [3] proposed a low-coherence light source method, which captures four phase-shifting interferograms simultaneously using a micro-polarized array. Limitations in the production process of micro-polarized arrays may be the bottleneck for improvements of the spatial resolution of this type of interferometer. Moreover, for a large-aperture interferometric system, the optical uniformity aberration caused by stress birefringence cannot be completely eliminated due to factors such as glass material manufacturing and mechanical support [4]. The aberration can cause contrast blur and wavefront measurement error. Szwaykowski et al. [5] presented a simultaneous phase-shifting module, which captures three phase-shifting interferograms simultaneously using three charge-coupled devices (CCDs). This configuration can make full use of the CCD target to achieve high-resolution measurement. However, the measurement accuracy is limited by the systematic error caused by the non-common-path structure of the interferometer. Although the off-axis aberration can be eliminated by switching the light sources, the measurement efficiency is still affected. This method also applied to an interferometer with a large aperture of 300 mm [6]. Abdelsalam et al. presented the possibility of performing instantaneous phase-shifting Fizeau interferometry by using a quarter waveplate with high flatness as a reference [7]. However, quarter waveplates with high flatness and large

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aperture are difficult to fabricate; thus, the aperture of the interferometer is limited. In addition to the polarizing interferometric methods, Sykora and de Groot also presented a type of dynamic Fizeau interferometer using the single-frame carrier fringe method [8]. However, the employment of high-density linear carrier frequency in these designs produce a systematic error, caused by non-common-path of the coherent beams in the interferometer, which need correction. Moreover, the errors of refractive index uniformity and stress birefringence are more pronounced in large-aperture transmitted optics including the collimating lens and transmitted reference flat of the Fizeau interferometer, which limits the development of such interferometer to the large aperture.

In this study, we present a 600-mm aperture dynamic Fizeau interferometer, where simultaneous phase shifting is achieved by changing the positions of four point sources, which is designed for a certain point source geometry. The point sources of the interferometer are not required to be polarized, yet, the reference and test beams are inclined to each other. The interferometer can achieve high-resolution measurement of 600-mm aperture optics with a precision of λ/10 in unstable environments.

2. Theory

2.1. Optical layout

The optical layout of the proposed interferometer is shown in Fig. 1. Four spherical wavefronts emitted from the point source array are transmitted through the beam-splitting film and then collimated by the collimating lens. Each collimated beam is reflected by the reference and test mirrors and forms a pair of coherent beams. All the coherent beams are returned to the imaging system and simultaneously form four phase-shifting interferograms in different positions of the detector, thereby realizing dynamic measurement.

2.2. Principle of simultaneous phase shifting

In conventional Fizeau interferometer, the incident beam is perpendicular to the reference surface and the phase-shifting interferograms are obtained by changing the distance between the reference and test surfaces, while the incident angle on the reference surface is changed to achieve phase shifting in the proposed interferometer. The principle of simultaneous phase shifting is illustrated in Fig. 2. The reference and test surfaces form a wedge depicted by an angle α. SA is an incident ray of the collimated beams that meets the reference surface at point A. The corresponding reflected and refracted rays are represented by AP and AB, respectively. After further reflection at B on the test surface and subsequent refraction at C on the reference surface, the emergent ray CP meets the first ray AP at P. The optical path difference between the reference and test wavefronts can be expressed as

$$\Delta = n'(AB + BC) + n(CP - AP), \tag{1}$$

where n and n' are the refractive indexes above and below the reference surface, respectively. According to the geometric relationship, we can obtain

$$AB + BC = \frac{2\rho \sin\alpha \cos\alpha}{\cos(\theta' - 2\alpha)}, \tag{2}$$

$$CP - AP = \frac{-2\rho \sin\alpha \sin\left(\theta - \frac{\phi}{2}\right) \sin(\theta' - \alpha)}{\cos\frac{\phi}{2} \cos(\theta' - 2\alpha)}, \tag{3}$$

where ρ is the distance of A from the apex O of the wedge and ϕ is the angle between the reflected ray and the refracted ray. θ' is the refractive angle, which is calculated by $n' \sin\theta' = n \sin\theta$, where θ is the incident angle. According to the coordinate system shown in Fig. 2, the normal vectors of the reference and test surface are written as $\vec{N_r} = (0, 0, 1)$ and $\vec{N_t} = (\sin\alpha, 0, cos\alpha)$, respectively. Suppose the incident ray vector $\vec{S} = (\cos x, \cos y, \cos z)$, then the rays reflected by reference and test surfaces can be expressed as $\vec{S_r} = (\cos x, \cos y, -\cos z)$ and $\vec{S_t} = (n/n' \cos x - 2\sin\alpha\cos\theta_t, n/n' \cos y, \sqrt{1 - (n/n' \cos x)^2 - (n/n' \cos y)^2} - 2\cos\alpha\cos\theta_t)$, respectively, where $\cos\theta_t = n/n' \sin\alpha \cos x + \cos\alpha\sqrt{1 - (n/n' \cos x)^2 - (n/n' \cos y)^2}$. Thus, we can obtain

$$\cos\phi = \frac{\vec{S_r} \cdot \vec{S_t}}{|\vec{S_r}| \cdot |\vec{S_t}|} = \sin^2 y \cos 2\alpha + n/n' \cos^2 y + n/n' \cos^2 x - \cos^2 x. \tag{4}$$

As the interferometer aperture is 600 mm, $x \to \pi/2$, $y \to \pi/2$, $\alpha \to 0$, $\theta \to 0$, $\theta \gg \alpha$, such that $\phi \approx 2\alpha$. Using Eqs. (1)(4),

$$\Delta = \frac{2\rho \sin\alpha \cos\alpha}{\cos(\theta' - 2\alpha)} - \frac{2\rho \tan\alpha \sin(\theta - \alpha) \sin(\theta' - \alpha)}{\cos(\theta' - 2\alpha)} \approx 2n'h\cos\theta', \tag{5}$$

where $h = \rho \tan\alpha$. Eq. (5) indicates that phase shift can be introduced into the interferogram by changing the incident angle. According to Fig. 1 and Fig. 2, $\tan\theta' = d/f$, where d is the offset from

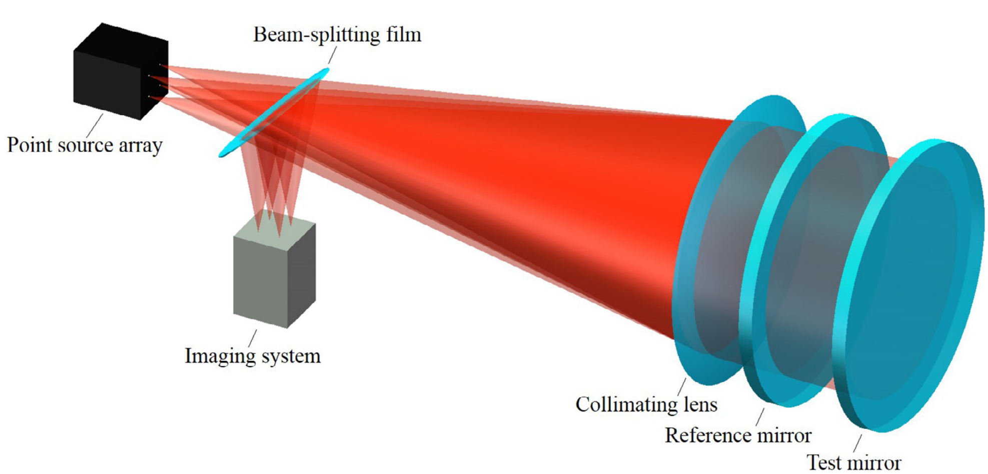

Fig. 1. Optical layout of the proposed interferometer.