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Multi-Scale Stochastic Resonance Spectrogram for fault diagnosis of rolling element bearings

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ABSTRACT

It is not easy to identify incipient defect of a rolling element bearing by analyzing the vibration data because of the disturbance of background noise. The weak and unrecognizable transient fault signal of a mechanical system can be enhanced by the stochastic resonance (SR) technique that utilizes the noise in the system. However, it is challenging for the SR technique to identify sensitive fault information in non-stationary signals. This paper proposes a new method called multi-scale SR spectrogram (MSSRS) for bearing defect diagnosis. The new method considers the non-stationary property of the defective bearing vibration signals, and treats every scale of the time-frequency distribution (TFD) as a modulation system. Then the SR technique is utilized on each modulation system according to each frequencies in the TFD. The SR results are sensitive to the defect information because the energy of transient vibration is distributed in a limited frequency band in the TFD. Collecting the spectra of the SR outputs at all frequency scales then generates the MSSRS. The proposed MSSRS is able to well deal with the non-stationary transient signal, and can highlight the defect-induced frequency component corresponding to the impulse information. Experimental results with practical defective bearing vibration data have shown that the proposed method outperforms the former SR methods and exhibits a good application prospect in rolling element bearing fault diagnosis.

1. Introduction

Rolling element bearing counts among the most important components of the machines in industry applications. The normal operation of the machinery system would be influenced if a bearing in the system is faulty, and the faulty bearing may also cause some unexpected and dangerous consequences. Therefore, precise condition monitoring and diagnosis are needed to discover incipient defects that occur on the bearings. Vibration analysis is generally used for this purpose, but it is difficult to identify incipient defects because of the background noise [1]. The background noise often comes from the working environment as well as some other coupled machine components, which increases difficulty in recognizing the weak signal of

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incipient defects. Hence, the challenge of recognizing the bearing defect is to find a more effective and efficient way to enhance the weak and imperceptible defect information from the noisy background.

In weak signal detection, stochastic resonance (SR) is a useful tool that can utilize the noise for weak periodic signal enhancement [2,3]. Plenty of researchers established the SR theory well and applied it in a lot of areas [4–8]. In the signal processing field, with this technology, the enhanced output signal could be obtained by making use of the additional noise in a nonlinear dynamic system. To detect the bearing defective frequency, the SR theory can be taken as a good tool as well [9]. However, according to the adiabatic approximation and the linear response theory, the classical theory of SR needs small parameters, which means that the driving signal's frequency/amplitude value should not be bigger than 1 [10–12]. With the purpose of applying the SR in a broader range, especially in the area of rotating machine defect identification, the SR strategies that can solve large parameter problems have been explored since more than ten years ago [13–22], e.g., frequency-shifted and re-scaling SR [16], twice sampling SR [20], adaptive step-changed SR [21], and multi-scale noise tuning SR (MSTSR) [17,18].

The large parameter stochastic resonance (LPSR) can be categorized into two kinds: one is frequency transformation and the other type is parameter tuning. Each of them can solve some types of large parameter problems but may cause some underlying problems likewise. The frequency transformation methods may lead the output signal into a distortion situation. The parameter tuning methods do not have to worry about the distortion problem but it may not be so effective when the noise of different scales overwhelms the weak signal. The MSTSR method addressed the influence of different scales of noise [17–19]. By this method, the multi-scale noise was tuned to be an approximate $1/f^{\beta}$ type form. However, the transient vibration signal has the non-stationary property and the noise are randomly distributed. Under this situation, not all scales of noise (e.g., in out-of-resonance band) can play a sensitive role in enhancing the defect-induced frequency component.

Considering the non-stationary property of the defective bearing vibration signals, this paper investigates the SR performance in the time-frequency distribution (TFD). In this study, a new method called Multi-Scale Stochastic Resonance Spectrogram (MSSRS) was proposed to improve the effectiveness in detecting weak signal of incipient defects. The main motivation of the new method is as follows: (1) the defect-induced transients mainly locate at a specific band in the TFD, thus only the noise in this band can actuate the SR effect; (2) the TFD at each frequency corresponds to an envelope modulated on a specific frequency, so there is a modulation system for each frequency scale in the TFD. The new method thus treats every scale of the TFD as a modulation system at a specific frequency. Since useful transient information is just contained in specific scales of the measured signal, the noise in different modulation systems will have different effect on enhancing the defect information with the SR technique. This characteristic can be well reflected in the 2-D representation of MSSRS by the proposed method that is theoretically described in Section 2. The MSSRS is sensitive to identify the defect information because of the sensitivity of SR in enhancing the periodic component in a limited resonance band in the TFD. This proposed SR model is adequate for diagnosing the bearing defects (especially the mixed mechanical faults) and its results are much more effective as compared with the former methods, which were affirmed by the experimental defective bearing vibration data in Section 3. In the rest of the paper, following Sections 2 and 3, Section 4 summarizes the conclusions.

2. Proposed method

In this paper, a method called MSSRS was proposed to recognize the periodic transient signal. The scheme of MSSRS is illustrated in Fig. 1. Instead of realizing SR in the time domain of input signal, the new method treats every scale of the TFD as a modulation system, and realizes the SR in each modulation system of the input signal. Collecting all results of these scales, we can then generate a 2-D representation of MSSRS. The new spectrogram is hoped to sensitively identify the periodic component in specific scales. The following presents the theoretical description with a simulation demonstration of the proposed method.

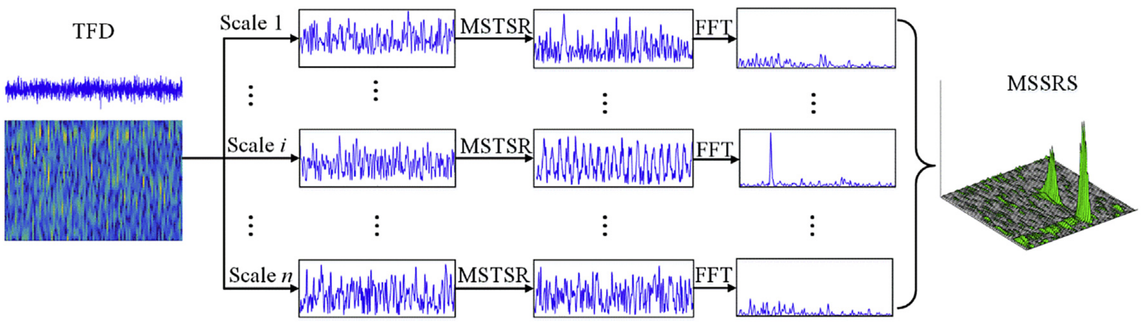

Fig. 1. Scheme of the proposed MSSRS.