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A Frequency-Weighted Energy Operator and complementary ensemble empirical mode decomposition for bearing fault detection

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ABSTRACT

Signal processing techniques for non-stationary and noisy signals have recently attracted considerable attentions. Among them, the empirical mode decomposition (EMD) which is an adaptive and efficient method for decomposing signals from high to low frequencies into intrinsic mode functions (IMFs). Ensemble EMD (EEMD) is proposed to overcome the mode mixing problem of the EMD. In the present paper, the Complementary EEMD (CEEMD) is used for bearing fault detection. As a noise-improved method, the CEEMD not only overcomes the mode mixing, but also eliminates the residual of added white noise persisting into the IMFs and enhance the calculation efficiency of the EEMD method. Afterward, a selection method is developed to choose relevant IMFs containing information about defects. Subsequently, a signal is reconstructed from the sum of relevant IMFs and a Frequency-Weighted Energy Operator is tailored to extract both the amplitude and frequency modulations from the selected IMFs. This operator outperforms the conventional energy operator and the enveloping methods, especially in the presence of strong noise and multiple vibration interferences. Furthermore, simulation and experimental results showed that the proposed method improves performances for detecting the bearing faults. The method has also high computational efficiency and is able to detect the fault at an early stage of degradation.

1. Introduction

In order to have an efficient diagnosis of faults occurring in rolling element bearings, researchers have extensively investigated different signal processing techniques to accurately extract fault characteristics from vibration signals. Among them, one of the most popular is the Empirical Mode Decomposition (EMD) [1]. Furthermore, improved methods have evolved from EMD method [2–7]. The ensemble EMD (EEMD) is a noise assisted method which presents a significant improvement on the EMD [8–12]. Even though ensemble EMD has effectively resolved the mode mixing which is the major drawback of the EMD method, it is time consuming for implementing large enough ensemble means. To avoid this

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weakness, the complementary EEMD (CEEMD) is proposed [13]. Indeed, the CEEMD not only overcomes the mode mixing, but also eliminates the residual of added white noise persisting in the IMFs and saves computational time.

Recently, Wang et al. [14] studied the computational complexity of the EMD algorithm and proposed a fast algorithm which proves that the time complexity of the EMD/CEEMD is actually equivalent to that of the Fourier Transform. However, relevant IMFs must be selected for obtaining reliable results when performing the EMD/CEEMD process. Lots of techniques have been proposed to identify most sensitive IMFs. In [15], the authors compared the spectra of sifted IMFs with the spectrogram of measured vibration response resulting from a swept-sine excitation and the IMF with a concurrent resonance frequency band is selected as relevant. Following such purpose, Cho et al. defined an index labeled Power-Harmonic Ratio (PHR) [16]. The higher value of PHR identifies the IMFs with higher average power containing fault related frequency peaks. The idea adopted in [5] and [17] is to consider the IMFs which have a poor correlation with the original signal as irrelevant ones and assume a threshold that can be set to discriminate between relevant and irrelevant IMFs. Other techniques based on energy and/or correlation measures were developed for identifying the most representative IMFs after the EMD process [18–21]. Moreover, Intrinsic Mode Entropy (IMEn) was developed to measure entropy over accumulative sums of IMFs obtained by the EMD [22]. Likewise, Hu and Liang employed Multivariate EMD-based IMEn to a multivariate neural data [23] and obtained the IMEn by computing the sample entropy over the cumulative sums of the IMFs extracted by the MEMD.

In this paper, a new method is proposed for selecting relevant IMFs from the CEEMD process. It is based on three indexes; kurtosis, energy and approximate entropy. Subsequently, a reconstructed signal from the relevant IMFs is treated to extract information about bearing defect. Herein, the authors adopt an alternative operator using the envelope-derivative of the signal called Frequency-Weighted Energy Operator (FWEO). This envelope-derivative operator improves the performance over the Teager-Kaiser Energy Operator (TKEO) [24,25] and enveloping method, especially in the presence of strong noise and multiple vibration interferences.

2. Theoretical background

2.1. CEEMD method

As known, the EMD method [1] presents a major drawback of mode mixing and the Ensemble EMD (EEMD) [8] is then developed in the aim to overcome this drawback. Using the EEMD process, the components with truly physical meaning can be extracted from the signal through the help of added noises. However, the EEMD is time consuming for implementing the large enough ensemble mean and suffers from the residual of the added white noise. To further eliminate the residual of the added white noise and enhance the calculation efficiency of the EEMD algorithm, Yeh et al. presented the complementary EEMD that is a noise-improved method [13].

To avoid the shortcomings of EMD and EEMD, the Complementary EEMD adds a pair of white Gaussian noises to the original signal [12]. By using this procedure, the CEEMD saves a computational time and reduces the final white noise residue. The procedure is as follows:

1) Because a single white noise cannot solve all intermittent signals, a pair of white noise ($\omega_n(t)$) is added to the original signal $x(t)$ to build a positive mixture $x_1(t)$ and a negative mixture $x_2(t)$:

$$\begin{aligned} x_1(t) &= x(t) + \omega_n(t) \\ x_2(t) &= x(t) - \omega_n(t) \end{aligned} \tag{1}$$

2) Then, $c_{ij}^{+}(t)$et $c_{ij}^{-}(t)$ are two ensembles of IMFs obtained from decomposing the positive and negative mixtures by the EMD, with $c_{ij}^{+}(t)$ (respectively $c_{ij}^{-}(t)$) is the jth IMF obtained with addition of the ith positive noise (respectively negative noise);
3) After that, the final IMF calculated by:

$$IMF_j = \frac{1}{2N}\sum_{i=1}^{N}\left[c_{ij}^{+}(t) + c_{ij}^{-}(t)\right] \tag{2}$$

So, the original signal $x(t)$ can be expressed by:

$$x(t) = \sum_{j=1}^{N} IMF_j(t) + r_n(t) \tag{3}$$

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