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Defect information detection of a spare part by using a dual-frequency line-scan method

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ABSTRACT

The surface defect of a moving spare part is measured by a line-scan system online. The experimental system is combined with a line-scan CCD, a LCD projector, a translation stage, and a personal computer. The deformed fringe patterns of the spare part can be captured and stored in the personal computer. The Fourier transform method is used to extract the fringe deformation. Following the geometric relationship between the fringe deformation and the surface height, the full-field surface 3D information can be obtained. Furthermore, the projection dual-frequency composite grating technique is used to solve 2π phase ambiguity problem because of some bigger surface defect steps. Some experimental results are presented to prove the feasibility of the proposed method and the inspection system.

1. Introduction

As we know, the projection grating profilometry has been widely used in 3-D profile measurement, including machine vision, industry monitoring, biomedicine, etc. [1–6]. Before using this technique and detection system we can get the full field measurement results with higher speed measurement procedure and resolution. However, in the practical industry these measurements must be applied for the online production. Thus, these techniques have been introduced into the automated profile and surface defect information measurement of a moving spare part as an essential requirement in industrial inspections, such as the highway surface deformation detection and the quality inspection of productions online. The application of a line-scan or TDI camera has been reported for the dynamic inspection of rotating objects [7–9]. Fourier transform profilometry (FTP) method are proposed to extract the 3D surface profile information. However, in Fourier transform phase extracting, the 2π phase ambiguity problem may still take place after a phase traditional 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 [10–14]. However, this method has not been introduced into the dynamic surface inspection.

In this paper, the line-scan CCD camera is used to construct an image detection system to detect the surface profile or defect information of a moving object such as a spare part. As only one frame of fringe pattern can be obtained, the Fourier transform method is used to evaluate the fringe deformation. The dual-frequency projection grating technique is also used to solve the 2π phase ambiguity problem.

2. Experimental system

The configuration of the experimental setup for the 3D surface height information measurement is based on the conventional projection grating systems [3], so this method and experimental system can be developed for the industrial production quality inspection. As shown in Fig. 1, the detected spare part can be put onto the motorized translation stage. A sinusoidal grating is projected onto the detected object surface by a LCD projector at an angle, and the angle is set as 30° in the following experimental results of this article. The fringe direction is parallel to the moving direction of the object. A line-scan CCD camera is used to capture the moving object. The optical axis of the camera is normal to the reference plane and the line scan direction is perpendicular to the moving direction. The captured images which contain some useful height information are stored in the computer for next process.

3. Projection grating profile measurement principle

The parallel cosine function modulated intensity is projected onto the detected spare part at an incidence angle. When the detected object is moving in y-axis, the fringe pattern is captured by a line-scan CCD camera line by line. The fringe deformation can be obtained much more accurately in full field by the phase method

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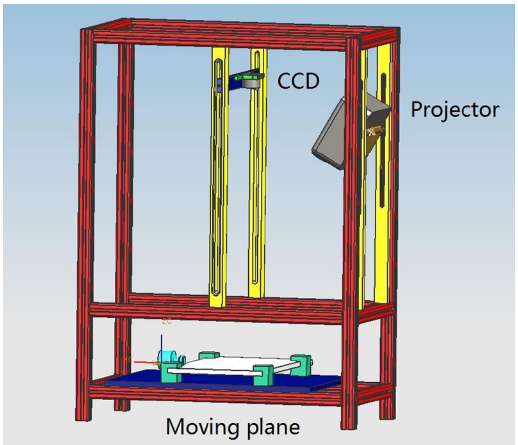

Fig. 1. 3D map of the experimental setup.

named the Fourier transform technique [3]. The intensity recorded by the CCD camera can be expressed as

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

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 object. Hence, we can get the surface height by obtaining the phase change of the fringe pattern. As only one frame of fringe pattern can be captured by the line-scan CCD camera in the moving object inspection, Fourier transform method is normally used to extract the phase change [4].

4. Dual-frequency Fourier transform method

It is well known that 2π phase ambiguity problem may still take place after the traditional phase unwrapping processing when the surface of the object has a large height step. The dual-frequency projection gratings profilometry can be used to solve such issue [10–14]. Assuming f_1 is the spatial frequency of the lower frequency fringe pattern, $\Phi_1(x, y)$ is the phase change, and $\Phi'_1(x, y)$ is the principal phase. The spatial frequency of the lower frequency must be small enough to eliminate the 2π phase ambiguity in the phase extracting procedure. For the higher spatial frequency f_2, $\Phi_2(x, y)$ is the phase change, and $\Phi'_2(x, y)$ is the principal phase. The relationship between $\Phi(x, y)$ and $\Phi'_1(x, y)$ is

$$\begin{cases} \Phi_1(x, y) = \Phi'_1(x, y) + 2\pi n_1(x, y) \\ \Phi_2(x, y) = \Phi'_2(x, y) + 2\pi n_2(x, y) \end{cases}. \quad (2)$$

Under the same experimental condition, the surface height of one point obtained by the two kinds of fringe patterns can be expressed as follows

$$\begin{cases} h(x, y) = k_1 \Phi_1(x, y) \\ h(x, y) = k_2 \Phi_2(x, y) \end{cases}, \quad (3)$$

where k_1 and k_2 are two constant values which are correlated with the system parameters. From Eqs. (2) and (3), we can get

$$n_2(x, y) = (\mathrm{INT})\left\{\frac{k_1}{k_2}\left(n_1 + \frac{1}{2\pi}\Phi'_1(x, y)\right) - \Phi'_2(x, y)\right\}, \quad (4)$$

where $(\mathrm{INT})\{\cdot\}$ denotes rounding to the nearest integer. Substituting $n_2(x, y)$ into Eq. (2), the actual phase without 2π ambiguity can be obtained.

However, as the digital gratings with different frequencies must be projected at the same time in the moving spare part profile inspection, two spatial frequencies projection gratings are composited together for projecting. After Fourier transform procedure, two different filter windows are used to obtain the corresponding terms in the frequency domain, respectively. Firstly, the phase change corresponding to the higher frequency fringe pattern is extracted, and the high slope information of the object surface can be obtained. However, as the pitch of this grating is not long enough to overcome the big surface height discontinuous, there would be 2π phase ambiguity in the phase distribution after a traditional phase unwrapping process. And then, the phase change corresponding to the lower frequency fringe pattern is extracted by the same way.

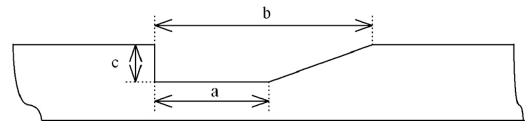

Fig. 2. Sketch map of the cross section.

5. Experimental results and analysis

A specimen is used to prove the feasibility of the proposed composite dual-frequency FTP for moving spare part inspection. The sketch map of the cross section of the detected specimen is shown in Fig. 2. There are discontinuities on the surface, and the large height step is $c = 6$ mm. The other sizes of the specimen are $a = 18$ mm and $b = 30$ mm. The pitch ratio between the higher frequency grating and the lower frequency grating is 2/5. Thus, $k_1/k_2 = 5/2$. The pitch of the higher frequency grating is 2.3 mm.

The specimen is fixed on the controlled translation stage. The composite dual-frequency grating is projected onto the surface of the specimen. One frame of deformed fringe patterns captured by the line-scan CCD camera is shown in Fig. 3(a). Fig. 3(b) is

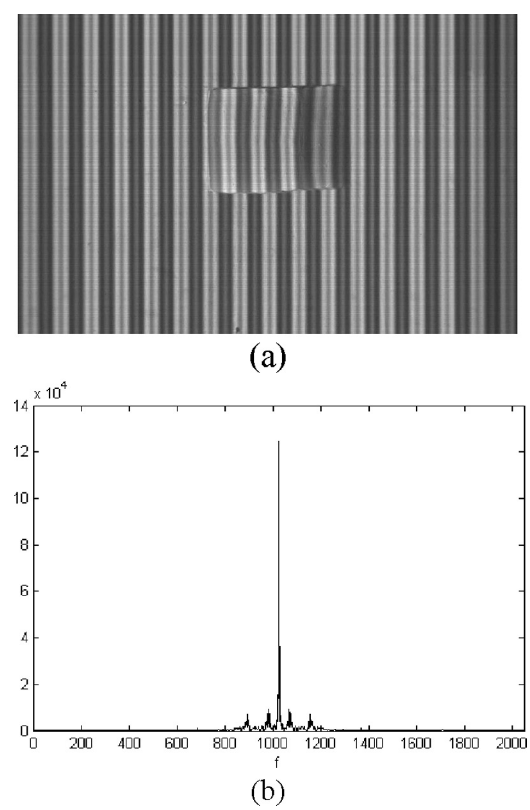

Fig. 3. (a) Fringe pattern and (b) 1-D frequency spectrum.