Mechanical Systems and Signal Processing 28 (2012) 443–457

Contents lists available at SciVerse ScienceDirect

Mechanical Systems and Signal Processing

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

Multiscale noise tuning of stochastic resonance for enhanced fault diagnosis in rotating machines

Qingbo He*, Jun Wang, Yongbin Liu, Daoyi Dai, Fanrang Kong

Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China, Hefei, Anhui 230026, PR China

ARTICLE INFO

Article history:
Received 9 July 2011
Received in revised form
19 October 2011
Accepted 25 November 2011
Available online 27 December 2011

Keywords:
Fault diagnosis
Rotating machine
Stochastic resonance
Wavelet transform
Multiscale noise tuning

ABSTRACT

The interference from background noise makes it difficult to identify incipient faults of a rotating machine via vibration analysis. By the aid of stochastic resonance (SR), the unavoidable noise can, however, be applied to enhance the signal-to-noise ratio (SNR) of a system output. The classical SR phenomenon requires small parameters, which is not suited for rotating machine fault diagnosis as the defect-induced fault characteristic frequency is usually much higher than 1 Hz. This paper investigates an improved SR approach with parameter tuning for identifying the defect-induced rotating machine faults. A new method of multiscale noise tuning is developed to realize the SR at a fixed noise level by transforming the noise at multiple scales to be distributed in an approximate $1/f$ form. The proposed SR approach overcomes the limitation of small parameter requirement of the classical SR, and takes advantage of the multiscale noise for an improved SR performance. Thus the method is well-suited for enhancement of rotating machine fault identification when the noise is present at different scales. A new scheme of rotating machine fault diagnosis is hence proposed based on the SR with multiscale noise tuning and has been verified by means of practical vibration signals carrying fault information from bearings and a gearbox. An enhanced performance of the proposed fault diagnosis method is confirmed as compared to several traditional methods.

1. Introduction

Rotating machinery plays a significant role in a wide range of industrial applications, such as aerospace, transportation vehicles, power generators, etc. The rotating machine faults can cause violent vibration on the machine, and even endanger normal machine operation. Therefore, accurate health monitoring and diagnosis system is needed to identify incipient fault that may occur in a rotating machine. However, the defect-induced fault signal of the rotating machine is often corrupted by the noise coming from other coupled machine components and working environment, which makes some incipient faults not easy to be recognized. The challenge of fault recognition requires enhancing the weak fault information from heavy background noise.

The stochastic resonance (SR) has been proposed to enhance the output signal of a nonlinear dynamic system by means of noise addition to the system [1–3]. This idea has also been applied for identifying the defect-induced fault characteristic frequency in mechanical system by means of the active role of noise [4]. It should be noted that there is an important issue

* Corresponding author. Tel.: +865513607985.
E-mail address: qbhe@ustc.edu.cn (Q. He).

0888-3270/$ - see front matter
doi:10.1016/j.ymssp.2011.11.021

to be addressed in the study. The conventional theoretical developments of SR mainly focus on small parameters including very low driving frequency ($\ll 1$ Hz), because of the restriction of the adiabatic approximation or linear response theory [5–7]. Nevertheless, large parameter problems (the values of the driving frequency and/or amplitude and/or noise intensity can be much larger than 1) may usually be involved in real world. For example, the defect-induced frequencies of a running bearing are usually much higher than 1 Hz. Therefore, the large parameter stochastic resonance (LPSR) has been studied and several improvements have been achieved during the past decade [4,8–14]. In summary, these LPSR methods can be classified as two types: frequency transformation and parameter tuning. Each of them can be used to deal with some kinds of large parameter problems, but may also be confronted with potential problems as well. The former type of methods discussed in the literature [8–12] transform the high frequency to be the one smaller than 1 Hz by several techniques, such as the frequency modulation technique [8], the frequency re-scaling technique [9–11], and the frequency-shift combining re-scaling technique [12]. All of these transformations are operated in the frequency domain, so some distortion may be introduced to the time domain (e.g., time resolution) of the output signal as compared to the original signal. The latter type of methods that have been proposed in the references [4,13,14] based on scale normalization can avoid the distortion problem, but it is still not effective when the weak signal is submerged in the noise at different scales (e.g., for the non-stationary vibration signal).

This paper investigates the SR technique with parameter tuning for rotating machine fault diagnosis, and presents a new method based on multiscale noise tuning to overcome the limitation of traditional parameter tuning approach. The parameter tuning is essentially equivalent to a kind of frequency scaling, and hence it can be used to deal with large frequency problems. To address the effect of the noise at different scales, a mechanism is explored that the SR can be induced by the noise at different limited bands of noise. We thus proposed a principle to realize the SR by tuning multiscale noise according to the property of $1/f$ noise [15]. The proposed SR model takes the merit of multiscale noise tuning to enhance detection of the weak signal with large frequency, and is well-suited for rotating machine fault diagnosis. The theoretical background of the proposed SR method with multiscale noise tuning is presented in Section 2, where a new fault diagnosis scheme is subsequently proposed based on the SR model. Then in Section 3, experimental studies by some practical defective bearing signals and a faulty gearbox signal are conducted to confirm the effectiveness of the proposed method for enhancing rotating machine fault identification in comparison with traditional envelope spectrum, wavelet transform, and parameter tuning-based SR methods. Finally, conclusions are drawn in Section 4.

2. Theoretical background

2.1. Bistable SR model

The SR has been theoretically developed in bistable systems. To describe the SR, the overdamped motion of a Brownian particle in a bistable potential in the presence of noise and periodic force is considered as follows:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = -U'(x) + A_0\sin(2\pi f_0 t + \varphi) + n(t) \tag{1}$$

where $U(x)$ denotes the reflection-symmetric quartic potential as below:

$$U(x) = -\frac{a}{2}x^2 + \frac{b}{4}x^4 \tag{2}$$

Let $n(t) = \sqrt{2D}\xi(t)$ with $\langle n(t), n(t+\tau)\rangle = 2D\delta(t)$, where D is the noise intensity and $\xi(t)$ represents a Gaussian white noise with zero mean and unit variance. Then Eq. (1) can be written as

$$\frac{\mathrm{d}x}{\mathrm{d}t} = ax - bx^3 + A_0\sin(2\pi f_0 t + \varphi) + \sqrt{2D}\xi(t) \tag{3}$$

where a and b are barrier parameters, which are positive real parameters. A_0 is the periodic signal amplitude and f_0 is the driving frequency.

For the bistable model, the most important feature is that the output amplitude depends on the noise intensity D as shown as follows [3]:

$$\bar{x}(D) = \frac{A_0\langle x^2\rangle_0}{D}\frac{r_k}{\sqrt{r_k^2 + \pi^2 f_0^2}} \tag{4}$$

where r_k is the Kramers rate as

$$r_k = \frac{1}{\sqrt{2}\pi}\exp\left(-\frac{\Delta U}{D}\right) \tag{5}$$

and $\langle x^2\rangle_0$ is the D-dependent variance of the stationary unperturbed system ($A_0 = 0$). Eq. (4) means that the output amplitude first increases with increasing noise level, reaches a maximum, and then decreases again. This is the celebrated SR effect. Thus, via the SR phenomenon, the response of the system can be manipulated by changing the noise level.