Optics and Lasers in Engineering 88 (2017) 243–254

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

# 3-D surface profilometry based on modulation measurement by applying wavelet transform method

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ARTICLE INFO

*Article history:*
Received 20 January 2016
Received in revised form
20 August 2016
Accepted 27 August 2016

*OCIS codes:*
120.6650
110.2650
070.2590
120.2830

*Keywords:*
Surface measurements
Fringe analysis
Wavelet transform
Height measurements

ABSTRACT

A new analysis of 3-D surface profilometry based on modulation measurement technique by the application of Wavelet Transform method is proposed. As a tool excelling for its multi-resolution and localization in the time and frequency domains, Wavelet Transform method with good localized time-frequency analysis ability and effective de-noizing capacity can extract the modulation distribution more accurately than Fourier Transform method. Especially for the analysis of complex object, more details of the measured object can be well remained. In this paper, the theoretical derivation of Wavelet Transform method that obtains the modulation values from a captured fringe pattern is given. Both computer simulation and elementary experiment are used to show the validity of the proposed method by making a comparison with the results of Fourier Transform method. The results show that the Wavelet Transform method has a better performance than the Fourier Transform method in modulation values retrieval.


## 1. Introduction

3-D surface profilometry based on the structured light illumination with advantages of non-contact, non-destructive, quick speed and high accuracy has been increasingly used in many areas such as 3-D sensing, quality control, biomedical engineering, industry monitoring, etc. This technique can be divided into two types according to the structure of measurement system. One is the optical 3-D surface profilometry based on trigonometric measurement principle [1–10] that there exists an angle between the projection optical axis and the observation optical axis. Another is the optical 3-D surface profilometry based on vertical measurement principle [11–17] that the direction of observation is the same as that of the projection. The technique of the first type includes Moiré profilometry [1–3], Fourier Transform Profilometry (FTP) [4,5], Phase Measurement Profilometry (PMP) [6,7], Wavelet Transform Profilometry (WTP) [8–10], etc. This technique mostly uses the fringe phase as the information carrier. A sinusoidal fringe pattern is firstly required to project onto the surface of the measured object. Then a deformed fringe pattern is captured by a CCD camera from a different view angle. The shape of the tested object can be reconstructed through the phase retrieving and phase-height mapping. The measurement accuracy can be improved by increasing the angle between the projection axis and the observation axis. While the technique of the second type includes Modulation Measurement Profilometry (MMP) [11–14] and the 3-D surface profilometry based on fringe contrast analysis [15,16]. For this technique, the heights of the testing objects are encoded into the fringe defocus, and the direction of observation is the same as that of projection. The object with sharp change in surface can be measured by retrieving the modulation and searching the position of the maximum modulation values in Modulation Measurement Profilometry or by calculating the contrast and searching the position of the maximum contrast in 3-D surface profilometry based on fringe contrast analysis.

For the optical 3-D surface profilometry based on trigonometric measurement principle, the bigger the angle between the projection axis and the observation axis, the higher the measurement accuracy. However, the requirement of this angle may causes shadows or occlusion in the processing of measurement, what's worse, phase truncating or spatial discontinuities may also become the problem influencing the measurement especially for the object with rapid height variation. Therefore, the application of the optical 3-D surface profilometry based on trigonometric measurement principle is restrained to a certain extent. The raizing of the optical 3-D surface profilometry based on vertical

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http://dx.doi.org/10.1016/j.optlaseng.2016.08.020
0143-8166/

measurement principle becomes a good resolution to the above mentioned limitations. It avoids not only the existence of shadows and occlusion by applying coaxial and coimage plane optical systems, but also phase truncating and spatial discontinuities by the calculation of the relationship between the modulation (or contrast) value and the distance from the position of measured object to that of the projection system to obtain the height distribution instead of phase calculation. In the Modulation Measurement Profilometry, two techniques are usually used for the calculation of modulation value from each captured fringe pattern. One is phase shifting technique [11,12], another is Fourier Transform technique [13,14]. For the former technique, at least three fringe patterns are required to be captured to obtain the modulation value at each scanning position, which needs a great deal of images to be captured. So this technique needs much time in the measurement. It isn't convenient to the practical application. While for the latter technique, only one fringe pattern is required to be captured to obtain the modulation value at each scanning position, which reduces both acquizition time and storage space. However, for this technique, modulation values for each captured fringe pattern are retrieved by Fourier Transform and filtering operation. The application of the filtering operation could well result in the loss of the details, especially for the complex object.

To avert this shortcoming, this paper introduces the Wavelet Transform method [8] into the modulation value calculation for each fringe pattern. The Wavelet Transform method excels at multi-resolution and spatial localization. Due to the ability of analyzing the fringe pattern in the two domains, it will be more efficient than the Fourier Transform method in which only spectral information is given. The application of Wavelet Transform method in analyzing fringe pattern results in a series of wavelet coefficients, which shows how close the information of the fringe pattern is to the particular wavelet. The modulation values can be obtained from the wavelet coefficients at the wavelet ridge position. Because the Wavelet Transform provides powerful multi-resolution analysis in both time and frequency domain, it is robust to noize and can well extract the signal characteristic. These characters make the Wavelet Transform method complete the reconstruction with higher precizion than that of the Fourier Transform method. In order to extract the modulation of fringe pattern more effectively, an appropriate wavelet base function should be selected. This paper selects Morlet wavelet as the base function to complete modulation calculation because it is consisted of a sine wave and a cosine wave and has good localization in both spatial and frequency domains, which is mostly applied in fringe pattern analysis to retrieve the phase.

The organization of this paper is as follows: In Section 2, the principle of Modulation Measurement Profilometry is given. In Section 3, the theory of Morlet Wavelet Transform and the expression of Morlet Wavelet Transform applied in analyzing fringe patterns are presented. In Section 4, computer simulation is carried out to show the capability of the Morlet Wavelet Transform in modulation calculation by making a comparison with that of the Fourier Transform. While in Section 5, a practical experiment is conducted for establishing the feasibility and effectiveness of the proposed approach. Lastly, a conclusion is drawn in Section 6.

## 2. Principle of modulation measurement profilometry

The upper portion of Fig. 1 shows the principle of the Modulation Measurement Profilometry. Putting a sinusoidal grating in an imaging system, the fringe pattern with the largest modulation can be captured on the imaging plane of the grating, while in the front and the back position of this imaging plane, the modulation of the captured fringe pattern will become smaller because of defocusing. In the direction of light axis, a modulation distribution exists and different modulation values correspond to different distances between the object and the projecting system. For fringe patterns captured from plane 1 to plane $N$ shown in Fig. 1, if the modulation values from the same point in the fringe patterns are calculated, a curve just like the bottom portion of Fig. 1 can be obtained, which represents the modulation distribution for this imaging system. For clarity, the modulation values from the same position in five frames of fringe patterns including one on the imaging plane of the grating are given, which respectively marked by red dot in the modulation curve.

In the case of geometric optical approximation and ideal image formation, the image of a sinusoidal grating through lens imaging system is still a sinusoidal pattern. In this paper, vertical grating is used and the light intensity distribution on the focal plane can be expressed as [13]

$$I(x, y) = \frac{R(x, y)}{M^2}\left\{ I_0 + C_0(x, y)\cos\left[ 2\pi f_0 x + \Phi_0(x, y)\right]\right\} \tag{1}$$

where $M$ represents the transverse magnification of the

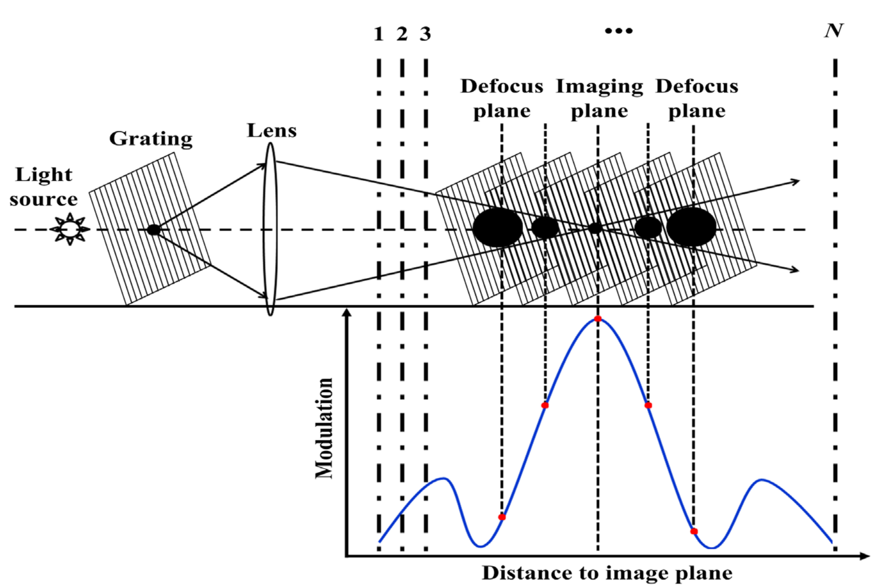


**Fig. 1.** Imaging system of grating.