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Repetitive transient extraction for machinery fault diagnosis using multiscale fractional order entropy infogram

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ABSTRACT

The presence of repetitive transients in vibration signals is a typical symptom of local faults of rotating machinery. Infogram was developed to extract the repetitive transients from vibration signals based on Shannon entropy. Unfortunately, the Shannon entropy is maximized for random processes and unable to quantify the repetitive transients buried in heavy random noise. In addition, the vibration signals always contain multiple intrinsic oscillatory modes due to interaction and coupling effects between machine components. Under this circumstance, high values of Shannon entropy appear in several frequency bands or high value of Shannon entropy doesn't appear in the optimal frequency band, and the infogram becomes difficult to interpret. Thus, it also becomes difficult to select the optimal frequency band for extracting the repetitive transients from the whole frequency bands. To solve these problems, multiscale fractional order entropy (MSFE) infogram is proposed in this paper. With the help of MSFE infogram, the complexity and nonlinear signatures of the vibration signals can be evaluated by quantifying spectral entropy over a range of scales in fractional domain. Moreover, the similarity tolerance of MSFE infogram is helpful for assessing the regularity of signals. A simulation and two experiments concerning a locomotive bearing and a wind turbine gear are used to validate the MSFE infogram. The results demonstrate that the MSFE infogram is more robust to the heavy noise than infogram and the high value is able to only appear in the optimal frequency band for the repetitive transient extraction.

1. Introduction

Fault diagnosis of rotating machinery is of great significance in ensuring its long-term safe running with reliability and efficiency. Usually, vibration signals excited by mechanical faults contain rich condition information and are widely used for diagnosis [1]. In previous studies, advanced signal processing techniques such as wavelet transform [2], empirical mode decomposition [3], singular value decomposition and stochastic resonance were used to reveal faulty signatures embedded in vibration signals. As a noticeable faulty signature, repetitive transients have been extensively investigated for fault diagnosis of rotating machinery. Owing to the abilities to indicate not only non-Gaussian components in a signal but also their locations in frequency domain, spectral kurtosis (SK) is effective for extracting repetitive transients and has attracted

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considerable attention [4]. Antoni [5] proposed the kurtogram based on SK to process a wider class of non-stationary signals. Afterwards, much research has been done to make the kurtogram more powerful [6–11].

Recently, protrugram [12] was proposed to detect the repetitive transients with a low signal-to-noise ratio by measuring kurtosis from envelope spectrum rather than time-domain signal. Then the relationship between kurtosis and envelope-based indexes was analyzed [13]. Motivated by this work and inspired by the concept of thermodynamics, Antoni [14] proposed a new method named as infogram by measuring the entropy of both squared envelope (SE) and squared envelope spectrum (SES) of signals. The SE infogram was developed to detect impulsiveness in time domain, while the SES infogram was designed to detect cyclostationarity in frequency domain. Then the average infogram was expected to detect both impulsiveness and cyclostationarity of repetitive transients. Despite its advantages in detecting repetitive transients, infogram still has some shortcomings which may limit its performance. Initially, infogram is a fast filtering algorithm rather than an optimal filtering algorithm. To solve this problem, Wang [15] extended the infogram to a novel Bayesian inference based on optimal wavelet filtering for bearing fault characteristic identification. Furthermore, average infogram is a compromise between SES infogram and SE infogram, and just represents the larger value, which leads to less effectiveness in repetitive transient extraction. In order to improve the efficiency of average infogram, Li et al. [16] proposed multiscale clustered grey infogram by combining both spectral entropy in a grey fashion with multiscale clustering. In addition, one may notice that spectral entropy used in the infogram measures repetitive transients on a single scale and an increase in the entropy may not always be associated with an increase in dynamical complexity, so several high values appear in different frequency bands. It is difficult to select the optimal frequency band from these frequency bands and misjudgment may be made for the fault diagnosis. This shortcoming is also mentioned by Antoni [14], which stated that more generally, the proposed infograms may also become difficult to interpret – at least in an automated way – when high values appear in several different frequency bands and thus the analysis effort grows proportionally with the number of frequency bands where the signal has to be demodulated and the envelope spectra computed. Therefore, a more accuracy entropy should be proposed for infogram.

In this paper, based on multiscale entropy [17,18], a more accurate calculation indicator is designed to overcome the above mentioned shortcoming in infogram for extracting repetitive transients. The multiscale entropy has been widely used in physiologic time series [19] and intelligent identification for fault diagnosis [20,21]. However, the application of multiscale entropy in signal processing for fault diagnosis is relatively rare. The multiscale entropy shares the some properties with Shannon entropy. They are both able to evaluate the similarity and regularity of the vibration signals, measure the disorder in a system, be a measure as kurtosis to detect out-of-equilibrium perturbations in a system and to measure the information. When a fault occurs on a rotating machinery, the vibration will be generated cyclically. Then the self-similarity of the vibration signal will increase and can be evaluated by multiscale entropy. In addition, the multiscale entropy is able to quantify the entropy of the vibration signals on range of scales rather than on the single scale. Thus the multiscale entropy is considered to replace the Shannon entropy to design a robust infogram.

Though the regularity and the similarity can be better evaluated by multiscale entropy, the multiscale entropy is not immune to the noise. Considering fractional order shows higher sensitivity to the signal evolution and is useful for describing dynamics of complex systems [22–24], the multiscale entropy infogram will be further extended to the fractional domain for designing a generalized multiscale entropy infogram. The influence of the fractional order selection on the MSFE infogram will be investigated and the optimal fractional order will be decided for diagnosis of rotating machinery. With the help of MSFE infogram, the frequency band of high value just represents the optimal frequency band, which will be demonstrated by simulations and experiments.

The rest of this paper is organized as follows. In Section 2, MSFE infogram is proposed initially and then parameter selections of this method are discussed. Section 3 is devoted to demonstrating the advantages of MSFE infogram compared with infogram by a simulation case. In Section 4, real vibration signals from both a locomotive bearing and a wind turbine gear are used to verify the effectiveness of the proposed method, respectively. Finally, the conclusions are drawn in Section 5.

2. The proposed MSFE infogram

2.1. MSFE infogram

The MSFE infogram is proposed in this section for extracting repetitive transients and further diagnosing mechanical faults more accurately.

The flowchart of the proposed MSFE infogram is shown in Fig. 1 and its detailed procedures is described as follows.

Step 1: The discrete-time signal $x(n)$ $n = 1, 2, \ldots, L-1$ is decomposed to different sub-signals at different decomposition depths by filter banks like the fast kurtogram. Let $x(n; f, \Delta f)$ denote complex envelope of the discrete-time signal in a frequency band, and then SE is written as

$$\varepsilon_x(n; f, \Delta f) = |x(n; f, \Delta f)|^2 \tag{1}$$

By the discrete Fourier transform (DFT) of SE, SES is obtained