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Sparsity-enhanced signal decomposition via generalized minimax-concave penalty for gearbox fault diagnosis

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ABSTRACT

Vibration signals arising from faulty gearboxes are often a mixture of the meshing component and the periodic transient component, and simultaneously contaminated by noise. Sparsity-assisted signal decomposition is an effective technique to decompose a signal into morphologically distinct components based on sparse representation and optimization. In this paper, we propose a sparsity-enhanced signal decomposition method which uses the generalized minimax-concave (GMC) penalty as a nonconvex regularizer to enhance sparsity in the sparse approximation compared to classical sparsity-assisted signal decomposition methods, and thus to improve the decomposition accuracy for gearbox fault diagnosis. Even though the GMC penalty itself is nonconvex, it maintains the convexity of the GMC regularized cost function to be minimized. Hence, similar to the classical L1-norm regularization methods, the global optimal solution can be guaranteed via convex optimization. Moreover, we present and validate a straight-forward way to choose transforms and set parameters for the proposed method. Through simulation studies, it is demonstrated that the proposed sparsity-enhanced signal decomposition method can effectively decompose the simulated faulty gearbox signal into the meshing component and the periodic transient component. Comparisons with the classical L1-norm regularized signal decomposition method and spectral kurtosis show that the proposed method can accurately preserve the amplitude of the periodic transient component and provide a more accurate estimation result. Experiment and engineering case studies further verify that the proposed method can accurately estimate the periodic transient component from vibration signals, which demonstrate that the proposed method is a promising tool for gearbox fault diagnosis.

1. Introduction

Gearboxes are used extensively for the transmission of speed and power in mechanical systems, such as wind turbines, aero-engines, helicopters, automobiles, and mining equipment. However, gearboxes are extremely prone to various faults when operated continuously in a harsh working environment. If a fault occurs in the key gear during its operation, it may cause an abnormal operation or system failure, which results in long downtimes, increased maintenance loss, or even casualties. For example, gearbox failures are regarded as one of the most serious causes of breakdown in wind turbines, and the reliability of

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gearboxes is an important concern in the wind energy industry [1–3]. Therefore, condition monitoring and fault diagnosis of gearboxes have attracted considerable attention during the past decades [4].

Vibration signals generated by mechanical faults are important indicators of machinery operating condition, and contain information not only about the machine health condition but also the severity of the fault [5,6]. For a fault-free gear pair, the vibration signal of the gearbox tends to be dominated by the meshing frequency and its harmonics [7]. When there exists a localized fault on the gear, such as spall, pit or breakage, it will interact with another gear and thus generate a series of transients which are periodic at the inverse of the shaft rotational frequency [8]. Therefore, the vibration signal arising from a faulty gearbox system is usually a mixture of the meshing component and the periodic transient component, and these two components are polluted by heavy background noise from other machine components and the working environment [9]. How to accurately estimate the periodic transients corresponding to the fault from the complex noisy signal is a key task for gearbox fault diagnosis.

Over the past decades, various signal processing methods have been widely studied and applied to vibration signal analysis and fault diagnosis, such as short-time Fourier transform (STFT) [10], wavelet transform [11–13], empirical mode decomposition [14–16], spectral kurtosis (SK) [17–20], stochastic resonance [21–23] and time-frequency analysis [24–29]. These contributions have greatly enriched researches in machinery fault diagnosis. However, the effectiveness of most above-mentioned methods is diminished by two inevitable limitations. First, most of these methods reduce the amplitude of the component of interest while eliminating the noise and interference. If the signal of interest is preserved, the noise or interference is also preserved simultaneously. Second, most of the aforementioned methods analyze signals in the frequency domain or in the time-frequency domain. Vibration signals collected from faulty gearboxes are a combination of the meshing component, the periodic transient component, and noise. However, the meshing component and the periodic transient component not only overlap in the time domain but they may also overlap in the frequency domain. Hence, these two mixed components are difficult to decompose by these methods.

As a new branch of the signal processing method, sparse representation has received considerable attentions and has been widely used in the field of machinery fault diagnosis [30–35]. Sparsity-assisted signal decomposition using morphological component analysis (MCA) has proven to be a useful technique for machine fault signal decomposition. MCA is implemented via sparse representations and optimization and it is designed to separate additively-mixed components in a signal using morphological diversity rather than frequency or scale information [36]. It was first used for the separation of texture and piecewise smooth components in an image, and later widely used in a variety of fields. Abrial et al. extended MCA to the analysis of spherical data map [37]. Yong et al. generalized MCA to separate multi-channel EEG signal sources [38]. Farshchian et al. used MCA with two STFTs to separate the wing-beat signature from the body signature of radar bird data [39]. Considering that many complex signals arising from physiological and physical processes are often a mixture of components with different oscillation behaviors, Selesnick proposed a sparsity-assisted signal decomposition method using MCA and wavelet transform to decompose a signal into its components [40]. Cai et al. introduced the sparsity-assisted signal decomposition method using MCA to gearbox fault diagnosis in which the faulty gearbox vibration signal is separated into the meshing component and the periodic transient component [41]. The effectiveness of the sparsity-assisted signal decomposition method using MCA in faulty gearbox vibration signal decomposition is based on the fact that the meshing component and the periodic transient component possess different morphologies. Subsequently, other researchers began to study the usage of sparsity-assisted signal decomposition via MCA for gearbox fault diagnosis. Li et al. introduced the kernel spectral regression framework into MCA to diagnose the marine propulsion gearbox fault [42]. Yu et al. employed the principle of the minimum entropy of information to select the optimal dictionary for the transient component representation and proposed an improved MCA for signal decomposition to diagnose compound faults in gearboxes [43]. Zhang et al. proposed a resonance-based sparse signal decomposition with a comb filter method using MCA for gearbox multi-fault diagnosis [44]. These studies provide new insights on how to extract fault features for gearbox fault diagnosis. In these studies, the L1-norm is classically used to regularize the MCA problem because the L1-norm induces sparsity most effectively among convex penalties [45]. However, the L1-norm regularizer often underestimates the high-amplitude components of the sparse coefficients and tends to underestimate the signal of interest while eliminating noise and interference signal [46], which may cause missed alarm or underestimation of the fault severity.

In recent years, researches have addressed the design of penalties to strongly promote sparsity. Nonconvex sparsity-inducing penalties can provide a more accurate estimation of the high-amplitude component. However, most nonconvex penalties do not seek to maintain the convexity of the cost function to be minimized. Hence, the cost function is generally nonconvex and has extraneous suboptimal local minimizers. Blake, Zisserman and Nikolova designed convexity-preserving nonconvex penalties, and these penalties were further developed [47–50]. However, these penalties are separable, so when they are parameterized to maintain cost function convexity, they can only improve on the L1-norm penalty to a very limited extent. Recently, Selesnick proposed a novel class of nonconvex penalty functions, named the generalized minimax-concave (GMC) penalty, which can induce sparsity effectively while maintaining the cost function convexity [51]. Theoretical analysis proves that it is easy to prescribe the GMC penalty to maintain the convexity of the cost function to be minimized. Hence, the cost function has no suboptimal local minimizers and can be minimized via convex optimization comprising simple computations. The superiority of the GMC penalty is that it can effectively enhance the sparsity level in a sparse approximation problem and achieve a more accurate estimation of the signal of interest.

In this paper, we propose a sparsity-enhanced signal decomposition method for gearbox fault diagnosis by using the GMC penalty to improve the signal decomposition performance of the L1-norm regularized MCA. The paper proves that the convexity of the sparsity-enhanced MCA cost function can be maintained by prescribing the GMC penalty appropriately, and provides an