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Investigation on the kurtosis filter and the derivation of convolutional sparse filter for impulsive signature enhancement

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ABSTRACT

Minimum Entropy Deconvolution (MED) filter, which is a non-parametric approach for impulsive signature detection, has been widely studied recently. Although the merits of the MED filter are manifold, this method tends to over highlight the dominant peaks and its performance becomes less stable when strong noise exists. In order to better understand the behavior of the MED filter, this study first investigated the mathematical fundamentals of the MED filter and then explained the reason why the MED filter tends to over highlight the dominant peaks. In order to pursue finer solutions for weak impulsive signature enhancement, the Convolutional Sparse Filter (CSF) is originally proposed in this work and the derivation of the CSF is presented in details. The superiority of the proposed CSF over the MED filter is validated by both simulated data and experimental data. The results demonstrate that CSF is an effective method for impulsive signature enhancement that could be applied in rotating machines for incipient fault detection.

1. Introduction

Impulsive signature detection has been widely studied in the area of rotating machinery. The impulsive signature, produced by the mechanical impacts between rotating components, always signifies defective components or potential machine breakdowns. Taking the roller bearing [1–3] for example, when the rollers periodically strike a defective area on the raceway surface, a series of impulses can be generated due to the periodical impacts. In regards to the gears [4–6], the local defects on a gear tooth might change the contact stiffness, the bending stiffness as well as the shear stiffness, which will produce a series of impulses in the vibration signal during meshing.

Impulsive signature detection (ISD) has been always challenging for rotating machinery, since the sensor data is usually convoluted by the system impulse response function and corrupted by the ambient noise [7–10]. One of the most effective tools for ISD is the Spectral Kurtosis (SK) proposed by Randall [9,11]. SK finds the frequency band with maximum Kurtosis value by searching through a dyadic filter bank. Even though SK can effectively determine the resonance frequency band in frequency domain, it is still incapable of recovering the original impulse train [12–14] introduced by mechanical defects. Another widely used method for ISD is the wavelet transform [15]. Theoretically, the Wavelet transform pursues a sparse

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representation of measured signal by the wavelet basis. However, the selection of proper mother wavelet is essentially a multi-dimensional optimization problem, and improper choice of the mother wavelet or tuning parameters might lead to contradictory results.

Based on recent literatures, Blind Deconvolution (BD) algorithms started to be accepted as effective methods for ISD in the area of vibration signal processing [4,7,8]. BD attempts to achieve an inverse filter that reverses the convolution process without explicit knowledge of the impulse response function. Successful implementation of BD involves two major tasks, which are recovering the impulse response function (or source wavelet) and obtaining the sparse representation of the input signal [16]. In the setting of rotating machinery, BD pursues an inverse filter to counteract the transmission path effect, and it is thus considered effective for impulsive signature enhancement. Among all the BD algorithms, Minimum Entropy Deconvolution (MED) [17–19] and its variants (generalized MED) [4] have been successfully applied to rotating machines for fault signature enhancement. MED filter is a non-parametric approach that is originally proposed in Geophysics [17,19]. It pursues an inverse filter and a sparse presentation of the measured signal by maximizing the Kurtosis norm – the fourth order moment, of the input signal. The generalized MED [20] maximizes the higher order moment of the input instead and it is able to give sparser results than MED filter according to the study about planetary gear in [4]. Other recent BD algorithms for image deblurring [21] and Ground Penetrating Radar (GPR) data processing [22] seek to optimize finer sparse priors using alternative minimization strategy. These BD algorithms are not suitable for the condition monitoring of rotating machinery, since they put too much emphasis on the exact recovery of the source wavelet rather than uncovering the impulsive patterns in the input data. Besides, the alternative minimization strategy in these algorithms is computationally expensive and is often found effective for less noisy data.

In this study, classic BD algorithms as the MED filter and one of its variant – the OMED (Optimal MED) filter, are mainly investigated. It is found in practice that both MED and OMED tend to over highlight the outliers in the measurements which are irrelevant to the system faults. The investigation of the MED and OMED filter in this work implies that this undesirable character of over highlighting the dominant peak is actually caused by using the Kurtosis norm (or D norm) as a sparse criterion. One recent study [23] about different sparse criteria indicates that alternative sparse criteria with enhanced performance are available, for example the l_1 norm, the l_1/l_2 norm, the Gini index, etc. Therefore, this study proposes to use the l_1/l_2 norm as alternative sparse criterion because it has been proved to be effective in different applications [21,24], and it has been widely studied in different fields, such as compressed sensing [25,26], dictionary learning [27,28], etc. The optimization of the l_1/l_2 norm in the proposed method is addressed by standard L-BFGS instead of alternative minimization, enlightened by Ref. [29].

The major novelty of this paper lies in that we treat the ISD as a feature learning problem and we originally propose the Convolutional Sparse Filter (CSF) for impulsive signature enhancement by minimizing the l_1/l_2 norm. The proposed CSF is found to be superior to the MED filter in several aspects. Firstly, it will not over highlight the dominant peak and it is robust to outliers. Secondly, the proposed CSF is able to recover the impulsive signature almost perfectly in the time domain, even when strong background noise exists. In order to better describe the theoretical novelty in this work, the mathematical analysis of the kurtosis norm has been presented and the reason why the MED filter tends to over highlight the dominant peak has been also explained geometrically. Additionally, the proposed CSF method does not require any prior knowledge from the signal or the system under study.

The remainder of the paper is organized as follows. In Section 2, the kurtosis norm is studied and the MED filter is derived and discussed. In Section 3, the convolutional sparse filter is proposed and a multiple layer structure is also proposed for weak signature enhancement. In Section 4, benchmark tests with MED filter are presented based on both the simulation data and the experimental data. The conclusion remarks of this paper are presented in Section 5.

2. Discussion on kurtosis and minimum entropy deconvolution filter

In this section, the characteristics of the kurtosis norm as a signal sparse measure are summarized and the derivation of the MED filter is presented. It is found in practice that the MED filter tends to over highlight the dominant peak while averaging the rest. In order to explain this undesirable feature of the MED filter, the equivalence between the Kurtosis norm and the D-norm is firstly described, and the undesirable feature of the MED filter is further uncovered by a geometrical explanation of the D-norm.

2.1. Geometrical analysis for kurtosis norm

The kurtosis of signal $\mathbf{y} \in \mathbb{R}^N$ is defined as the normalized forth moment of $\mathbf{y}$:

$$\mathrm{kurt}(\mathbf{y}) = \frac{\sum_i y_i^4}{\left(\sum_k y_k^2\right)^2} \tag{1}$$

If we define the Euclidian norm (l_2 norm) as:

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