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Bearing fault identification by higher order energy operator fusion: A non-resonance based approach

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ABSTRACT

We report a non-resonance based approach to bearing fault detection. This is achieved by a higher order energy operator fusion (HOEO_F) method. In this method, multiple higher order energy operators are fused to form a single simple transform to process the bearing signal obscured by noise and vibration interferences. The fusion is guided by entropy minimization. Unlike the popular high frequency resonance technique, this method does not require the information of resonance excited by the bearing fault. The effects of the HOEO_F method on signal-to-noise ratio (SNR) and signal-to-interference ratio (SIR) are illustrated in this paper. The performance of the proposed method in handling noise and interferences has been examined using both simulated and experimental data. The results indicate that the HOEO_F method outperforms both the envelope method and the original energy operator method.

1. Introduction

Rolling element bearings are widely used in various mechanical systems and among the most failure-prone machine components due to their harsh working conditions, heavy load and delicate structure. Fast and simple methods for bearing fault detection are highly desirable. However, noise and vibration interferences from different mechanical and electrical sources can severely obscure the bearing signal collected from sensors and make it very challenging to reliably detect bearing faults.

For the above reasons, a variety of signal analysis methods has been proposed. Most of the methods focus on the analysis of vibration signals because they are information-rich and can be easily obtained. Through various time-domain [1–6], frequency-domain [7,8] and time–frequency analysis [9–15] methods have been proposed by researchers, the most widely accepted approach is probably the high-frequency resonance (HFR) technique which also lays foundation for several other methods. The main idea of the HFR method is based on the observation that the contact between damaged bearing surface and its mating surface generate impact which excites the structural resonance. The HFR method involves identifying the resonant frequency band where the signal-to-noise ratio (SNR) is higher than the other frequency regions, filtering the signal based on the identified resonant frequency band, amplitude demodulating filtered data, and then analyzing the resulting envelope spectrum to find the fault associated with a characteristic frequency. Obviously, the effectiveness of the HFR methods largely depends on whether the resonant frequency band, i.e., the passband of the filter, can be identified correctly. As such, many studies have been proposed to determine the center frequency and best bandwidth of the bandpass filter [16–19].

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However, obtaining the resonance information is often expertise-demanding and time-consuming. The site operators may not always have such expertise and time for this purpose. As such, a simple non-resonance based approach is desirable in an industrial environment. Bozchalooi and Liang [20] presented a parameter-free bearing fault detection approach. This approach takes advantage of the signal differentiation to reduce unwanted vibration interference contents. Furthermore, a non-resonance method is proposed by Liang and Bozchalooi [21] stemming from the energy operator (EO). Its simplicity and improved signal-to-interference ratio (SIR) make it suited for reliable on-line applications. Recently, a higher-order analytic energy operator (HOAEO) method has been proposed by Faghidi and Liang [22]. Its main focus is on extracting information from both the real and imaginary parts of the analytic form of a signal.

In this paper, a new methodology for non-resonance based method is proposed to detect bearing faults. This method applies higher order EO fusion, guided by optimization of a global feature extraction objective, to handle intense noise and strong interferences. The rationales of this method are:

a) Comparing with the second order (traditional) energy operator (to simplify discussion, the second order energy operator will simply called energy operator hereafter), the signal-to-interference ratio (SIR) can be further improved by higher order EOs.
b) The application of higher order EOs may also amplifies the higher frequency noise and interferences, and thus ill-specified higher order EO weights can adversely affect the effectiveness of a higher order EO method.
c) The difficulty in b) can be mitigated by optimized fusion of higher order EOs due to the noise canceling effect of the different higher order EOs.

The proposed higher order energy operator fusion (HOEO_F) method focuses on the integration of higher order EOs in such a way that each of them can best contribute to fault feature extraction with minimal amplification of high-frequency noise and interferences. The proposed new method is simple, easy to implement and has good capability to handle both noise and interferences. It should be noted that even though several higher order EOs are incorporated in this method, they are not applied sequentially. Instead, they are fused into a single step transform, which makes it computationally efficient.

The paper hereafter is organized as follows: Section 2 illustrates the effect of applying higher order EOs on signal-to-interference ratio. In Section 3, the new method, HOEO_F, is described and its effects on SNR and SIR improvements are also illustrated. In Sections 4 and 5, the proposed method is evaluated using simulated signals and experimental data respectively. Finally, the conclusion is given in Section 6.

2. Energy operator, higher order energy operator and their effects on signal-to-interference ratio

In this section, the traditional energy operator (simply called energy operator, and EO for short hereafter) is briefly reviewed, its explicit expression for faulty bearing signal with multiple interferences is presented and its effect on SIR is examined afterwards. Then the mathematical expression of the higher order energy operator is derived and its effect on SIR is compared with that of the EO.

2.1. The energy operator and its expression for faulty bearing signals with multiple vibration interferences

The energy operator is defined in continuous format as [23,24]

$$\psi\,(r(t)) = \mathrm{EO}_2(r(t)) = \left(\frac{\mathrm{d}r(t)}{\mathrm{d}t}\right)^2 - r(t)\frac{\mathrm{d}^2 r(t)}{\mathrm{d}t^2} \tag{1}$$

The discrete form of the energy operator is given by [23,25]

$$\psi_d\,(r(n)) = r^2(n) - r(n-1)r(n+1) \tag{2}$$

To examine the effect of energy operator on SIR in the context of bearing fault detection, the explicit expression of EO for a faulty bearing signal with multiple vibration interferences is derived first. For simplicity, we consider the bearing signal with multiple vibration interferences expressed as follows

$$r(t) = x(t) + v(t) \; = \; A\,e^{-\beta(t)}\,\cos\left(\omega_r t + \varphi\right) \, + \sum_{k=1}^{K} L_k\,\cos\,\omega_{Ik} t \tag{3}$$

where A is the amplitude of the fault signal, β is the structural damping characteristic, ω_r is the frequency of the excited resonance, ω_{Ik} represents the frequency of kth interference component, L_k denotes the amplitude of the kth interference component, $x(t)$ is the vibration signal containing fault generated impulse, $v(t)$ contains multiple vibration interferences. Due to practical reason, we assume that the excited resonance frequency is much higher than interference signal frequency ω_{Ik} for all k's.