Mechanism and Machine Theory 110 (2017) 73–84

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

A touchdown bearing with surface waviness: Friction loss analysis

Oskari Halminen[a,*], Javier F. Aceituno[b], José L. Escalona[b], Jussi Sopanen[a], Aki Mikkola[a]

[a] Department of Mechanical Engineering, Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland
[b] Department of Mechanical and Manufacturing Engineering, University of Seville, Camino de los Descubrimientos s/n, 41092 Seville, Spain

ARTICLE INFO

Keywords:
Multibody simulation
Touchdown bearing
Waviness
Friction losses

ABSTRACT

This paper presents a model for analysis of the chaotic turbulence in a touchdown bearing due to surface waviness. A multibody model of a bearing with surface waviness is presented. The model estimates the work done by the friction forces between the bearing components. Different waviness orders in the bearing inner and outer ring are examined by analyzing the friction losses in the touchdown bearing. The obtained results are compared with results reported in the literature. The proposed model supports selection of appropriate surface manufacturing accuracy for touchdown bearings to mitigate undesirable effects from surface waviness in a potential contact event.

1. Introduction

In certain applications, such as pumps and fans, high rotational speed is often favored, because it brings a number of advantages, for instance, smaller footprint. High-speed systems frequently use active magnetic bearings (AMBs) to achieve further benefits, for example, greater rotational speed with less vibration. However, since unexpected failures like a sudden shutdown of the AMBs or overloading of the AMB system can occur, touchdown bearings are typically used as a mechanical backup system to ensure a safe coast-down [1]. Standard API 617 states that a touchdown bearing should be able to withstand two contact events due to shutdown of the AMBs and ten contact events due to overload of magnetic forces during its operational life [2].

Ball bearings are often used for touchdown bearings, and cageless bearings are preferred to prevent possible cage breakdown. In a typical touchdown event, the first contact between the rotor and inner ring of the bearing is the most harmful since the tangential velocity difference is as high as the rotor surface velocity and the impulsive force in the first contact can be 20 times the weight of the rotor. In a successful dropdown, the rotor movement stabilizes after a few initial bouncing contacts. In the steady operation phase following dropdown, the bearing load is approximately the weight of the rotor and the contact between the rotor and inner ring is mostly a rolling contact with slight slipping.

The studied system comprises the rotor and a lubricated touchdown bearing with balls and rigid rings. Contacts between the rotor and bearing components are modelled using Hertz contact theory and friction between the components is described using Stribeck's model [3].

Several different models of ball bearings have been proposed in the literature. An analytical model of a ball bearing is presented in the paper by Hamrock [4], which was applied for touchdown bearing use in Schmied and Pradetto [5] and Fumagalli [6]. In Cole et al. [7], a model is proposed that includes two degrees of freedom for each ball.

* Corresponding author.
E-mail addresses: oskari.halminen@lut.fi (O. Halminen), aceituno@us.es (J.F. Aceituno), escalona@us.es (J.L. Escalona), jussi.sopanen@lut.fi (J. Sopanen), aki.mikkola@lut.fi (A. Mikkola).

http://dx.doi.org/10.1016/j.mechmachtheory.2017.01.002
Received 3 October 2016; Received in revised form 2 January 2017; Accepted 6 January 2017
0094-114X/

An advanced model of a ball bearing modelled with a discrete element method (DEM) approach was proposed in a paper by Machado et al. [8]. In their model, contact forces are calculated using an analogy to spring dampers, and model estimations of electrical resistance in the contact are based on electromechanics and Hertz surfaces. Their model was verified against measurements.

Detailed multibody models were proposed by Bovet et al. [9] for regular ball bearings for helicopter use, and for touchdown bearings in Halminen et al. [10]. In these multibody models, friction forces are calculated based on instantaneous velocity differences between the bodies, whereas in earlier models, friction was modelled using idealizations in the kinematic system.

In real systems, surface waviness always exists in the bearing races due to manufacturing tolerances and material properties. In addition, surface waviness outside tolerances is often found, for example, due to wear on the surfaces, and in the case of touchdown bearings, as a result of previous contact events.

Fundamental research of surface waviness in ball bearings has been published in the literature. Aktürk [11] noted the relation between vibration frequencies, number of harmonic waves and rotational speed. In their model, Sopanen and Mikkola [12,13] applied defects and waviness in the surfaces of the inner race and outer race. Bai and Xu [14] and Yuan et al. [15] adopted a multibody based approach but used only a simplified model for ball modelling. Xu and Li [16] included waviness in a multibody model of a simple ball bearing-related mechanism. They concluded that the dynamical response of the system depends on the number of balls in the bearing. Waviness in touchdown bearings is also considered in Halminen et al. [17], where it was noticed that waviness changes the frequency of the rotor's pendulum movement.

Touchdown phenomena generate heat, and it is therefore important to predict frictional heat losses in the bearing. In bearing studies, losses due to friction forces are a critical aspect of design, as a significant part of the operational life of a bearing depends on the amount of friction generated. Operational conditions that are relatively unpredictable occur in touchdown bearings during a contact event, caused by the high velocities involved and the effects of the clearance between the rotor and touchdown bearing. Even more destructive for the system is a possible whirling motion of the rotor that can occur as a result of rotor dropdown. Analysis of losses due to friction forces is therefore an important aspect of analysis of the wear of touchdown bearing components.

Loss models of ball bearings have been developed both for conventional and touchdown usage. Losses from friction were compared in papers examining double-decker bearings for conventional use in Prashad [18], and for touchdown bearing use in Zhu et al. [19] and Jin et al. [20]. The work by Prashad [18] concluded that losses can be decreased by using a double-decker bearing. In the paper by Zhu et al. [19], it was found that the heat energy generated after the initial shock of the dropdown remains almost unchanged, whereas Jin et al. [20] found that the heat energy keeps growing in a similar way as during the touchdown event. The differences between the findings presented in the three papers can be explained by differences in the systems studied, and differences in the friction and loading.

In the papers by Sun [21], Keogh and Yong [22] and Zhao et al. [23], simplified models of bearings were used to study thermal growth in a contact event between the rotor and touchdown bearings.

Bovet et al. [9], using an advanced multibody model, studied energy losses between the balls and inner race, and between the balls and outer race. In their study, losses in contact between the inner race and balls were found to be larger than losses between the balls and outer race; the lower losses were the result of the inertial forces that cause the balls to adhere to the outer race.

The objective and scientific contribution of this work focuses on losses in a model of a touchdown bearing. The paper investigates touchdown bearing losses within a multibody model framework that includes bearing waviness. The extent of disorder that surface waviness may create in a touchdown bearing can be evaluated by comparison of the work caused by friction forces for different amplitudes and combinations of surface waviness. In this study, the effect of waviness is studied by examining energy losses in the contact between the inner race and balls and in the contact between the outer race and balls. The model results are compared to results in the literature. Using the model, specifications for exterior tolerances can be designed such that surface waviness does not produce substantial heat generation in the bearing during a touchdown event.

2. Modelling of the system

In the multibody simulation model, the independent bodies included in the model are the rotor, the inner ring, the balls, and the outer ring. The housing of the bearing is attached rigidly to the outer ring and, by springs and dampers, to the ground. The generalized coordinates used for the two-dimensional body i are given by vector $\mathbf{q}_i$ as:

$$\mathbf{q}_i = [R_{X,i} \quad R_{Y,i} \quad \theta_i]^T, \tag{1}$$

where $R_{X,i}$ and $R_{Y,i}$ are the Cartesian components of the center of the body i, and θ_i is the orientation coordinate of the body i. Only one constraint is used in the model of the bearing. This constraint is used to prevent rotation of the outer ring. The ideal cageless touchdown bearing, where no surface waviness is applied, is modelled using a multibody approach as proposed in [10].

2.1. Coordinates, constraints and forces assumed in the model

The bodies modeled in the bearing system are the rotor, inner ring, outer ring and 17 balls. Accordingly, the number of coordinates in the system is 60. As the only constraint is imposed on the rotation of the outer ring, the model has 59 degrees of freedom.

Contact forces are calculated for each contact between the rings and balls, and between adjacent balls, as shown in Fig. 1. In