The fault feature extraction and classification of gear using principal component analysis and kernel principal component analysis based on the wavelet packet transform

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Abstract

The vibration signal of a gear system is selected as the original information of fault diagnosis and the gear system vibration equipment is established. The vibration acceleration signals of the normal gear, gear with tooth root crack fault, gear with pitch crack fault, gear with tooth wear fault and gear with multi-fault (tooth root crack & tooth wear fault) is collected in four kinds of speed conditions such as 300 rpm, 900 rpm, 1200 rpm and 1500 rpm. Using the method of wavelet threshold de-noising to denoise the original signal and decomposing the denoising signal utilizing the wavelet packet transform, then 16 frequency bands of decomposed signal are got. After restructuring the decomposing signal and obtaining the signal energy in each frequency band, the signal energy of the 16 bands is as the shortlisted fault characteristic data. Based on this, using the methods of principal component analysis (short for PCA) and kernel principal component analysis (short for KPCA) to extract the feature from the fault features of shortlisted 16-dimensional data feature, then the effect of reducing dimension analysis are compared. The fault classifications are displayed through the information that got from the first and the second principal component and kernel principal component, and these demonstrate they have a different and good effect of classification. Meanwhile, the article discusses the effect of feature extraction and classification that caused by the kernel function and the different options of its parameters. These provide a new method for a gear system fault feature extraction and classification.

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0. Introduction

Gear transmission is the basic form of mechanical transmission, and it has the advantages of a compact structure, stable transmission ratio, large transmission power, high transmission efficiency long service life, etc. So, it is widely used on the transmission system of machine tools, vehicles, construction machinery and other machinery equipment. Its running state is directly related to the working effect of the entire mechanical equipment. However, due to reasons of the complex structure of the gear transmission system itself and poor working conditions, it is very prone to damage, break and other faults. According to statistics, 80% of the failures are caused by the gear faults while there are gears in the mechanical transmission system, and gear faults also account for about 10% in rotating machinery failures [1]. Therefore, the failure analysis and fault diagnosis of the gear transmission system and its various components are a very important research...
Fault diagnosis generally includes three main components, namely characteristic signal detection, feature extraction and fault classification. The feature extraction of faults is generally divided into feature selection and feature extraction, and the theory and method of fault feature selection and extraction are the most active research area in fault diagnosis discipline. Feature extraction is an important step in fault identification. If the feature extraction is incorrect or incomplete and it will inevitably lead to erroneous classification and false positives. How to extract the effective fault characteristic information from the complex dynamic mechanical signals is the key to solve the problem of large-scale complex mechanical and electrical equipment fault diagnosis. Traditional method of signal processing can not take into account the signals’ localization characteristics and overview that show in the time domain and frequency domain analysis and it is powerless to analyze and process nonlinear and nonstationary of complex electromechanical device signals. Although modern signal processing methods provides the possibility for the analysis of non-linear, non-Gauss and non-stationary signals, it has its own unique advantages and disadvantages, such as short-time Fourier transform has no cross-term interference but the time–frequency resolution is low [5,6]; Wigner distribution has a high resolution of time–frequency and it is always real function. Whether it is real signal or complex signal, but for the multi-component signal, Wigner distribution will be serious cross-interference and resulting in false frequency components [7].

Wavelet transform (WT) is a multi-resolution analysis method, which has a good time–frequency localization features. Through the wavelet of the “stretching” and “translation”, it can obtain good time domain resolution from high-frequency part which the duration is very short; it obtains good frequency domain resolution in the low-frequency component analysis, and it is a powerful tool in dealing with non-stationary signal [8,9]. Wavelet transform has been widely used in signal and image processing, speech analysis, numerical computation, pattern recognition, quantum physics, fault diagnosis and other fields [10] and is considered to be a major breakthrough in the tools and methods. Hansang Kim utilize wavelet analysis to predict the location of structural damage identification [11]; Pinzheng Zhang and Huazhong Shu of Southeast University in China adopt a method that combines wavelet analysis and neural network to study face recognition [12]. The wavelet packet transform is a form of wavelet transform. The method for mechanical fault diagnosis based on redundant second generation wavelet package transform, neighborhood rough set and support vector machine is presented in Ref. [13], which was applied to vibration signals for achieving high classification performance in mechanical equipment fault diagnosis [13]. The length of decomposition results of traditional wavelet packet transform (WPT) will decrease by half in the next level for downsampling, then the length of sequences in the last level will become very short, and this is very inconvenient for further analysis of these sequences. One kind of WPT (convolution WPT) based on convolution definition is put forward to overcome the defect of traditional WPT [14]. And wavelet packet transform has also been received a wide range of applications.

Feature extraction based on spatial transform is to transform the original sample data into a new space to make the data between the different classes have maximum separation in the new space, or to make the data in new space have the best ability to describe the original data. Transform feature extraction technology is divided into linear and nonlinear, respectively, based on linear transformation and nonlinear transform. PCA (Principal Component Analysis) [15] method is optimal dimension compression technology whose feature is based on the minimum mean square error. Namely, in the same dimensions, the data transformed from the original using the method of principal component analysis will contain most of the original data information. This method is based on second-order statistics of the data (namely based on the corresponding covariance matrix) for analysis and extracts each irrelevant characteristic component. By solving the characteristic equation and choosing the eigenvector corresponding larger eigenvalue as transformation axis. This ensures the converted data with minimal loss relative to the original data. By introducing a kernel function, Kernel Principal Component Analysis (KPCA) [16] implicitly maps the input space into a nonlinear feature space, and in the feature space linear principal component analysis can be conducted. Since the mapping is non-linear, KPCA is a method of nonlinear principal component analysis. Compared with PCA, if the original data exists with complex non-linear relationship, KPCA is more suitable for the feature extraction and can achieve the purpose that reacts the original data in the greatest degree while compressing the dimensions of the original data [17]. Therefore, KPCA can simplify the steps and process of feature extraction and it can be better used in feature extraction and classification of the fault.

1. Wavelet packet transform and wavelet packet frequency band energy

Wavelet packet decomposition can provide a more meticulous analysis method to signal. Through dividing the frequency band to multi-layer, wavelet packet decomposition can further decompose the high frequency part which is no decomposed in multi-resolution analysis. Therefore, it has also a high resolution ratio in the high frequency part. According to the characteristics of the analyzed signal wavelet packet decomposition can adaptively select the appropriate frequency band to matches with the signal spectrum. So it enhances the time–frequency resolution ratio, and it has extensive application value [18–21].

Wavelet packet function \( \psi_{jk}(t) \) can be expressed as:

\[
\psi_{jk}(t) = 2^{j/2} \psi(2^jt - k), \quad i = 1, 2, 3, \ldots
\]

(1)

The \( j \) layer and the \((j + 1)\) layer have the following comparison expression:

\[
f_j(t) = Hf_j(t) + Gf_{j+1}(t)
\]

(2)