Mechanism and Machine Theory 117 (2017) 148–159

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Research paper

Analysis of non-uniform abrasion evolution for cylindrical roller bearings

Xiuxing Yin[a], Haigang Gu[b,*], Guang Feng[c]

[a] Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061, USA
[b] The State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou,310027, PR China
[c] Hangzhou Advance Gearbox Group Co. Ltd., China

A R T I C L E I N F O

Article history:
Received 23 February 2017
Revised 16 June 2017
Accepted 20 June 2017

Keywords:
Cylindrical roller bearing
Elasto-hydrodynamic lubrication
Lubricant film
Non-uniform loading
Contact deformation
Abrasion evolution

A B S T R A C T

In this paper, the effects of non-uniform loading on the performances and abrasion evolution of cylindrical roller bearings are explored and analyzed both theoretically and experimentally. The elasto-hydrodynamic lubrication phase of roller bearings is modeled and the lubricant film thickness is calculated. A comprehensive calculation method is subsequently proposed to analyze non-uniform contact loading distribution due to the combined radial and moment loads. Furthermore, increased metallic contact due to the breakdown of the lubricant film during the abrasive wear phase is investigated, and the contact deformation and stress distributions are analyzed accordingly. A test rig is designed and built to experimentally investigate these influences under different loading conditions. The experimental results demonstrate that the wear and deformations of the bearing raceway surfaces can be significantly promoted by the non-uniform loading due to the sliding motions between asperities of the bearing contact surfaces. Polishing wear of the bearing surfaces, such as surface induced cracks and material delamination, is expected when the bearing is further exposed to long-term non-uniform loading. Numerical simulation results are also obtained and analyzed to investigate the effects of material flexibility on the bearing responses, which show that the material flexibility can reduce bearing responses.

1. Introduction

Cylindrical roller bearings are extensively employed in industry to support rotating shafts, radial loads, sun and planet gears in mechanical applications such as rotating machinery and planetary gearboxes. These bearings commonly operate under rough and complicated loading conditions, which cause wear, abrasion, surface damage, or even premature faults, leading to significant long-term downtimes and economic losses [1]. Thus, it is of primordial importance to analyze and identify the evolution of the bearing damage behavior so as to secure safe operations and maintain high reliability and efficiency of these bearing systems.

Many recent investigations are mainly focused on bearing faults analysis, whereas relatively few literature concerns the process of abrasion initiation and propagation between the bearing contact surfaces or the internal dynamical behavior of these bearings. A methodology was proposed in [2] for the dynamic analysis of rigid-flexible multibody systems with elasto-hydro-dynamic lubricated cylindrical joints by taking into bearing misalignment. The bearing lubrication was analyzed by

* Corresponding author.
E-mail address: haiganggu@126.com (H. Gu).

http://dx.doi.org/10.1016/j.mechmachtheory.2017.06.015
0094-114X/

using the natural coordinate formulation with the lubricant pressure determined through the resolution of the Reynolds' equation. The main outcomes were numerically validated by using commercial software. The elasto-hydro lubrication condition for the cylindrical joints supporting a geared system was analyzed in [3] based on a finite-short bearing approach. The lubrication forces developed at the cylindrical joints were obtained by solving the Reynolds' equation via the finite difference method. The analysis results were validated by using two numerical examples of application. An approach was proposed in [4] to diagnose bearing faults by integrating the least squares support vector machines and empirical mode decomposition. The incipient failures in large slewing bearings were detected in [5] by using the multivariate and multiscale statistical process monitoring method. The discrete time wavelet coefficients were used in [6] to identify the faults in rotor/magnetic bearings. The influences of rolling-element bearing faults on induction motor were investigated in [7] and a fault detecting method was developed by detecting stator current variations. The authors in [8] have developed their bearing fault detection methods based on frequency domain discrete wavelet transform. The rotor speed signals were applied in [9] to detect the ball bearing faults during variable rotor speed conditions. A methodology was proposed in [10] to detect faults of low-speed rolling element bearings by using an acoustic emission signal. The frequency characteristics of different bearing components were used in [11] for fault diagnosis of planet bearings. Although the above-mentioned bearing fault diagnosis methods maybe reasonably applied to detect bearing failures with potential simplicity or reliability, they did not reveal the intrinsic reasons behind these bearing failures and did not provide the in-depth and solid basis for these methods. Further, the employed fault diagnosis methods, such as the support vector machines and neural networks, are always time-consuming and cannot be implemented in real time.

Other studies focused on quasi-static or dynamical analyses of bearings under loading conditions. The influence of the load directions on the characteristics of a five pad tilting-pad journal bearing was investigated in [12] by using a different preload factor for each pad. The fretting damage of liner-bearing interaction was modeled in [13] by using combining finite element discrete element method and cut boundary displacement method. The ultimate hydrodynamic load carrying capacity of water-lubricated plain journal bearings was analyzed in [14] under misalignment effects. The effect of non-uniform preload on the static and rotational performances of the spindle system was investigated in [15] under external radial loading conditions. A modeling approach was presented in [16] for predicting the internal dynamic behavior of ball bearings under merely high moment loads.

Most of the above-listed literature simply considers axial or radial loading conditions and generally assumes the even loading distributions on the inner race of bearings. However, roller bearings are actually subject to non-uniformly distributed loads caused by rough operating conditions, manufacturing or assembly errors. Such loads not only can deteriorate the contact status in roller bearings, but also can lead to the relative tilting of the bearing and cause the deflections of bearing elements.

In this paper, a comprehensive calculation method is developed to evaluate the behaviors and abrasion evolution for cylindrical roller bearings under external non-uniformly distributed loads such as the combination of radial load and moment, which seems largely ignored in the literature. The effects of external non-uniform loads on the bearing are modeled in three phases: elasto-hydrodynamic lubrication phase, non-uniform loading phase, and abrasive wear phase. In the elasto-hydrodynamic lubrication phase, the lubricant film between the rolling elements and raceways is analysed and the minimum lubricant film thickness is calculated. In the non-uniform loading phase, the non-uniform contact loading distribution due to the combined radial and moment loads is reasonably calculated in four different cases. In the abrasive wear phase, increased metallic contact and wear of the raceway surfaces due to the rupture of the lubricant film under non-uniform loading are investigated. Experiments have also been conducted to identify the bearing behaviors and evaluate the proposed abrasion evolution phases by exerting the non-uniformly distributed loading on bearings in a test rig. Numerical simulations are conducted to investigate the influences of material flexibility on the bearing responses by using the commercial software ANSYS.

2. Elasto-hydrodynamic lubrication phase

As illustrated in Fig. 1, this cylindrical roller bearing typically consists of an outer race, cylindrical rolling elements, cage and an inner race. The outer race is rigidly connected to housings, whereas the inner race is fixed onto the rotating spindle with cylindrical interference connection between them. The rolling elements run in the tracks between the races and are commonly guided by the cage that guarantees the uniform spacing of the elements.

Initially, under normal operating conditions, the contact interface between the races and the rolling elements are fully lubricated and this forms the elasto-hydrodynamic contact between the races and rolling elements. The rolling elements are submersed in lubricant oil and are subjected to evenly distributed external radial loads that cause the deformations of rolling elements and the lubricant film.

This elasto-hydrodynamic contact can be basically described by the Dowson lubrication theory [17] or the well-known Navier–Stokes and Reynolds equations [18]. Taking the contact surface between the inner race and the rolling element in Fig. 2 as an example, there exists structural deformation of the rolling elements due to the hydrodynamic pressure from the lubricant film. This pressure increases gradually from the inlet, but decreases significantly around the outlet due to the hydrodynamic effects. A pressure peak always occurs around the outlet and then the pressure decreases to zero.

The thickness of the fluid lubricant is generally constant along most of the contact surfaces and there exists a necking effect around the outlet where the minimum-thickness film occurs.