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Application of an improved minimum entropy deconvolution method for railway rolling element bearing fault diagnosis

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ABSTRACT

Minimum entropy deconvolution is a widely-used tool in machinery fault diagnosis, because it enhances the impulse component of the signal. The filter coefficients that greatly influence the performance of the minimum entropy deconvolution are calculated by an iterative procedure. This paper proposes an improved deconvolution method for the fault detection of rolling element bearings. The proposed method solves the filter coefficients by the standard particle swarm optimization algorithm, assisted by a generalized spherical coordinate transformation. When optimizing the filters performance for enhancing the impulses in fault diagnosis (namely, faulty rolling element bearings), the proposed method outperformed the classical minimum entropy deconvolution method. The proposed method was validated in simulation and experimental signals from railway bearings. In both simulation and experimental studies, the proposed method delivered better deconvolution performance than the classical minimum entropy deconvolution method, especially in the case of low signal-to-noise ratio.

1. Introduction

As one of the commonest types of rotating machinery failure, the rolling element bearing fault can cause serious accidents and damages. Therefore, the condition monitoring and fault diagnosis of the rolling element bearings is important for maintenance strategy and operation safety. Because vibration signals measured from rotating machinery are subjected to various external interferences, they are almost non-stationary and are contaminated by strong noise from other machines. In many cases, this noise submerges the fault signal in both the time and frequency domains. The demand for effective, rapid identification the location of faults in rolling element bearings has increased, promoting the development of fault diagnoses based on vibrational and acoustic emission signals and signal processing techniques. To date, the signals from rotating machinery have been analyzed by a large number of techniques, including autoregressive models [1,2], spectral kurtosis and kurtogram [3–7], cyclostationary methods [8,9], wavelet based approaches [10–12], empirical mode decomposition [13–15], and matching pursuit order tracking [16,17], The techniques utilized in the fault diagnosis of element bearings are comprehensively reviewed [18].

Impulsive components can be detected by the basis pursuit method [19], which constructs the vibrational signal as a linear combination of transform bases or atoms from a dictionary. To improve the signal representation, researchers have proposed different atom-dictionary construction methods for different applications [20,21]. Yang et al. [22] applied of the basis pursuit method in feature extraction from measured vibration signals. Qin et al. [23] iterated the basis pursuit method in signal-component separation of multicomponent vibration signal. Structural damage has also been detected by a multi-stage method

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based on basis pursuit and particle swarm optimization (PSO) [24]. Other application of basis pursuit can be found in Refs. [25] and [26].

The most widely-used deconvolution approach is minimum entropy deconvolution (MED), which also detects the impulsive components in fault signals. The MED technique aims to enhance the impulses in raw vibration signals by maximizing the kurtosis of the filtered signal. In recent years, EMD has been widely employed for extracting fault information from the raw vibration signals mixed with strong noise. Endo and Randall combined the MED technique and autoregressive model into a new deconvolution technique [27] and demonstrated its efficiency by analyzing the fault signals of a gearbox. Sawalhi et al. [28] proposed an MED-based algorithm that enhances the surveillance capability of spectral kurtosis, and validated its performance in experimental results. To improve the classical MED, McDonald et al. [29] introduced the theory of maximum correlated kurtosis deconvolution (MCKD) technique, and validated its effectiveness by comparing the simulated signals with the vibration signals of a gearbox. With its good deconvolution performance, MCKD provides a powerful tool for deconvolving the periodic impulses in rolling-element bearing fault detection [30,31]. However, despite the proven effectiveness of MCKD, its application is limited by the excessive model parameters and complicated resampling process. To resolve these problems, Miao et al. [32] proposed the improved maximum correlated kurtosis deconvolution (IMCKD) method, which iteratively updates the fault period from the autocorrelation function of the envelope signal of the filtered signal. The IMCKD method was validated by analyzing the bearing fault signals in simulations and experiments. Li et al. [33] proposed $l_0 - norm$ MED, which decreases the influence of the additive noise by controlling the output sequences. However, the parameters selection scheme was not provided, and the $l_0 - norm$ MED was not analyzed theoretically. Raj and Murali [34] successfully analyzed the signals of faulty bearing by Lucy-Richardson deconvolution, a Bayesian-based iterative algorithm for image processing.

In the MED technique and its extended versions, the coefficients of the finite impulse response (FIR) are obtained by an iterative algorithm that begins with an initial value. This algorithm tends to select only the local optimal solution of the filter coefficients in the deconvolution problem, especially when the filter size is large. Moreover, the results of the iterative algorithm are sensitive to the initial iterative solution, meaning that different initial iterative values lead to different filter coefficients with different deconvolution performances. Consequently, the performance of the MED technique may degrade when analyzing signals with low signal-to-noise ratios. To avoid this degradation, the filter coefficients in MED should be solved by a convergent algorithm.

The present paper optimally solves the filter coefficients in a deconvolution problem by a new approach based on the PSO algorithm. Since the original version was proposed in 1995 [35], the PSO algorithm has attracted a surge of attention and is now applied in diverse fields, especially those involving complex, high-dimensional optimization problem. The PSO algorithm is a population-based global optimization technique inspired by the social behavior of birds hunting for food. Taking advantage of great performance, the standard PSO algorithm [36] is used to solve the optimal solution of the filter coefficients of the deconvolution problem. Our new approach transforms the vector of filter coefficients to a point on the surface of a hypersphere by a generalized sphere coordinate transformation. To obtain the angle parameters of the high-dimensional spherical coordinates, we maximize the kurtosis of the filtered signal by standard PSO. The filter coefficients are then calculated using the generalized spherical coordinate transformation formula. Because the optimal solution of the filter obtained from standard PSO is unaffected by the initial solution, the new deconvolution, (called PSO–MED) is more robust than traditional MED. The effectiveness of PSO–MED is verified first in simulations of the bearing fault signals, and next in actual signals in a high-speed train bearing experiment. The traditional MED and PSO–MED deliver the same great performance at high signal-to-noise ratio, but the PSO–MED outperforms traditional MED when the signal-to-noise ratio is low. The experimental results confirm the applicability of the proposed PSO–MED to fault diagnosis of railway rolling element bearings.

The rest of this paper is organized as follows. Section 2 overviews the MED technique, and Section 3 introduces the proposed PSO–MED technique. Section 4 presents and compares the simulated results of the classical MED and the proposed PSO–MED. Section 5 applies the PSO–MED to high-speed train bearing diagnosis, and compares its performance to that of classical MED. Conclusions are drawn in Section 6.

2. Review of minimum entropy deconvolution

The MED is designed to eliminate the effect of the transmission path by optimizing the finite impulse response (FIR) filter. Let $x_n (n = 1, 2, \ldots, N)$ be a sequence of input vibration signals, containing white noise and other interfering signal components, such as random impulses and harmonics. The output signal produced by the input signal x_n and an FIR filter $\boldsymbol{f} = [f_1, f_2, \ldots, f_L]$ with L coefficients can be expressed as follows:

$$y_n = \sum_{l=1}^{L} f_l x_{n-l} \tag{1}$$

where y_n should as far as possible match the impulse signal excited by the bearing fault. Assuming an impulsive fault signal with high kurtosis, the selected MED filter must maximize the kurtosis of the output signal. The kurtosis of an output signal $\boldsymbol{y}$