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Minimum entropy deconvolution optimized sinusoidal synthesis and its application to vibration based fault detection ☆

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ABSTRACT

In this paper, a minimum entropy deconvolution based sinusoidal synthesis (MEDSS) filter is proposed to improve the fault detection performance of the regular sinusoidal synthesis (SS) method. The SS filter is an efficient linear predictor that exploits the frequency properties during model construction. The phase information of the harmonic components is not used in the regular SS filter. However, the phase relationships are important in differentiating noise from characteristic impulsive fault signatures. Therefore, in this work, the minimum entropy deconvolution (MED) technique is used to optimize the SS filter during the model construction process. A time-weighted-error Kalman filter is used to estimate the MEDSS model parameters adaptively. Three simulation examples and a practical application case study are provided to illustrate the effectiveness of the proposed method. The regular SS method and the autoregressive MED (ARMED) method are also implemented for comparison. The MEDSS model has demonstrated superior performance compared to the regular SS method and it also shows comparable or better performance with much less computational intensity than the ARMED method.

1. Introduction

Defects and malfunctions of critical components like bearings and gears in rotating machinery can cause severe damage to the entire machine. Moreover, rotating machinery failures can lead to costly downtime and may result in economic losses, and even claim lives. Many faults in rotating machines lead to a series of impacts. The resulting vibration signals then have repetitive characteristic fault signatures as the mechanical components rotate. Non-stationary vibration signals contain rich information about machinery health conditions, and can be used for in-situ, non-intrusive fault detection for rotating machines. Numerous vibration signal based techniques, ranging from frequency domain [1–3], to time domain [4–9], and to time-frequency domain approaches [10–14] have been applied for fault detection of rotating machines [15].

Recently, monitoring techniques are greatly improved with the development of miniature sensors and wireless communication techniques. Therefore, time-series methods have received extensive attention in application of machine fault detection [16,17]. The general aim of time-series modeling is to study the past observations of a time series to develop a model that represents the characteristics of the whole series [18]. The model is then used to predict the future sample and to compare to the measured value. This error in prediction, also called the residual, is well-suited to extracting features

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associated with a vibration fault. The autoregressive (AR) model is a common time-series analysis method that can be used to detect the fault without knowledge of the physical model of the system [19,20]. However, as a pure time-series method, the AR model makes no explicit use of the frequency information of the signal and may be of high order. In addition, priori knowledge of the vibration under no-fault conditions is needed for data-fitting.

Based on the characteristics of vibration signals of rotating equipment, fault detection of impulsive signatures such as rotor rubbing, bearing inner or outer-race faults, and gear tooth faults can be improved by considering a sinusoidal restriction [21]. A sinusoidal synthesis (SS) based fault detection method was proposed in [22] and it was successfully adopted for steam turbine fault detection. The frequency information of the signal can be fully used in developing the sinusoidal synthesis model. However, it is insensitive to phase properties, which can differentiate noise from characteristic impulsive fault signatures.

Kalman filtering is an effective means of estimating the time-varying coefficients and is widely applied in speech parameter estimation problems [23,24]. Recently, the theory of adaptive filtering and estimation has also been applied to estimating frequencies and amplitudes of sinusoidal signals [25–28]. Minimum Entropy Deconvolution (MED), originally proposed by Wiggins for applications on seismic recordings [29], was adopted for gear fault detection together with the AR method by H. Endo et. al. [19]. It was shown that, the autoregressive MED (ARMED) resulted in improved performance over the traditional AR method. The MED algorithm can make use of higher-order statistical characteristics, in particular the kurtosis, of the signal. Kurtosis is defined as the fourth moment of the distribution and measures the relative peakedness or flatness of a distribution as compared to a normal distribution [30]. Kurtosis provides a measure of the size of the tails of a distribution and is used as an indicator of major peaks in a set of data. Kurtosis has been used for diagnosing bearing, and gearbox faults [15]. Recently, a new Maximum Correlated Kurtosis Deconvolution method was proposed and shown to be effective in detecting periodic fault signatures [31]. However, it requires priori knowledge of the fault period, and for non-integer fault periods, it requires an additional resampling preprocessing stage [32].

Based on the existing work [19,22,31], this paper outlines a MED based sinusoidal synthesis (MEDSS) filter designed for fault detection in rotating machinery. First, a time domain linear filter, in the form of state-space model, is proposed in which the sinusoidal frequency properties are explicitly incorporated. This filter can predict future vibration samples based on a sum of sinusoidal components, while the number of sinusoids can be unknown. In the process of building the SS model, the MED technique is applied to optimize the model parameters. The MED algorithm is more sensitive to the phase relationship (which differentiates white noises from impulses) by using higher-order statistical properties compared to the autocorrelation measurements like AR [19]. Thus it is effective in deconvolving the impulsive sources from a mixture of signals. Therefore, the MEDSS model is insensitive to the strong background noises encompassing other vibration sources and is more sensitive to characteristic fault with impulsive signatures. Finally, a time-weighted-error Kalman filter is designed for estimating the parameters of the MEDSS model. This makes it possible to synthesize the vibration signal with a low order but time-varying MEDSS model. The advantages of low computation complexity and recursive form from linear predictors are retained in this method. The scheme proposed in this work is limited to detection of defects in rotating elements that have localised sharp leading and trailing defect edges [33], which typically generate strong impulsive signatures.

The remainder of the paper is organized as follows: The MEDSS model is designed and its application in fault detection is proposed in Section 2 as the main results. In Section 3, three simulation examples are provided to illustrate the fault detection performance for fault-free, high signal-to-noise ratio (SNR) faulty and low SNR faulty conditions. A practical application example for rubbing fault detection in an industrial steam turbine is given in Section 4, followed by a conclusion in Section 5.

2. The MEDSS model and its application to fault detection

The sinusoidal synthesis approach has been widely adopted in the sound production model [34] and can be applied in vibration signal synthesis [22]. The rotating machinery vibration signal consists of three significant components: 'a sinusoidal component due to time varying loading, a broad-band impulsive component due to characteristic impulsive fault signatures, and random noise' [35]. Therefore, the measured vibration signal with periodic characteristic impulsive fault signatures can be represented as follows:

$$y_m[k] = y_o[k] + d[k] + v[k], \tag{1}$$

where $y_m[k]$ is the measured discrete signal at time kT; where T is the sampling time; $y_o[k]$ is the nominal fault-free vibration signal; $d[k]$ denotes the periodic impact fault signal, and $v[k]$ is the noise that may contain vibrations from other sources in the machine under inspection. $y_o[k]$ can be represented as the combination of a finite number of harmonic components as follows:

$$y_o[k] = \sum_{i=1}^{m} A_i \cos(kT\omega_i + \phi_i), \tag{2}$$

where m is the number of sinusoidal components; $A_i \in \mathbb{R}_+$ is the amplitude of the ith component; ω_i is the corresponding

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