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Study on rolling bearing on-line reliability analysis based on vibration information processing☆

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ABSTRACT

The failure of rolling bearing is the foremost cause to the failure and breakdown of rotating machines. As the bearing vibration signal is full of periodic and nonlinear characteristics, using common time domain or frequency domain approaches cannot easily make an accurate estimation for the bearing healthy condition. In the paper, an efficient and effective fault diagnostic approach was proposed to accommodate the requirements for both real-time monitoring and accurate estimation of different fault types and their severities. Firstly, a four-dimensional feature extraction algorithm using entropy and Holder coefficient theories was proposed for extracting health status feature vectors from the vibration signals, and secondly a gray relation algorithm was employed for achieving bearing fault pattern recognition intelligently using the extracted feature vectors. The experimental study has illustrated the effectiveness of the proposed approach in comparison with the existing artificial intelligent methods, and can be suitable for on-line health status monitoring.

1. Introduction

Rolling bearings are the main parts in rotational machines, such as gas turbine engines, steam turbine engines, and electrical machines. Failure of these bearings is the foremost cause of the failure and breakdown of rotating machines, which costs enormous property loss [1,2]. To maintain rotating machine operating reliably, it is essential to building an effective bearing health status estimation mechanism. Recently, hybrid information systems with advanced information processing techniques are designed to deal with complex hybrid information [3,4]. Vibration-based bearing diagnostic approaches have been attracting full attention in the near past because of its advantages of extracting health status-related features based on vibration signals [5,6].

Recently, extensive signal processing approaches have been applied in rolling element bearing off-line health status estimation. As the result of the nonlinear factors, such as stiffness, friction, and clearance, vibration signals carry nonlinear and nonstationary performance at different operating conditions. Moreover, vibration signals involve operation information related to both the bearing itself and other rotating components of the machine. To assess the bearing health status, vibration

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information of other components is often considered as background noises [7]. The slight bearing health status information may be submersed under the background noise. Therefore, the common time domain or frequency domain signal processing approaches may not easily obtain an accurate estimation result about the bearing health status, even the advanced signal processing approaches, e.g., Hilbert transform, fractional Fourier transform, and wavelet transform. As the nonlinear dynamics theory [8,9] develops, many nonlinear analysis techniques have been used to recognize the complicated bearing nonlinear dynamic behaviors [10]. The most commonly used method to extract and refine the health status information from the vibration signals is to combine some novel signal processing approaches, such as combining empirical mode decomposition, wavelet package transform, higher order spectra, and Hilbert transform [11]. Empirical judgments by experts are often employed. Recently, the procedure of bearing fault diagnosis is increasingly taken as a process of pattern recognition with the assistance of artificial intelligence (AI) approaches [12], and its reliability and real-time performance are primarily determined by the effectiveness of the fault feature extraction algorithm and pattern recognition algorithm [13]. Nowadays, some entropy-based feature extraction methods (e.g., hierarchical entropy [14], fuzzy entropy [15], sample entropy [16], approximate entropy, and hierarchical fuzzy entropy) were utilized for extracting fault feature vectors based on the bearing vibration signals. In the paper, we exploit a four-dimensional feature extraction algorithm using entropy and Holder coefficient theories, which are fit for processing complicated periodic and nonlinear problem, for extracting fault feature vectors based on vibration signals. When the feature extraction is ready, a pattern recognition method is required to implement the fault diagnosis automatically. Nowadays, different pattern recognition approaches have been employed for mechanical fault diagnosis, and the most common methods are support vector machines [17] and artificial neural networks [18–20]. The training of artificial neural networks requires a lot of fault samples, which are difficult to obtain in practice. The support vector machines are based on statistical learning theory and have better generalization than artificial neural networks under a smaller number of samples [21]. However, the accuracy of support vector machines is essentially determined by choice of their optimum parameters [22], and thus a multi-class concept or an optimization algorithm has been used to improve the effectiveness of support vector machines. In this paper, to balance the accuracy and real-time performance, a gray relation algorithm was used to achieve fault pattern recognition based on the extracted four-dimensional feature vectors.

The rest of the paper is organized as follows. Firstly, the methodology of the proposed approach is introduced in Section 2, and secondly the experimental study of the proposed approach is illustrated in Section 3, and at last, the conclusion is presented in Section 4.

2. Methodology

In this paper, a simple and efficient fault diagnostic approach is proposed to accommodate the requirements of both real-time monitoring and accurate estimation of different fault types and also different severities for rolling element bearing. Firstly, a four-dimensional feature extraction algorithm using entropy and Holder coefficient theories is proposed to extract the dominant characteristic vectors from the bearing vibration signals. Secondly, the gray relation algorithm is used to achieve fault pattern recognition based on the extracted four-dimensional feature vectors.

2.1. Feature extraction

As a measure for information uncertainty, entropy is an important concept in the information theory. Suppose the event set is X, and the probability set for the event set is an n-dimensional probability vector $P=[p_1,p_2,..., p_n]$, and satisfy:

$$0 \le p_i \le 1 \tag{1}$$

and

$$\sum_{i=1}^{n} p_1 = 1 \tag{2}$$

Then the entropy E is defined as follows:

$$E(P) = E(p_1, p_2, .., p_n) = -\sum_{i=1}^{n} p_i \log p_i \tag{3}$$

Therefore, entropy E can be taken as an entropy function for the n-dimensional probability vector $P=(p_1,p_2,..., p_n)$. Shannon entropy theory points out that, if there are many possible outcomes for an event and the probability for each possible outcome is $p_i(i=1, 2, ..., n)$, whose sum is equal to 1, then the information obtained from a possible outcome can be expressed by $I_i=\log_a(1/p_i)$, and the information entropy defined for the time series is as follows:

$$S = -k\sum_{i=1}^{n} p_i \log_e p_i \tag{4}$$

When $k = 1$, S stands for a Shannon entropy E_1 and can be used to depict the uncertainty degree of signals. Based on the definition of Shannon entropy E_1, the definition of Exponential entropy E_2 is also introduced for the feature extraction purpose. Suppose the probability for each possible outcome is p_i, and its information content can be defined as:

$$\Delta I(p_i) = e^{1-p_i} \tag{5}$$

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