Application of EMD in Fringe Analysis: New Developments

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ABSTRACT

Empirical mode decomposition (EMD) based methods have been widely used in fringe pattern analysis, including denoising, detrending, normalization, etc. The common problem of using EMD and Bi-dimensional EMD is the mode mixing problem, which is generally caused by uneven distribution of extrema. In recent years, we have proposed some algorithms to solve the mode mixing problem and further applied these methods in fringe analysis. In this paper, we introduce the development of these methods and show the successful results of two most recent algorithms.

Keywords: Empirical mode decomposition, mode mixing problem, fringe analysis.

1. INTRODUCTION

Fringe pattern analysis is a key step in optical metrology. EMD is a popular time-frequency analysis tool for fringe analysis, because it is data-driven and suitable for analyzing non-stationary signals. In early years, EMD is used to de-noise speckle patterns [1], and later to remove the fringe background in the Fourier transform profilometry (FTP) [2]. Even though EMD is an excellent time-frequency tool, it suffers from the mode mixing problem, which often appears due to intermittent noise. Ensemble EMD (EEMD) is an improvement of EMD to solve the mode-mixing problem, and has been used for denoising of fringe patterns [3]. However, EEMD is very time-consuming. For example, it needs about half an hour to process a fringe pattern with 512×512 pixels using a PC (6-core CPU 3.2GHZ, 16GB RAM) if the ensemble size is 200, therefore EEMD is not suitable for real applications. Moreover, if the fringe pattern has large deformation, the IMFs of EEMD will present some spurious modes, causing large measurement errors. To efficiently cope with the mode mixing problem, recently we proposed a novel algorithm named regenerated phase-shifted sinusoids assisted EMD (RPSEMD) [4]. This method adds some designed sinusoids to fill into the vacancy of the uneven distribution of the extrema. The design of the sinusoids is adaptive according to the characteristics of the tested signal and thus is intelligent. As a result, the mode mixing problem can be resolved effectively. In addition, the whole decomposition process is efficient as very few sinusoids need to be added. We have applied this algorithm to fringe analysis, and based on the decomposition results, a classification method is also proposed to separate the noise component, the phase modulation component and the background component [5].

The methods mentioned above are one-dimensional, which have to process a fringe pattern line by line. Naturally bi-dimensional EMD (BEMD) has been introduced for fringe analysis. Similar to 1D, the BEMD methods are mainly used to de-noise a fringe pattern [6] and remove background [7]. Some work focuses on the issues of normalization of fringe patterns combined with the partial Hilbert transform or Hilbert spiral transform. Furthermore, color fringe patterns can also be analyzed by BEMD in fringe projection profilometry [8]. Unfortunately, the bi-dimensional EMD (BEMD) is not immune to the mode mixing problem. Consequently, bi-dimensional EEMD (BEEMD) has been proposed, but again, the computation is very slow [9] and even slower than EEMD. A selective reconstruction using fast and adaptive BEMD (FABEMD) is proposed to accurately normalize a fringe pattern [10, 11]. These methods [10, 11] are more effective than others. However, they only combine the strong information in different bi-dimensional intrinsic modes (BIMF) to avoid but not to solve the mode mixing problem. Right now, we are working on a new block-sized and sinusoids-assisted BEMD (BSBEMD) method to resolve these problems. BSBEMD is an extension of RPSEMD to 2D. Compared with EMD, BEMD has more difficulties in determining extrema and constructing envelopes of the extrema, because there lacks a standard definition of extrema in a 2D space and also lacks established ways to construct envelopes. Thus the mode mixing problem will be caused not only due to the uneven distribution of extrema but also due to the improper construction of envelopes, which will become more difficult if the image size is large. In BSBEMD, an image is cut into a few blocks, which will be analyzed individually. The proposed algorithm is based on morphological operations and

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convolution operations, making the computation very fast. Typically, only several seconds is needed to process a 512×512 fringe pattern. We consider the BSBEMD a competitive tool for fringe analysis, as it is able to achieve both high accuracy and efficiency.

2. RESULTS OF RPSEMD AND BSBEMD

2.1 RPSEMD Algorithm

We aim to present a glance of processing capabilities of RPSEMD by showing an example. The technical details are skipped, which can be found in [5] and [6]. A fringe pattern is simulated with complicated phase, varying background and noises, as shown in Fig. 1 (a). The fringe pattern is processed by RPSEMD, and the obtained IMFs are classified by the noise-signal-background strategy in [5] according to the properties of different components. The obtained noise map is shown in Fig. 1(b) where little useful signal was lost. The varying background is reconstructed as Fig. 1(c). Subtracting the noise and background, we obtain the phase modulation signal which was Hilbert transformed to retrieve the phase. The unwrapped phase is displayed in Fig. 1(d) and its 3D view is shown in Fig. 1(e). Furthermore, we compute the errors of the retrieved phase compared with the ideal phase, where the standard deviation is 0.1118 rad and the largest error is 1.2728 rad. As RPSEMD has to run line by line, the processing time of the whole image adds up to about 4 mins. Although RPSEMD is much better than EEMD, further acceleration is necessary to make it useful for real applications.

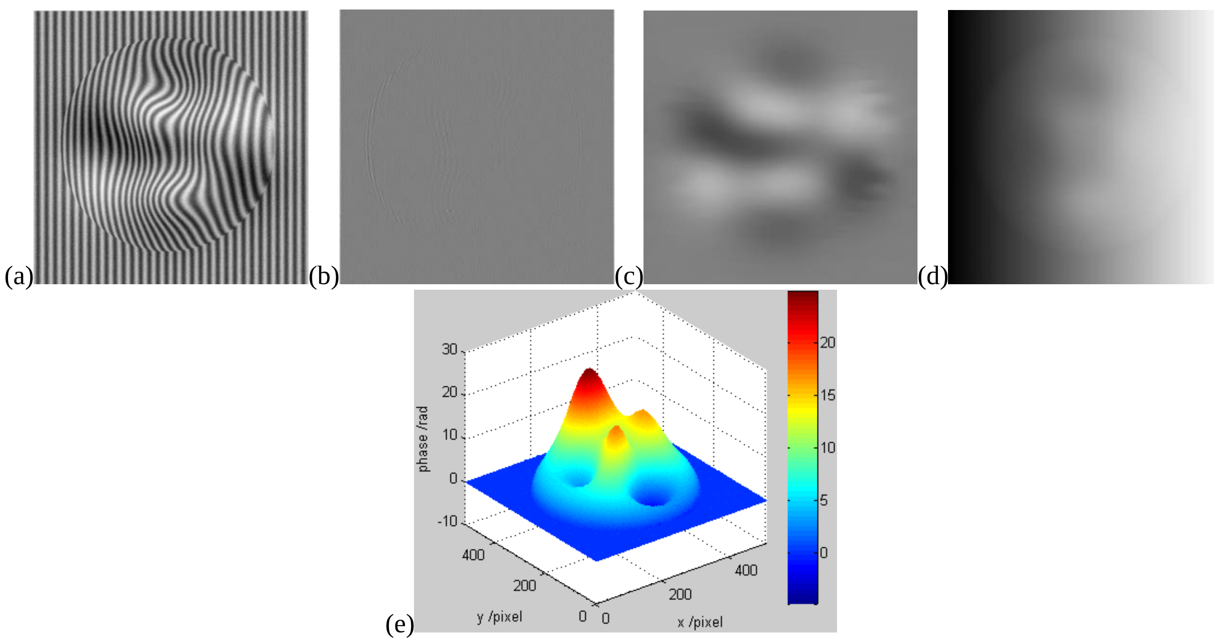

Figure 1. (a) A complicated fringe pattern; (b) the obtained noise; (c) the obtained background; (d) the unwrapped phase; (e) the retrieved 3D phase.

2.2 BSBEMD Algorithm

BSBEMD results are presented here. Figure 2 is another complicated fringe pattern with noise, complicated modulation and varying background, and additionally it contains fringes with various directions, which cannot be well processed by RPSEMD. Figures 2 (b)-(g) show the decomposition results of Fig. 2(a) using the BSEMD. The results are not seriously affected by the mode mixing problem. Figure 2(b) is considered as the noise component, while Fig.2 (g) is considered as the background. With noise and background removed, the summation of the remaining bi-dimensional IMFs (BIMFs) yields the phase modulation signal. To enhance the fringe, we perform amplitude demodulation to normalize the useful carrier fringe by the Hilbert spiral transform proposed in [10], where the modulus is calculated as

$$\left|A(x,y)\right| = \sqrt{s^2(x,y) + \left|F^{-1}\{P(\zeta_1,\zeta_2)F\left[s(x,y)\right]\}\right|^2} \quad (1)$$

where $s(x, y)$ denotes the reconstructed useful carrier fringe, F and F^{-1} denotes the Fourier transform and inverse Fourier transform respectively, and $P(\zeta_1, \zeta_2)$ is the spiral phase function on Fourier domain, which is defined as

$$P(\zeta_1, \zeta_2) = \frac{\zeta_1 + j\zeta_2}{\sqrt{\zeta_1^2 + \zeta_2^2}} \tag{2}$$

where (ζ_1, ζ_2) are the spectral domain coordinates, and j is the imaginary unit. The result of normalization is shown in Fig. 2(h), which is promising for further use. The decomposition result of BSBEMD can be used for various goals from practical needs. Furthermore, in processing this fringe pattern, only 6 seconds are needed in using MATLAB.

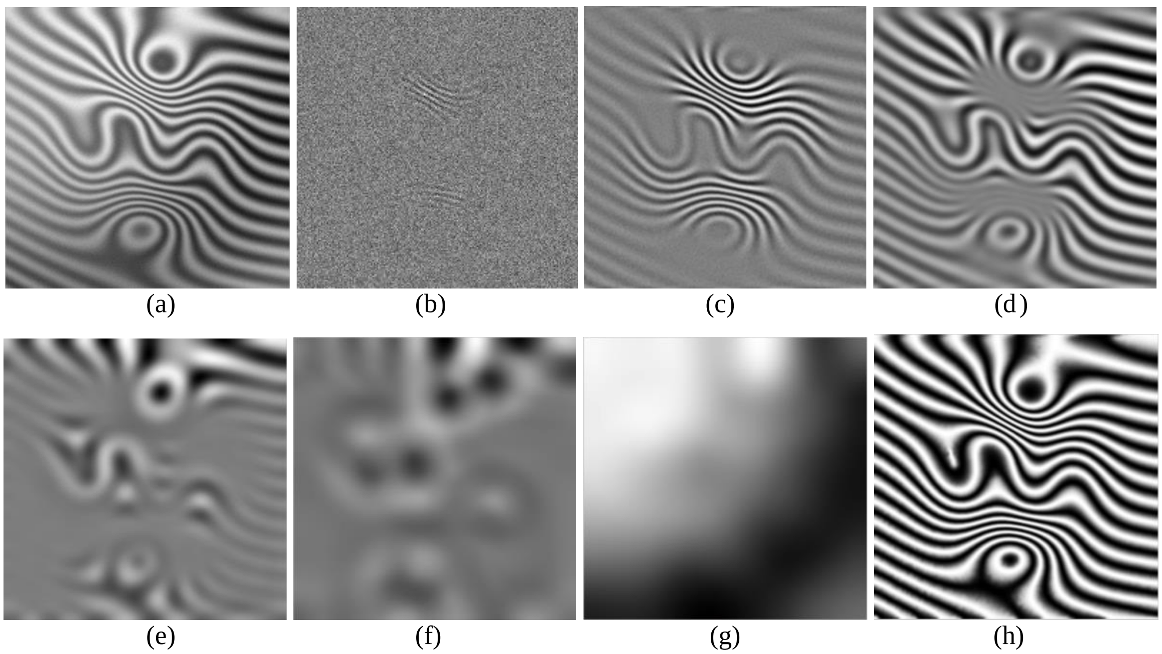

Figure 2. (a) A complicated fringe pattern with varying directional fringe; (b)-(f) the obtained BIMFs and (g) the residue; (h) the normalized phase modulation signal.

3. CONCLUSION

In this paper, the development of applications of EMD and BEMD methods in fringe analysis is introduced. The results of two newly proposed methods, RPSEMD and BSBEMD, are presented, to show their capabilities in fringe analysis. The mode mixing problem can be resolved successively by both methods. The good performance of BSBEMD has been observed and will be more extensively evaluated. In the next work, the automatic classification of the resulted BIMFs needs to be studied. Its application in analyzing fringe patterns, either with or without a carrier frequency, will also be investigated, for denoising, detrending, phase retrieval or even its use in real-time measurement system.

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