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Temporal heterodyne shearing speckle pattern interferometry

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ABSTRACT

Shearing speckle pattern interferometry is a full-field speckle interferometric technique used to determine surface displacement derivatives. In this paper, a new measurement system of real-time heterodyne shearography interferometry is presented. This system combined with heterodyne measurement, shearography interferometry and time domain signal processing technology can dynamically detect the out-of-plane displacement gradient. The principles and system arrangement are described. Using the Jones matrix, the mathematical expression of light intensity distribution passing through this system is deduced. A preliminary experiment was performed to demonstrate the performance of this new device, and simulations were conducted using the finite element method. Comparison of results shows that quantitative measurement of the displacement derivative has been achieved.

1. Introduction

As a significant topic in the industry, surface displacement measurement has attracted attention from researchers from different domains. Among the proposed methods, digital shearing speckle pattern interferometry (DSSPI), in which images speckle through a shearing device that overlaps the speckle pattern on an identical but laterally displaced version of itself, is outstanding because of its advantages in the full-field measurement of out-of-plane displacement gradients. These advantages include an optical configuration more resilient to environment disturbances and vibrations than other interferometric techniques [1]. However, conventional DSSPI employs a phase-shifting technique that requires three or more images with artificial phase shifts for each step during deformation. Therefore, conventional DSSPI cannot meet the requirements of dynamic measurement [2]. Temporal speckle pattern interferometry (TSPI) was introduced to shearography to overcome this disadvantage [3]. By analysing speckle pattern, TSPI extracts the phase in a timely manner and guarantees accuracy.

In previous research, we proposed a temporal digital shearing speckle pattern interferometry system [4]. Here we try to improve its disturbance immunity by coupling it with heterodyne measurement. Different from what is commonly used to generate carrier frequencies, such as a rotating wave-plate which is limited by the frequency of mechanical rotation or an expensive dual-frequency laser [5], we employ an electrically controlled electro-optical frequency shifter using a lithium niobate (*LN*) crystal placed at the centre of two transverse electric fields perpendicular to each other. *LN* crystals are stable under general conditions and can provide a large array of carrier frequencies by adjusting the frequency of the electric fields applied to it. Moreover, no target or moving parts are required and the carrier frequency can be adjusted flexibly.

In recent research, some methods aiming to introduce heterodyning to speckle interferometry have been fairly progressive. However, in most of them, mechanical structures were adopted to generate the beat frequency [6–8], and none of them attempted to couple heterodyning with shearography. In other words, no such system has been put forward. Therefore, here we bond DSSPI with heterodyning, aiming to build a system with both high immunity and instantaneity. When bonded with heterodyning, DSSPI shows extensive application prospects due to its ability to realize full-field temporal measurement in a jamming environment. The result of the experiment compared with a finite element method (FEM) simulation shows that our efforts are successful and the theory is feasible.

2. Principles

2.1. DSSPI

The system configuration to measure the out-of-plane displacement derivative in x-direction is shown in Fig. 1. The light beam from the semiconductor laser is diffusely reflected by the surface of the object after expanding. The shearing device, which is a Wollaston prism in our apparatus, divides the light beam into two identical but staggered beams that are polarized perpendicular to each other [9]. To make the

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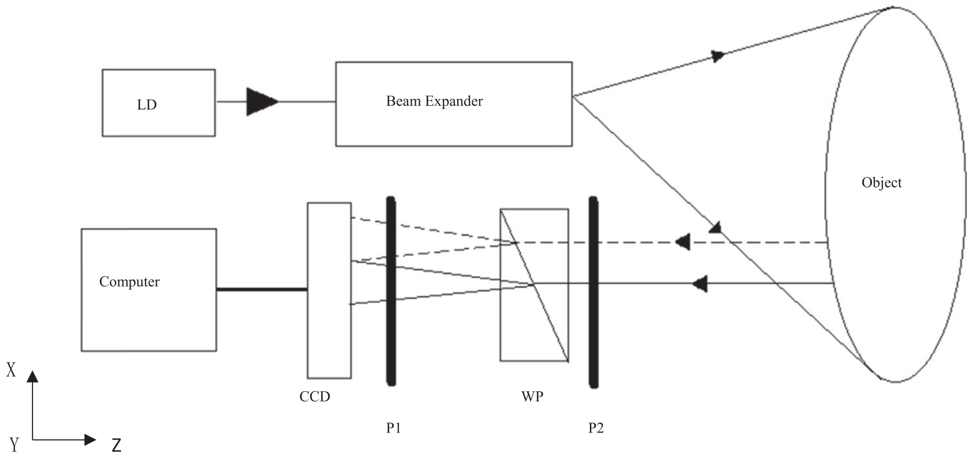

Fig. 1. The optical layout of a digital shearing speckle pattern interferometer based on Wollaston Prism (WP).

polarization directions consistent with each other, a polarizer is placed before the CCD camera. When captured by the CCD, the beams interfere and the light field intensity is assumed to be

$$I = I_0(1 + \gamma \cos \varphi_0), \tag{1}$$

where I_0 is the intensity of the background light, γ is the contrast of the fringes and φ_0 is a random phase factor.

When a tiny deformation occurs on the surface of the object, the light field phase changes. The speckle patterns before and after the deformation are recorded, and the phase can be extracted by several algorithms. In particular, the relationship between the displacement derivative and the phase difference $\Delta\varphi$ can be expressed as [10].

$$\frac{\partial w}{\partial x} = \frac{\Delta\varphi \cdot \lambda}{4\pi\Delta x}, \tag{2}$$

where $\partial w/\partial x$ is the displacement derivative in the x-direction; λ is the wavelength of the laser and Δx is the distance of the two shearing points, which is related to the splitting angle of the Wollaston prism. This means that the displacement derivative is directly proportional to the phase change, and the derivative can be solved if the phase variation is known.

In order to complete a comprehensive measurement, different constructions can be adopted. For example, the derivative of in-plane displacement can be extracted by introducing a collimated light beam for illumination [11].

2.2. Wavelet transformation

In a conventional DSSPI system, phase-shifting devices are widely used to extract the phase information, which means that dynamic measurement cannot be achieved. To address this problem, TSPI was introduced to shearography based on the Michelson interferometer of C. Jonathan, who obtained the phase information using Fourier Transformation (FT) rather than phase-shifting devices [3]. In this paper, wavelet transformation, which is believed to be more suitable for analysing non-stationary signals, is employed to extract the phase information of the measured object [12,13].

The continuous wavelet coefficient can be expressed as

$$W_f(a, b) = |a|^{-\frac{1}{2}} \int I(x, y, t) \cdot \psi^*(\frac{t - b}{a}) dt, \tag{3}$$

where a is the scale parameter; b the shift parameter; $I(x, y, t)$ the intensity distribution shown in Eq. (1) and ψ^* is the mother wavelet, chosen carefully to maximize the amplitude of the wavelet coefficients. The phases and amplitudes of the light field are given by the expressions [14].

$$A(a, b) = \sqrt{(Im(W_f(a, b)))^2 + (Re(W_f(a, b)))^2}, \tag{4}$$

$$\varphi(a, b) = \arctan(\frac{Im(W_f(a, b))}{\mathrm{Re}(W_f(a, b))}), \tag{5}$$

where $Im(W_f(a, b))$ is the imaginary part and $Re(W_f(a, b))$ the real part of $W_f(a, b)$. After unwrapping the phase, the displacement derivative in Eq. (2) can be solved [15].

2.3. Heterodyne

KH_2PO_4 (KDP) and *$LiNbO_3$ (LN)* are well known as technologically important electro-optical crystal materials. Compared to *KDP*, *LN* crystals are of high hardness, are highly deliquescence proof and benignly transmit light between the wavelengths of 0.4 and 5 μm [16,17]. Considering the crystal characteristics and the requirements of our system, *LN* is regard as more suitable than *KDP*.

As shown in Fig. 2, the incident linearly polarized beam is assumed to be

$$\mathbf{V_1} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \exp(-i\omega_0 t). \tag{6}$$

When the voltages are applied in both the x- and y-directions, the *LN* crystal causes a phase difference between the ordinary and extraordinary rays [14]. This phenomenon can be regarded as a *1/n* wave plate rolling at an angular velocity of *ω/2,* with a Jones matrix as follows:

$$\mathbf{T_{LN}} = \begin{bmatrix} \cos\frac{\pi}{n} + i\sin\frac{\pi}{n}\cos\omega t & i\sin\frac{\pi}{n}\sin\omega t \\ i\sin\frac{\pi}{n}\sin\omega t & \cos\frac{\pi}{n} - i\sin\frac{\pi}{n}cos\omega t \end{bmatrix}, \tag{7}$$

where ω is the rotating frequency of the electric fields.

Passing through the crystal, the emanated light from the quarter-wave plate can be represented as

$$\mathbf{V_2} = \mathbf{T_{qwp}} \cdot \mathbf{T_{LN}} \cdot \mathbf{V_1} = \frac{cos\frac{\pi}{n}}{\sqrt{2}} \begin{bmatrix} 1 \\ -i \end{bmatrix} \exp(-i\omega_0 t) + \frac{sin\frac{\pi}{n}}{\sqrt{2}} \{ i \begin{bmatrix} 1 \\ 0 \end{bmatrix} \exp[-i(\omega_0 + \omega)t] + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \exp[-i(\omega_0 - \omega)t] \}. \tag{8}$$

It can be seen that the first item represents a left-circularly polarized light with a frequency similar to the incident light, and the second and third items are linearly polarized light with frequencies shift ed by$\pm\omega$, respectively.

2.4. Heterodyne shearography system

As shown in Fig. 3, the system combines a shearography system and a heterodyne device. A linearly polarized light beam from the semiconductor laser with frequency ω_0 is polarized to a given degree by the