Background Intensity Removal in Fourier Transform Profilometry: A Comparative Study

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Abstract: We study the removal of the background intensity of fringe patterns via Empirical Mode Decomposition and the Hilbert Transform. Simulation results show that the latter provides a suitable background compensation with minimal error 3D-reconstruction.

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1. Introduction

In Fourier Transform Profilometry (FTP) [1], a filtering procedure is performed to obtain the fundamental frequency spectrum in the frequency domain. This means frequency aliasing between the zero spectrum and the fundamental spectrum has a great influence on the measurement accuracy and measurable slope of height variation. If the zero frequency component and the high order spectra component interfere the useful fundamental spectra, the reconstruction precision of FTP will decrease greatly. To avoid this disadvantage, we test two recently proposed methods for removing the background intensity so as to improve FTP reconstruction precision. The first method is based on the piece-wise Hilbert transform [2]. The second method is based on Bi-dimensional Empirical Mode Decomposition (BEMD) [3], but the decomposition is carried out by morphological operations taking advantage of fringe images [4].

2. Background Removal

2.1. Morphological-based BEMD

The deformed fringe pattern is not periodic stationary, because the projected sinusoidal pattern is modulated by the tested object. For analyzing non-stationary signals, BEMD can decompose the deformed fringe pattern into Intrinsic Mode Functions (IMF) varying from high frequency to low frequency. Thus, removing the background is a simple operation. However, the decomposition is time consuming. To overcome this problem Zhou et al., [4] proposed a fast algorithm for empirical mode decomposition based on morphological operations and 2D convolution. In their work, extrema are not local maxima (minima), but are the pixels on the ridges (troughs) of a fringe pattern. After finding the ridges (troughs) by morphological operations the envelopes are estimated by a weighted moving average algorithm. The sifting procedure concludes when two modes are extracted, namely, a single IMF and a residue. The IMF corresponds to the fringe pattern without the background.

2.2. Piece-wise Hilbert Transform

The Hilbert transform can be seen as a 90-degree phase-shifter. Because the background intensity and contrast of the deformed fringe vary slowly throughout the image, they can be regarded as locally constant in a small region. Applying twice the Hilbert transform removes the DC component from a signal. However, because the background intensity varies, Luo et al. [2] proposed a piece-wise Hilbert transform per each half-period of the deformed fringe patterns.

3. Experiments and Results

In order to test realistically the considered background removal techniques we introduced three background modulation functions: (i) a negative slope from the bottom-left corner to the top-right corner of the image. This attempts to reproduce uneven illumination commonly found in fringe projection when the projector is tilted. (ii) A centered

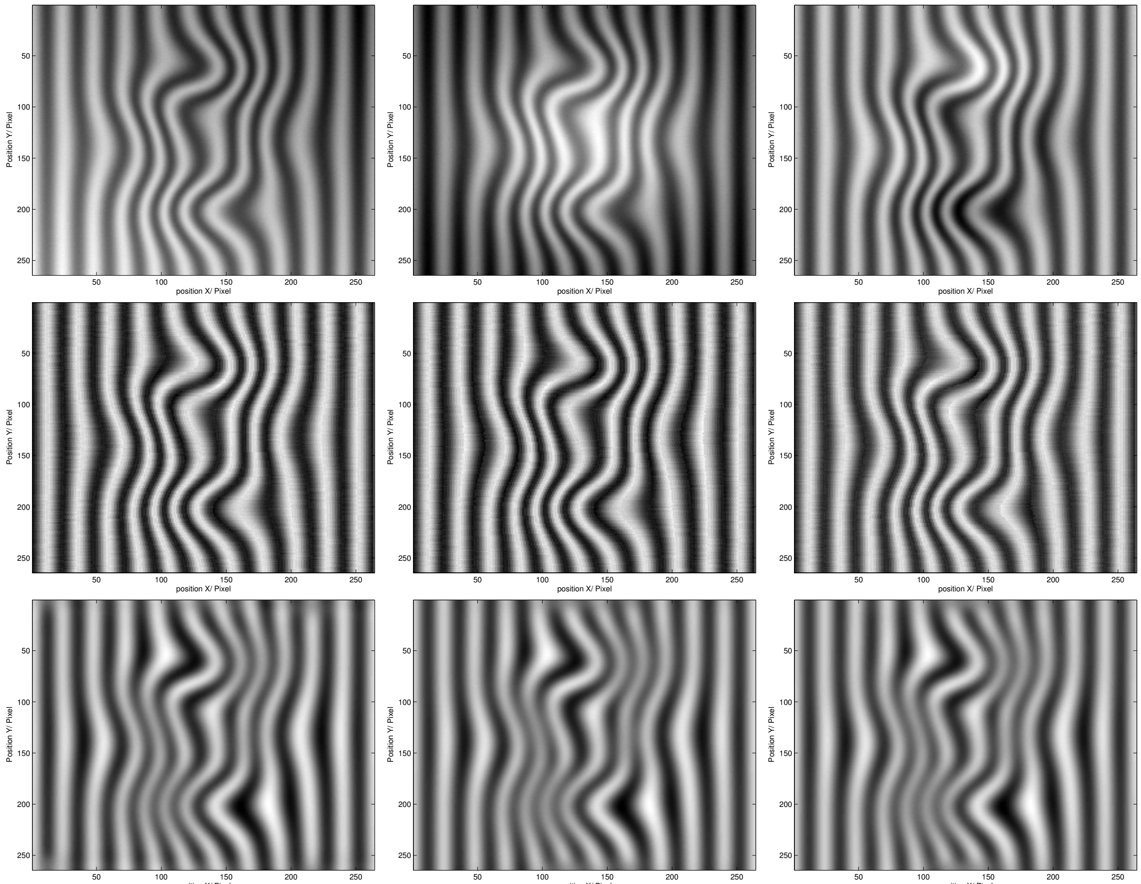

Fig. 1. (From left to right) Top-row: Deformed fringe patterns with different background modulation. Middle-row: the images after twice piece-wise Hilbert Transform. Bottom-row: After MOBEMD processing.

Gaussian function. This is also an approximation to commonly found uneven illumination. (iii) A more complex illumination modulation given by $-0.4 \times \frac{\text{peaks(.)}}{\max \text{peaks}}$, where peaks(.) is the MATLAB function as suggested in Ref. [2]. The object for reconstruction is 0.95peaks(.).

In the top row of Fig. 1 the deformed fringe patterns with different background modulation are shown. In the middle and bottom row, the processed images with twice piece-wise Hilbert transform and MOBEMD are shown. The images processed with the Hilbert Transform are inverted because of the 90-degree phase shift. However, the background intensity has been successfully removed. Despite the fact that MOBEMD also removes the background, it also reduces the contrast of the fringes which may introduce errors in the 3D reconstruction.

The 3D reconstructions and the error maps for the case in which the background intensity is modulated by a linear function are shown in Fig. 2. The rms reconstruction errors are 0.65 mm, 0.069 mm, and 0.38 mm. For the Gaussian distribution the rms errors are 0.046 mm, 0.070 mm, and 0.122 mm. And for the modulation with $-0.4 \times \frac{\text{peaks(.)}}{\max \text{peaks}}$ the rms errors are 0.061 mm, 0.056 mm, and 0.120 mm, respectively. Despite the errors, conventional FTP is significantly robust, mainly due to the filtering that is carried out. However, the piece-wise Hilbert Transform reduces the reconstruction errors by properly removing the slowly changing background. MOBEMD, while still removing the background intensity, its negative effect on lowering fringe contrast prevents it from being particularly useful.

4. Conclusions

In this work we have presented a comparative study with two recent techniques for removing the background intensity on fringe images for 3D Fourier Transform Profilometry. From our preliminary results, we have determined that the Piece-wise Hilbert Transform provides a suitable approach for removing the background and maintaining fringe

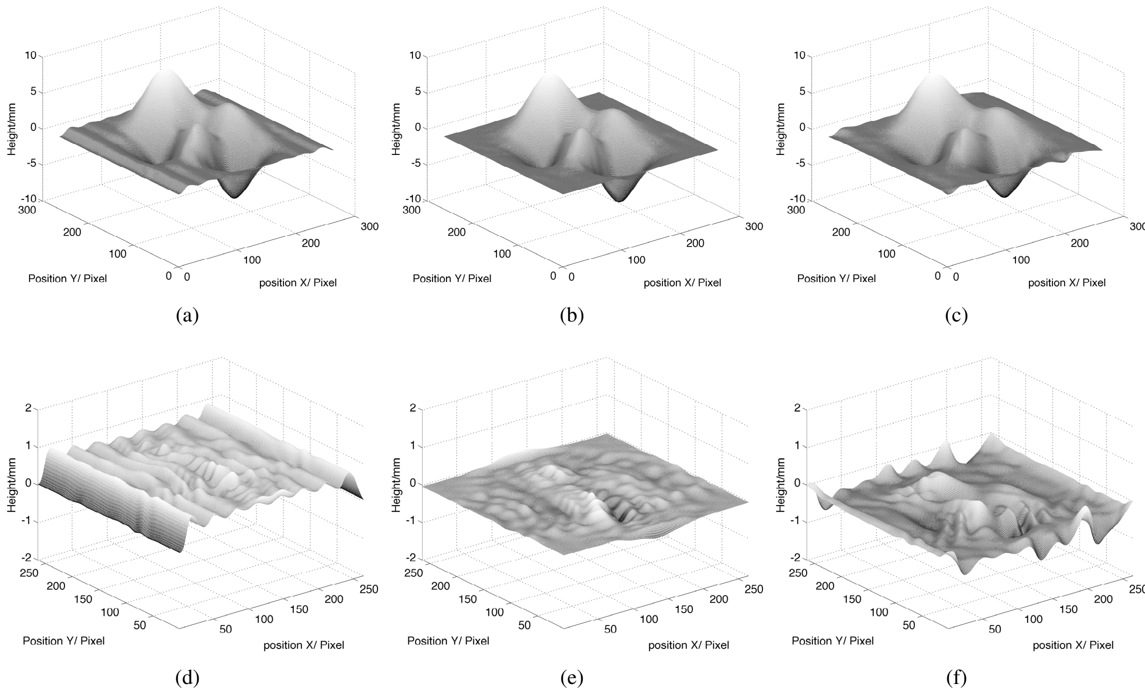

Fig. 2. 3D Reconstruction from deformed fringe pattern with background illumination modulated with a linear function by (a) conventional 2D FTP, (b) after PHT, and (c) MOBEMD. (d)-(f) The corresponding error maps.

fidelity.

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