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Pseudo-fault signal assisted EMD for fault detection and isolation in rotating machines ☆

Dheeraj Sharan Singh *, Qing Zhao

Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Canada

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ABSTRACT

This paper presents a novel data driven technique for the detection and isolation of faults, which generate impacts in a rotating equipment. The technique is built upon the principles of empirical mode decomposition (EMD), envelope analysis and pseudo-fault signal for fault separation. Firstly, the most dominant intrinsic mode function (IMF) is identified using EMD of a raw signal, which contains all the necessary information about the faults. The envelope of this IMF is often modulated with multiple vibration sources and noise. A second level decomposition is performed by applying pseudo-fault signal (PFS) assisted EMD on the envelope. A pseudo-fault signal is constructed based on the known fault characteristic frequency of the particular machine. The objective of using external (pseudo-fault) signal is to isolate different fault frequencies, present in the envelope . The pseudo-fault signal serves dual purposes: (i) it solves the mode mixing problem inherent in EMD, (ii) it isolates and quantifies a particular fault frequency component. The proposed technique is suitable for real-time implementation, which has also been validated on simulated fault and experimental data corresponding to a bearing and a gear-box set-up, respectively.

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1. Introduction

A complex electromechanical system containing rotating equipment degrades slowly and might lead to a catastrophic failure, if kept on running. In the current state of art, we need robust, real-time and efficient condition monitoring system, which not only detects a fault after it has happened, but also predicts an upcoming fault. This kind of system not only helps in saving life and money by avoiding catastrophic failures but also increases MTBF (mean time between failures). Condition monitoring is based on being able to monitor the current condition and predict the future condition of machines, while in operation. Thus, it means that information must be obtained externally about internal defects, while the machines are in operation. In the domain of rotating machinery, vibration is an important indicator of the slowly evolving degradation in the system [1]. Although vibration signatures contain critical information about the status of the system, analyzing these signatures have many challenges. Vibration signatures from the faults in rotating machines are often transient, which manifest periodic impulse-like behavior [2]. In addition, vibration signatures from different sources travel distinct paths to get modulated before reaching the sensor. As a consequence, the measured vibration signature is sensitive to the sensor

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* Corresponding author.
E-mail addresses: dheeraj@ualberta.ca (D.S. Singh), qingz@ualberta.ca (Q. Zhao).

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placement and contains many complex oscillatory modes. Hence, effective signal processing and feature extraction techniques are necessary to first demodulate and then extract meaningful information from the vibration signature.

Some of the prevalent faults in rotating machines are associated with a localized fault interacting with the rotating component, generating an impact. This phenomenon excites different resonant vibration modes in the system, appearing as amplitude modulated waveforms, in the measured vibration signal. Different faults have distinct characteristic (repetition) frequencies, which need to be estimated for precise fault diagnostics. The above-mentioned physical effects have been widely explored and used by engineers and researchers for fault detection and diagnosis. Of the various techniques applied to detect such patterns in vibration waveforms, demodulation and enveloping based methods are most popular. Enveloping based techniques generally require filtering the signal with a band pass filter. Center frequency selection of such band pass filters has been a challenging task. Several techniques based on spectral kurtosis [3], wavelets [4] and Empirical Mode Decomposition [5] have been suggested to address this problem. However, automation of this process is necessary in order to develop a reliable on-line instrumentation for fault detection.

Empirical Mode Decomposition (EMD) [6] method was introduced to overcome the shortcomings of wavelet transform. Since then, EMD has been widely applied in different applications. An improved form of EMD known as Ensemble Empirical Mode Decomposition (EEMD) method [7] was proposed to solve the problem of mode-mixing found in EMD. Several researchers worked on automatic selection of decomposed components, known as intrinsic mode function (IMF) [8–10]. A new method similar to EMD known as local mean decomposition (LMD) has been used to diagnose bearing fault [11]. EMD and LMD come under the category of adaptive non-parametric T–F methods. Adaptive parametric time–frequency (T–F) methods such as matching pursuit and basis pursuit have also been used for diagnosis [12,13]. Flandrin et al. pointed out that EMD acts as a dyadic filter bank, when applied to structured broadband stochastic processes such as fractional Gaussian noises [14]. Further, a fully data driven signal-filtering method based on EMD is proposed in [15]. The filtering scheme is based on partial reconstruction of the signal using the IMFs that correspond to the most important structures of the signal (low-frequency modes).

In recent research work, engineers and researchers have widely used EMD and its modified versions, to detect and diagnose faults of bearings [5,16], gears [8,17] and rotors [18] in rotating machinery. It has also been used to identify structural parameter changes and detect incipient faults. Yang et al. [19] proposed a method to identify multi-degree-of-freedom (MDOF) linear systems using measured free vibration time histories. For MDOF systems, the normal modes have been assumed to exist. In this method, the measured response data, which are polluted by noises, are first decomposed into modal responses using the EMD approach with intermittency criteria. Shi et al. developed an identification approach for linear time-varying dynamical systems, which is based on the Hilbert transform and the empirical mode decomposition method with free vibration response signals [20]. A recent work done by Yu and Ren [21] presented an EMD based stochastic subspace identification procedure for operational modal analysis of structures. They also demonstrated this method on real data obtained from a bridge and showed that the identification of vibration characteristics is easier in decomposed signal in comparison to the original signal. EMD method in conjunction with the model identification procedure has been used to estimate modal parameters of a system. The output-only measurements can be decomposed into modal response functions by means of the EMD technique, which will help in bypassing unwanted modal components and fake frequencies. In [22] concept of an IMF is coupled with the concept of the phase of a time-domain signal, which is further used to determine the relative phase response between two successive degrees of freedom. The change in relative phase response is further used for detection of the structural damage.

Recently EMD has been extended to handle multivariate signals; it started with EMD extension to handle complex signals, which includes complex EMD [23], rotation invariant complex EMD [24] and bivariate EMD [25]. These methods rely on simultaneous decomposition of complex signals, which aligns IMFs based on their frequency bandwidth. Rehman et al. further introduced multivariate EMD [26], which extracts same number of IMFs for all the input signals which are modally aligned based on their frequency content. Hence, MEMD acts as a multichannel dyadic filter bank [27]. Recently, a noise assisted-MEMD has been proposed, which adds independent white Gaussian noise channels to input signal and then extracts modally aligned IMFs using MEMD. This results in better signal decomposition with least mode-mixing [28].

This paper proposes the idea of injecting a detection signal known as pseudo-fault signal to the envelope of the signal for mode separation and fault isolation. The idea bears certain similarity with active fault diagnosis (AFD). The active approach to failure detection consists in acting upon the system on a periodic basis using an auxiliary test signal, also known as detection signal, in order for the system to exhibit abnormal behaviors. One drawback of AFD is that these signals might interfere with the system performance. Therefore, designing such signals has been a challenging task. Initially, Zhang [29] and Kerestecioglu and Zarrop [30] worked on designing auxiliary input signals as linear inputs of stochastic models with objective of optimizing detector performance. Nikoukhah et al. [31] presented a method for constructing a minimum energy detection signal by assuming that systems can be modeled with two separate linear systems for normal and failed behaviors. Campbell et al. [32] extended this work to handle more than two models and certain type of nonlinearities. Later, Niemenn and Poulsen [33] presented an AFD technique for closed loop systems, by introducing a fault signature matrix as a central transfer function, whose elements depend on parametric faults. Traditionally many earlier fault detection schemes modeled faults as abrupt changes in system behaviors, which were not able to detect incipient faults effectively. Nikoukhah et al. [34] extended multi-model AFD framework for incipient fault detection by modeling fault as a drift in system parameters.

This paper has addressed the challenges involved in EMD based fault detection and proposes an enhanced methodology

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