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Elimination of nonlinearity in modulation measurement profilometry by Wavelet Transform

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ABSTRACT

Modulation measurement profilometry applies coaxial and coimage plane optical systems to reconstruct the surface shape of the measured object, in which, the direction of the grating projection is the same as that of CCD to capture the images. This technology completes the reconstruction by the extraction of modulation values instead of phase information. It can effectively avoid the shadows, shutoff and calculation of phase unwrapping and accomplish the shape measurement for object with complex surface. However, in the practical application, the measurement precision is usually affected by the nonlinearity of CCD's photoelectric response. In order to avoid the influence of high-order harmonics on fundamental spectrum, Wavelet Transform is introduced into fringe analysis and modulation extraction. With the merits of local analysis and multi-resolution, this method can obtain higher measurement precision by comparing with the Fourier transform method. Both computer simulation and practical experiment testified the validity of the proposed method.

1. Introduction

With the merits of non-contact, non-invasion, fast speed, high precision, high efficiency and large information capacity, the optical three-dimensional surface shape measurement technology [1–4] based on the structured light illumination has been widely used in industrial inspection, national defence and military, biomedicine, digital preservation of cultural heritage, construction of 3D animation and network virtual.

This technology can be divided into two categories according to the structure of measurement system, one category is based on trigonometric measurement principle; another category is based on vertical measurement principle. For the former category in monocular vision, an angle exists between the optical axis of the projection system and that of observation system, and the bigger the angle is, the higher the measurement accuracy will be. These technologies complete the reconstruction of the measured object by extracting phase information in the fringe patterns including Moiré profilometry [5,6], Phase Measurement Profilometry (PMP) [7–10], Fourier Transform Profilometry (FTP) [11–13] and Wavelet Transform Profilometry (WTP) [14–16]. While for the latter category, the direction of projection is exactly the same as that of the observation. This category completes the reconstruction of the measured object by calculating modulation values in the fringe patterns. Similarly, phase shifting method [17], Fourier Transform method [18,19] and Wavelet Transform method [20] can be applied to calculate the modulation values.

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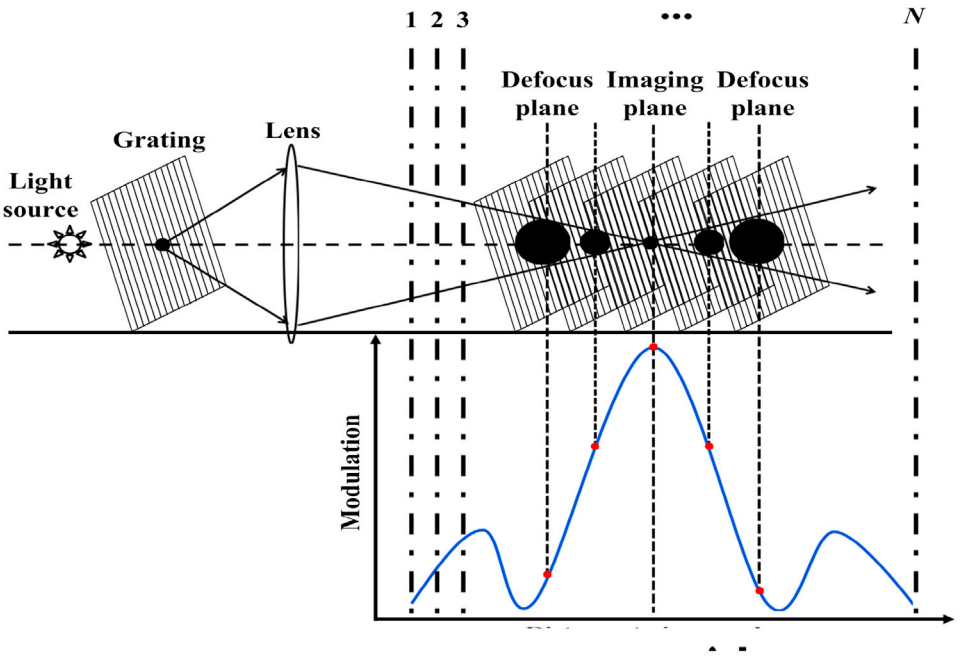

Fig. 1. Imaging system of grating.

For the optical three-dimensional surface shape measurement technology based on trigonometric measurement principle, the height of the tested object is encoded in the deformation of the fringe pattern, and the fringe phase is used as the information carrier. These technologies usually have high measurement precision. However, the existence of shadows and occlusion makes it fail to get correct reconstruction of measured object with complex surface. For the optical three-dimensional surface shape measurement technology based on vertical measurement principle, the application of coaxial optical system for projection and observation can effectively avoid these problems. In these measurement systems, the height of the tested object is encoded in the fringe defocus, and the modulation of the fringe pattern is used as the information carrier. Phase shifting method is a multi-frames fringe analysis technique, which can be used to extract the modulation values of fringe pattern. This method has the merit of high precision. However, it requires at least three frames of fringes for each scanning position to extract the modulation values. Too many images increase the workload and much time is needed to capture the fringe patterns in the measurement, so, this technique is not suitable to the application of dynamic measurement. Fourier Transform method and Wavelet Transform method belong to single-frame fringe analysis techniques, and only one fringe is required to be captured to calculate the modulation values at each scanning position, so both of them are suitable to be applied in static measurement and dynamic measurement.

Fourier Transform method was firstly proposed in 1983. As a global analysis method, it is more suitable to deal with stationary signal instead of non-stationary signal like fringe pattern. When measuring complex object, the application of the filtering operation makes this approach fail to retain the details of the measured object. When the nonlinearity of CCD's photoelectric response is also taken into the consideration, errors will become bigger. Wavelet Transform method is a time-frequency analysis technique. With the advantages of multi-resolution strategy and local analysis capability, this method can obtain higher measurement accuracy.

In this paper, the Wavelet Transform method is introduced in the modulation profilometry to eliminate the nonlinearity. Besides the theory of this method in fringe analysis, the expression of this method in nonlinear elimination for modulation extraction is deduced. Both computer simulations and practical experiments are used to verify its advantages by make a comparison with the Fourier Transform method.

2. Principle of modulation measurement profilometry

The imaging system of grating is show in Fig. 1. When put a sinusoidal grating on the flat plane, the clearest fringe pattern can be captured on the imaging plane of the grating, which corresponds to the largest modulation value. While in the front and the back position of this imaging plane, due to defocus, the fringe will gradually become blurred that the modulation value will also undergone a change (become smaller), so, if modulation values of the whole images from plane 1 to plane *N* in Fig. 1 are calculated, a similar curve shown at the bottom portion of Fig. 1 can be obtained by extracting the modulation values from the same point in the fringe patterns. Actually, it represents relationship between the modulation value and the distance from the object to the projecting system.