

Temperature fringe method with phase-shift for the 3D shape measurement

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ABSTRACT

Linear laser fast scanning thermography technology has a good application prospect in the nondestructive detection of defects. Meanwhile, due to the modulation of the surface topography, the thermal response fringes excited by the line laser are distorted in the scanning process, whereby the three-dimensional topography of the specimen can be reconstructed. However, the accuracy of this method is currently limited by unfavorable factors, such as background noise of the specimen surface and the extraction error of the deformed temperature fringes. In this paper, by optimizing the initial position difference during line laser scanning and converting the laser fringes with specific position difference into temperature fringes with specific phase difference, the phase shift technique is combined with the temperature fringe method. What's more, some post-processing algorithms were developed to further develop the temperature fringe method and greatly improve the accuracy of the method. By measuring some specimens with different shapes and different colors, the results show that the technology and algorithms developed here can obtain the three-dimensional shape of the measured specimen with high accuracy while having a non-destructive testing function, without interference from the surface color of the specimen.

1. Introduction

Accurate 3D shape information is an essential characteristic of any object, which plays an increasingly important role in many fields (1–5), such as machine vision, industrial automatic detection, and biometrics, etc. In recent years, the 3D shape measurement technology (6–10) has made remarkable progress in measurement systems and measurement methods.

Among them, the projection fringe technology (11,12), as one of the optical measurement technologies, has gradually become a very active research field due to its advantages of non-contact, high precision, the whole field and quite high speed (4,13). However, in the measurement process, some problems, such as the surface color of the measured object, ambient light noise, and the 'shadow' caused by the geometry of the object, will affect the measurement accuracy of the method. Using simultaneously three channels of red, green and blue colors of a CCD camera, the recently developed color fringe projection technology (14–17) can extract three fringe patterns from a color composite fringe pattern, which greatly improves the speed of 3D shape measurement. However, this method has chromatic aberration and crosstalk between color channels in visible wavelength, causing the phase to jump and abruptly change, although some methods have been proposed to solve these problems (18–20). Invisible infrared light can also be used as a light source for fringe projection (21–23), and the measurement based

on infrared light can be applied in surveillance and other related fields, for example face recognition in hidden environments (24). However, some infrared-insensitive materials can affect the grayscale contrast of fringes, such as lower temperature objects, and inorganic materials. At the same time, the temperature fringe method, based on the linear laser fast scanning thermography technology (25–30), has opened up new ideas for the development of projection fringes. The excited thermal response fringes when the line laser scanning the specimen surface are deformed due to the modulation of the topography. By analyzing the deformation information carried in the temperature fringes, this method can complete the reconstruction of the 3D shape while having the non-destructive testing function. However, at present, this method is still in the initial trial period, and the measurement accuracy is limited by some unfavorable factors, such as background noise of the specimen surface and the extraction error of the deformed temperature fringes. Therefore, it is necessary to further develop the temperature fringe method and improve the detection accuracy of this method.

In this paper, the temperature fringe method still in the research stage is combined with the phase shift technique. By optimizing the initial position difference during line laser scanning and converting it into temperature fringes with specific phase difference, the obtained phase changing information in the temperature fringes is utilized to measure the three-dimensional shape of the tested object. Meanwhile, an adaptive temperature threshold extraction algorithm developed here can better preserve the effective deformation information carried by

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the temperature fringes, and a sinusoidal gray interpolation algorithm developed here can add sinusoidal grayscale changes to the binarized fringe image, which further developed the temperature fringe method and greatly improved the accuracy of the method. The experimental verification shows that using the technology and algorithms developed here, the 3D shape of the specimen surface can be measured with high accuracy.

2. Principle

2.1. The principle of temperature fringe method

When line laser emitted from a transmitter is projected onto the specimen surface, the specimen absorbs the energy to form a linear thermal response area on the surface, which will be deformed due to modulation of the specimen shape. By analyzing the deformed temperature fringe images, the reconstruction of the 3D surface shape of the measured specimen is finally completed. The specific process of this method is as follows: the single-line laser discontinuously scans the specimen surface at an optimized fixed spacing, and IR camera collects the thermal images to obtain the sequence thermal images of the single-line laser orderly scanning specimen surface in the time domain; the acquired thermal images of each frame is preprocessed like smoothing and filtering, which is helpful for subsequent extraction of temperature fringes; an appropriate temperature value is selected as the threshold to extract the unique temperature fringe present in thermal images of each frame, and the extracted fringe pattern is a binarized image; all the binarized images in the time series are accumulated to obtain a full-field fringe deformed image; a sinusoidal gray-scale variation is added to the full-field fringe deformed image, and the final temperature fringe image for phase shifting calculation is obtained; by optimizing the initial position difference in the process of single-line laser scanning and repeating the above steps, a plurality of temperature fringe images with specific phase difference can be obtained; by using phase shift technique, phase change informa-

tion of specimen surface is utilized to complete the measurement of the 3D surface shape.

When the temperature fringe is extracted, the noise point existing on the specimen surface will cause abnormal temperature and distort the shape of the linear thermal response, which makes it difficult to extract the temperature fringe. To eliminate this influence, an adaptive temperature threshold algorithm was developed. Take a thermal image as an example. The principle is to sort a column of elements in this thermal image from small to large according to their temperature distribution, and then automatically select the 9th highest temperature value (determined by the width of the thermal response area) as the threshold and retain the position of the temperature point greater than the threshold (the temperature threshold of each column element is determined by its own temperature distribution). Repeating this process for each column element in the thermal image to complete the extraction of the entire temperature fringe.

At the same time, a sinusoidal gray interpolation algorithm was developed to add sinusoidal grayscale variation to the full-field binarized image. By automatically recognizing the position of each fringe in the binarized fringe image, each pixel in each column between adjacent two fringes is then uniformly assigned a gray value in the sinusoidal grayscale variation (0–255) according to the distance between the adjacent two fringes, and all grayscale curves satisfy the same sinusoidal function. After adding sinusoidal grayscale variation, the final temperature fringe image is obtained to provide phase information for subsequent application of the phase shift technique.

2.2. The phase shifting technique in the temperature fringe method

In the experiment, the single-line laser discontinuously scans the specimen surface at an optimized fixed spacing. After temperature fringes are extracted, each temperature fringe is accumulated in time sequence into a full-field fringe deformed image (as shown in Fig. 1a), which can avoid interference from the thermal response zone of two ad-

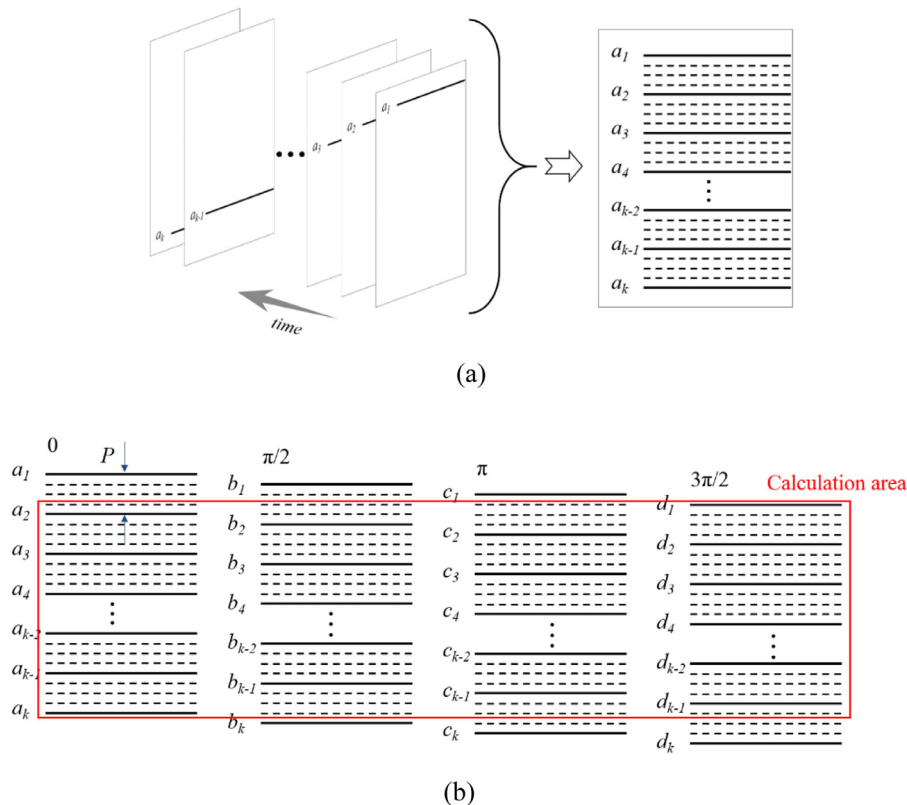


Fig. 1. Illustration of phase shift technique. (a) single fringe accumulating on time series. (b) scanning mode used to obtain the phase-shifted images.

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