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Measurement of displacement using phase shifted wedge plate lateral shearing interferometry

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ABSTRACT

In present communication, a simple technique for measurement of displacement using phase shifted wedge plate lateral shearing interferometry is described. The light beam from laser is expanded and illuminates a wedge plate of relatively large angle. Light transmitted through the wedge plate is converged onto a reflecting specimen using a focusing lens. Back-reflected wavefront from the specimen is incident on the wedge plate. Because of the tilt and shear of the wavefront reflected from the wedge plate, typical straight line fringes appear. These fringes are superimposed onto a sinusoidal grating forming a moiré pattern. The orientation of the moiré fringes is a function of specimen displacement. Four step phase shifting test procedure has been incorporated by translating the grating in phase steps of $\pi/2$. Necessary mathematical formulation to establish correlation between the 'difference phase' and the displacement of the specimen surface is undertaken. The technique is automatic and provides resolution and expanded uncertainty of 1 μm and 0.246 μm, respectively. Detailed uncertainty analysis is also reported.

1 Introduction

Displacement may be defined as a change in the relative position of an object in reference to a fixed point. It may also be referred to as the shortest path length between the final position and the initial position of the object under motion. Precise measurement of displacement or position plays an important role in engineering metrology. Various optical methods have been devised for measurement of displacement. These may be categorized as: time of flight measurement, geometrical measurement, and phase measurement.

Time of flight optical sensors determine displacement by measuring the time it takes for the light to travel from the source to the target and back [1]. The distance is therefore given by the one-way time-of-flight multiplied by the speed of light. The technology has been explicitly used in devices based on the radar, the lidar, and the active acoustic techniques [2,3]. Lasers have been used for very long range distance measurement (up to many miles); for relatively shorter distances LED sources have also been used.

Geometrical techniques consist of variants of triangulation [4,5] and moiré projection [6,7]. Triangulation refers to a procedure in which, the distance or position is determined from the considerations based on the geometries of similar triangles. In projection moiré, image of a grating is projected onto the test surface using projection system. A moiré pattern is finally obtained using a detector grating located on the same side of the projection system, but in a different direction. Here, the coordinate transformation is induced based on the principles of geometry. This results in either the variation in orientation or spacing of the moiré fringes. By analyzing these moiré fringes, data pertaining to the displacement variable is obtained.

Phase measurement techniques use principle of superposition of waves to yield the data regarding the phase difference between the interfering waves. The phase difference carries information regarding position of the specimen surface. On comparing the phase of waves corresponding to two different states of the specimen, the information regarding displacement of the specimen is retrieved. Phase measurement based methods comprise various forms of interferometry [8–11], diffraction [12,13] and speckle [14–17] based techniques. More details regarding the methods and techniques of displacement measurement can be obtained from a review article by Berkovic and Shafir [18]. Interferometric techniques provide almost unparalleled sensitivity and resolution. The results are accurate, precise, and there exist provision for digital recording, storage and retrieval of data. However, interferometric techniques are sensitive to the environmental perturbations as the interfering beams travel widely separated paths. Hence, these

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cannot be used outside the laboratory conditions. This has led to the interest of scientific community towards the common path lateral shearing interferometry.

Lateral shearing interferometry has been applied for wide range of applications such as in 3D surface mapping [19], temperature measurement [20], detection of singularity [21], collimation testing [22] etc. Besides being less sensitive to external perturbations, these interferometers realize geometries which are compact in size and relatively inexpensive. In lateral shearing interferometry, the test wavefront is displaced laterally with respect to the original wavefront and the two beams travel along the same path. The uncertainty due to refractive index of air and extraneous disturbances cancel out. In common superposed region of the wavefronts, typical shear fringes appear which provide information regarding gradient of the wavefront phase in the direction of shear. Wide range of techniques for implementing lateral shear have been reported in literature [23].

Advances in automatic detection and fast processing speed of computers have resulted in development of automated interferogram analysis techniques, leading to the improvement in measurement characteristics of the optical techniques. Spagnolo and Ambrosini [24] used grating shearing interferometric setup based on Talbot effect and Fourier Transform Method (FTM) for the measurement of distance. The technique is suitable for out-of-laboratory applications as it requires low mechanical stability. However, the major disadvantage lies in the fact that distance can only be measured modulo $(1/2)Z_T$, where Z_T is the Talbot distance. Later, this work was extended towards the measurement of displacement using Talbot effect with a Ronchi grating [25].

Measurement of distance using wedge plate lateral shearing interferometry and Fourier transform fringe analysis was proposed by Mehta et al. [26]. The proposed set-up is simple and easy to use. As per the technique, the displacement of specimen leads to the variation in the angle of shearing interferometric fringes. From the shearing interferometric fringes phase data has been reconstructed using Fourier fringe analysis technique. However, the required mathematical formulation correlating the displacement with the phase data has not been undertaken. Hence, the quantitative measurement of distance is not possible. Also, the shearing interferometric fringes have been analyzed using FTM, which requires manual selection of the main frequency component of the fringe pattern. Computational complexity of the algorithm used for FTM analysis is more, hence different approaches such as wavelet transform, Gabor transform etc. have also been proposed.

To counter the limitation of FTM such as the need for introduction of bias fringes, computational complexity etc., many researchers have proposed techniques of incorporating phase shifting procedures in the wedge plate lateral shearing interferometry [27–30]. Ingenuity is required because wedge plate interferometer is a common path interferometer, wherein it is not easy to incorporate the time varying path difference between the interfering wavefronts. In present communication, we report investigations undertaken towards testing the applicability of phase shifted wedge plate lateral shearing interferometry for the measurement of displacement. Measurement of displacement with resolution of 1 μm and expanded uncertainty of 0.246 μm has been achieved. The set-up is simple and uses compact geometry.

2 Basic principle

The schematic of experimental arrangement for measurement of displacement using phase shifted wedge plate interferometry is shown in Fig. 1. Wedge plate P_1 laterally shears the wavefronts reflected from the specimen. A mirror PM acts as a specimen in the experimental set-up. Corresponding to the relative displacement

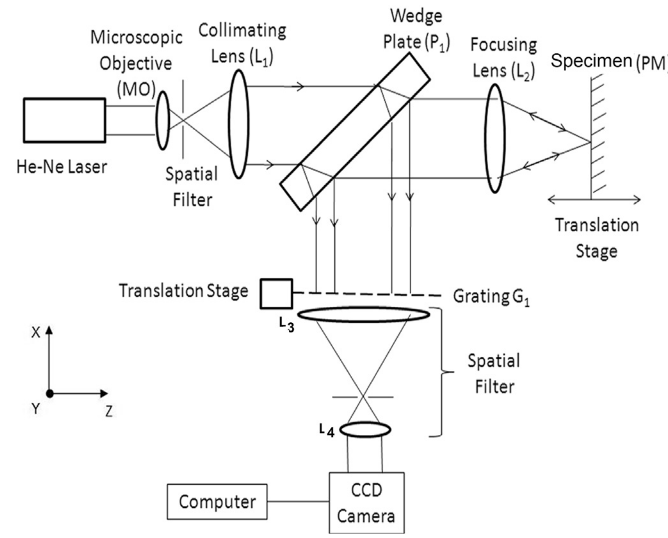

Fig. 1. Schematic of experimental arrangement for measurement of displacement using wedge plate lateral shearing interferometry.

of the specimen with respect to the focusing lens, the wavefront emerging from the lens will be diverging, plane or converging. The phase of wavefront emerging from the lateral shearing interferometer is determined using phase shifting technique. The phase function ϕ of lens of focal length 'd' under quadratic approximation is given by [31–33]

$$\phi(x, y) = \frac{\pi}{\lambda d}\left(x^2 + y^2\right) \tag{1}$$

where, $(x, y)$are the planar co-ordinates of the test lens. After taking the partial derivative of the phase with respect to 'x', following relation is obtained.

$$\frac{\partial\phi(x, y)}{\partial x} = \frac{2\pi x}{\lambda d}$$

Let the specimen be displaced by an amount Δd, the corresponding variation in the phase gradient $\frac{\partial\phi}{\partial x}$ can be given by,

$$\Delta\left(\frac{\partial\phi(x, y)}{\partial x}\right) = \frac{2\pi x}{\lambda}\Delta\left(\frac{1}{d}\right)$$

$$\Delta\left(\frac{\partial\phi(x, y)}{\partial x}\right) = -\frac{2\pi x}{\lambda d^2}\Delta d \tag{2}$$

By rearranging above equation, we have

$$|\Delta d| = \frac{\lambda d^2}{2\pi x}\Delta\left(\frac{\partial\phi(x, y)}{\partial x}\right) \tag{3}$$

where, $\Delta d = d_2 - d_1$ is the displacement of the specimen from position d_1 to d_2 (defocussing distance of the test lens) and $\Delta\left(\frac{\partial\phi(x,y)}{\partial x}\right) = \frac{\partial\phi_2(x,y)}{\partial x} - \frac{\partial\phi_1(x,y)}{\partial x}$, is the corresponding variation in the 'difference phase'. Here $\frac{\partial\phi_2(x,y)}{\partial x}$, and $\frac{\partial\phi_1(x,y)}{\partial x}$ are the slope values (for fixed value of x coordinate) with respect to mirror position at d_2 and d_1, respectively.

The lens system used to form image at the camera phase plate has a magnification of 'm'. By combining Eqs. (1) and (3), we obtain an expression for the displacement 'Δd' of specimen

$$\Delta d = \frac{\lambda d^2}{2\pi m x}\Delta\left(\frac{\partial\phi(x, y)}{\partial x}\right) \tag{4}$$

In shearing interferometry, the interferogram directly provides $\frac{\partial\phi(x,y)}{\partial x}$ information. We use phase shifting interferometry to analyze the interferograms and directly determine the 'difference