Optik 122 (2011) 1245–1248

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Surface profile inspection of a moving object by using dual-frequency Fourier transform profilometry

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ARTICLE INFO

Article history:
Received 27 February 2010
Accepted 3 August 2010

Keywords:
FTP
Moving object
Phase unwrapping
Dual-frequency

ABSTRACT

The 2π phase ambiguity caused by surface isolations and large height step can be solved by dual-frequency projection grating profilometry. However, in the Fourier transform profilometry (FTP) of a moving object, only one single deformed fringe pattern can be obtained. In order to introduce the dual-frequency technique into the FTP of moving object, a novel experimental system is designed to capture two fringe patterns with different frequency at the same time. A grating structure comprising two regions with different frequencies is projected upon the surface of the detected object. Two line-scan CCD cameras are used to capture the surface images encoded by the two kinds of patterns, respectively. By getting the corresponding image intensity at the same point of the object surface in the two acquired images, the dual-frequency technique is applied to extract the real phase without phase ambiguity. The surface profile of a specimen with a large height step is measured to prove the feasibility of the proposed method. The experimental results show that the proposed method can solve the 2π phase ambiguity problem successfully in the surface profile inspection of a moving object.

1. Introduction

Projection grating profilometry has been widely used in 3D sensing, machine vision, industry monitoring, etc. because of the advantages of high speed measurement, full field measurement and high resolution [1–6]. In recent years, this technique has also been introduced into the automated profile and deformation measurement of a moving object as an essential requirement in industrial production inspections.

The application of a TDI camera has been reported for the dynamic inspection of rotating objects [7,8]. Digital moiré method and Fourier transform profilometry (FTP) are used to obtain the surface profile information. However, the 2π phase ambiguity problem may still take place after a traditional phase unwrapping process when the detected object has a large surface step. The dual-frequency Fourier transform profilometry has been proposed to deal with this issue in static surface profile inspection [9–11]. Thus, it is a big challenge to introduce this method into the surface profile inspection of a moving object.

In this paper, the line-scan CCD cameras are used to construct an image detection system to detect the surface profile of a moving object. The dual-frequency projection grating technique is also used to solve the 2π phase ambiguity problem.

2. Principle of the dual-frequency FTP

In the projection grating FTP, the intensity recorded by a CCD camera can be expressed as

$$I(x, y) = a(x, y) + b(x, y)\ \cos\,[2\pi f_0 x + \Phi(x, y)] \qquad (1)$$

where $a(x, y)$ is the background intensity, $b(x, y)$ is the amplitude of the gratings, f_0 is the spatial frequency, and $\Phi(x, y)$ is the phase change caused by the surface height of the detected object. Eq. (1) shows that the signal $\Phi(x, y)$ is modulated by a constant high-frequency signal f_0. A demodulating technique is performed to obtain the phase change.

Eq. (1) can be written as

$$I(x, y) = a(x, y) + c(x, y)\ \exp\,(j2\pi f_0 x) + c^*(x, y)\exp\,(-j2\pi f_0 x) \qquad (2)$$

where $c(x, y) = [b(x, y)/2]\exp\{j[\Phi(x, y)]\}$, and $c^*(x, y)$ is the complex conjugate of $c(x, y)$. The Fourier transform of $I(x, y)$ with respect of x becomes

$$F[I(x, y)] = A(f, y) + C(f - f_0, y) + C^*(f + f_0, y) \qquad (3)$$

where $F[\,]$, $A(\,)$ and $C(\,)$ represent the Fourier spectra, and C^* is the complex conjugate of C.

As the frequencies of $a(x, y)$, $b(x, y)$ and $\Phi(x, y)$ are much lower than f_0, the function $C(f - f_0, y)$ can be filtered by an adequate window in the frequency domain. And then, $C(f, y)$ can be obtained by spectrum shift center processing. Taking inverse Fourier transform of $C(f, y)$, we can get $c(x, y)$. Thus, the phase change of the deformed

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doi:10.1016/j.ijleo.2010.08.007

pattern is

$$\Phi(x,y) = \arctan\left\{\frac{\mathrm{Im}[c(x,y)]}{\mathrm{Re}[c(x,y)]}\right\} + 2n\pi = \arctan\frac{G}{F} + 2n\pi = \varphi(x,y) + 2\pi n \quad (4)$$

where $F = \mathrm{Re}[c(x,y)]$ and $G = \mathrm{Im}[c(x,y)]$ represent the real and imaginary parts of $c(x,y)$, respectively. $\varphi(x,y)$ is the principal phase which is in the range of $(-\pi, \pi]$. A phase unwrapping procedure should be taken to get the continuous real phase distribution $\Phi(x,y)$.

However, the 2π phase ambiguity problem may still take place after traditional phase unwrapping processing when the surface of the object has a large height step in somewhere. The dual-frequency projection grating profilometry can be used to solve such issue. In the measurement procedure, two different-frequency gratings are used to obtain the phase changes, respectively. Firstly, one frame of digital grating with higher frequency is projected upon the detected object, by which the high slope information of the object surface variation can be obtained. However, as the wavelength of this grating is not long enough to overcome the big surface height discontinuous, the 2π phase ambiguity will occur in the phase distribution after a traditional phase unwrapping process. Secondly, the other digital grating with lower frequency is projected upon the detected object. The biggest deformation of the fringe caused by the surface height discontinuous should be smaller than the wavelength of the projected grating. So that the real phase change can be extracted correctly.

Assuming the spatial frequency of lower frequency fringe pattern is f_1, the phase change is $\Phi_1(x,y)$, and the principal phase is $\varphi_1(x,y)$. On the other side, the spatial frequency of higher frequency fringe pattern is f_2, the phase change is $\Phi_2(x,y)$, and the principal phase is $\varphi_2(x,y)$. As we know,

$$\begin{cases} \Phi_1(x,y) = \varphi_1(x,y) + 2\pi n_1(x,y) \\ \Phi_2(x,y) = \varphi_2(x,y) + 2\pi n_2(x,y) \end{cases} \quad (5)$$

By using the same detection system, the surface height of one point obtained by the two kinds of fringe patterns can be expressed as follows

$$\begin{cases} h(x,y) = k_1\Phi_1(x,y) \\ h(x,y) = k_2\Phi_2(x,y) \end{cases} \quad (6)$$

where k_1 and k_2 are two constant values corresponding to different fringe patterns which are correlated with the system parameters. From Eqs. (5) and (6), we can get [9,10]

$$n_2(x,y) = (INT)\left[\frac{k_1}{k_2}n_1 + \frac{k_1}{2\pi k_2}\varphi_1(x,y) - \varphi_2(x,y)\right] \quad (7)$$

where $(INT)[\ ]$ denotes rounding to the nearest integer. Substituting $n_2(x,y)$ into Eq. (5), the real phase $\Phi_2(x,y)$ without 2π ambiguity can be obtained.

3. Principle of the proposed method

In the profile measurement of a moving object, the key point is capturing two frames of deformed fringe patterns with different frequencies at the same time. A novel experimental system is designed to project and capture the two different gratings at the same time. The experimental system is shown in Fig. 1. A parallel digital grating is projected upon the detected object at an incidence angle of α. As shown in Fig. 2, the grating structure is comprised of two regions with different frequencies. Two line-scan CCD cameras are used to capture the surface images encoded by the two kinds of gratings, respectively. The optic axis is normal to the reference plane, and the distance between the two scan lines is d. The captured images are stored in a personal computer. The detected object is fixed on a moving displacement device. Thus, each row of the object surface can be modulated and captured twice when the object is moving at a constant velocity. The lower frequency fringe pattern is recorded by the scan line 1 and the higher frequency fringe pattern is recorded by the scan line 2.

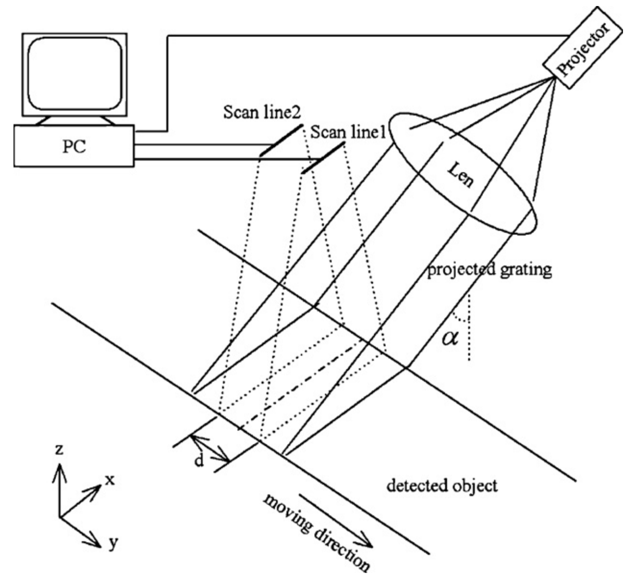

Fig. 1. Sketch map of experimental system.

The corresponding y-coordinate of the same point at the object surface will be different in the two frames of fringe patterns captured by the two line scan CCD cameras. By getting the corresponding image intensity of the same point at the object surface in the two acquired images, the dual-frequency FTP is applied to extract the real phase without 2π phase ambiguity. Assuming the difference of the y-coordinate at the same surface point in the two images is Δy, the corresponding image intensity of one surface point in the two captured images can be denoted as $I_1(x,y)$ and $I_2(x,$

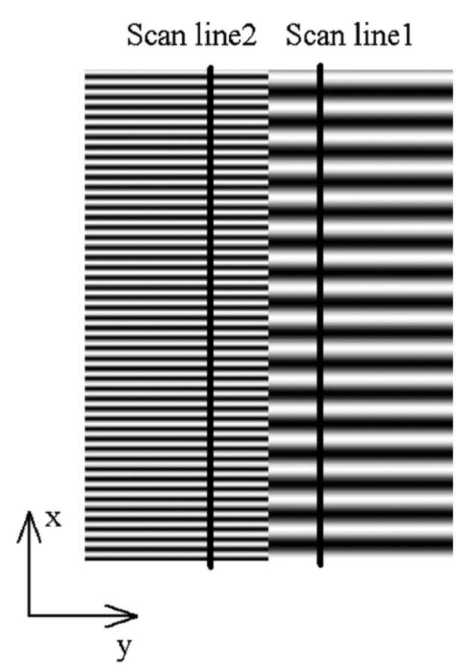

Fig. 2. Composite fringe pattern.