



Eliminating zero spectra in Fourier transform profilometry by application of Hilbert transform



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ABSTRACT

Hilbert transform has the features of inducing a phase shifting of 90 degree and removing the DC component. We propose a novel method based on the piecewise Hilbert transform to suppress the background intensity of the deformed fringe pattern using only one fringe pattern in Fourier transform profilometry according to the approximation that the background of the fringe is a slowly varying function and its distribution in each half period of the fringe can be regarded as a constant. In the method, Hilbert transform deals with each segmented fringe section to remove the DC component and then forms a result fringe whose background intensity is suppressed well by putting the fringe pieces together. The proposed method can enlarge the measurement range and reduce the measurement error of FTP. The theoretical analysis is given. Computer simulations and experimental results demonstrate the effectiveness of the proposed method.

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1. Introduction

Optical 3D measurement techniques based on the structured light illumination are widely used in various kinds of research fields including biomedicine, industry inspection, dynamical process analysis and machine vision, etc because of the characteristics of non-contact, full field analysis and high speed. Among them, Fourier Transform Profilometry (FTP) can reconstruct the shape of the measured object from only one fringe or at most two fringes by Fourier transform, filtering in frequency domain and inverse Fourier transform. After proposed by M. Takeda and K. Muloh [1] in 1983, FTP is deeply studied and widely used [2–10]. Fourier transform provides excellent frequency resolution without spatial localization ability and the measurement range of Fourier transform profilometry is limited. If the zero frequency component and the high orders spectra component interfere the useful fundamental spectra, the reconstruction precision of FTP will decrease greatly. In order to overcome the disadvantage of Fourier transform, all kinds of methods have been proposed, such as the technology of quasi-sinusoidal projection and π phase shifting for suppressing the zero frequency component and high orders spectra component [2], composite stripe projection technology for eliminating zero frequency component [4], color fringe projection technology for improving the accuracy and measurement range of FTP [5,6], wavelet transform method, empirical mode

decomposition and Neural network, etc [7–15], to overcome the disadvantages of FTP. These techniques have their own applications according to the property of the measured objects. For example, π shifting technique needs to capture two fringe patterns with π phase difference to eliminate the background intensity by subtracting operation, which improves the accuracy and measurement range but influences the real-time of FTP. It is a reliable method for measuring the static objects with high accuracy. In the method of projecting composite stripe, the background intensity can be eliminated from only one captured composite deformed fringe, but higher resolution of the CCD is needed to keep the separation between the useful component and the other components.

As we all know that the deformed fringe pattern is not periodic stationary anymore, because the projected sinusoidal fringe is modulated by the tested object. For analyzing the non-stationary fringe signal, Empirical mode decomposition combining with Hilbert transform is useful, in which Empirical mode decomposition decomposes the deformed fringe into Intrinsic Mode Functions (IMFs) varying from high frequency to low frequency. Then the separation of the zero frequency from the spectra would be operational [8–10], while Hilbert transform can be seen as 90 degree phase-shifter. If the background intensity of the fringe is eliminated by Empirical mode decomposition, a result analytic function can be obtained by Hilbert transform, from which the phase information can be calculated by the ratio of the imaginary part and the real part of the analytic function. The phase accuracy is high by this method, but the decomposition process is time-consuming.

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Because the background intensity and contract of the deformed fringe are slowly varying functions, the background distribution in each half period of the fringe can be regarded as a constant approximately [11,12]. Hilbert transform has the features of 90 degree phase shift and removing the DC component. Here a new method based on twice piecewise Hilbert transform is proposed to suppress background component of the fringe pattern. The method can suppress zero frequency component well and improve the measurement accuracy and range of FTP using only one fringe pattern. The theoretical analysis is given, and computer simulations and experiments are used to verify our analysis.

The organization of the paper is as follows: In Section 2, we give the principle of FTP and Hilbert transform. In Section 3, computer simulations are carried to compare the results obtained from the traditional FTP and FTP combining with Hilbert transform, respectively. While in Section 4, the experiments are applied to verify the effectiveness of proposed method. Last but not least, the conclusion is made in Section 5.

2. Principles

2.1. The principle of the Fourier transform profilometry

The scheme of the FTP measuring geometry is shown in Fig. 1 [1,7].

The optical axes of projector lens P1P2 crosses that of the camera lens I1I2 at point O on the reference plane which is perpendicular to the figure plane. L_0 is the distance between point I2 and point O, d depicts the distance between P2 and I2. A and C are points on the reference plane. h is the height of the point D on the tested object $h(x, y)$. A sinusoidal grating image is projected onto the object surface. The deformed fringe pattern captured by CCD is expressed as:

$$f(x, y) = a(x, y) + b(x, y)\cos[2\pi f_0 x + \varphi_0(x, y) + \varphi(x, y)] \quad (1)$$

Where $a(x, y)$ represents the background intensity, and $b(x, y)$ is the fringe contrast. f_0 denotes the carrier frequency. $\varphi_0(x, y)$ denotes the original phase caused by the non-telemetric light path of the measurement system, corresponding to the phase on the reference plane. $\varphi(x, y)$ denotes the modulation phase caused by the tested object.

The Fourier spectrum of Eq. (1) can be expressed as:

$$F(u, v) = A(u, v) + C(u - f_0, v) + C^*(u + f_0, v) \quad (2)$$

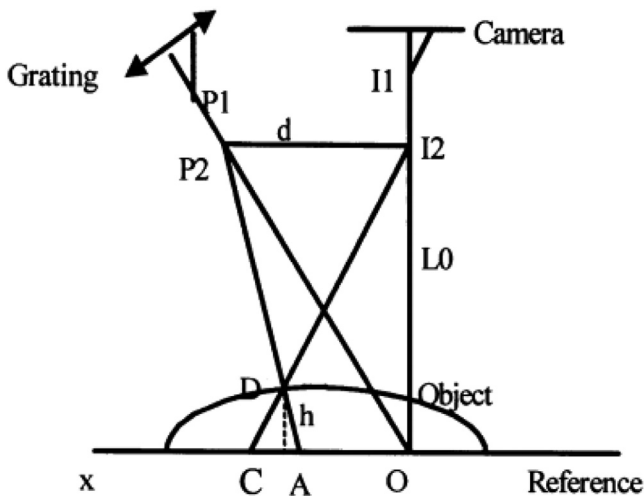


Fig. 1. Scheme of the FTP measuring geometry.

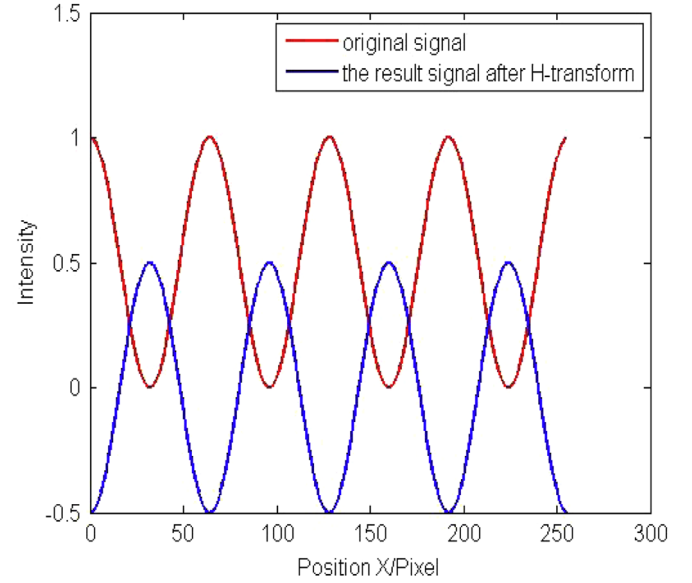


Fig. 2. Scheme of twice Hilbert transform.

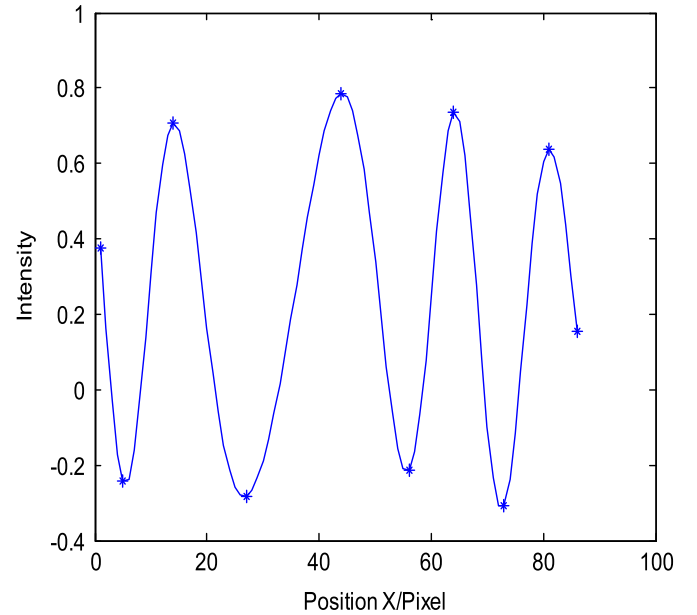


Fig. 3. A segment of a captured fringe pattern.

Where, superscript “*” expresses complex conjugate. $A(u, v)$ represents the zero spectra, corresponding the spectra of background component $a(x, y)$. $C(u - f_0, v)$ denotes the fundamental spectra contained the useful information of the measured object. $C^*(u + f_0, v)$ is the conjugate of $C(u - f_0, v)$. A suitable filter is used to select one of the fundamental spectra, such as $C(u - f_0, v)$. A complex exponential signal can be obtained by calculating the inverse Fourier transform of $C(u - f_0, v)$, which is expressed as:

$$g(x, y) = \frac{1}{2}b(x, y)\exp\{j[2\pi f_0 x + \varphi_0(x, y) + \varphi(x, y)]\} \quad (3)$$

From Eq. (3), the phase distribution $2\pi f_0 x + \varphi_0(x, y) + \varphi(x, y)$ can be obtained by extracted the complex angle of the complex signal. A reference fringe is dealt with to obtain the original phase $\varphi_0(x, y)$ caused by the non-telemetric light path of the system. The phase map $\varphi(x, y)$ corresponding to the height distribution of the measured object can be obtained. Considering $L_0 \gg h(x, y)$ in the practical measurement, the relationship between the height

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