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Mechanical equipment fault diagnosis based on redundant second generation wavelet packet transform

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ABSTRACT

Wavelet transform has been widely used for the vibration signal based mechanical equipment fault diagnosis. However, the decomposition results of the discrete wavelet transform do not possess time invariant property, which may result in the loss of useful information and decrease the classification accuracy of fault diagnosis. To overcome this deficiency, a novel fault diagnosis method based on the redundant second generation wavelet packet transform is proposed. Firstly, the redundant second generation wavelet packet transform is constructed on the basis of second generation wavelet transform and redundant lifting scheme. Secondly, the vibration signals are decomposed by redundant second generation wavelet packet transform and then the faulty features are extracted from the resultant wavelet packet coefficients. Finally, the extracted fault features are given as input to classifiers for identification. The proposed method is applied for the fault diagnosis of gearbox and gasoline engine valve trains. Test results indicate that a better classification performance can be obtained by using the proposed fault diagnosis method in comparison with using second generation wavelet packet transform based method.

1. Introduction

Growing demand for high quality production requires that deviation of machine conditions from its normal setting should be identified and fixed promptly to reduce costly machine downtime and maintain high productivity. As a result, research on effective mechanical equipments health monitoring and diagnosis has been enhanced in recently years [1,2]. Since the vibration signal collected from these equipments during operation contains valuable information about the machine or part condition, vibration analysis has been adopted widely as a means for machine failure identification [3]. The vibration signal is often a mixture signal which simultaneously contains stationary, non-stationary and noisy components. Therefore, the information for maintenance decisions is not readily available from these vibration data unless the appropriate signal processing techniques are chosen [4].

The wavelet transform (WT), as a state-of-the-art tool for signal processing, has focused much attention on both theoretic analysis and engineering applications in many fields. WT can be used for multi-scale analysis of a signal through dilation and translation, so it can extract signal features from both time domain and frequency domain effectively. Consequently, WT has been successfully applied for the condition monitoring and fault diagnosis of electromechanical equipment [5]. A drawback of WT is that the frequency resolution is rather poor in the high-frequency subband which the faulty characteristics always exist in. The wavelet packet transform (WPT), a generalization of wavelet bases, is alternative bases formed by taking linear combinations of usual wavelet functions [6,7]. WPT divides the frequency space into various parts and allows a better

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time–frequency localization of signals. In recent years, WPT has been used as a popular method in the field of condition monitoring and fault diagnosis [8–12]. In application of WT and WPT, it is crucial for selecting a proper wavelet function for a special problem and the engineering experiences show that the wavelet function should be selected according to the fault feature to be detected [13].

The second generation wavelet transform (SGWT) is a new wavelet construction method using lifting scheme in the time domain. It abandons the Fourier transform as design tool for wavelets, and wavelets are no longer defined as translates and dilates of one fixed function. Compared with classical WT, SGWT possesses several advantages, including possibility of adaptive and nonlinear design, in-place calculations, irregular samples and integral transform [14–16]. Recently, the applications of SGWT and second generation wavelet packet transform (SGWPT) to condition monitoring and fault diagnosis of electromechanical equipment deserve more attentions [17–20].

Unfortunately, SGWT does not have the property of time invariant. Using SGWT, the decomposition results of a delayed signal are not the time-shifted version of those of the input signal, which may lead to the loss of useful faulty information for feature extraction and fault diagnosis. The redundant lifting scheme possesses time invariant property and overcomes the disadvantage of lifting scheme by getting rid of the split step and zero padding of prediction operator and update operator. The approximation and detail signals at all levels are the same length as the input signal in the redundant lifting scheme [21–23].

In this paper, on the basis of SGWT and redundant lifting scheme, the redundant second generation wavelet packet transform (RSGWPT) is constructed, and then fault diagnoses of mechanical equipments are performed by using the proposed RSGWPT. The rest of the paper is organized as follows. In Section 2, the fundamental theory of SGWT and SGWPT is reviewed briefly. In Section 3, the construction method of RSGWPT is introduced. The fault diagnosis method based on RSGWPT is described in Section 4. In Section 5, the proposed fault diagnosis method is applied to diagnose different states of a gearbox and the valve trains on a gasoline engine. The comparison results with SGWPT based fault diagnosis method are also shown. Finally the conclusions have been drawn in Section 6.

2. Review of second generation wavelet transform

2.1. Second generation wavelet transform

Second generation wavelet transform, proposed by Wim Sweldens, is a new wavelet construction method using lifting scheme. It can be seen as an alternate implementation of classical discrete wavelet transform. The main feature of the second generation wavelet transform is that it provides an entirely spatial domain interpretation of the transform, as opposed to the traditional frequency domain based constructions [15]. The decomposition stage of SGWT consists of three steps: split, prediction and update.

In the split step, an approximate signal a_l at level l is split into even samples and odd samples.

$$a_{l+1} = a_l(2i), \qquad d_{l+1} = a_l(2i+1) \tag{1}$$

In the prediction step, a prediction operator P is designed and applied on a_{l+1} to predict d_{l+1}. The resultant prediction error d_{l+1} is regarded as the detail coefficients of a_l.

$$d_{l+1}(i) = d_{l+1}(i) - \sum_{r=-M/2+1}^{M/2} p_r a_{l+1}(i+r) \tag{2}$$

where p_r are coefficients of P and M is the length of p_r.

In the update step, a designed update operator U is applied on d_{l+1}. Adding the result to the even samples, the resultant a_{l+1} is regarded as the approximate coefficients of a_l.

$$a_{l+1}(i) = a_{l+1}(i) + \sum_{j=-N/2+1}^{N/2} u_j d_{l+1}(i+j-1) \tag{3}$$

where u_j are coefficients of U and N is the length of u_j.

Iteration of the above three steps on the output a, and then the detail and approximation coefficients at different levels are generated.

The reconstruction stage of SGWT is a reverse procedure of the decomposition stage, which includes inverse update step, inverse prediction step and merging step.

$$\begin{cases} a_{l+1}(i) = a_{l+1}(i) - \displaystyle\sum_{j=-N/2+1}^{N/2} u_j d_{l+1}(i+j-1) \\ d_{l+1}(i) = d_{l+1}(i) + \displaystyle\sum_{r=-M/2+1}^{M/2} p_r a_{l+1}(i+r) \\ a_l(2i) = a_{l+1}, \qquad a_l(2i+1) = d_{l+1} \end{cases} \tag{4}$$