Optik 125 (2014) 6722–6726

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Period correction method for binary fringe defocused projection

Yanjun Fu*, Zhigang Wang, Jie Yang, Guangyu Jiang

Key Laboratory of Nondestructive Testing (Ministry of Education), Nanchang Hangkong University, Nanchang 330063, China

ARTICLE INFO

Article history:
Received 25 November 2013
Accepted 5 July 2014

Keywords:
Three-dimensional shape measurement
Fringe projection profilometry
Defocusing

ABSTRACT

Binary fringe defocused projection can resolve the problem caused by the nonlinear gamma of the projector. Owing to the intersecting axis measurement system, the broadening of the fringe period on the reference plane can cause measurement errors. Non-uniform periodical binary fringe defocused projection is utilized to overcome this problem. After appropriate defocused projection of non-uniform periodical binary fringe, uniform periodical sinusoidal fringe can be obtained on the reference plane. This method can prevent the nonlinear gamma effect and broadening of the fringe period, and filter high harmonics and high-frequency noise. Three-dimensional (3-D) shape measurement experiments of standard flat are performed with four-step phase-shift method. Experimental results demonstrate that the proposed method exhibits high measurement precision. Highly accurate 3-D measurements of large objects can also be performed with the proposed method.

1. Introduction

Fringe projection profilometry (FPP) offers the advantages of non-contact operation, full-field acquisition, high resolution, and fast data processing. FPP is widely applied in many fields, including product inspection, robot vision, virtual reality, and quality control [1–3].

The nonlinear gamma of the projector is one of the main problems affecting the measurement accuracy of FPP. Su and Zhang et al. [4,5] proposed the binary fringe defocused projection method to address this problem. After appropriate defocused projection, sinusoidal fringe can be obtained on the reference plane. The nonlinear gamma of the projector is avoided because the method utilizes only two kinds of gray value (0 and 255). The exposure time of the charge-coupled device (CCD) need not be controlled precisely. The camera and the projector do not need to be strictly synchronous. High-speed and real-time measurements are obvious advantages [6–10]. Zuo, Li, and Ayubi et al. [11–13] conducted further research on binary fringe defocused projection.

The fringe period is broadened on the reference plane when the intersecting axis measurement system is employed in oblique-angle projection. This occurrence causes measurement errors. Greater errors are introduced when larger objects are measured. Numerous correction methods were proposed to solve this problem. Wang and Du [14] determined the relationship and the modified height expression of the fringe cycle of the virtual reference surface x' and that of the reference surface. Sansoni et al. [15] demonstrated that in intersecting axis systems, the original standard sinusoidal grating does not have a fixed value after being projected to the reference surface when oblique-angle projection is employed. Height errors occur when the fringe cycle on the reference surface is taken as a fixed value. An error compensation algorithm was proposed as a corrective measure. Cao [16] proposed a novel method to modify the periods of projected grating. He analyzed the wrapped phase distribution of the reference plane through static phase measuring profilometry and modified the periods of projected grating gradually with an iterative algorithm. Zhang and Fu et al. [17–19] proposed a novel uneven fringe projection technique to obtain evenly spaced fringes in the measurement volume. Chen and Quan [20] determined the relationship between the fringe cycle of the projection surface and that of the reference surface. The authors also determined the phase on the reference surface through the least-squares method. Cheng et al. [21] analyzed orthographic projection and oblique-angle reception and obtained the height expression of the measured object. Maurel et al. [22] indicated that fringe cycle varies from 0.35 cm to 0.4 cm from left to right. The expression of the fringe cycle on the reference surface is obtained when oblique-angle projection is employed. Rajoub et al. [23] determined the relationship between the phase and height of a measured object based on geometric analysis. Salas et al. [24] determined the mathematical relationship of three coordinates, namely, projection, object, and camera coordinates. A mapping relationship between the 3D shape and the phase is obtained independently on an equivalent wavelength.

* Corresponding author. Tel.: +86 15970440608.
E-mail address: fyjpkh@sina.com.cn (Y. Fu).

http://dx.doi.org/10.1016/j.ijleo.2014.08.069

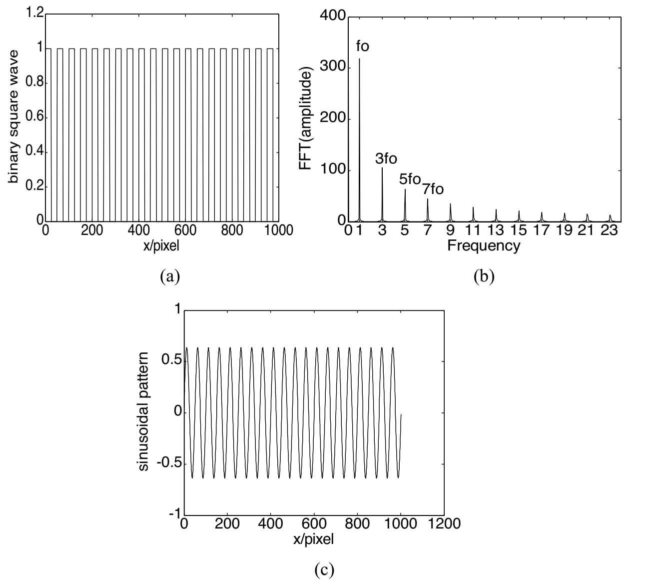

Fig. 1. Theory of sinusoidal fringe generation by defocusing a binary square wave: (a) the binary square wave, (b) the odd harmonics of the binary square wave, and (c) the ideal sinusoidal fringe.

However, the abovementioned methods merely resolved fringe period broadening when the projector is in focus. The problem of period broadening in defocus was not addressed. Fringe period broadening and nonlinear gamma are the main error sources. A method of defocused projecting non-uniform binary fringe is proposed in this paper. The method can overcome the errors caused by nonlinear gamma and fringe period broadening. Non-uniform binary fringe, which can correct the error caused by fringe period broadening, is obtained with the mathematical model of the relationship between the coordinate and phase on the projector plane. The experimental results verify that the proposed method can resolve the errors caused by the nonlinear gamma of the projector and fringe period broadening. Moreover, high harmonics and high-frequency noise are eliminated owing to the low-pass filtering effects of defocusing; thus, measurement accuracy is improved.

2. Principle

2.1. Defocusing theory

In general, the normalized binary fringe with a period of 2π can be described as

$$y(x) = \begin{cases} 0, x \in [(2n-1)\pi, 2n\pi] \\ 1, x \in [2n\pi, (2n+1)\pi] \end{cases} \tag{1}$$

here n is an integer number. The binary fringe can be expanded as a Fourier series. It includes the odd harmonics:

$$y(x) = 0.5 + \sum_{k=0}^{\infty} \frac{2}{(2k+1)\pi} \sin[(2k+1)x] \tag{2}$$

Ideal sinusoidal patterns can be generated by properly defocusing. Fig. 1 gives the theory of sinusoidal fringe generation by defocusing binary fringe. Fig. 1(a) is the binary fringe. Fig. 1(b) gives the odd harmonics of the binary fringe. If the frequency of f_0 is filtered, then an inverse Fourier transform is performed to get the ideal sinusoidal fringe, as shown in Fig. 1(c). The filter effect is the same as properly defocusing [4]. If the projector is properly defocusing, the ideal sinusoidal fringe can be generated, too.

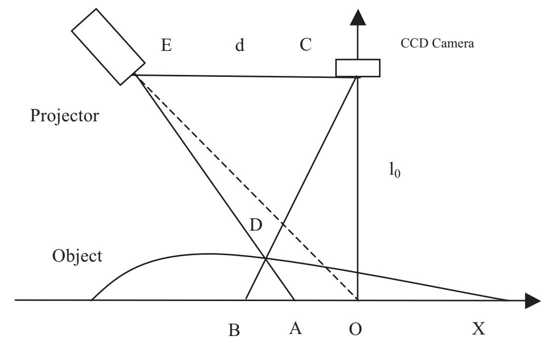

Fig. 2. Measurement system.

2.2. Measurement system

The experimental system setup is shown in Fig. 2. The fringe pattern is on an oblique angle projected onto the measured object, and the image is captured by a CCD camera. The optical axis of the projector and that of the CCD camera intersect at point O, which is the origin. Point E is the optical center of the projector and point C is the optical center of the imaging lens of the CCD camera. Points E and C have the same distance from the reference plane. The value of the distance is l_0 and d is the distance between the CCD camera and the projector. The phase of point D on the object plane is the same as that of Point A on the reference plane; that is, $\phi_D = \phi_A$. Points D and B are imaged at the same point in the CCD camera. Then,

$$AB = \frac{\phi_B - \phi_A}{2\pi f} = \frac{\phi_B - \phi_D}{2\pi f} = \frac{\Delta\phi}{2\pi f} \tag{3}$$

where $f = 1/P$ is the fringe frequency on the reference plane, P is the space period of the fringe, and $\Delta\phi$ is the phase difference between the corresponding point on the object and the reference planes. Triangles ABD and ECD are similar, and $d/AB = (l_0 - h)/h$. Subsequently,

$$h = \frac{l_0 \Delta\phi}{2\pi f d + \Delta\phi} \tag{4}$$

The parameters l_0, d, and f are obtained by calibration. After the verticality and parallel calibration of the system, standard gauge blocks are used to calibrate l_0, d, and f_0. The degree of defocusing is controlled by manually adjusting the focal length of the projector. If $\Delta\phi$ is calculated, h is obtained through Eq. (4). The 3-D profilometry of the measured object is then obtained.

2.3. Correction theory

A schematic of oblique-angle projection is shown in Fig. 3. X is the x axis of the reference plane. X' is the x axis of the virtual reference plane perpendicular to the optical axis of the projector. X'' is the x axis of the projector plane. When l_0 is 159.004 ± 0.022 cm, d is 74.002 ± 0.017 cm and T, the fringe cycle of the surface X', has a value of 2.860. Fig. 4 shows that the fringe period gradually increases as X increases [18].

Sinusoidal grating fringe contains the period correction function with four-step phase-shift method [18]:

$$\phi(x'') = \frac{2\pi f M x''(l_0^2 + d^2)}{l_0 \bullet \sqrt{l_0^{\,2} + d^2} - Mx''d} + 2\pi f \frac{NT}{4}, \quad N = 0, 1, 2, 3 \tag{5}$$

where M is magnification. Fig. 5(a) shows the non-uniform sinusoidal grating fringe generated by Eq. (5). Intensity is between 0 and 1, and the threshold can be set as 0.5. When the intensity of the sinusoidal grating is greater than 0.5, it becomes 1; otherwise, it is 0. Fig. 5(b) shows the non-uniform binary fringe after threshold transform.