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Envelope harmonic-to-noise ratio for periodic impulses detection and its application to bearing diagnosis

Xiaoqiang Xu [a], Ming Zhao [a], Jing Lin [a,b,*], Yaguo Lei [a,b]

[a] Shaanxi Key Laboratory of Mechanical Product Quality Assurance and Diagnostics, Xi'an Jiaotong University, Xi'an, Shaanxi Province 710049, People's Republic of China
[b] State Key Laboratory of Manufacturing System Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi Province 710049, People's Republic of China

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ABSTRACT

Rolling element bearings are one of the fundamental and most important elements in machines and their failures are among the foremost frequent causes of machine breakdown. Vibration and acoustic signals from faulty bearings are typically a mixture of fault-induced periodic impulses and other components. Traditional time-domain features like root-mean-square (RMS) and kurtosis fail to utilize the periodicity property of the impulses, which makes them invalid in some circumstance. Impulses occurring at specific period is the key characteristic of corresponding defect. In the paper, a novel feature named envelope harmonic-to-noise ratio (EHNR) is proposed for periodic impulses detection. The properties of EHNR are illustrated by simulations and bearing full life cycle degradation data. Moreover, an EHNR-based method is proposed to locate periodic impulses in frequency domain. A simulation and a locomotive bearing test rig are used to verify the proposed method. The proposed method has better performances than kurtosis-based method.

1. Introduction

Bearings are of paramount importance to almost all kinds of rotating machinery and are the most commonly used machine elements in industrial applications. An unexpected bearing failure may cause the machinery breakdown, along with significant economic losses. Early detection of the bearing failure is essential to prevent the machines from fatal breakdown. Researches on the causes and analysis of bearing failures have been extensively conducted for four decades [1]. Various techniques are developed for detection of bearing defects, and they may be broadly classified as vibration and acoustic analysis, temperature measurements and wear debris analysis. Among them, vibration and acoustic analysis are the most widely used techniques due to their intrinsic advantage of revealing bearing failure [2].

Time-domain features like variance, skewness and kurtosis always serve as the basis of many advanced techniques for bearing diagnostics including spectral-kurtosis [3], minimum entropy deconvolution (MED) [4], artificial neural network (ANN) [5], etc. Different feature-based techniques in fact may derive very different results, thus it is necessary to recognize the deficiency of current classic time-domain features. The presence of a bearing defect would cause an increase in the vibration and noise level. Overall root-mean-square (RMS) value of the measured signal is applied in industry to measure vibration intensity and indicate the incipient defect [6]. However, RMS value has limited applications because it is not sensitive to defect at its early stage when the defect contributes little energy. And it only reflects the amplitude of the original signal and fail to show any detailed wave shape information concerning the defect. Vibration impulses is another significant signature of bearing defect. Kurtosis value was first utilized by Dyer and Stewart [7] for bearing diagnostics, and it suggested that a value greater than 3 is an early symptom of bearing failure. Spectral kurtosis (SK) proposed by Dwyer [8] is a developed method to locate the impulsive components in frequency domain. Antoni [3,9,10] developed the theory of SK and put forward the kurtogram for optimal frequency band selection to improve signal-to-noise ratio (SNR) of measured signal. Spectral kurtosis has been widely applied to rotating machine diagnostics [11,12]. However, the kurtosis-based techniques may derive invalid results in the presence of relatively strong non-Gaussian noise containing high peaks or for a relatively high repetition rate of fault impulses [13]. Randall and Antoni [14] also mentioned that the kurtogram is very sensitive to large random impulses and the final envelope spectrum may not reveal fault impulses, even though the SK is high. In conclusion, RMS is a reliable parameter but not capable of indicating early fault and it normally requires data collected in

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* Corresponding author at: No. 28 Xianning West Road, Xi'an, Shaanxi 710049, People's Republic of China.

E-mail address: jinglin@mail.xjtu.edu.cn (J. Lin).

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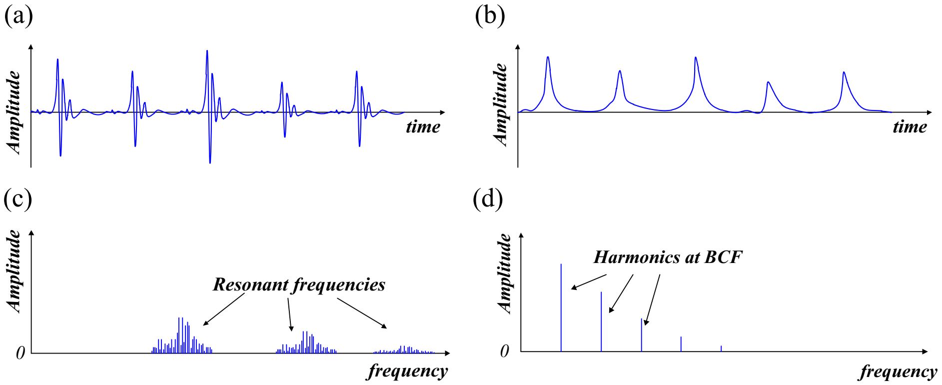

Fig. 1. (a) Bearing fault-induced periodic impulses; (b) envelope of signal (a); (c) frequency spectrum of signal (a); (d) envelope spectrum of signal (a) i.e., the frequency spectrum of envelope (b) after removing zero-frequency component.

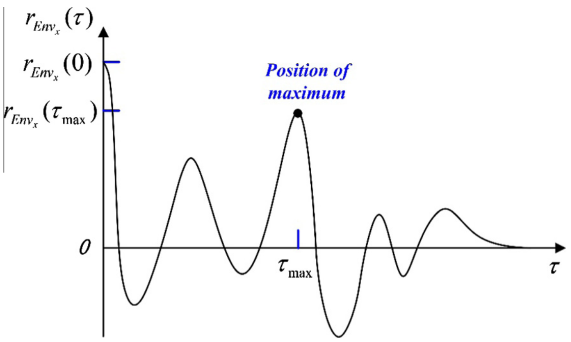

Fig. 2. Autocorrelation spectrum of signal $Env_x(t)$.

healthy condition as benchmark. Kurtosis-based techniques focus on finding the most significant impulses in the measured signal but not robust enough. Moreover, both classic features fail to utilize the periodicity information of the fault-induced impulses.

The harmonic-to-noise ratio (HNR) is suitable to character the periodicity of bioacoustics because the signal is mainly harmonics and noise. And it has been extensively used in human phonetics as a diagnostic tool for the quantification of vocal changes [15,16]. Owren and Linker [17] suggest the HNR as a useful tool in animal bioacoustics, and Riede et al. [18] applied the HNR to dog barks to differentiate healthy dogs from disordered dogs. The HNR is also utilized in speech coding, speech recognition and speaker recognition [19,20]. But the vibration/acoustic signals of bearings differ from bioacoustics a lot because the fault-induced periodic impulses are modulated at resonance frequencies. Thus the HNR does not apply to bearing diagnostics directly. Vibration and acoustic signals of faulty bearing are typically a mixture of fault-induced periodic impulses and other components. In the paper, the envelope harmonic-to-noise ratio (EHNR) is proposed to character the periodicity of the fault-induced impulses. Simulations and full-life bearing data are used to illustrate the property of the EHNR, and it suggests that the EHNR might be useful as a novel feature for indicating the fault-induced periodic impulses. Moreover, an EHNR-based method is also proposed to locate the periodic impulses in frequency domain. Its efficiency is verified by a simulation and a locomotive bearing test rig. The results of kurtosis-based method are given for comparison, and the proposed method shows better performance.

The remaining part of this paper is organized as follows. The EHNR algorithm calculation for bearing diagnostics is given in Section 2. In Section 3, the properties of the EHNR are illustrated by simulation, and the EHNR-based method is proposed in this section. The performances of the EHNR are further discussed using bearing a full life cycle degradation data in Section 4 case 1. In Section 4 case 2, the proposed EHNR-based method is validated by a locomotive bearing test rig. Finally, conclusion is drawn in Section 5.

2. EHNR calculation

Periodic impulses spaced at specific period corresponding to the bearing characteristic frequency (BCF) is the bearing fault signature, as shown in Fig. 1(a). Fault impact would excite multiple resonant frequencies as presented in Fig. 1(c). The higher harmonics smear over one another with even a small amount of slippage of rolling element. Envelope analysis by Hilbert transform can help to simplify the signal significantly by shifting the frequency analysis from the very high range of resonant frequencies to the much lower range of the fault frequencies [14]. The envelope and the envelope spectrum of original signal are given in Fig. 1 (b) and (d). Fig. 1(d) shows clear harmonics at BCF even with slippage of rolling element, and the envelope signal can be treated as a sum of two parts: harmonics and noise components. It suggests that calculating the envelope harmonic-to-noise ratio (EHNR) rather the HNR of original signal can be an effective way for periodic impulses detection.

The EHNR algorithm can be calculated as follows.

(1) Obtain the envelope signal $Env_x(t)$ by Hilbert transform of the measured signal $x(t)$ and remove the zero-frequency component,

$$\hat{x}(t) = H\{x(t)\} = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{x(\tau)}{t-\tau}d\tau \tag{1}$$

$$Env'_x(t) = \sqrt{x^2(t) + \hat{x}^2(t)} \tag{2}$$

$$Env_x(t) = Env'_x(t) - mean(Env'_x(t)), \tag{3}$$

where $\hat{x}(t)$ is the version of the original signal $x(t)$ with a 90° phase shift, $Env'_x(t)$ is the direct envelope signal and $Env_x(t)$ is the envelope signal after removing the DC component from $Env'_x(t)$.

(2) Compute the autocorrelation of $Env_x(t)$,

$$r_{Env_x}(\tau) = \int Env_x(t)Env_x(t+\tau)dt, \tag{4}$$

where τ is the time lag. By the definition of autocorrelation, the best candidate for the vibration/acoustic pitch period of the signal can be found from the position of the maximum of the autocorrelation function of the signal, while the periodicity of the signal can be found from the relative height of this maximum.