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Detecting impact signal in mechanical fault diagnosis under chaotic and Gaussian background noise ☆

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ABSTRACT

In actual fault diagnosis, useful information is often submerged in heavy noise, and the feature information is difficult to extract. Traditional methods, such like stochastic resonance (SR), which using noise to enhance weak signals instead of suppressing noise, failed in chaotic background. Neural network, which use reference sequence to estimate and reconstruct the background noise, failed in white Gaussian noise. To solve these problems, a novel weak signal detection method aimed at the problem of detecting impact signal buried under heavy chaotic and Gaussian background noise is proposed. First, the proposed method obtains the virtual reference sequence by constructing the Hankel data matrix. Then an M-order optimal FIR filter is designed, which can minimize the output power of background noise and pass the weak periodic signal undistorted. Finally, detection and reconstruction of the weak periodic signal are achieved from the output SBNR (signal to background noise ratio). The simulation shows, compared with the stochastic resonance (SR) method, the proposed method can detect the weak periodic signal in chaotic noise background while stochastic resonance (SR) method cannot. Compared with the neural network method, (a) the proposed method does not need a reference sequence while neural network method needs one; (b) the proposed method can detect the weak periodic signal in white Gaussian noise background while the neural network method fails, in chaotic noise background, the proposed method can detect the weak periodic signal under a lower SBNR (about 8–17 dB lower) than the neural network method; (c) the proposed method can reconstruct the weak periodic signal precisely.

1. Introduction

To ensure the safety, make a reasonable maintenance plan, save the cost of maintenance for machine, fault diagnosis have become a popular research direction in the past few years [1–3]. Fault diagnosis usually means that detecting impact signal from the background noise. The background noise sometimes is the white Gaussian noise, but it can be a chaotic background more often [4,5]. The impact signal, which often contain important feature information, can be boiled down to the weak periodic signal [6–8].

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Impact signals are a common form of vibration signal in mechanical engineering, and often contain important information as to the operating condition of mechanical equipment, enabling them to be one of the most important sources of information about mechanical fault features. Therefore various signal processing methods have been widely researched. The main technology of weak signal detection can be divided into two aspects.

One detection method is stochastic resonance (SR). Stochastic resonance (SR), as a nonlinear signal processing method which can be used to extract weak signal features from the vibration signal by right of its unique advantage of using noise to enhance weak signals instead of suppressing noise [9–14].

Another detection method is obtaining the useful signal by suppressing the background noise. The background suppression methods explore the different geometry characteristic between periodic signal and background noise in phase space to detect the weak periodic signal [15–22]. Neural network method is a representative type of background suppression method [17–22].

However, the above methods have the following flaws. 1) Stochastic resonance (SR) has a good performance when the background noise is white Gaussian noise. But failed in chaotic background noise, for the reason that chaotic background noises are generated from nonlinear dynamic system which can destroy the performance of stochastic resonance (SR). 2) Background suppression methods have the following flaws, (a) the background suppression methods usually required some background noise as a reference sequence to estimate and reconstruct the background noise. A reference sequence usually means a period background noise which does not contain any impact signal. But in practical applications, it is difficult to obtain a stable reference sequence. (b) It is hard to reconstruct the weak periodic signal accurately. (c) Some methods are sensitive to noise [17–22].

Noticed that the second-order statistics property of background noise is stationary [23,24], to solve these problems above, we proposed a method to detect and reconstruct the weak periodic signal under chaotic background. This method constructs a Hankel data matrix firstly, then pass the weak periodic signal undistorted while minimizing the power of strong chaotic background. Then, an M-order optimal FIR filter can be obtained to acquire the optimal weight vector. The optimal weight vector is obtained by solving the extremum problem of mathematics, so the optimal weight vector can acquire the optimal output SBNR. Finally, we can detect the weak periodic signal and estimate its magnitude and phase accurately based on the output SBNR.

Simulation results show that, compared with the available methods, the proposed method has the following advantages. (1) The proposed method can detect weak periodic signal under chaotic noise background, while stochastic resonance (SR) method cannot do; (2) when the background noise is white Gaussian noise, the proposed method has the same performance with stochastic resonance method in [14]; (3) In chaotic noise background, the proposed method can detect the weak periodic signal over $SBNR = -55$ dB without any reference sequence, while neural network method in [21] do with the reference sequence over $SBNR = -50$ dB; (4) when there is white Gaussian noise ($SNR = -10$ dB), the proposed method can detect the weak periodic signal precisely, but neural network method in [21] cannot do; (5) The proposed method can reconstruct the weak periodic signal precisely; while neural network method in [21] reconstruct the weak periodic signal with big error.

2. Problem analysis

In actual fault diagnosis situation, the background noise can be regarded as a white Gaussian noise or a chaotic noise background, the impact signal can be boiled down to the weak periodic signal [4–8]. So the problem of detecting impact signal in mechanical fault diagnosis transform into problem of detecting the weak periodic signal from background noise.

Suppose there is an observation sequence $x(n)$:

$$x(n) = s(n) + b(n) \tag{1}$$

where $s(n) = \beta \cdot e^{j\omega n}$ is the weak periodic signal, β is the complex amplitude of the weak periodic signal (including initial phase and amplitude), ω is the frequency. $b(n)$ is the strong background noise, which can be a white Gaussian noise or a chaotic background noise.

Weak periodic signal detection in background noise is to detect the weak periodic signal $s(n)$ in $x(n)$.

3. The proposed method

In this section, we propose a method to detect the weak periodic signal under chaotic and Gaussian background noise. The proposed method can also reconstruct the weak periodic signal accurately.

Noticed that the second-order statistics property of background noise is stationary [23,24], we construct a Hankel data matrix to get the second-order statistics information firstly, and then design an optimal FIR filter to estimate the magnitude and phase of the periodic signal. Finally, we estimate the frequency of the weak periodic signal precisely based on the output SBNR (signal to background ratio), and reconstruct the weak periodic signal.