RESILIENT INFRASTRUCTURE

June 1–4, 2016

STRUCTURAL MODAL IDENTIFICATION USING AN IMPROVED EMPIRICAL MODE DECOMPOSITION

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ABSTRACT

Empirical mode decomposition (EMD) has shown significant promises in signal decomposition of vibration data of civil engineering structures. Owing to its self-adaptive time-frequency decomposition capability, it is widely used in system identification of both linear and nonlinear structures. Unlike EMD which uses only single sensor, multivariate EMD (MEMD) is recently explored as a modal identification tool utilizing multichannel vibration measurements. In this paper, the performance of MEMD is investigated by integrating with another powerful signal separation technique to undertake modal identification under a wide range of applications. The proposed EMD method is validated using a suite of numerical studies.

Keywords: Signal decomposition, modal identification, empirical mode decomposition, MEMD, multiple sensors, blind source separation.

1. INTRODUCTION

Output-only modal identification has shown significant effectiveness in health monitoring, retrofitting and rehabilitation of large-scale civil infrastructure. Numerous time and frequency domain algorithms are studied in the literature, and relevant literature on this topic is vast (Maia and Silva 2001; Staszewski and Robertson 2007). More recently, powerful signal processing methods including blind source separation (BSS) (Antoni et al. 2004; Sadhu 2013, Sadhu and Narasimhan 2013), empirical mode decomposition (EMD) (Darryll and Liming 2006; Hazra et al. 2012) and Hilbert-Huang transform (Huang et al. 1998; Yang et al. 2003; Yang et al. 2004) are studied in a broad range of applications of structural health monitoring including human-induced vibration, control and damage detection techniques.

Compared to other time-frequency decomposition tools like wavelet or Wigner-Ville distribution, EMD is capable of dealing with nonlinear and non-stationary signals using adaptive bases and therefore has significant flexibility in handling a wide range of signals found in structural condition assessment. With its classical form, EMD works with just a single sensor vibration measurement to extract a subset of modal information (Yang et al. 2003). On the other hand, multivariate EMD (MEMD) is able to utilize multichannel signals in generating a time-frequency map (Rehman and Mandic 2010). In this paper, a MEMD-based signal processing technique is employed on multiple sensor vibration measurements to identify the linear normal modes in a structural system.

Standard EMD method utilizes a single vector of data (corresponding to a single sensor) at a time. This means when multiple channels of data are processed, one cannot be sure whether their frequency content and the joint information will match (Rehman and Mandic 2010. Recognizing these limitations, traditional EMD is extended to its multivariate version suitable for multichannel signals (Rehman and Mandic 2010). In multivariate EMD (MEMD), multidimensional envelopes are firstly developed by utilizing the projections of the raw signal along different directions, and then the average of these envelopes is used as the local mean. This method is explored in bio-medical (Julien et al. 2011) as well as mechanical systems (Zhao et al. 2012).

While MEMD alleviates the issue of using a single sensor for decomposition, the issue of mode-mixing is still prevalent in this method, as with the standard EMD. Recently, MEMD is integrated with Ensemble EMD (EEMD) to address the mode mixing in vibration signals (Sadhu 2015). In this paper, the performance of MEMD is further improved where the mode mixing is alleviated using the principles of blind source separation. The proposed method is illustrated using a suite of numerical studies.

2. EMPIRICAL MODE DECOMPOSTION USING MULTI-CHANNEL MEASUREMENTS

EMD primarily uses a single data channel for frequency extraction and is blind to others when multiple channels are available. While dealing with the measurements of multiple sensors as typically found in modal applications, EMD algorithm faces two problems:

1. It is likely that the decomposition of IMFs from different channels of measurements will not match, either in the number of identified frequencies, or in their frequency content.
2. The combined information between multichannel sensors is not exploited because signals from multiple sensors are treated individually.

In this time-frequency decomposition method, multidimensional envelopes are initially developed by projecting vibration data along different directions. The average of these envelopes is then denoted as the local mean. For a general case of n-dimensional signal, a set of uniformly distributed points on a unit $(n$-1$)$-sphere (Rehman and Mandic 2010; Rehman and Mandic 2011) are generated and the resulting intrinsic mode functions (IMFs) are obtained using three dimensional projections. The details of this method can be found in this reference (Rehman and Mandic 2011).
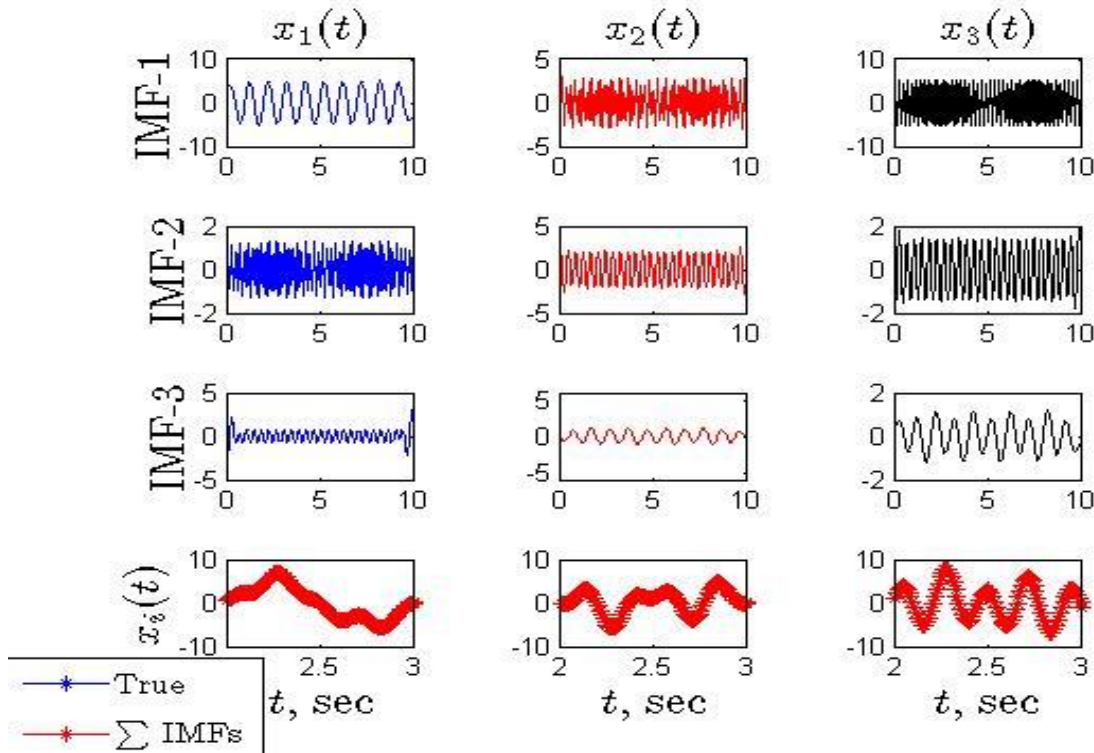

Figure 1: Performance of the MEMD method under sine example

A mixture of three sine signals with frequencies 2, 3.5 and 4.8 Hz is considered to illustrate the performance of MEMD method. Fig 1 shows the separated sine signals obtained from these mixtures. It can be seen that each signal has three IMFs corresponding to three sine frequencies. Moreover, MEMD is able to separate those frequencies using three measurements. In order to simulate a real-life scenario, three closely-spaced frequencies with 0.9, 1.3 and 3.8 Hz are used and the identification results are shown in Fig. 2. The results confirm the accuracy of the MEMD method in this case well.

However, under the presence of low energy modes or measurement noise, it is observed that there is significant mode-mixing and the MEMD method itself is unable to delineate them. In order to solve this problem. Independent component analysis (ICA), a higher-order statistics-based BSS, is integrated with MEMD to separate modal-mixing in the resulting IMFs of vibration data.
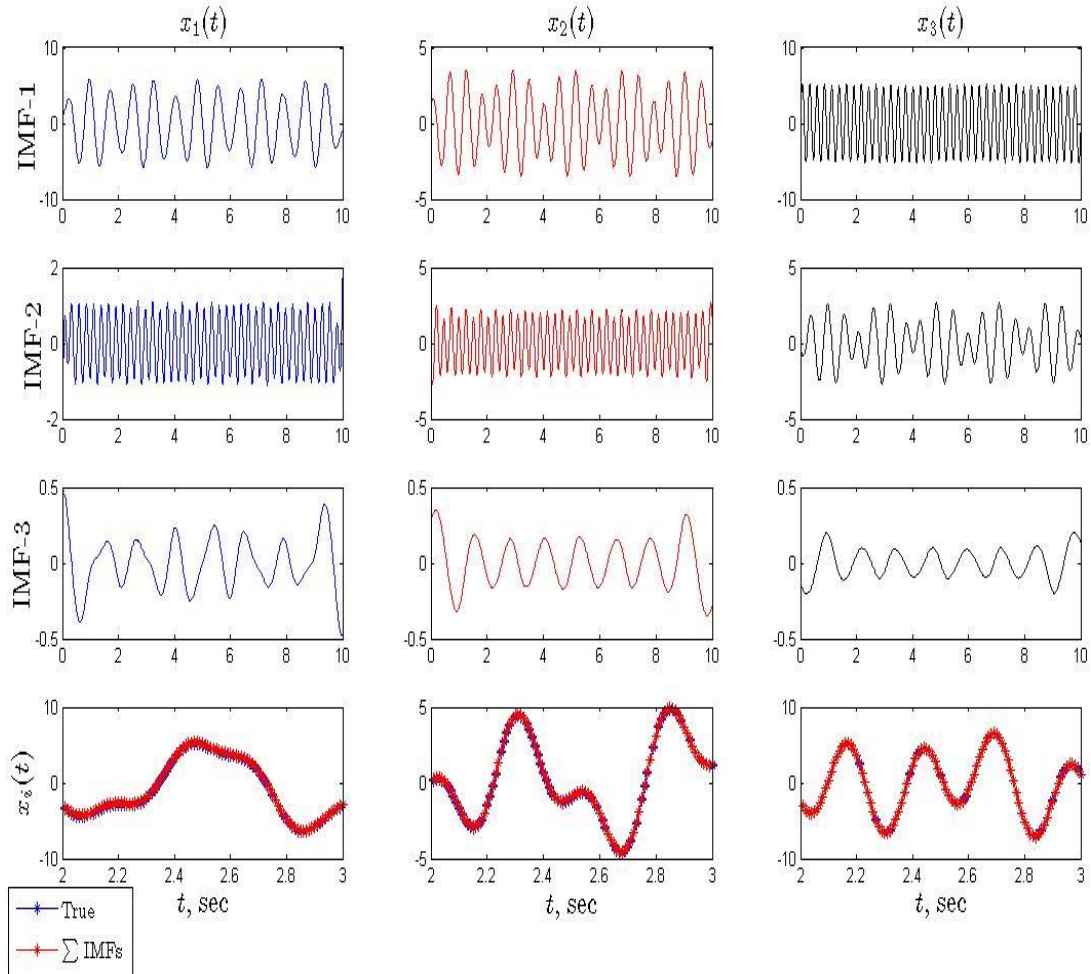

Figure 2: Performance of the MEMD method under sine example with closely-spaced frequencies

3. NUMERICAL SIMULATIONS

A 5-storey numerical building model is utilized to demonstrate the proposed method. The model is excited by white Gaussian noise at floor locations. The vibration data is now analyzed using MEMD, and the resulting IMFs of three typical vibration measurements are shown in Fig. 3. The results reveal significant mode mixing in last three modal responses. ICA is then performed over the IMFs containing modal responses with mixed modes and the resulting modal responses are shown in Fig. 4. The performance of the proposed method is also evaluated under different measurement noise (i.e. signal-to-noise (SNR)) and tabulated in Table 1. It reveals significant accuracy in modal assurance criteria (MAC) even under the presence of 10% measurement noise.
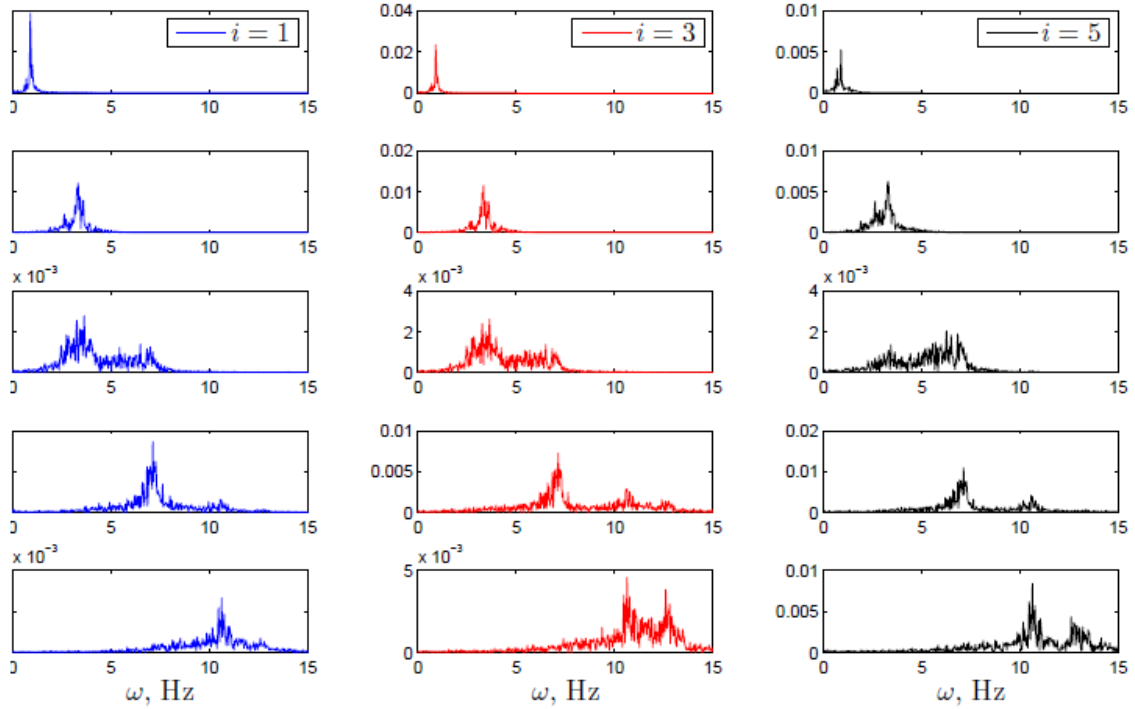
Figure 3: Modal responses of the 5-DOF building model obtained using the MEMD method

Table 1: Identification results using the proposed method

Mode	IMF		MAC	
	ω, Hz	ς, %	SNR=100	SNR=10
1	0.91	1.9	1.0	0.99
2	3.39	1.95	0.995	0.99
3	7.1	2.03	0.99	0.98
4	10.67	2.1	1.0	0.99
5	12.67	1.99	0.99	0.98

4. CONCLUSIONS

The MEMD method is explored as an attractive tool for modal identification employing multichannel vibration measurements. The modal response separation capability of MEMD is improved using blind source separation. The proposed modal identification is illustrated using a numerical study. The future work is reserved towards full-scale validation of the improved method and addressing other practical challenges like closely-spaced modes and fewer sensor measurements.
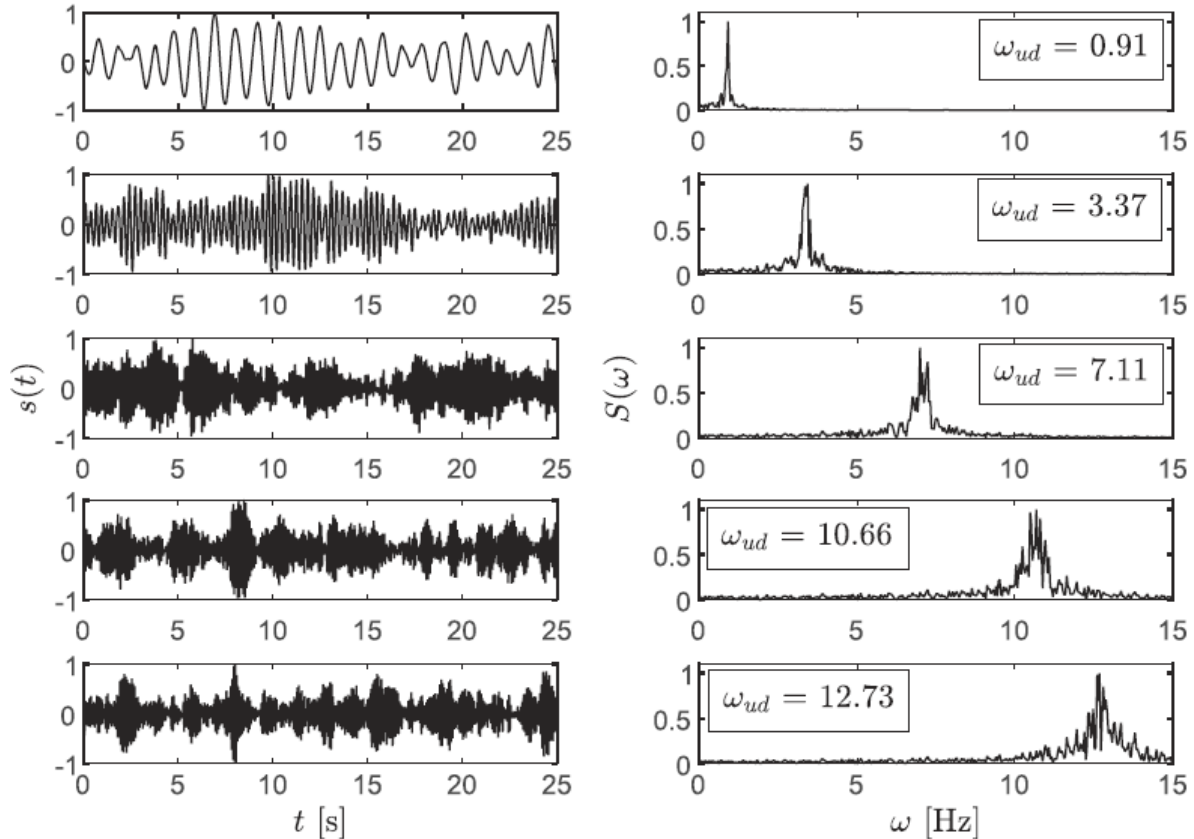
Figure 4: Separated modal responses using the improved MEMD method

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