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Multifractal entropy based adaptive multiwavelet construction and its application for mechanical compound-fault diagnosis

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A B S T R A C T

Compound-fault diagnosis of mechanical equipment is still challenging at present because of its complexity, multiplicity and non-stationarity. In this work, an adaptive redundant multiwavelet packet (ARMP) method is proposed for the compound-fault diagnosis. Multiwavelet transform has two or more base functions and many excellent properties, making it suitable for detecting all the features of compound-fault simultaneously. However, on the other hand, the fixed basis function used in multiwavelet transform may decrease the accuracy of fault extraction; what's more, the multi-resolution analysis of multiwavelet transform in low frequency band may also leave out the useful features. Thus, the minimum sum of normalized multifractal entropy is adopted as the optimization criteria for the proposed ARMP method, while the relative energy ratio of the characteristic frequency is utilized as an effective way in automatically selecting the sensitive frequency bands. Then, The ARMP technique combined with Hilbert transform demodulation analysis is then applied to detect the compound-fault of bevel gearbox and planetary gearbox. The results verify that the proposed method can effectively identify and detect the compound-fault of mechanical equipment.

1. Introduction

Owing to the severe and long-term working conditions, several key components of the machinery can be easily damaged simultaneously, which is called compound-fault. This kind of fault will be much more harmful than the general mono-fault; so diagnosis of incipient compound-fault is significantly meaningful. However, the following problems increase the great difficulty in the early detecting of compound faults: (a) It results from several parts, which in turn affects divided parts of machinery with diverse forms and levels. (b) The various faults add together and interfere with each other, which make the extraction of fault feature more complicated. [1].

Recently, a number of methods for compound-fault diagnosis have been investigated based on the dynamic theory, such as bearing modeling [2,3], gear modeling [4–6] and rotor modeling [7]. However, the complexity and non-repeatability of the compound-fault indicate that the diagnosis is very challenging. Thus, some vibration signal analysis

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techniques have been developed to solve this issue. For example, McFadden [8] studied vibration response of the multiple point defects on the inner-race of the rolling element bearing. Feng [9] deduced the vibration signal models of the fault planetary gearboxes. A novel hybrid intelligence method was proposed in [10,11] and was applied to the compound faults of engine bearing; Wang [12] introduced an adaptive spectrum kurtosis to extract the bearing multi-fault features, while Li [13] proposed independent component analysis and fuzzy k-nearest neighbor algorithm which were applied on the extraction of multi-fault feature in rotating machineries. Wang [14] successfully separated multiple fault signatures in rotating machinery using dual-tree complex wavelet transform; Jiang [15] used the improved EEMD with multiwavelet packet for rotating machinery multi-fault diagnosis, and Li [16] proposed the multiple manifolds analysis approach to extract manifold information from the bearing vibration signals with different faults; A model based on principal component analysis and a neural network for the multi-fault diagnosis of sensor systems were proposed by Zhu [17]; Tang [18] applied support vector machine trained by chaos particle swarm optimization in the multi-fault classification of rotating machinery; while Jing [19] introduced a blind source separation technique in separation of the vibrational features produced by several faults existing in a rotor; Purushotham [20] researched on the wavelet analysis and hidden Markov model in detecting the multi-fault diagnosis of rolling bearing elements, and Abbasion [21] constructed the wavelet denoising and support vector machine for classification of rolling element bearings multi-fault; Tsoumas [22] applied wavelet analysis of the current space vector in the induction motor mixed fault diagnosis; Vafaei [23] provided a fore-running technique which is very appropriate in isolating particular frequency components for bearing systems, etc. Previous attempts and researches have achieved initial successes, but novel technique should be developed regarding the diversity of compound faults.

As a trend of wavelet theory, multiwavelet uses two or more wavelet basis functions to match more features of compound faults, thus it can generate a possible solution to detect compound-fault. The traditional multiwavelet, such as GHM, CL and Hermite, may decrease the accuracy of fault detection for fixed basis functions independent of the vibration signal. Lately, as the two-scale similarity transform (TST) [24] and lifting (LF) [25] scheme are found to be greatly fit for adaptive multiwavelet construction, they are widely used in faults diagnosis. Such as, Yuan applied two-scale similarity transform (TST) [26], Wang utilized lifting (LF) [27] and Chen adopted time domain lifting [28] constructed the adaptive multiwavelet and acquired good results in rotating machinery faults diagnosis, respectively. Chen [29,30] also applied multiwavelet in compound-fault diagnosis. He [31,32] improved and integrated the construction of multiwavelet. While in the construction process, the optimizing indicators are limited and defective, such as, even though the kurtosis is extremely sensitive to the initial fault of rolling bearing, it doesnot do well in monitoring the condition of gears; and the envelope spectrum entropy varies from the different envelopment analysis. Therefore, in order to reflect comprehensive information of compound-fault, an optimized indicator should be developed using adaptive construction.

However, the vibration signals of abnormal equipment are both irregular and nonstationary. Fortunately, the fractal dimension is a useful tool to characterize the nonlinearity and complexity of dynamic system [33] and broadly applied to the field of fault diagnosis. In contrast to mono-fractal, as a new trend of fractal geometry method, multifractal is powerful in analyzing more complex signals and accurately describing local scaling behaviors, according to the singularity, which can reveal the essential characters of the faults [34]. However, the traditional multifractal spectrum computation methods are mathematically intractable. In this paper, the problem can be solved through wavelet modulus maxima (WTMM) by combining the advantages of wavelet singularity diagnosis. In order to correctly identify the fault type and the damage level, this method combines the normalized information entropy and multifractal spectrum to construct the normalized multifractal entropy that can represent the character index of compound-fault.

In order to diagnose compound-fault effectively, an adaptive multiwavelet method is proposed in this paper. Firstly, the optimization objective normalized multifractal entropy is imported into symmetrical lifting (SymLift) scheme and the new adaptive multiwavelet is constructed based on the cubic Hermite multiwavelet. Secondly, the resolutions in the time and frequency domain have been enhanced via the redundant multiwavelet packet decomposition, and the histogram of the relative energy ratio of the characteristic frequency of the concerned component is computed. Finally, sensitive frequency band is selected to diagnose the compound-fault property, according to the relative energy ratio. This method is applied to analyze the experimental signals of the bevel gearbox and planetary gearbox. The results indicate that the compound-fault can be distinguished and extracted effectively. At the same time, the performance of the proposed method is compared to redundant wavelet packet with Db8, ARMP with the optimization objective of kurtosis, spectral kurtosis and EMD method.

The rest of this paper is organized as follows. In Section 2, the redundant multiwavelet packet transform is reviewed briefly. In Section 3, the adaptive multiwavelet construction based on symmetric lifting (SymLift) scheme through the minimum sum of normalized multifractal entropy is proposed. Then this method is applied to the experimental compound-fault from the bevel gearbox and planetary gearbox to demonstrate its performance in Section 4. Conclusions are given in Section 5.