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Toward a 3D dynamic model of a faulty duplex ball bearing

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ABSTRACT

Bearings are vital components for safe and proper operation of machinery. Increasing efficiency of bearing diagnostics usually requires training of health and usage monitoring systems via expensive and time-consuming ground calibration tests. The main goal of this research, therefore, is to improve bearing dynamics modeling tools in order to reduce the time and budget needed to implement the health and usage monitoring approach.

The proposed three-dimensional ball bearing dynamic model is based on the classic dynamic and kinematic equations. Interactions between the bodies are simulated using non-linear springs combined with dampers described by Hertz-type contact relation. The force friction is simulated using the hyperbolic-tangent function. The model allows simulation of a wide range of mechanical faults. It is validated by comparison to known bearing behavior and to experimental results. The model results are verified by demonstrating numerical convergence.

The model results for the two cases of single and duplex angular ball bearings with axial deformation in the outer ring are presented. The qualitative investigation provides insight into bearing dynamics, the sensitivity study generalizes the qualitative findings for similar cases, and the comparison to the test results validates model reliability.

The article demonstrates the variety of the cases that the 3D bearing model can simulate and the findings to which it may lead. The research allowed the identification of new patterns generated by single and duplex bearings with axially deformed outer race. It also enlightened the difference between single and duplex bearing manifestation. In the current research the dynamic model enabled better understanding of the physical behavior of the faulted bearings. Therefore, it is expected that the modeling approach has the potential to simplify and improve the development process of diagnostic algorithms.

1. Introduction

Insofar as they reduce friction and wear, ball bearings constitute an essential part of rotating machinery. Rotating machinery breakdown is often the result of a bearing failure.

First bearing dynamics models were based on analytical solutions. A general analysis of a standard bearing done by Harris [1] used the equivalent contact stiffness to define the loading zone and the maximum load acting on a rolling element.

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Nomenclature

A	Distance between the raceway groove curvature centers
A_i	The value of the i element of the acceleration spectrum
C_1	Friction model coefficient
C_d	Diametral clearance
D	Bearing pitch diameter
D_d	Damping coefficient
F	Force
$\boldsymbol{I}$	Moment of inertia
N	Number of balls in the bearing
R	Location vector, radius of the raceway torus
a	Acceleration
c	Dissipation coefficient
d	Ball diameter
e	Coefficient of restitution, error
f	Normalized curvature, order
k	Stiffness
m	Mass
n	Contact stiffness exponent
r_i	Radius of curvature of the inner raceway
$\vec{r}_o$	Location of the outer ring center
$\vec{r}_{i-j}$	Location of the closest point to the ball on the center of the inner ring groove relative to the center of the inner ring
$\vec{r}_{i-o}$	Location of the inner ring center relative to the outer race
$\vec{r}_j$	Location of the j ball relative to the outer ring
v	Velocity
Z	Running index
Ω	Body system angular velocity
Δt	Time step
α	Contact angle
δ	Deflection of the ball into the raceway
$\dot{\delta}$	Penetration velocity
$\dot{\delta}^{(-)}$	Collision velocity
μ	Friction coefficient
θ	Rotational coordinate
ρ_j	Location of the j ball relative to the inner ring
ϕ	Azimuth
ψ	Angular extent of the load zone
ω	Angular velocity

The vibration pattern generated by a faulty radial bearing were established by McFadden and Smith [2]. Their model includes simulation of the measured vibration considering the bearing loading zone, the decay of the vibration impulse response produced by the fault, the relative location of the fault according to the accelerometer, and the transfer function between the bearing and the accelerometer.

Tandon and Choudhury compiled a more precise description of bearing dynamics under the influence of local faults [3,4]. Using Lagrange's equations for each normal mode, they evaluated the outer ring vibration separately. The final solution was presented as a series representing a superposition of the ring vibrations in all the normal modes.

To simulate the influence of raceway waviness on bearing dynamics, Lynagh et al. used the equivalent rolling element stiffness [5].

The influence of the waviness on bearing dynamics was examined by Harsha et al. [6]. They used a numeric solution that enabled the consideration of the effect of gravity and the separation of rolling element-inner and -outer ring interactions. Allowing eccentricity of the inner and outer rings and separation of the interactions, in turn, improved model accuracy.

Most of the above-mentioned studies, however, address radial bearing simulation and assume two-dimensional dynamics, an assumption that restricts the variety of bearings and faults to which the simulations are applicable.

To address the limitations of modeling bearing dynamics from a two-dimensional perspective, Harris and Mindel [7] developed a 5 degrees of freedom model of healthy ball bearing dynamics. Tandon and Choudhury [3] developed an analytical model that assumes each interaction between the ball and the fault results in the vibration impulse shape function. Aspects of axial and duplex bearings were investigated by other researchers. Alfares and Elsharkawy [9] and Bai et al. [10] examined the effects of axial preloading of angular contact ball bearings on the dynamics of rotor-bearing systems. Cao and Xiao examined the effects of different parameters on a double-row spherical roller bearing [11]. Gunduz et al. investigated the effect of bearing preloads on a double row angular contact ball bearing [12], and Gunduz and Singh formulated its stiffness matrix [13]. Only, Sopanen and Mikkola [8] and Tkachuk and Strackeljan [14] addressed the dynamic response of the bearing to a fault using a 3D model.

This article presents a new, three-dimensional (3D) dynamic ball bearing model and its application to single and duplex angular ball bearings with axial deformation in their outer rings. The qualitative investigation presented here gives insight into bearing dynamics, the sensitivity study generalizes the qualitative findings for similar cases, and the comparison to the test results provides additional verification of the reliability of the new model.

The study presents the expected vibration pattern in case of axial deformation and the expected difference between the dynamic behavior of the faulty single and duplex bearings.

2. Bearing model

In this section we describe the assumptions of the model and bearing geometry. The dynamic equations are developed based on the assumption that the bearing parts behave as rigid bodies and that during contact, the local deformation of the