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Sparsity-based algorithm for detecting faults in rotating machines

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ABSTRACT

This paper addresses the detection of periodic transients in vibration signals so as to detect faults in rotating machines. For this purpose, we present a method to estimate periodic-group-sparse signals in noise. The method is based on the formulation of a convex optimization problem. A fast iterative algorithm is given for its solution. A simulated signal is formulated to verify the performance of the proposed approach for periodic feature extraction. The detection performance of comparative methods is compared with that of the proposed approach via RMSE values and receiver operating characteristic (ROC) curves. Finally, the proposed approach is applied to single fault diagnosis of a locomotive bearing and compound faults diagnosis of motor bearings. The processed results show that the proposed approach can effectively detect and extract the useful features of bearing outer race and inner race defect.

1. Introduction

Rotating machinery is one of the most common types of mechanical equipment and plays a significant role in industrial applications. Early detection of faults developing in rotating machinery is of great importance to prevent economic loss and personal casualties [1]. Rolling element bearings and gearboxes are two kinds of widely used components in rotating machines and their failures are among the most frequent reasons for machine breakdown.

Much attention has focused on vibration-based diagnosis of mechanical faults in rotating machines [2]. The detection of periodically occurring transient vibration signatures is of vital importance for vibration-based condition monitoring and fault detection of rotating machinery [3]. However, these useful transient features are usually buried in heavy background noise and other irrelevant vibrations. To address this problem, many signal processing methods have been introduced, such as singular value decomposition (SVD) [4], empirical mode decomposition (EMD) [5], and methods based on different wavelet transforms, e.g., dual-tree wavelet in [6], harmonic wavelet in [7], and tunable Q-factor wavelet (TQWT) in [8]. These methods have achieved successful applications in the field of machinery fault diagnosis.

The formulation of a suitable optimization problem can be an effective approach for machine fault diagnosis; for example, conventional basis pursuit denoising (BPD) is introduced in [9] to detect machinery fault, wherein the Morlet wavelet is chosen for the sparse representation of the signal of interest. Recently, an algorithm, called 'overlapping group

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shrinkage' (OGS) was developed for estimating group-sparse signals in noise [10]. The OGS algorithm was initially formulated as a convex optimization promoting group sparsity by a convex regularization. In order to promote sparsity more strongly, an improved version of OGS was developed, which utilizes a non-convex regularization [11]. The superiority of denoising group-sparse signals using the approach presented in [11] indicates its potential for effectively extracting periodic transient pulses.

This paper aims to develop an approach for rotating machinery fault diagnosis based on a periodic group-sparse signal representation. The signature of localized faults of the gear teeth and bearing components generally exhibit periodic transient pulses when a rotating machine is operated at a constant speed [12]. Meanwhile, the large-amplitude signal values are not only sparse but also tend to form groups [13]. Several neighborhood-based denoising methods have been developed for machinery fault diagnosis utilizing this property, such as customized wavelet [14] and overcomplete rational-dilation discrete wavelet transform [15] thresholding by incorporating neighboring coefficients. Our approach is based on a signal model intended to capture the useful impulsive features for machinery fault diagnosis. In particular, this paper addresses the problem of estimating x from a noisy observation y. We model the measured discrete-time series, y, as

$$y_n = x_n + w_n, \quad n = 0, \ldots, N-1, \tag{1}$$

where the signal x is known to have a periodic group-sparse property and w is white Gaussian noise. A group-sparse signal is one where large magnitude signal values tend not to be isolated; instead, these large magnitude values tend to form groups. Note that the proposed signal model (1) does not utilize any transform (i.e., no Fourier or wavelet transform).

Convex optimization is commonly used to estimate sparse vectors from noisy signals, where we solve the optimization problem with the prototype

$$x^* = \arg\min_x \left\{ F(x) = \frac{1}{2}\|y - x\|_2^2 + \lambda \Phi(x) \right\}, \tag{2}$$

where $\lambda > 0$ is a regularization parameter and $\Phi: \mathbb{R}^N \to \mathbb{R}$ is a sparsity-promoting penalty function (regularizer). Conventionally, the regularizer $\Phi(x)$ is a convex function, e.g. ℓ_1-norm. An enhanced, more general approach [16], is to allow the regularizer to be non-convex but to constrain it so that the total objective function F remains convex. This approach is advantageous because non-convex regularization can more accurately recover sparse signals than convex regularization can. Yet, since the non-convex regularizer is chosen so that F is convex, the problem has a unique solution, and it can be reliable found using convex optimization.

In this paper, we adopt ideas from [16] and [10], and present a method for estimating periodic-group-sparse signals in noise. We propose its use for detecting faults in rotating machinery, where the fault characteristic frequency (period of the group-sparse pulses) is used as prior knowledge. Similar to the approach in [11], the non-convex regularization term in the proposed method is properly chosen so as to ensure that the total objective function F is convex; however, in contrast to [11], where each group has to be contiguous, we allow grouping with intervals, and furthermore periodicity.

As a consequence, in this work, the regularization term Φ in (2) is formulated specifically to utilize the periodicity of the impulsive fault features. The aim of our approach is to capture the useful impulsive features for the purpose of machinery fault diagnosis. Additionally, it has the potential to separate compound fault features by utilizing different periods of the periodic transient pulses corresponding to different fault frequencies (e.g., various defect frequencies of rolling element bearings). The proposed approach reduces to a non-periodic group-sparse signal denoising method, i.e., we can utilize the sparsity-based OGS approach [11] if we do not have prior knowledge of the period of the group-sparse transients. Thus, the proposed sparsity-based approach is a generalization of the non-convex regularized OGS [11].

The paper is organized as follows. A brief review of OGS with convex and non-convex regularization is given in Section 2. Section 3 presents a method for denoising periodic group sparse signals. In Section 4 a simulation study is performed to validate the effectiveness of the proposed method. Section 5 applies the proposed periodic group sparse denoising method to fault diagnosis of motor bearings for further validation of its effectiveness. Finally, conclusions are summarized in Section 6.

2. Review

In this section, we give short reviews of overlapping group shrinkage (OGS) [10] and majorization–minimization (MM) [17].

2.1. Overlapping group shrinkage (OGS)

There are several advantages to formulating sparse estimation as a convex optimization problem. The most basic advantage is that the problem can then be very reliably and efficiently solved using convex optimization methods [18]. Although a non-convex regularizer can promote sparsity more strongly, it generally leads to a non-convex optimization problem with non-optimal local minima [19]. To avoid the formulation of a non-convex optimization problem, one may utilize a non-convex regularizer Φ designed so as to ensure the total objective function is convex.

The problem of denoising a group sparse signal was addressed in [10] which utilized convex optimization. An improved method was proposed in [11], which utilized non-convex regularization designed to ensure convexity of the objective function. The problem is solved efficiently by an iterative algorithm based on majorization–minimization (MM) [17]. The