Journal of Sound and Vibration 364 (2016) 67–76

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Vibration response mechanism of faulty outer race rolling element bearings for quantitative analysis

Lingli Cui [a], Yu Zhang [a], Feibin Zhang [b,*], Jianyu Zhang [a], Seungchul Lee [c]

[a] *Beijing Engineering Research Center of Precision Measurement Technology and Instruments ,Beijing University of Technology, Chao Yang District Beijing 100124, China*
[b] *Engineering College of Jiangxi Agricultural University, Jiangxi, China*
[c] *Department of Human and Systems Engineering, Ulsan National Institute of Science and Technology, 50 UNIST-gil, Ulsan 44919, Republic of Korea*

ARTICLE INFO

Article history:
Received 14 November 2014
Received in revised form
26 September 2015
Accepted 17 October 2015
Handling Editor: I. Trendafilova
Available online 8 December 2015

Keywords:
Rolling element
bearings
vibration response
quantitative analysis
fault diagnosis

ABSTRACT

For the quantitative fault diagnosis of rolling element bearings, a nonlinear vibration model for fault severity assessment of rolling element bearings is established in this study. The outer race defect size parameter is introduced into the dynamic model, and vibration response signals of rolling element bearings under different fault sizes are simulated. The signals are analyzed quantitatively to observe the relationship between vibration responses and fault sizes. The impact points when the ball rolls onto and away from the defect are identified from the vibration response signals. Next, the impact characteristic that reflects the fault severity in rolling element bearings is obtained from the time interval between two impact points. When the width of the bearing fault is small, the signals are presented as clear single impact. The signals gradually become double impacts with increasing size of defects. The vibration signals of a rolling element bearings test rig are measured for different outer race fault sizes. The experimental results agree well with the results from simulations. These results are useful for understanding the vibration response mechanism of rolling element bearings under various degrees of fault severity.

1. Introduction

As a type of widely used universal component in the mechanical equipment, rolling element bearings directly affect the dynamic performance, running accuracy, reliability and service life of the whole equipment. Hence, it is necessary to diagnose and detect the faults in rolling bearings, to prevent early failure. The fault development of rolling element bearings is usually a dynamic process and the fault degree gradually increases from a low level. The early damage detection is in demand not only for high precision machines but also for general engineering equipment because minor faults often can lead to large faults or catastrophic results. However, the rolling element bearings should be replaced when the fault reaches a certain degree. Therefore, the service life of mechanical equipment can be extended and production costs can be lowered through the quantitative diagnosis of fault degree in rolling element bearings.

* Corresponding author at: Engineering College of Jiangxi Agricultural University, 330045, China; Beijing Engineering Research Center of Precision Technology and Instruments, Beijing University of Technology, Beijing,100124, China.
E-mail addresses: acuilingli@163.com (L. Cui), yuzh_2014@163.com (Y. Zhang), zhfb_2014@163.com (F. Zhang), zhjy_1999@bjut.edu.cn (J. Zhang), seunglee@unist.ac.kr (S. Lee).

http://dx.doi.org/10.1016/j.jsv.2015.10.015
0022-460X/

With the development and improvement of the fault diagnosis technology for rolling element bearings, research on the fault diagnosis of rolling bearings has attracted considerable attention, and various new methods are being proposed [1]. Sopanen [2,3] found that the diameter clearance has a significant effect on the level of vibration as well as on the natural frequencies using a dynamic model of a deep-groove ball bearing. Sassi [4] developed a new application called bearing toolbox to simulate the vibratory response of bearings to the excitations produced by localized defects. Zimroz [5] developed a technique based on adaptive schur filter for bearing local damage detection. The method is well-suited to analyze the non-stationary signals and it is potentially to use in bearing and gearbox monitoring. Zimroz et al. [6] also proposed a novel method of time–frequency map enhancement and further processing for feature extraction in local damage detection. It can clearly detect the local damage. But detection of cyclic impulses related to damage is not possible for that original raw vibration signal contains strong non-informative contribution. Tadina [7] improved a comprehensive model of a ball bearing to obtain the vibration response due to different sizes of localized defects. Petersen [8] developed a method for calculating and analyzing the quasi-static load distribution and varying stiffness of a radially loaded double row bearing with a raceway defect of varying depth, length, and surface roughness. Moazen [9] proposed a bearing model that takes the finite rolling element size into consideration. While, some progress in the quantitative faults diagnose of bearing has been achieved by the researchers in China and other countries. Antoni et al. [10] proposed a method of modulation intensity distribution that can help to estimate the size of bearing fault, while it requires a relative long times in the diagnose process. Dowling [11] revealed a phenomenon similar to double impacts in fault signals of rolling bearings owing to phase changes. In the following year, Epps [12] discussed the phenomenon in more detail. They noted that the double impacts occurred when the ball rolled in and out of the fault. The first impact is considered the step response of low-frequency components, and the second one is the impact response of high-frequency components. Sawalhi [13] used the method of minimum entropy deconvolution (MED) and spectrum kurtosis (SK) to analyze the experimental signals of bearing faults with considerable noise. The results showed that the double impact phenomenon can be clearly attributed to fault signals of the outer ring of the bearing after denoising treatment. Randall [14] used the minimum entropy deconvolution method to separate the impulses from entry into, and exit process from an individual fault, which give information on the fault size. Then they find that the entry procedure of the damage zone is step signal but the exit is impulse. Baydar and Ball [15] examined whether acoustic signals could be used effectively to detect the various local faults in gearboxes using the smoothed pseudo-Wigner Ville distribution with three types of progressing local faults. Result indicated that acoustic signals are very effective for the early detection of faults. Recently, Jiang [16] used signal complexity and morphological filtering method to analyze the fault signals of rolling bearing quantitatively. Shen [17] adopted a diagnostic method based on Support Vector Regression (SVR) to diagnose bearing faults quantitatively. A bearing fault severity measurement method based on the Lempel–Ziv complexity and the continuous wavelet transform was proposed by Hong. The result indicated that the Lempel–Ziv complexity was proportional (for outer race faults) or inversely proportional (for inner race faults) to fault size (severity) for all rotational speeds [18]. Several time–frequency analysis methods are compared and analyzed in the quantitative diagnosis of outer race fault based on the Lempel–Ziv complexity [19]. Zhao [20] combined the approximate entropy theory with the Empirical Mode Decomposition (EMD) algorithm. The method to distinguish between the step components and impact components was realized through empirical mode recombination of the components. The existence of double impact phenomenon was further verified, and it was feasible to realize quantitative diagnosis through separation methods. Kong [21] extracted the double impacts from bearing faults by using Ensemble Empirical Mode Decomposition (EEMD) and complex morlet wavelet method. Wang [22] proposed a new adaptive dictionary based on matching pursuit algorithms to construct the atoms with double impact components. Good results were obtained in the fault diagnosis using experimental and engineering signals, with research on algorithms constituting the majority of these.

However, faults in rolling bearings still need to be quantitatively analyzed from the aspect of bearing defective mechanism. Randall et al created a dynamic model of a gearbox that compared to lumped parameter models and reduced finite element method. And the dynamic model was used to simulate the vibration signals in the presence of local inner and outer race faults. While this paper just highlights the plausibility of fault simulation in machine condition monitoring [23]. Patil developed a mathematical model for the ball bearing vibrations due to defect on the bearing race. With this model the effect of the defect size and its position have been simulated and also the spectral components have been predicted. But the prediction of the actual amplitudes of vibration is not possible by the model [24]. Ahmadi established a double-row spherical roller bearing model and applied it to the quantitative performance analysis of bearings and investigated and explained the path of a rolling element in the defect zone and the nature of the entry and exit events of the two main features that appear in the vibration signal of a defective bearing [9,25]. Singh analyzed the contact force of the rolling element entry and exit of the defect with the explicit finite element method. The finite element model presented in the paper can be used to investigate the vibration characteristics of bearings with more complex defect geometries [26]. To diagnosis the bearing fault quantitatively, not only the dynamic model should be developed but also the experiment signal have to be analyzed.

In this paper, we analyzed the bearing fault of outer race quantitatively from the aspect of vibration mechanism. First, we establish the vibration model of outer race faults in rolling element bearings, and next, the vibration response of rolling element bearings under different fault severity is quantitatively analyzed in this paper. The scale of outer race faults is changed to simulate the vibration response for different defect sizes. The impact characteristics when the ball rolls in and out of the defect with different fault sizes are analyzed. Furthermore, the time interval between the two impacts is extracted from the simulation signals. Next, the results are compared with the theoretical calculated values to verify the correctness of