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Eliminating the influence of source spectrum of white light scanning interferometry through time-delay estimation algorithm

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ABSTRACT

In white light scanning interferometry (WLSI), the accuracy of profile measurement achieved with the conventional zero optical path difference (ZOPD) position locating method is closely related with the shape of interference signal envelope (ISE), which is mainly decided by the spectral distribution of illumination source. For a broadband light with Gaussian spectral distribution, the corresponding shape of ISE reveals a symmetric distribution, so the accurate ZOPD position can be achieved easily. However, if the spectral distribution of source is irregular, the shape of ISE will become asymmetric or complex multi-peak distribution, WLSI cannot work well through using ZOPD position locating method. Aiming at this problem, we propose time-delay estimation (TDE) based WLSI method, in which the surface profile information is achieved by using the relative displacement of interference signal between different pixels instead of the conventional ZOPD position locating method. Due to all spectral information of interference signal (envelope and phase) are utilized, in addition to revealing the advantage of high accuracy, the proposed method can achieve profile measurement with high accuracy in the case that the shape of ISE is irregular while ZOPD position locating method cannot work. That is to say, the proposed method can effectively eliminate the influence of source spectrum.

1. Introduction

With the development of specific manufacturing technology, MEMS device and semiconductor chip have been widely used, and the corresponding three-dimension (3D) profile measurement with high accuracy and rapid speed is becoming more and more needed [1]. Atomic force microscopy (AFM) possesses high resolution, but there are some limitations in the scanning speed and the measuring range for 3D profile measurement [2,3]. Though single-wavelength interferometry reveals the advantages of whole-field, high accuracy, non-contact and non-destruction [4], the phase-ambiguity problem make it is suitable for only smooth surface measurement due to its measuring range of height is less than λ/2 [5]. To address this, white light scanning interferometry (WLSI) is introduced through using zero optical path difference (ZOPD) position locating method, so the corresponding measuring range of height is enlarged [6]. To date, WLSI has been widely used in 3D profile measurement, automatic processing, product quality control and other fields [7].

As we know, WLSI utilizes a broadband light as the illumination source, if the optical path difference between the object beam and reference beam is smaller than the coherence length of illumination source, the interference signal will appear. Thus, the intensity distribution of a measured point of sample can be described as a cosine function modulated by an envelope [8]. If the optical path difference between the object beam and reference beam is equal to zero, the intensity maximum of interference signal, named as the zero optical path difference (ZOPD) position, can be observed [9]. Typically, by using a piezoelectric ceramic transducer (PZT) stage drives the measured object, the interference signal reflecting the ZOPD position can be achieved. Following, by searching for ZOPD position of each pixel, the profile of the measured object can be constructed. That is to say, ZOPD position locating is an important research content of WLSI. To date, many ZOPD position location methods of WLSI have been reported. In general, these methods are classified into two types. One type is to search for the peak position of interference signal envelope (ISE), such as the barycenter method [10], Fourier transform [11] and Hilbert transform [8]. The other one is to determine ZOPD position location through introducing the phase retrieval algorithm, such as spatial frequency domain analysis [9,12], continuous wavelet transform [13], windowed Fourier transform [14]

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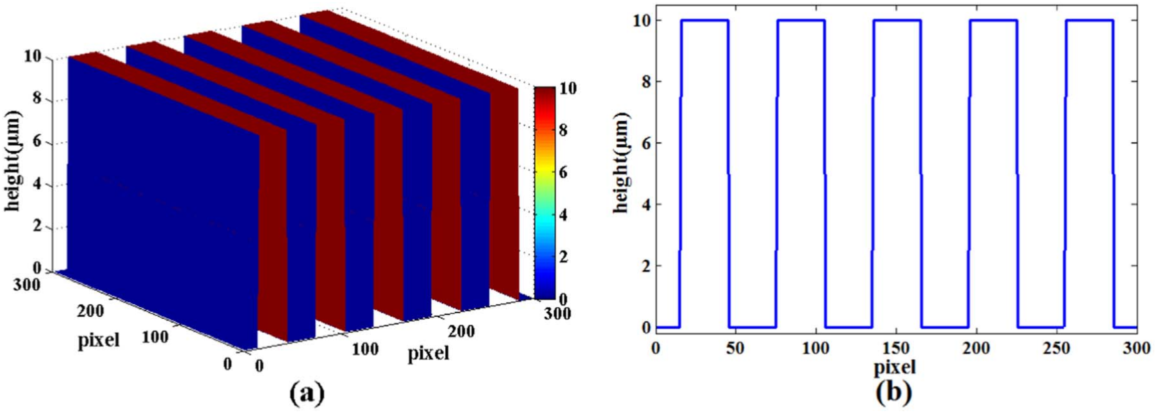

Fig. 1. (a) Profile of the simulated object; (b) the corresponding cross-section distribution of (a).

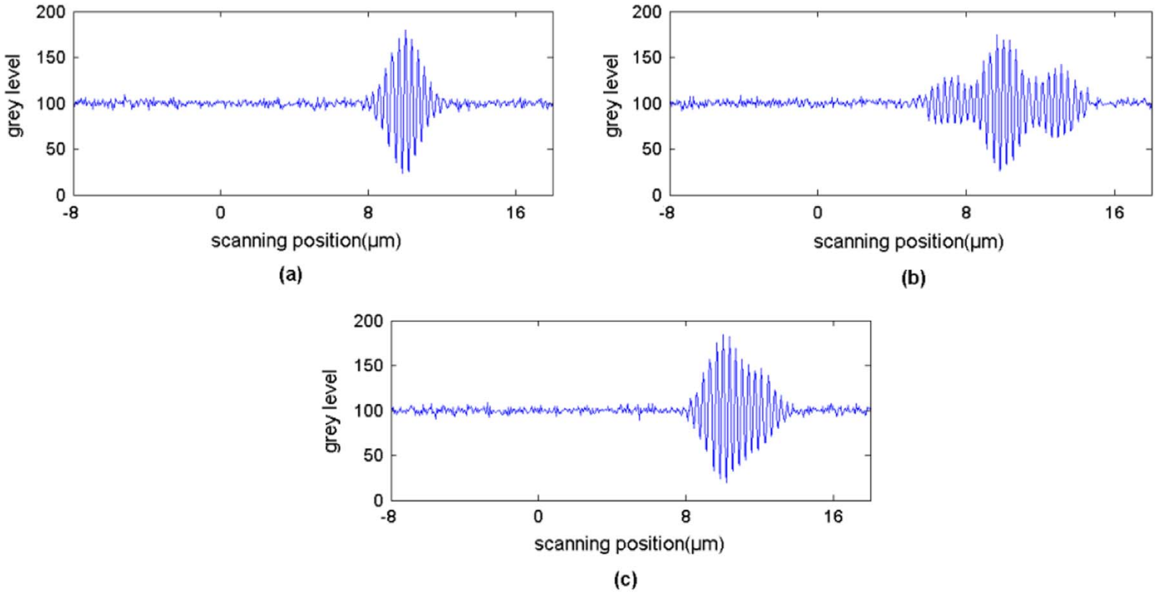

Fig. 2. The simulated intensity distribution of interference signal in pixel (100, 100) with different envelope functions, (a) symmetric distribution $g1$; (b) multi-peak distribution $g2$; (c) asymmetric distribution $g3$.

and white light phase-shifting method [15,16]. However, the above methods are suitable only for the ISE with symmetrical shape, if the shape of ISE is irregular, the error of ZOPD position locating will appear. Specially, various broadband sources with different spectral distribution are utilized in WLSI, so the shape of ISE will be different. Though several researches about the error of ZOPD position locating induced by broadband source have been reports [17,18], how to achieve accurate ZOPD position locating for different broadband sources is still required.

In this study, we introduce time-delay estimation (TDE) method [19,20] into WLSI, in which the broadband source is thought as a signal generator, and interference signals come from different object points are handled as the homologous time-delay signals. Thus the profile of the measured object can be calculated through calculating the time-delay of the interference signal of each pixel, reflecting the relative displacement of ZOPD position of each pixel. Next, we will present the principle, and then give the simulation and experimental result to verify the feasibility of ISE shape through using the proposed method.

2. Principle

According to the principle of TDE, two homologous signals with noise captured by two receivers can be respectively expressed as [20]

$$\begin{aligned} x_1(t) &= \alpha f(t) + n_1(t) \\ x_2(t) &= \beta f(t+D) + n_2(t) \end{aligned} \tag{1}$$

where $f(t)$ denotes the practical intensity of signal; $n_1(t)$ and $n_2(t)$ denote the noise; D is the time-delay between $x_1(t)$ and $x_2(t)$; there is no the correlation relationship between $f(t)$ and $n_1(t)$ or $n_2(t)$. Following, we utilize the cross-correlation method to calculate the time-delay D through using the cross-correlation function $R_{x_1x_2}(\tau)$

$$R_{x_1x_2}(\tau) = \int_0^{\infty} x_1(t)x_2(t-\tau)dt \tag{2}$$

Clearly, when $R_{x_1x_2}(\tau)$ reaches the maximum, τ is equal to the time-delay D. In the practical situation, the cross-correlation method usually leads to the calculating error of D due to the influence of noise. To address this, the generalized cross-correlation method is employed to remove the noise through the filter processing. If $I_1(f)$ and $I_2(f)$ are respectively the Fourier transform spectra of $x_1(t)$ and $x_2(t)$, the corresponding cross-power spectrum can be expressed as

$$G_{x_1x_2}(f) = I_1(f)[I_2(f)]^* \tag{3}$$

where * represents the complex conjugate operation. Then, $R_{x_1x_2}(\tau)$ can be expressed as

$$R_{x_1x_2}(\tau) = \int_{-\infty}^{\infty} G_{x_1x_2}(f)\exp(j2\pi f\tau)d\tau \tag{4}$$