Mechanical Systems and Signal Processing 98 (2018) 890–901

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Theoretical investigation of the upper and lower bounds of a generalized dimensionless bearing health indicator

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A R T I C L E I N F O

Article history:
Received 15 December 2016
Received in revised form 20 May 2017
Accepted 30 May 2017

Keywords:
Generalized dimensionless health indicator
Upper and lower bounds
Noncentral chi-square distribution
Squared envelope analysis
Performance degradation assessment

A B S T R A C T

Bearing-supported shafts are widely used in various machines. Due to harsh working environments, bearing performance degrades over time. To prevent unexpected bearing failures and accidents, bearing performance degradation assessment becomes an emerging topic in recent years. Bearing performance degradation assessment aims to evaluate the current health condition of a bearing through a bearing health indicator. In the past years, many signal processing and data mining based methods were proposed to construct bearing health indicators. However, the upper and lower bounds of these bearing health indicators were not theoretically calculated and they strongly depended on historical bearing data including normal and failure data. Besides, most health indicators are dimensional, which connotes that these health indicators are prone to be affected by varying operating conditions, such as varying speeds and loads. In this paper, based on the principle of squared envelope analysis, we focus on theoretical investigation of bearing performance degradation assessment in the case of additive Gaussian noises, including distribution establishment of squared envelope, construction of a generalized dimensionless bearing health indicator, and mathematical calculation of the upper and lower bounds of the generalized dimensionless bearing health indicator. Then, analyses of simulated and real bearing run to failure data are used as two case studies to illustrate how the generalized dimensionless health indicator works and demonstrate its effectiveness in bearing performance degradation assessment. Results show that squared envelope follows a noncentral chi-square distribution and the upper and lower bounds of the generalized dimensionless health indicator can be mathematically established. Moreover, the generalized dimensionless health indicator is sensitive to an incipient bearing defect in the process of bearing performance degradation.

1. Introduction

Bearing-supported shafts are widely used in various machines. Due to harsh working environments, bearing performance degrades over operating time. More specifically, except a sudden bearing failure, bearing performance should gradually degrade from a normal condition to a failure condition. Thus, bearing fault diagnosis and prognostics [1–3] become an emerging topic in recent years and they can be used to prevent unexpected bearing failures and accidents. Bearing performance degradation assessment aims to find a bearing health indicator so as to evaluate the current health condition of a

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http://dx.doi.org/10.1016/j.ymssp.2017.05.040
0888-3270/

bearing. In contrast, bearing prognostics aims to predict bearing remaining useful life in near future, which is to infer the period from the current operating time to the time when a bearing fails. From such comparison, it is undoubted that bearing performance degradation assessment is the basis of bearing prognostics because bearing prognostics needs observations of bearing health indicators to build a statistical model [4,5]. Some fundamentals relevant to bearing fault diagnosis and prognostics should be introduced before our literature review is conducted on bearing performance degradation assessment. When a bearing suffers a defect on the surface of either an outer race or inner race, a roller striking the defect causes a transient which will repetitively occur because of periodic rotation of a shaft. In view of this point, a bearing defect frequency that is used to approximately measure how often a transient is repeated strongly depends on the rotating speed of the shaft and the geometry of the bearing. Besides repetitive transients, a resonance phenomenon happens and causes energy of these repetitive transients to be mainly located at one of the resonant frequency bands. Consequently, to extract bearing fault signatures from a high-frequency band, envelope analysis is required to be performed [6]. The envelope analysis basically contains two aspects including band-pass filtering and envelope extraction. The purpose of the band-pass filtering is to retain one of the resonant frequency bands and remove the influence of other strong low-frequency vibration components and heavy noises. The purpose of envelope extraction is to transfer energy of bearing fault signatures at the high-frequency band to a low-frequency band and demodulate the signal obtained by the band-pass filtering. The combination of the band-pass filtering and the envelope extraction is beneficial to identification of the bearing defect frequency and its harmonics.

Based on the principle of the envelope analysis for bearing fault feature extraction, in the past years, many signal processing and data mining based methods were proposed to construct bearing health indicators so as to assess bearing performance degradation. As a pioneered research work, Qiu et al. [7,8] used Morlet wavelet transform to denoise bearing vibration signals and employed self-organizing map for abnormal bearing health detection to evaluate the current health condition of a bearing. Ocak et al. [9] considered wavelet packet node energies calculated from normal bearing data as an input to a hidden Markov model and then they evaluated any deviation from the trained hidden Markov model to track bearing performance degradation. Pan et al. used wavelet packet transform to extract wavelet packet node energies and they respectively used support vector data description [10] and fuzzy c-means [11] to construct bearing health indicators for bearing performance degradation assessment. Yu [12] used locality preserving projections to extract new features from some common fault features and then constructed a bearing health indicator based on Gaussian mixture models. Miao et al. [13] used a wavelet to design a comblet filter to enhance weak fan bearing vibration signals and calculated the energy of the frequency spectrum of the denoised signals as a health indicator to evaluate the fan bearing degradation. Dong and Chen [14] constructed a bearing health indicator based on the integration of cyclic power spectrum. To speed up the extensive calculation time of the cyclic power spectrum, Wang and Shen [15] developed an equivalent cyclic health indicator that was constructed from squared envelope spectrum analysis because integration of the cyclic power spectrum at one of the resonant frequency bands was mathematically equal to the squared envelope spectrum obtained from the squared envelope analysis with band-pass filtering. Besides the above health indicators designed for the bearing performance degradation assessment, Antoni and Randall [16,17] mathematically proposed a spectral kurtosis indicator to characterize bearing fault signals. The main idea of the spectral kurtosis indicator is to check an abnormally high kurtosis value at some specific frequency bands so as to indicate the presence of a bearing fault. According to the analytical expression of the spectral kurtosis indicator, some mathematical properties of the spectral kurtosis indicator were revealed [16]. Firstly, the spectral kurtosis indicator decreases with the repetition rate of impulses generated by a bearing defect. Secondly, the spectral kurtosis indicator increases with a sampling rate. Thirdly, the spectral kurtosis indicator increases with the intensity of fluctuations of impulses. Additionally, a statistical threshold was designed by Antoni and Randall [16] to indicate occurrence of a transient signal. Borghesani et al. [18] mathematically found the link between kurtosis, squared envelope and squared envelope spectrum, and their result showed that the kurtosis is the sum of amplitudes of the squared envelope spectrum at a whole cyclic band. Then, they proposed a bearing health indicator based on the sum of amplitudes of a narrow cyclic band instead of the whole cyclic band so that the bearing health indicator is more sensitive to an early bearing defect in the process of bearing degradation. Based on the work of Borghesani et al. [18] and the early work of Antoni [16], Antoni [19] used entropy instead of kurtosis to develop infogram for detection of repetitive transients, such as bearing fault signals. The result showed that the entropy is better than the kurtosis to detect the repetitive transients in the cases of impulsive noise and low relaxation time of the transients compared with their rate of repetition.

Even though the aforementioned research works were able to successfully assess bearing performance degradation, some limitations are still left in these works. Firstly, except the kurtosis, most bearing health indicators are dimensional, which connotes that these health indicators are prone to be affected by varying operating conditions, such as varying speeds and loads. Secondly, the upper and lower bounds of most health indicators are not theoretically established, which connotes that the upper and lower bounds of these health indicators are uncertain and highly depend on historical bearing degradation data including normal and failure data. In other words, bearing performance degradation assessment is not really realized and only deviations from a normal health condition are achieved. To solve these problems, in this paper, we focus on theoretical investigation of the upper and lower bounds of a generalized dimensionless bearing health indicator (GDBHI) and its application to bearing performance degradation assessment. The main contributions of this paper are summarized as follows. Firstly, squared envelope distribution of transients caused by a bearing defect is mathematically derived in the case of additive Gaussian noises. Here, the squared envelope analysis is considered instead of the envelope analysis. This is because a bearing fault signal consisting of the transients is cyclostationary rather than periodic and the squared envelope analysis has been mathematically proven to be equivalent to the cyclostationary analysis [20,21]. Consequently, the squared envel-