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An enhanced morphology gradient product filter for bearing fault detection

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ABSTRACT

This paper presents a signal processing scheme, namely enhanced morphology gradient product filter (EMGPF), for rolling element bearing fault detection. In this scheme, a morphology gradient product operation (MGPO) is firstly proposed to extract impulsive features of a raw signal according to a comprehensive investigation of the working mechanism of the reported morphological operations. Then, a higher-order spectrum analysis method, the third-order cumulant slice spectrum, is used to improve the performance of the MGPO based morphology filter for the purpose of highlighting fault features further. Experimental vibration signals were employed to evaluate the effectiveness of the proposed EMGPF. Results show that the proposed method has a superior performance in extracting fault features of defective rolling element bearing over four reported morphology filters.

1. Introduction

Mathematical morphology (MM) is a nonlinear signal processing methodology based on set theory, lattice theory, topology, and random functions [1–5]. It was originally introduced as an image processing tool by Matheron and Serra [1–3]. Later, Maragos and Schafer [4,5] extended MM to one-dimensional signal processing. Nowadays, mathematical morphology filter (often referred to as morphology filter (MF)) has been widely applied for mechanical fault detection and diagnosis [6–25].

The basic idea of MF can be summarized as follows: the geometric shape of the raw signal is transformed though an interaction with a pre-defined structure element (SE) using some morphological operation. This transformation eliminates noises and maintains the impulse features of the raw signal. From the basic theory of MF we know that MF mainly involves the selection of SE and the morphological operation. For the former, researches have shown that the SE type had little influence on the analysis results [18,23]. The latter, however, plays a decisive role for the analysis results of MF. Basic morphological operations include dilation, erosion, closing and opening [3]. Some advanced cascade and combined operations, such as morphological closing–opening operation and the average of closing and opening operations, can be achieved based on the above four basic operations.

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Various morphological operations have been applied in bearing vibration signal processing. For example, morphological closing operation was adopted by Nikolaou and Antoniadis [6], Patargias et al. [7], He et al. [8] and Wang et al. [9]. Dong et al. [10] used the average of closing and opening. Wang et al. [11] and Meng et al. [12] utilized the average of closing–opening and opening–closing, respectively, to remove the high frequency noise. The gradient between dilation and erosion was employed by Li et al. [13] and Raj and Murali [14] to extract the low frequency impulsive features. Also for impulsive features extraction, the gradient between closing and opening [13–18] as well as the gradient between closing–opening and opening–closing [19,20] were applied. Gong et al. [21] brought forth an asymmetric closing and opening gradient operation. Contrast with Refs. [13–18], the number of dilations and erosions are unequal in this scheme [21]. Van et al. [22] used two types of SEs simultaneously to construct closing–opening and opening–closing operations. However, as stated previously, the SE type had little influence on the analysis results [18,23], which implies that using different SEs in one operation [22] would not differ much from the operations presented in [19,20]. Hu and Xiang [24] proposed to use the difference value between the raw signal and the average of closing–opening and opening–closing operations as a new MM operation. Similarly, the sum operation of the difference value between the raw signal and closing as well as the difference value between the raw signal and opening is put forward by Deng et al. [25].

Although different operations have been developed for bearing vibration signal processing, the basic characteristics and application scenarios of these operations have not been investigated thoroughly. There are few retrievable documents that discuss the corresponding problems of MM operations. The reported closing, average or gradient operations have been shown to be inadequate in bearing fault detection, especially when high measurement noises are present [7,12,22,24,25]. If an improper operation is adopted, the MF may capture the impulses which are unrelated to the bearing faults and return a false diagnosis result.

This paper aims at proposing an enhanced MF which can improve the ability of fault detection on bearings comparing with current MFs. This improvement is implemented by exploring two directions: (1) propose a new type of MM operation; and (2) seek a lifting scheme for this operation further.

A thorough investigation of the reported MM operations is firstly conducted in this paper. These operations are classified into two categories: noise reduction-type operations and feature extraction-type operations. Two simulated signals are employed to compare and pictorially illustrate the characteristics of these operations and a new morphology gradient product operation (MGPO) is proposed on this basis. The proposed MGPO consists of two gradient operations: closing and opening gradient as well as closing–opening and opening–closing gradient. The reason of employing two gradient operations is that in the case of vibration signal analysis, to easily detect peaks, the variations in the signal amplitude are to be enhanced using gradient [14]. Hence, gradient operation is more sensitive to impulse extraction compared with a single MM operation or an average operation (see Section 3). With the product of two gradient operations, more impulsive information could be obtained.

The impulses extracted are not the more the better. The fundamental of MGPO makes the filtered signal inevitably obscure due to the presence of considerable noise. Gaussian noise is one of the most common noises in bearing vibration signals [20]. Any periodic and quasi-periodic signals can be considered as non-Gaussian signals and self-emitting signals from rotating machinery as well [26]. Therefore, a defective bearing vibration signal is basically a non-Gaussian signal. Luckily, higher-order spectrum (HOS) is theoretically zero for Gaussian noise [27]. When defective bearing vibration signal has additive Gaussian noise, a transform to HOS would suppress the Gaussian noise. What's more, one typical HOS technology, the third-order cumulant slice spectrum (TOCSS) [27] has the merits of detecting coupled frequency pairs of a signal and suppressing uncoupled frequency components [27]. Due to this property, the bearing fault features would be highlighted. Therefore, TOCSS is used to enhance the proposed MGPO based MF in the present paper.

In the following, Section 2 introduces the reported MM operations. Section 3 interprets the characteristics of these reported operations with two simulated signals. Section 4 proposes the TOCSS lifted MGPO scheme: enhanced morphology gradient product filter (EMGPF). Section 5 applies the proposed EMGPF technology to test rig signals of rolling element bearings and demonstrates its detection ability for two types of faults respectively. Conclusions are drawn in Section 6.

2. Reported morphological operations

Supposing that the input sequence $f(n)$ and the selected SE $g(m)$ are discrete data sets defined in $F = (0, 1, \ldots, N-1)$ and $G = (0, 1, \ldots, M-1)$ $(N \geq M)$, respectively, dilation and erosion are expressed as:

$$(f \oplus g)(n) = \max[f(n-m) + g(m)] \tag{1}$$

$$(f \,\Theta\, g)(n) = \min[f(n+m) - g(m)] \tag{2}$$

where $\oplus$ denotes the dilation and Θ represents the erosion.

Dilation and erosion gradient operation ($G_{D\&E}$) is defined as the arithmetic difference between the dilation and erosion [13,14]:

$$G_{D\&E}(n) = (f \oplus g)(n) - (f \,\Theta\, g)(n) \tag{3}$$