Mechanical Systems and Signal Processing 70-71 (2016) 995–1010

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Multi-frequency weak signal detection based on wavelet transform and parameter compensation band-pass multi-stable stochastic resonance

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ARTICLE INFO

Article history:
Received 11 October 2014
Received in revised form
21 August 2015
Accepted 1 September 2015
Available online 5 October 2015

Keywords:
Weak signal detection
Wavelet transform
Multi-stable stochastic resonance
Parameter compensation
Multi-frequency

ABSTRACT

In actual fault diagnosis, useful information is often submerged in heavy noise, and the feature information is difficult to extract. A novel weak signal detection method aimed at the problem of detecting multi-frequency signals buried under heavy background noise is proposed based on wavelet transform and parameter compensation band-pass multi-stable stochastic resonance (SR). First, the noisy signal is processed by parameter compensation, with the noise and system parameters expanded 10 times to counteract the effect of the damping term. The processed signal is decomposed into multiple signals of different scale frequencies by wavelet transform. Following this, we adjust the size of the scaled signals' amplitudes and reconstruct the signals; the weak signal frequency components are then enhanced by multi-stable stochastic resonance. The enhanced components of the signal are processed through a band-pass filter, leaving the enhanced sections of the signal. The processed signal is analyzed by FFT to achieve detection of the multi-frequency weak signals. The simulation and experimental results show that the proposed method can enhance the signal amplitude, can effectively detect multi-frequency weak signals buried under heavy noise and is valuable and usable for bearing fault signal analysis.

1. Introduction

Signal detection technology has been used in many fields, such as fault diagnosis, communications, seismic exploration and biomedical applications; therefore, it is a popular topic for researchers. The technology of signal detection can be divided into two aspects [1–3]. One is obtaining the useful signal by eliminating or suppressing the noise. Standard techniques, such as the wavelet denoising method, the adaptive filtering method, the empirical mode decomposition method, the local mean decomposition method and so on will inevitably weaken the useful signal while removing the noise. For example, the wavelet denoising method needs to select the appropriate wavelet basis; if the selection of the wavelet basis is improper, the final result will be different from the original signal. EMD has a boundary effect and produces many false mode components, which has an impact on the signal detection results [4–6].

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http://dx.doi.org/10.1016/j.ymssp.2015.09.003
0888-3270/

Another detection method is stochastic resonance (SR), which can detect signals by using the noise instead of removing the noise. Stochastic resonance is a physical phenomenon, which means that a signal can be improved when the noise level is increased or when specific noise is added to the system input section. Since the concept of SR was proposed by Benzi et al. in 1981 [7], SR has been widely used in signal processing, physics, biology, large mechanical fault diagnosis and other fields [8–16]. In contrast to the traditional denoising methods, SR utilizes noise instead of eliminating it to improve the signal-to-noise ratio, allowing detection of weak signals. The output signal of a nonlinear dynamic system can be enhanced by adding noise to the system based on the SR mechanism. In recent years, SR has been a hot research topic in the field of signal processing due to its advantages in weak signal detection [17–24]. The traditional SR method focuses mainly on small-parameter signal. To achieve the detection of high frequency weak signals usually implies a need to adjust the system parameters, to scale the transformation or to use other technical means.

Many scholars have studied the detection and identification of single-frequency signals in strong noise. In practical engineering applications, however, the signal is generally multi-frequency, containing both low frequency and high frequency components. As described in the literature [25], convert the high frequency components into low frequency components by scaling, and then detect the multi-frequency signal using the bistable stochastic resonance system. Wang et al. [26] put forward a method for detecting the signal frequency by using an automatic regulation system for the frequency modulation signal and a continuous approximation of the measured signal frequency, but this method needs to know the signal frequency in advance; therefore, this method of detecting the signal has certain restrictions. Tao et al. [27] proposed a method of multi-frequency periodic weak signal detection based on a single-well potential stochastic resonance which only needs one adjustable parameter. This method can make the system reach the optimum state and is applicable in the detection of multi-frequency signals.

The majority of the existing methods for detecting multi-frequency weak signals are based on monostable or bistable stochastic resonance systems. When the signal-to-noise ratio is very low, we cannot detect the signal frequency with the bistable or monostable stochastic resonance method. The noise metastatic capacity of a multi-stable stochastic resonance system is better than the bistable stochastic resonance system; therefore, using the multi-stable stochastic resonance method to obtain frequency is more accurate than the bistable stochastic resonance method. However, there are no reports on the detection of multi-frequency weak signals using the multi-stable stochastic resonance method so far. The parameter compensation method, as opposed to double sampling, adds the signal modulation heterodyne method and does not need to know the frequency of the signal and is not affected by sampling frequency. In addition, it only needs to know the approximate frequency of the signals, which makes it easier to detect the high frequency signals.

In this paper, a novel weak signal detection method based on wavelet transform and parameter compensation to produce a band-pass multi-stable stochastic resonance is proposed. The rest of this paper is organized as follows. Section 2 provides a brief introduction to the principles of multi-stable SR and describes how to construct a common model for multi-stable SR. Section 3 introduces the decomposition of multi-scale wavelets. Section 4 describes the method of parameter compensation and compares the performance of the proposed method with the simulation and experimental data, as well as presenting the computational results for an experimental example. Finally, Section 5 provides the conclusions.

2. Principles of multi-stable SR

The model for multi-stable SR is a multi-stable nonlinear system driven by periodic signals and white noise. It takes advantage of the synergistic effects between the input signal and noise in the nonlinear system, transferring noise energy into useful signals that resonate, thus achieving the identification weak signals. The Langevin equation can be written as follows [28]:

$$dx/dt = k[-dU(x)/dx + s(t) + \eta(t)] \tag{1}$$

where k is the relaxation time scale, $s(t) = \sum_{i=1}^{n} A_i \sin(2\pi f_i t)$ is the input signal, A_i is the periodic signal amplitude, f_i is the driving frequency, and $\eta(t) = \sqrt{2D}\varepsilon(t)$ with $<\eta(t)\eta(t+\tau)> = 2D\delta(t)$ representing the noise item, in which D is the noise intensity and $\varepsilon(t)$ represents Gaussian white noise with zero mean and unit variance.

The multi-stable nonlinear system $U(x)$ driven by the periodic signal and white noise generates the output stochastic resonance response $x(t)$, as shown in Fig. 1.

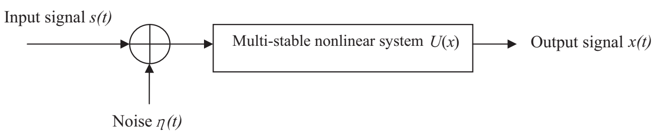

Fig. 1. Multi-stable nonlinear system.