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Sparse representation based on local time–frequency template matching for bearing transient fault feature extraction

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A B S T R A C T

The transients caused by the localized fault are important measurement information for bearing fault diagnosis. Thus it is crucial to extract the transients from the bearing vibration or acoustic signals that are always corrupted by a large amount of background noise. In this paper, an iterative transient feature extraction approach is proposed based on time–frequency (TF) domain sparse representation. The approach is realized by presenting a new method, called local TF template matching. In this method, the TF atoms are constructed based on the TF distribution (TFD) of the Morlet wavelet bases and local TF templates are formulated from the TF atoms for the matching process. The instantaneous frequency (IF) ridge calculated from the TFD of an analyzed signal provides the frequency parameter values for the TF atoms as well as an effective template matching path on the TF plane. In each iteration, local TF templates are employed to do correlation with the TFD of the analyzed signal along the IF ridge tube for identifying the optimum parameters of transient wavelet model. With this iterative procedure, transients can be extracted in the TF domain from measured signals one by one. The final signal can be synthesized by combining the extracted TF atoms and the phase of the raw signal. The local TF template matching builds an effective TF matching-based sparse representation approach with the merit of satisfying the native pulse waveform structure of transients. The effectiveness of the proposed method is verified by practical defective bearing signals. Comparison results also show that the proposed method is superior to traditional methods in transient feature extraction.

1. Introduction

Rolling element bearings have been widely applied in rotating machines of modern industry. Due to mechanical movements, they are easily damageable. Then mechanical faults may develop and cause serious economic losses. Therefore, it is vital for condition-based maintenance (CBM) of bearings in ensuring safety, minimizing breakdowns and reducing the production costs [1–2]. There are various techniques for bearing fault monitoring and diagnosis, such as temperature monitoring, pressure analysis, current signature analysis, oil analysis, vibration and acoustic analysis. Among them, vibration or acoustic analysis has been widely studied and applied in the area of bearing fault diagnosis [3–7]. In the acquired signals, the periodic transient impulses often reflect important physical information related to the defective bearing dynamics [6].

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Nevertheless, in practice the defect-induced transient impulses are often too weak to be distinguished in the complex data corrupted by a large amount of background noise. Therefore, it is of great importance to extract intrinsic transient characteristics from strong background noise and identify the bearing faults at early stages for a reliable diagnosis [7].

To well extract transient characteristics from the defective signals, various techniques have been developed for bearing fault diagnosis, e.g., the time-domain averaging method [8], band-pass filtering [9], frequency-domain thresholding [10], wavelet transform (WT) [11], time–frequency analysis (TFA) [12], empirical mode decomposition (EMD) [13], sparse representation [14–17] and manifold learning [18]. Among these techniques, sparse representation, including matching pursuit (MP) [14], orthogonal matching pursuit (OMP) [15], k-means singular value decomposition (K-SVD) algorithm [16] and basis pursuit de-noising (BPDN) algorithm [17], possesses a good denoising effect and thus has been effectively applied in signal processing, especially the transient representation for bearing fault diagnosis. This paper mainly focuses on the sparse representation approach to effectively extract the transient fault feature of rolling element bearings.

Sparse representation means that a signal can be represented as a linear superposition of a few sparse atoms selected from an overcomplete dictionary. It can be served as decomposition and reconstruction problems [19–20], where the sparse decomposition is subject to a kind of ill-posed problem. On this ill-posed problem, a large amount of fruitful research have been accomplished for mechanical fault diagnosis [14–17,21–29]. These works can be mainly divided into two aspects: sparse expression optimization problem and atom function model construction. Many works have been done on the optimization and improvement for sparse representation, such as K-SVD algorithm [16,21], BPDN algorithm [17], shift-invariant sparse coding (SISC) algorithm [22], split variable augmented Lagrangian shrinkage algorithm (SALSA) [24]. According to these optimization procedures, the signal can be expressed by learned sparse components or sparse atoms [14–17,21–23]. Meanwhile, the atom function modeling is also a focus study for dictionary construction in recent years. Many related works have been done in transient model dictionary for transient feature extraction research [11,22,24–29]. They mainly focused on how to sparsely describe the signals based on the designed dictionary through parameter optimization with the aforementioned methods. For example, Morlet wavelet [11] and adaptive wavelet filter [25] have been applied in gear fault diagnosis. Shen et al. [26] introduced a Doppler transient model based on Laplace wavelet for locomotive bearing fault diagnosis. Cui et al. proposed an improved impulse dictionary with two peaks for one impulse [14] and a new step-impulse dictionary [27] to reveal the characteristics and mechanism of rolling bearing faults. Wang et al. [28] builds a double-side asymmetric transient model with Levenberg–Marquardt (LM) method for fault feature extraction of rotating machines.

This paper considers two remained issues to be addressed for the sparse representation study. The first issue is that specific atom function construction cannot guarantee natural waveform structure keeping in sparse representation of an analyzed signal. In current studies, different atom functions are constructed based on the physical mechanism of the transients for bearing transient feature extraction [14,23,26–29]. The waveforms (including amplitude and phase) of the analyzed data are required to match with the manually constructed atom function in the time or the frequency domain [21–25,27–29]. If the waveform structure doesn't satisfy the designed atom function, the sparse representation effect would be greatly influenced. Second, due to complex parameters to be determined for the transient model, there needs excessive computational cost. There are also some related references [23,26] assuming the same parameters (frequency and/or damping ratio) for sparse representation and searching only one parameter while fixing other parameters in each operation [14]. Actually, due to the varying of the speed, the load or the changing of the environment in a dynamic process, the transients caused by the localized defect are not the same as each other in the acquired signals yet.

The study in this paper investigates the time–frequency (TF) domain sparse representation for bearing transient feature extraction. Currently, there are little works in TF domain operation for bearing signal sparse representation of transient features. The motivation of this study is to employ the image sparse expression for searching the sparse TF structures while maintaining the phase of raw signal in TF domain. Due to the capability of energy distribution in the TF domain, TFA is beneficial for non-stationary signal analysis in bearing fault diagnosis. TFA processes the signal in the time and frequency domains simultaneously and so can avoid losing useful transient characteristics in denoising. Many researchers have attempted to remove the noise in TF plane with a synthetic consideration of both kinds of information [12,18,30,30–31]. This paper considers a sparse representation approach in the TF domain for effectively capturing the transient fault characteristics (the correct TF structures) in the noisy background. Furthermore, as the original phase keeps the information of waveform structures in the raw signal, combining the sparse TF structures with the original phase information will improve the description errors of the reconstructed signal compared to the real vibration signal. Therefore, the TF domain sparse representation is hoped to obtain the natural transient structure of the analyzed signal.

Considering the benefits of TF domain sparse representation, this paper proposes an iterative TF matching extraction technique that is conducted on the TF plane for transient signal reconstruction. In this technique, an atom in the Morlet wavelet dictionary is employed to construct a local TF template. Matching the local TF template with the TF distribution (TFD) of the analyzed signal can extract the sparse TF structures. Combining the extracted TF structures with the phase of raw signal can then recover a new sparse time-domain signal. Although in this study a double-side symmetric wavelet atom is applied for TF matching, keeping the phase of raw signal will confirm that the transients of the bearing signal are not double-side symmetric waveforms yet. That is to say, this proposed technique can extract the natural pulse waveform structure of the real bearing vibration signal. This idea combines the merits of signal representation (in the TF domain) and sparse representation (via the MP), and is hoped to build an effective sparse signal reconstruction scheme for defective bearing signal analysis. Moreover, in the proposed method, to reduce the computational cost and provide an effective TF