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Research on bearing fault feature extraction based on singular value decomposition and optimized frequency band entropy

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ABSTRACT

Singular value decomposition (SVD) is widely used in condition monitoring of modern machine for its unique advantages. A novel relative change rate of singular value kurtosis (SVK) is proposed in order to determine the reconstructed order of singular values effectively. Since the bandwidth parameter of the band-pass filter designed by FBE need to be determined based on experience, obviously, there are significant deficiencies. Then, a optimized frequency band entropy (OFBE) method based on the principle of maximum kurtosis is proposed to optimize the bandwidth parameters. In addition, because the fault signal of the rolling bearing at the initial stage is very weak and submerged by ambient noise, SVD cannot extract fault features clearly, a new method for fault feature extraction of rolling bearing based on SVD and OFBE, named SVD-SVK-OFBE, is proposed. Firstly, the Hankel matrix is reconstructed from the original vibration signal in the phase space and the noise reduction is performed using SVD. Here, the relative change rate of singular value kurtosis is performed on the Hankel matrix to determine the reconstructed order. Secondly, the OFBE analysis is performed on the reconstructed signal to determine the center frequency and the bandwidth of the band-pass filter adaptively. The bandwidth of the designed band-pass filter is optimized by the kurtosis maximum principle. Thirdly, the reconstructed signal of SVD is filtered by the optimized filter, and the envelope demodulation analysis is performed on the filtered signal. Finally, the fault feature frequency is extracted and compared with the theoretical fault feature frequency to identify the fault type of the rolling bearing. The effectiveness and advantages of the method described in this paper are verified by the simulation analysis and experimental data analysis of the rolling bearing.

1. Introduction

Rolling bearing is an important component in rotating machinery, its failure is one of the main reasons which cause the failure and invalid of rotating machinery [1]. Therefore, the condition monitoring and fault diagnosis of rolling bearings have always been a hot and difficult point of mechanical equipment fault diagnosis [2,3].

In practical engineering applications, especially for early failures of rolling bearings, the weak modulation source and the noise of the surrounding equipment and environment makes the early fault signals particularly weak. Therefore, it is difficult to extract and identify the fault characteristic frequency [4,5]. When the rolling bearing with faults is operating, the vibration signal tends to show non-stationary characteristics obviously. And the signal changes significantly over time in frequency

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structure and amplitudes. How to extract the fault characteristic information from the non-stationary vibration signal has been the key issue and hotspot of rolling bearing fault diagnosis [6,7]. The singular value decomposition (SVD) technology has been widely used in the field of fault diagnosis of rotating machinery. The following reviews are conducted from the application of SVD reconstruction order determination methods and noise reduction methods. Laub [8] proposed the SVD theory and introduced some applications of SVD, as well as its algorithm implementation. Vautard et al. [9] found that the singular spectrum has good effect on short-time sequences under Gaussian random noisy. Kanjilal et al. [10] presented a selection method of effective singular values named singular value ratio (SVR). In reference [11], the entropy theory was applied in SVD and the Singular Entropy (SE) was utilized into signal analysis of rotating machine. Zhao [12] used difference spectrum of singular value in automatic selection of effective singular values. On this basis, Wang et al. [13] provided a method for determining the order of the model based on the relative rate of change of the singular value, and can select the effective singular value automatically. Hassani et al. [14] evaluated the empirical distribution of the eigenvalues of the matrix XX^T divided by its trace, where X is a random Hankel matrix. Its properties provide a reference for evaluating the k largest eigenvalues and the determination of the reconstruction order. Qiao et al. [15] proposed an adaptive and efficient singular value selection method based on the correlation coefficient for fault feature detection, and it achieved good effects to detect weak fault signals for rolling bearings. As mentioned above, many scholars have proposed effective singular value selection methods. And it has achieved good results to some extent.

According to the analysis principle of SVD, the contribution of random noise to each order is almost equal, that is, random noise is almost evenly distributed in each order. Therefore, the noise reduction effect of using SVD alone is often not ideal. So many researchers have been trying to combine it with other methods to achieve the extraction of features. In reference [16], Zhao et al. pointed out that signal processing effect of SVD is very similar to that of wavelet transform when Hankel matrix is used. An improved SVD method for gear fault identification based on Hilbert-Huang transform was proposed by Su et al. [17], and the problem of reconstructing a feature matrix of SVD is overcome. Wang et al. [18] used EMD and SVD to extract features, then feature vector matrices obtained are regarded as the input of the improved hyper-sphere-structured multi-class support vector machine (HSSMC-SVM) for classification. Muruganatham et al. [19] proposed a simple time series method for rolling bearing fault feature extraction using singular spectrum analysis (SSA) of the vibration signal. Wang et al. [20] presented a feature extraction method of rolling bearing based on SVD and kurtosis criterion, and its effectiveness is proven by simulated signal and actual data. Based on the traditional SVD theory, short-time matrix series (STMS) and singular value ratio (SVR) are introduced to the vibration signal processing by Cong et al. [21], and it has a good local identification capability in the rolling bearing fault diagnosis. Liu et al. [22] used an novel method which combining Hilbert-Huang transform (HHT), SVD, and Elman neural network. It has achieved good results in practical application. Jiang et al. [23] introduced the singular values (SVs) and ratios of neighboring singular values (NSVRs) to the feature extraction of vibration signals, and combined with selected SV-NSVR features, continuous hidden Markov model (CHMM) is used to realize the automatic classification. Based on local mean decomposition (LMD)-SVD and extreme learning machine (ELM), Tian et al. [24] proposed an intelligent fault diagnosis method, which can accurately diagnose and identify different fault types of rolling bearings under variable conditions. Liu et al. [25] developed a new fault diagnosis method that wavelet transformation, SVD, and LLE are assembled to extract the feature of a dataset for submersible plunger pump fault recognition. Han et al. [26] proposed a method for rolling bearing based on empirical mode decomposition (EMD) and the difference spectrum of singular value, and achieved satisfactory results. Combining sparse representation and shift-invariant K-SVD, Yang et al. [27] presented a new data-driven fault diagnosis method based on sparse representation and shift-invariant dictionary learning method. As can be seen from the above description, many scholars have conducted researches on different aspects of the noise reduction function of SVD, mainly focusing on the combination with other methods. Of course, in addition to the above-mentioned documents, there are many research literatures, which will not be repeated here.

The main works of this article are as follows: First, a novel relative change rate of singular value kurtosis (SVK) is proposed to determine the reconstructed order of SVD effectively. Therefore, we can obtain the method SVD-SVK. Second, since the bandwidth parameter of the band-pass filter designed by the FBE need to be determined based on man-made, a simple and effective optimization method based on the kurtosis maximum principle is proposed, i.e., the optimized FBE (OFBE) can be obtained. Finally, because of the almost equal contribution of noise to each order in SVD, which result that the ideal noise reduction effect cannot be obtained by only using SVD to de-noise the original signal under the condition of strong background noise. A new fault feature extraction method based on SVD-SVK and OFBE is proposed to solve this problem. The combination adaptive band-pass filter design capability of OFBE and pass-band noise reduction capability of SVD are used to extract the weak fault characteristic frequency of rolling bearing. In summary, we named the method proposed in this paper: SVD-SVK-OFBE. The specific ideas of this article are as follows: Firstly, SVD is applied to the original fault signal of rolling bearings. The order of reconstruction was determined by the SVK, and compared it with the relative change rate of the singular values (the relative change rate of the singular value is equivalent to that of the singular difference spectrum. The advantage of the former is that it was quantified). Secondly, the OFBE was used to the reconstructed signal to design band-pass filter and optimize the bandwidth. The reconstructed signal is filtered by the optimized band-pass filter to further improve its signal-to-noise ratio (SNR). Thirdly, the filtered signal is subjected to envelope demodulation analysis, the fault characteristic frequency of the rolling bearing is extracted. Finally, compared it with the theoretical feature frequency to determine the type of the rolling bearing's fault. The results of the analysis of the simulated signal and the experimental data illustrates the effectiveness and advantages of the method described herein.