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Research Article

Application of the Teager–Kaiser energy operator in bearing fault diagnosis

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ABSTRACT

Condition monitoring of rotating machines is important in the prevention of failures. As most machine malfunctions are related to bearing failures, several bearing diagnosis techniques have been developed. Some of them feature the bearing vibration signal with statistical measures and others extract the bearing fault characteristic frequency from the AM component of the vibration signal. In this paper, we propose to transform the vibration signal to the Teager–Kaiser domain and feature it with statistical and energy-based measures. A bearing database with normal and faulty bearings is used. The diagnosis is performed with two classifiers: a neural network classifier and a LS-SVM classifier. Experiments show that the Teager domain features outperform those based on the temporal or AM signal.

1. Introduction

Bearings are one of the most important elements of rotating machine and most faults are related with them. For this reason, bearing fault diagnosis has an extreme importance in monitoring procedures. An unexpected failure of a bearing can lead to a machine halt and may cause significant financial losses for the company.

Vibration signals generated by faulty bearings produce a distinct bearing signature. When rollers pass over the defect at a frequency related to the rotational frequency, bearing geometry and defect location, the supporting structure and the vibrational modes of the bearing will be excited by periodic impulses. These impulses appear as a very sharp rise that corresponds to the impact between a roller and the defect. Then, the impulse decays with an approximately exponential envelope as the energy is dissipated by the internal damping. This kind of signal can be viewed as an amplitude modulated signal in which the carrier is the resonance frequency of the bearing and the fundamental frequency of the modulating signal (the envelope) is the bearing characteristic frequency of the faulty bearing. In recent decades, much attention has focused on the development of new digital signal analysis methods for modeling bearing vibration signals so as to discriminate between normal operation and different faulty conditions.

Some conventional methods, after sampling the vibration signal $v(t)$ with sample frequency f_s, feature the vibration signal $v(n)=v(n/f_s)$ with statistical measures of first, second or higher order such as variance, skewness or kurtosis and with measures such as crest factor, impulse factor and root mean square which feature the impulsive nature of the bearing vibration signal [1].

Other methods model the vibration signals generated by faulty bearings as an amplitude modulated (AM) signal, defined as

$$v(n)=A(n)\cos(2\pi f_b n)=A\cos(2\pi f_{bf} n)\cos(2\pi f_b n) \quad (1)$$

where f_b is the resonance frequency of the bearing and $A(n)$ is the AM signal or signal envelope whose f_{bf} is the bearing fault characteristic frequency that have to be detected.

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The AM signal can be extracted using the high frequency resonance analysis or envelope analysis [2] which implies band-pass-filtering the $v(n)$ bearing vibration signal. Then, Fourier transform is used to obtain f_{bf}. The main disadvantage of this technique is the difficulty in the correct selection of the central frequency and the bandwidth of the band-pass filter.

Recent methods in bearing fault diagnosis include more advanced signal processing methods such as spectral kurtosis [3], wavelet analysis and empirical mode decomposition (EMD) [4]. Spectral kurtosis offers a way of designing optimal band-pass filter for bearing fault diagnosis. Wavelet analysis and EMD are time-frequency techniques that decompose the raw vibration signal in different frequency bands. Then, several features such as entropy or statistics are extracted from the different frequency bands.

Recently, as an alternative to obtain the AM signal from the raw vibration signal, [5,6] proposed the nonlinear Teager–Kaiser energy operator (TKEO) [7]. The AM signal and the frequency modulated (FM) signal from a mono-component AM–FM signal can be extracted using TKEO [9]. Li et al. [5] proposed TKEO to extract the AM signal (AM-TK signal) from bearing vibration signal, without using a band-pass filtering process, just with some simple operations over TKEO. Liang et al. [6] proposed the application of the TKEO over the raw bearing vibration signal without computing the AM signal. Then, the Fourier transform is applied and thef_{bf} is identified.

This paper proposes to use TKEO to obtain the vibration signal in the Teager–Kaiser domain (TK signal) and then to feature it with statistical and energy-based features. The objective is to show how the statistical and energy-based features extracted from the TK signal outperform the diagnosis results when extracting the same features from the raw time vibration signal (time signal), the AM signal obtained by pass-band filtering (AM signal) and the AM signal obtained by using the TKEO (AM-TK signal). A comparative analysis between statistical and energy-based features extracted from TK signal, AM-TK signal, AM signal and time signal has not been yet done in literature as authors knowledge. The features extracted from the TK signal are sorted by relevance order with the floating forward feature selection procedure. Finally, features from the different signals are evaluated (in order of relevance) with a neural network classifier. To validate the results obtained with the neural network classifier, a LS-SVM classifier is also used.

The remains of the paper is divided into five sections: method section, which is devoted to the envelope analysis and the Teager–Kaiser operator, database section, experiments section in which the procedure of the experiments is explained, results section and finally the conclusion section.

2. Methods

In this section, the conventional envelope analysis method and the Teager–Kaiser operator are explained.

2.1. Envelope analysis

The conventional analysis to obtain the amplitude demodulated signal ($A(n)$ in Eq. (1)) is called envelope analysis or high frequency resonance analysis [2]. This procedure implies the following steps: (i) band-pass filtering the bearing vibration signal, (ii) application of the Hilbert transform to the band-pass filtered signal, and (iii) low-pass filtering the resulting signal. The step (i) requires a visual inspection of the bearing vibration spectrum to estimate the central frequency and the bandwidth of the band-pass filter.

2.2. Teager-Kaiser transform

The Teager–Kaiser energy operator was derived by Kaiser in 1990 [7] to measure the energy of the mechanical process that generated a single time-varying signal. TKEO can detect modulations in AM–FM signals by estimating the product of their time-varying amplitude and frequency. It is considered as a high-resolution energy estimator. The TKEO for continuous time signals v(t) is

$$\psi_c[v(t)] = [\dot{v}(t)]^2 - v(t)\ddot{v}(t) \quad (2)$$

where $\dot{v}(t) = dv/dt$

It can be shown [7] that the discrete version of the TKEO is

$$\psi[v(n)] = v^2(n) - v(n-1)v(n+1) \quad (3)$$

Maragos et al. [9] developed a method to estimate the amplitude envelope (AM signal) and the instantaneous frequency (FM signal) of speech formant signals using the TKEO. The amplitude modulated signal can be extracted from TKEO (TK-AM signal) as follows [8]:

$$|A(n)| = \frac{2\psi[v(n)]}{\sqrt{\psi[v(n+1) - v(n-1)]}} \quad (4)$$

This technique has been applied in bearing fault diagnosis in [5] to extract the TK-AM signal without using a band-pass filter.

The direct application of TKEO over the raw vibration signal $v(n)$ (Eq. (3)) [6] can perform more effective bearing fault detection. In the TK domain the faulty samples can be easily discriminated because the TK signal highlights the characteristic impulse train which is due to the impact of the rollers with the defect. This effect can be seen in Fig. 1 which shows an example of TK signals for normal and fault conditions. Therefore, it is expected that features obtained from the TK signal will discriminate effectively between normal and fault bearing conditions without estimating the AM envelope. The direct computation of TKEO over the vibration signal has the following advantages: (i) it does not require the use of a band-pass filter. Therefore, the appropriate estimation of the central frequency and bandwidth of the band-pass filter is avoided. (ii) Three adjacent samples of the signal are used to compute the TKEO. This fact makes the TKEO implementation very simple and computationally efficient.

3. Database

To evaluate the proposal, the bearing vibration data from the Case Western Reserve University [10] are used in the experiments. The data were collected from an accelerometer mounted on an induction motor housing at the drive-end bearing and recorded at four different conditions: normal (N), inner race fault (IR), outer race fault (OR) and ball fault (B) with motor loads of 0–3 horsepower. The sample frequency is $f_s = 12$ kHz, the rotating frequency is about 30 Hz and the duration of each vibration file is 10 s. Data consist of four vibration files for normal condition and 12 vibration files for each kind of fault. In total, 40 files are used.

4. Experiments

In this section, a detailed explanation of the experimentation is shown. The different stages of the experimentation are divided into: preprocessing and feature extraction, where the vibration signal is transformed and the features are extracted; feature selection to sort the features by relevance order; and classification stage, where two classifiers are used to evaluate the discrimination ability of the features between normal condition, IR fault