Mechanical Systems and Signal Processing ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

The application of a general mathematical morphological particle as a novel indicator for the performance degradation assessment of a bearing

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A R T I C L E I N F O

Article history:
Received 21 February 2014
Received in revised form
23 May 2016
Accepted 31 May 2016

Keywords:
Performance degradation assessment
Indicator
Morphology erosion operation
General mathematical morphology particle

A B S T R A C T

Bearing performance degradation assessment is a key step of condition-based maintenance. In this paper, a novel indicator of bearing performance degradation assessment is presented based on the mathematical morphology (MM) theory for higher efficiency. Because the traditional mathematical morphology particle (MMP) is unable to exactly describe the bearing's performance degradation, we extended its definition to the general space to address the limited ability of the former definition. On the basis of the innovative definition, we used the morphology erosion operation instead of the morphology open operation to calculate the general mathematical morphology particle (GMMP) of the bearing's whole life data. The analysis of the simulation and practical application demonstrated that the proposed index is feasible and effective to indicate the performance degradation of the bearing.

1. Introduction

A rolling bearing is a key mechanical part of a ‘rotor-bearing’ system in rotating machinery because the heavy load bearing is also the unit that usually fails during operation [1–3]. As these failures will result in a high industrial cost or even disaster, considerable attention has been paid to the condition monitoring and fault prediction of a bearing [4,5]. Because of the advantages of improved fitness and validity, the method based on vibration signal analysis is extensively used for a bearing [6–8].

Recently, many research studies have been performed on the performance degradation assessment (PDA) of a bearing, as it is the fundamental part of bearing fault prediction [9–13]. PDA contains two important aspects. One aspect is to extract the appropriate features from the raw vibration signal that can reflect comprehensive performance degradation. The other aspect is to build an effective intelligent model that can be used to assess the machine state [14,15]. Proper features extraction is the key step of PDA, as it affects the precision of final assessment. Many investigations have been successfully applied in the performance degradation assessment of a bearing [11,12,16].

In this paper, we present an innovative signal processing scheme based on MM theory for the performance degradation

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http://dx.doi.org/10.1016/j.ymssp.2016.05.038
0888-3270/

Please cite this article as: H. Li, et al., The application of a general mathematical morphological particle as a novel indicator for the performance degradation assessment of a bearing, Mech. Syst. Signal Process. (2016), http://dx.doi.org/10.1016/j.ymssp.2016.05.038

assessment of bearings. MM theory was initiated by G.Matheron and J.Serra based on set theory and stochastic geometry [17,18]. As a powerful nonlinear methodology for the quantitative analysis of geometrical structures, MM theory has become a popular method in various aspects of signal processing in recent years [2]. Many articles focusing on applying MM theory for detecting machinery faults have been published because it can efficiently extract impulsive signals that are purely based on time-domain analysis with a fast calculation [27–31]. Related research studies on MM theory for mechanical signal processing can be summarized as the following three aspects. The first aspect is concerned with the MM operator: a variety of operators have been proposed and applied to the signal pretreatment, followed by fault feature extraction based on the four fundamental operators (erosion, dilation, open and close) [20–22,28,29,32]. The second aspect is concentrated on the study of MM structure elements(SE):many research studies referring to the shape, scale and construction algorithm of SE have been performed in recent years [20,22,30]. The third aspect is research on algorithms that combine MM theory with other theories: many such algorithms have been proposed and successfully used in mechanical signal processing, such as flexible mathematical morphology [33,34], morphological wavelet [31], and morphological neural algorithms [35,36]. The research studies mentioned above have not only proved the capability and efficiency of the MM theory in mechanical signal processing, but also promoted the development and prosperity of MM theory. However, the previous studies are mainly concerned with the fault diagnosis of mechanical equipment; to the best of our knowledge, papers that use MM theory in the performance degradation assessment of bearing have not been presented.

According to previous studies, we focus on the extraction of the degradation features based on MM theory. The mathematical morphological pattern spectrum (MMPS), which is based on MMP analysis and multi-scale morphological analysis, was reported to be able to distinguish different faults of a bearing [29]. Furthermore, according to our studies, MMPS can recognize different faults(based on the fact that performing a single scale MMP analysis can obtain its MMP),and the MMPS curves of the signal can be obtained by multi-scale MMP analysis, as the MMPS curves of different fault signals have diverse values, which enables the faults to be distinguished. According to further investigation, we found that the MMPS curves have no monotonicity, which results in the fact that performing the same scale MMP analysis on the signals of different degradation degrees may result in MMPs with the same amplitude, even exhibiting a trend of MMPs in contrast to the trend of the performance degradation process; as a result, the traditional MMP is not satisfactory to describe the performance degradation of a bearing. According to the problem, a novel morphological signal processing method named GMMP analysis is proposed and the GMMP is used as an indicator to describe the performance degradation process of bearings. To demonstrate the feasibility and effectiveness of this approach, GMMP is used to analyze the simulation data and practical data.

The remainder of this paper is organized as follows. In Section2, the basic theory of MMP is briefly introduced. Next, the proposed GMMP scheme is described, in detail, and an example is described based on which we contrast GMMP with MMP to highlight their concepts. In section3, by applying the GMMP and MMP analyses to the simulation signal, the good performance of the GMMP is demonstrated.Section4 first introduces the accelerated bearing life test, and then the vibration signals acquired from the experiment and the data from the Centre for Intelligent Maintenance System (IMS), University of Cincinnati are used to evaluate the GMMP technique. Our conclusions are presented in Section 5.

2. Fundamentals

2.1. Mathematical morphological particle analysis and mathematical morphological pattern spectrum

MMP analysis was proposed by Matheron as a tool used to collect image particles and shape characteristics. MMP analysis continues to be frequently used in the field of image analysis due to its simplicity and effectiveness. Currently, MMP analysis is widely used in many areas, such as for image shape and texture descriptions, image segmentation, image restoration and image noise reduction, and so on [37,38].

MMPS, which is based on MMP analysis, is an important method to extract shape information in image analysis, and it also represents the distribution of morphological particles corresponding to the variation scales. For the 1-D signal, MMPS can represent the shape variation of the signal undergoing different scale mathematical morphology operations. The MMPS of signal $f(n)$ can be calculated by using the following formula:

$$PS(f,\lambda,g)=\begin{cases}-\dfrac{dA(f\circ\lambda g)}{d\lambda} & \lambda\ge 0\\ -\dfrac{dA(f\bullet(-\lambda)g)}{d\lambda} & \lambda<0\end{cases} \tag{1}$$

where g is the unit SE, and λ is the scale of the SE.

The MMPS exists in both positive-negative regions: when $\lambda \ge 0$ represents the case of open operation MMPS, which corresponds to the structure information of the signal; $\lambda < 0$ represents the case of close operation MMPS, for which the negative section is the background of the positive section. Because the two parts provide equivalent information, the research studies on MMPS are mainly performed in the positive region. In conclusion, a set of grey values that diminish with the increasing of SE size can be obtained by performing the multi-scale morphological open operation to a signal. The difference of the grey value between adjacent scales is defined as MMP, and the curve of MMP for multi-scale is the MMPS.

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