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Bearing fault diagnosis based on an improved morphological filter

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ABSTRACT

The extraction of repetitive impacts from vibration signals plays an essential role in bearing fault detection. Among different signal processing algorithms, morphological filter (MF) has attracted lots of attention because it could directly extract the geometric structure of the impulsive feature and only needs little computation. However, the conventional MF and some current improvements are based on the local optima of the raw signal to de-noise the noisy signal and its faulty feature extracting capability would be greatly affected by the noise. In this paper, a new improved MF algorithm is proposed to overcome such deficiency. Firstly, morphological gradient (MG) operator is selected in this paper due to its capability of picking up both positive and negative impulses. Then, based on the relationship between the defect induced impulse and a harmonic function with the resonant frequency, the harmonic waveform in a period is adopted to instruct the construction of structuring element (SE). The improved MF can obtain the fault feature from low SNR signals. The processing results of a simulation signal and two sets of experimental signals and a set of comparisons verify the effectiveness and robustness of the proposed method.

1. Introduction

Rolling element bearing is widely applied in industry, whose condition monitoring and fault diagnosis are of great importance in ensuring the operational safety and preventing disasters. Among different processing techniques, vibration based measurement is the most widely employed one due to its high correlation with structure dynamics. Since periodic impulses will be generated by the interaction between bearing components with or without defect on their surface during the rotation process, leading to repetitive impacts in the collected vibration signal. Therefore, the impulses contain vital information about the component health status and the extraction of faulty impulses is the most essential task in vibration-based bearing fault diagnosis. However, such impulses are often corrupted by the noise coming from other coupled machine components and working environment.

In recent years, large amount of methods have been proposed to analyze the non-stationary dynamic signals of fault bearing, such as Wavelet transform (WT) [21], empirical mode decomposition (EMD) [6] and stochastic resonance [8]. All of them have been effectively applied to acquire the fault features of bearing. Unlike the aforementioned methods, morphological filter (MF) [16] is a time domain based algorithm and capable of directly extracting the geometric structure of the impulsive feature [10]. MF is a nonlinear analysis method, which could decompose a complex signal into various components reserving morphological features of the signal. Nikolaou and Antoniadis [15] initially applied a zero-valued flat structuring element (SE) to demodulate the fault signals and suggested that SE with the length of 0.6–0.7 times the pulse repetition period is appropriate for bearing fault

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diagnosis, which is called conventional MF in this paper. To adaptively select the length of flat SE, Dong et al. proposed a signal to noise ratio (SNR) norm to optimize it. To extract impulsive attenuation component from the original signal, Wang et al. [20] constructed a new SE with an impulsive attenuation function and two criterions were introduced to guide the parameter selection.

The existed SE conformation methods are highly depend on prior knowledge of the fault style and mono-scale analysis seems ineffectively because the defect property of bearing signal often scatters over various morphological scales without a known pattern. To overcome these problems, many scholars have attempted to exploit multi-scale MF which could adaptively determine the length of SE and be able to extract the fault information belonging to different scales. Zhang et al. [22] utilized the amplitude of positive peaks and the intervals between them to define the length and height of triangular SEs and the morphological analyses in different scales are averaged to obtain the de-noised signal. In view of the possible deficiency of averaging the results in different scales, Li et al. [12] introduced a multi-scale auto-correlation via morphological wavelet slices (MAMWS) approach to enhance the Fourier spectrum representation, which demonstrates better fault identifying ability. Given the complication of Zhang's method, Shen et al. [18] proposed a fast and adaptive varying-scale MF which could extract the fault information faster and better. To improve MF's resolution, Li and Liang [10] replaced the integer-scale mathematical morphology (ISMM) with the continuous-scale MM (CSMM) which was realized by interpolation and re-sampling. Then the frequency kurtosis criterion is employed to amalgamate the information of narrow bands and the optimal scale band is obtained to detect the bearing fault. Li et al. [9] compared the de-noising performance of eight types of morphological filters as well as the traditional envelope analysis and wavelet transform envelope based analysis, concluding that averaged multi-scale morphological dilation-erosion gradient ($AMMG_{DE}$) filter has the greatest potential for gear fault detection. However, these methods are all based on the local characteristics (peaks or valleys) of the raw signal. So the local peaks or valleys are usually retained while the other parts are flattened. Under some ideal conditions, owing to the fact that defect induced impulses would be local maximums in the obtained vibration signal, the processing results of these methods are mainly local peaks caused by defect and thus the fault feature can be strengthened. However, when the faulty impulses are greatly affected by other interferences, the processing results of them are mainly features begot by interferences. At this time, we cannot achieve the de-noising purpose and the fault features might even be weakened. Thus we cannot discern the fault characteristic frequency from either the time domain or the frequency domain.

To improve the MF's de-noising capability, we propose a new method which could effectively extract the defect-induced impulses from low SNR signals. The improved MF utilizes the morphological gradient (MG) operator and takes the waveform in a period of a sinusoidal function, whose oscillating frequency is the resonant frequency of the bearing system, as a basis to construct the new SE. As a result of the proposed method, the fault induced impulsive information can be highlighted from the background noise and thus the de-noising objective is fulfilled.

The rest of this paper is organized as follows. A brief illustration of the theoretical background of the proposed method is formulated in Section 2. The procedure of the whole algorithm and the simulation verification are depicted in the Section 3. Section 4 presents experimental evaluations of the proposed method are carried out. Conclusions are drawn in the last section.

2. Theoretical background

2.1. Morphological filter

Mathematical Morphology (MM) is based on set theory and has initially been introduced as an image processing method [14,17]. Then Nikolaou and Antoniadis [15] employed MM as a demodulation method to extract envelope of the bearing fault signal. Morphological filter (MF) is a nonlinear signal processing method, which modifies local characteristics of the signal through its interaction with SE. Supposing $p(n)$ and $q(m)$ are the original discrete signal and SE respectively, the four basic operators of MF, namely dilation, erosion, closing and opening, are defined as follows:

Dilation:

$$p \oplus q(n) = \max(p(n-m) + q(m)) \quad n = 0,1,2,\ldots,N-1 \quad m = 0,1,2,\ldots,M-1 \tag{1}$$

Erosion:

$$p \ominus q(n) = \min(p(n+m) - q(m)) \quad n = 0,1,2,\ldots,N-1 \quad m = 0,1,2,\ldots,M-1 \tag{2}$$

Closing:

$$p \cdot q(n) = (p \oplus q \ominus q)(n) \quad n = 0,1,2,\ldots,N-1 \tag{3}$$

Opening:

$$P \circ q(n) = (p \ominus q \oplus q)(n) \quad n = 0,1,2,\ldots,N-1 \tag{4}$$

By the application of different operators, diverse features can be extracted from the signal. Dilation can smooth positive peaks and reduce negative ones while erosion has an opposite effect. The closing operator is the cascade of dilation and erosion and thus it could be applied to obtain the positive peaks. In contrast, opening operator could maintain the negative peaks. To effectively extract fault information from the raw signal, the selection of a proper operator and the construction of SE are of great significance.

2.2. Improved morphological filter

Conventional MF and some current improved MF algorithms take advantage of the local optima existing in the raw signal to extract defect feature and thus peaks or valleys belonging to specified height or length scales are reserved while other parts are flattened. Under some ideal conditions, local maximums in acquired bearing signals represent the impulses caused by faults, and MF based