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Quantitative fault analysis of roller bearings based on a novel matching pursuit method with a new step-impulse dictionary

Lingli Cui [a,*], Na Wu [a], Chunqing Ma [a], Huaqing Wang [b]

[a] *Key Laboratory of Advanced Manufacturing Technology, Beijing University of Technology, Chao Yang District, Beijing 100124, China*
[b] *School of Mechanical, Electrical Engineering, Beijing University of Chemical Technology, Chao Yang District, Beijing 100029, China*

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ABSTRACT

A novel matching pursuit method based on a new step-impulse dictionary to measure the size of a bearing's spall-like fault is presented in this study. Based on the seemingly double-impact theory and the rolling bearing fault mechanism, a theoretical model for the bearing fault with different spall-like fault sizes is developed and analyzed, and the seemingly double-impact characteristic of the bearing faults is explained. The first action that causes a bearing fault is due to the entry of the roller element into the spall-like fault which can be described as a step-like response. The second action is the exit of the roller element from the spall-like fault, which can be described as an impulse-like response. Based on the quantitative relationship between the time interval of the seemingly double-impact actions and the fault size, a novel matching pursuit method is proposed based on a new step-impulse dictionary. In addition, the quantitative matching pursuit algorithm is proposed for bearing fault diagnosis based on the new dictionary model. Finally, an atomic selection mechanism is proposed to improve the measurement accuracy of bearing fault size. The simulation results of this study indicate that the new matching pursuit method based on the new step-impulse dictionary can be reliably used to measure the sizes of bearing spall-like faults. The applications of this method to the fault signals of bearing outer-races measured at different speeds have shown that the proposed method can effectively measure a bearing's spall-like fault size.

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1. Introduction

Roller bearings are important parts in rotating mechanical applications in industry, and bearing failure may cause catastrophic failures and costly downtime. Therefore, the condition monitoring and fault diagnosis of bearing are particularly crucial. To date, most existing researches focus on the qualitative analysis of bearing health condition and pattern recognition of fault type. But a bearing fault signal contains information not only about fault condition and fault type but also the severity of the fault. That means fault severity quantitative analysis is one of most active and valid way to realize proper maintenance decision.

In recent years, some researchers studied the quantitative diagnosis of mechanical faults. The most common method is based on energy value to assess the fault severity. A method was proposed to monitor the evolution of faults in gear systems

* Corresponding author.
E-mail addresses: acuilingli@163.com (L. Cui), adinala@emails.bjut.edu.cn (N. Wu).

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by calculating the energy density based on the continuous wavelet transform and EMD method, respectively [1,2]. Based on the theories of second-order cyclostationarity, cyclic energy indicator (CEI) is proposed for damage extent identification of roller element bearings [3]. A new automatic analysis method was introduced using a multivariate statistical fault classification and fuzzy logic to detect the cyclic bearing faults [4]. In addition, the evaluation index was introduced into the fault severity assessment by some scholars. Degradation index was introduced into the proportional hazards model, and the reliability size and changing trend of the equipment were realized [5]. The RMS, kurtosis index and peak index were investigated to the relationship with the size of bearing damage, and achieved a certain result [6]. A new version of the Lempel–Ziv complexity was proposed as a bearing fault severity measure based on the continuous wavelet transform. The result indicated that the Lempel–Ziv complexity is proportional (for outer-race fault) or inversely proportional (for inner-race fault) to fault size(severity) for all rotational speeds [7]. Dou and Zhao combined the Lempel–Ziv complexity with EMD method to the recognition of the roller bearing injury [8].

Most quantitative analysis methods reviewed above are measurement of fault severity trend based on energy value and evaluation indices of signals. There is no reliable fault size for diagnosis decisions and no quantitative relationship between fault severity and assess method.

Dowling [9] illustrated the change of the phase reversal of the movement of the ball, and note that there is a further peak after the phase change. This is a form of the seemingly double impact, and it might be a potential idea for the fault severity quantitative analysis. Epps and McCalion [10] made a detail statement of the phenomenon. The two points were named by them as the Point of Entry and Point of Impact. Sawalhi and Randall [11] presented an algorithm for enhancing the surveillance capability of SK by using the minimum entropy deconvolution (MED) technique. The results show that the use of the MED technique dramatically sharpens the pulses originating from the impacts of the roller elements with the spall and increases the kurtosis values to a level that reflects the severity of the fault. Moreover, it shows that each of the impulses originating from the impacts is made up of two parts, entry into and exit from the spall. They also proved that the entry into the fault can be described as a step-like response, with mainly low frequency content, while the impact excites a much broader frequency impulse-like response. Two methods were proposed to get a reasonable approximation of the measured fault widths under different speed conditions, and the method of separate treatment is somewhat better and is thus recommended [12]. The approximate entropy method and empirical mode decomposition (EMD) were applied to separate the entry–exit events, and estimated the size of the spall-like fault [13]. EMD [14] is a kind of signal time frequency analysis method. In recent years, many time frequency methods like Wigner-Ville [15], Wavelet packet transform [16], Hilbert-Huang [17] are also developed well in signal decomposition area. However, the fixed basis functions of each method limit a lot. Sparse Approximation [18] solved this problem and opened up the new idea of signal decomposition. Matching Pursuit (MP) [19] is a classic sparse approximation method. In this method, a series of atomic set called dictionary replace the traditional fixed basis function, these atoms could be constructed more flexible according to different requirement. The selected atoms will reconstructed the signal to obtain a more suitable analysis one.

Therefore, on the basis of seemingly double impact theory and roller bearing fault mechanism, a new seemingly double impact roller bearing fault mathematical theory model was proposed to establish a quantitative relationship between the spall fault size and the time interval of seemingly double impact actions in Section 2. Section 3 discusses the detail method to construct the new step-impulse dictionary with bearing fault size information based on the new fault feature model. Then the quantitative matching pursuit algorithm for bearing diagnosis was proposed based on the step-impulse dictionary. Section 4 mainly discusses the researches on simulation signals and experimental signals, and the results verified that the new bearing model and the matching pursuit algorithm based on step-impulse dictionary can be applied to the quantitative diagnosis of bearing spall-like fault.

2. Theoretical model for a single fault roller bearing with different spall fault sizes

The vibration signals measured from faulty bearings are periodical impulse series, and the modulation effect is caused by resonance and a non-uniform load distribution with considerable background noise. In traditional analysis of a bearing fault mechanism at a constant rotational speed, the impulses generated by a single-point fault are generally considered to be a single ideal unit impulse function (i.e., the period of the single-impact action approaches zero). However, this type of ideal unit impulse is only suitable for a roller bearing with an extremely small local defect. When the fault severity increases to a certain degree, the impulse generated from the fault is unlikely to be an ideal unit impulse; but is likely to be characterized by a double impact.

When there is a fault with a certain size on the bearing's outer-race, the roller element will first enter the fault and then exit from the fault, as shown in Fig. 1. Thus, there are two impact actions when the roller element passes the spall and thus two responses. Cui and Wang describe this phenomenon as a double impact; the impacts caused by entering into and exiting from a fault are both considered to be impulse responses [20]. However, the rationality of this seemingly double-impact response theory has not been verified, and this phenomenon was not related to the bearing fault severity or to the quantitative analysis of a faulty bearing. Sawalhi and Randall [12] confirmed that the two impacts are generated due to the entry into and exit from the spall: the first impact resembles a step-like response, and the second resembles an impulse-like response and is the more prominent event. Two distinct response patterns are shown in the experimental data from a turbo-machine-blade test rig at the Vibration and Acoustics Lab of University of New South Wales (UNSW). Based on that data, a new roller bearing fault feature model for different spall fault sizes was proposed that replaced a traditional single

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