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Smoothness index-guided Bayesian inference for determining joint posterior probability distributions of anti-symmetric real Laplace wavelet parameters for identification of different bearing faults

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ABSTRACT

Rolling element bearings are one of the most common components used in machines and they are used to support rotating shafts. Unexpected bearing failures may cause machine breakdown which results in economic loss. Detection of bearing faults is crucial to prevent bearing failures. Vibration based signal processing methods have been proven to be effective in identifying different bearing faults. Among different signal processing methods, wavelet analysis is widely investigated because it is able to highlight the similarity between wavelet functions with different wavelet parameters and impulses caused by bearing faults. In wavelet analysis, two topics are of great concern. The first is how to choose a suitable wavelet mother function for bearing fault diagnosis. In recent studies, an anti-symmetric real Laplace wavelet or impulse response wavelet has been experimentally proven to have a high similarity with impulses caused by bearing faults. Therefore, anti-symmetric real Laplace wavelet is chosen as the wavelet mother function in this paper. The second is how to determine the optimal wavelet parameters so as to enhance the ability of wavelet analysis. Based on the anti-symmetric real Laplace wavelet, smoothness index based Bayesian inference is proposed in this paper to establish joint posterior probability density functions of wavelet parameters, which reflect graphical relationships between wavelet parameters. The smoothness index is chosen because it is not only able to quantify bearing fault signals, but also has upper and lower bounds, compared with other metrics, such as wavelet entropy, Shannon entropy, kurtosis, sparsity measurement, etc. For Bayesian inference, a general particle filter is adopted to iteratively calculate and update joint posterior probability density functions of wavelet parameters. Once the joint posterior probability density functions of wavelet parameters are available, the optimal wavelet parameters are determined and an optimal wavelet filtering is conducted to extract bearing fault signatures. Real case studies are investigated to illustrate how the proposed method works. The results show that the proposed method can determine joint posterior probability density functions of wavelet parameters and is effective in identifying different bearing faults.

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1. Introduction

Rolling element bearings are one of the most common components used in machines and are widely used to support rotation shafts. Their failures are one of the most frequent reasons for accelerating machine breakdown. To prevent bearing failures, bearing faults must be immediately detected. A rolling element bearing consists of an outer race, an inner race, several rollers and a cage. When the rolling element bearing has a defect on the surface of one of its components, the impacts are generated by rollers striking the defect to excite the resonant frequencies of the structure between bearings and its adjacent transducers, which induces a modulating phenomenon. Therefore, envelopes of signals collected from vibration transducers installed on machines provide much fault information for bearing fault diagnosis [1]. In many cases, raw vibration signals are corrupted by heavy noises and low-frequency periodic signals, which interrupt the use of envelope analysis for identifying bearing fault signatures [2]. To solve this problem, a proper band-pass filter should be set to retain one of the resonant frequency bands for enhancing signal to noise ratios of bearing fault signals prior to demodulation with envelope analysis.

It is proven that wavelet analysis is an effective tool to exhibit impulses caused by bearing faults. Wavelet analysis [3] can be explained as inner product which aims to calculate the similarity between wavelet functions with different wavelet parameters and impulses caused by bearing faults [4,5]. Here, a wavelet function [3] should satisfy zero average and it is a wave-like oscillation with an amplitude which begins at zero, increases to maxima and then decreases to zero. By using wavelet analysis, impulses corrupted by heavy noises and low-frequency periodic signals can be clearly identified. In wavelet analysis, two aspects are of great concern. The first is how to choose a suitable wavelet mother function so as to identify bearing faults. This is because the similarity between the wavelet mother function and impulses caused by bearing faults plays a key role in the process of inner product. The more similar the wavelet function to impulses caused by bearing faults, the larger the wavelet coefficients. In other words, larger wavelet coefficients are used to represent impulses caused by bearing faults. Among lots of wavelet functions, Morlet wavelet attracted much attention in the past years because it has a similar shape with impulses caused by bearing faults [6–10]. Besides Morlet wavelet, anti-symmetric real Laplace wavelet [11] or impulse response wavelet [12] was investigated to extract bearing fault features. Recently, based on anti-symmetric real Laplace wavelet, Wang et al. [13] proposed a novel adaptive wavelet stripping algorithm which is able to peel simulated anti-symmetric real Laplace wavelets from real bearing fault signals. The spatial reconstruction of the simulated anti-symmetric real Laplace wavelets reflects random characteristics of real bearing fault signals. Moreover, the results show that the anti-symmetric real Laplace wavelet has a better similarity with real impulses caused by either an outer race defect or an inner race defect. Comparisons of real impulses caused by bearing outer and inner faults, a simulated anti-symmetric real Laplace wavelet, and the real part of a complex Morlet wavelet are plotted in order in Figs. 1(a)–(d), where it is found that the simulated anti-symmetric real Laplace wavelet is more similar to the real impulses caused by bearing faults because of its non-symmetric property.

In order to further explore the use of anti-symmetric real Laplace wavelet for extracting bearing fault features, smoothness index based iterative Bayesian inference is proposed in this paper to establish joint posterior probability density functions of wavelet parameters which clearly reflect the graphical relationship between wavelet parameters. Once the joint posterior probability density functions of wavelet parameters are obtained, the optimal wavelet parameters can be used to conduct an optimal wavelet filtering for extracting bearing fault features. Even though wavelet entropy [6], Shannon entropy [7], kurtosis [8] and sparsity measurement [14] are the candidates for the smoothness index [9,15] used in this paper, the smoothness index has specific upper and lower bounds for quantifying bearing fault signals. The smoothness index is limited to a range from 0 to 1. The closer the smoothness index to 1, the flatter the signal. The upper and lower bounds of the smoothness index are convenient to derive the joint posterior probability density functions of wavelet parameters.

The contributions of this paper are summarized as follows. Because anti-symmetric real Laplace wavelet is more similar to impulses caused by bearing faults, it is used in Bayesian inference. Its good performance is validated by three case studies and three comparisons with the fast kurtogram. Second, a smoothness index and anti-symmetric real Laplace wavelet based state space model is built because the smoothness index has specific upper and lower bounds and it makes Bayesian inference tractable. Thirdly, because the state space model developed in this paper is nonlinear, the recursive estimate of the joint posterior probability density function of anti-symmetric real Laplace wavelet parameters is not analytically determined. To solve this problem, a general particle filter [16] is used to iteratively conduct nonlinear Bayesian wavelet parameter estimation. According to our literature review, only limited references are related to solving optimization problems using the general particle filter [17,18]. Zhou et al. introduced the feasibility of the particle filter to solve a one-dimensional optimization problem [17]. Further, Eroğlu and Seçkiner [18] applied the particle filter to solve a wind farm layout optimization problem.

The organization of this paper is illustrated as follows. The theories of anti-symmetric real Laplace wavelet analysis and a general particle filter are introduced in Section 2. Smoothness index based iterative Bayesian inference for determining joint posterior distributions of anti-symmetric real Laplace wavelet parameters for bearing fault diagnosis is proposed in Section 3. Real bearing fault signals are analyzed and three comparisons with the fast kurtogram are conducted in Section 4. At last, conclusions are drawn in Section 5.