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Research paper

Formulation of five degrees of freedom ball bearing model accounting for the nonlinear stiffness and damping of elastohydrodynamic point contacts

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ABSTRACT

The knowledge of the dynamic behavior of rolling elements bearings and the contact properties have shown to be essential for model based fault diagnosis, lifetime estimation and reduction of noise in several industrial equipment application. This paper formulates the force and moments equilibrium of an angular contact ball bearing with five degrees of freedom accounting for the effects of the elastohydrodynamic (EHD) lubrication of its elements. A complete nonlinear model is derived and equivalent parameters for stiffness and damping of each contact were evaluated for different loading conditions. An iterative solution process was proposed to couple the bearing equilibrium and the EHD contact calculation, so as to generate the most suitable representation of the lubrication condition at the equilibrium point. The resulting reduced order model is promising to save computational costs and to make feasible the analysis of complex rotating systems supported by oil lubricated angular contact ball bearings.

1. Introduction

Due to the increasing interest on model-based fault diagnostics, overall precision improvement and noise reduction on rotating machinery, a great deal of attention has been paid to characterizing the dynamic behavior of angular contact ball bearings. As such components lay in the load transmission path between rotating and stationary parts, the correct definition of the rolling element and raceways interactions is crucial for properly characterizing the dynamic behavior of the rotating system. Considering that most vibration problems of rotating machinery are related to inherent variable compliances of the bearings, rotor and housing iterations [1], the characterization of the factor affecting such variable stiffness and damping of the contacts is essential.

Over the years, several authors have investigated, experimentally and theoretically, the dynamics of ball bearings. Early studies date back to the fundamentals of fatigue life prediction [2–4]. Harris and Mindel [5] presented the underlying development of classical ball bearings dynamics, including static and dynamic load distributions, accounting for all forces and moments acting on each bearing component. At the core of the model lays the dry contact formulation of Hertz [6] to deal with the element to raceway normal contact. Several authors [7–9] later expanded this classical model technique.

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Nomenclature

a	Hertzian contact length
A	Distance between centers of curvature of raceways
b	Hertzian contact width
C	Contact Damping
d	Exponent of the displacement in the expression of contact force
d_m	Pitch diameter
D	Ball diameter
DOF	Degree of freedom
E'	Reduced modulus of elasticity
EHD	Elastohydrodynamic
F	EHD contact force
f	Osculation
F_c	Inertial force
h	Film thickness
h_o	Approach between rigid bodies
H	Dimensionless film thickness
K	Contact stiffness
L	Dimensionless Moes lubricant parameter
m	Ball mass
M	Dimensionless Moes load parameter
M_g	Gyroscopic moment
p	Pressure distribution on contact
Q	Contact force
r	Raceways radius of curvature
R_x	Curvature ratio in x-direction
R_y	Curvature ratio in y-direction
$R1_x$	Radius of curvature in x-direction of solid 1
$R2_x$	Radius of curvature in x-direction of solid 2
$R1_y$	Radius of curvature in y-direction of solid 1
$R2_y$	Radius of curvature in y-direction of solid 2
t	Time
U_m	Relative velocity tangential to the contact area
x	Coordinate in flow direction
X	Ball equilibrium position
y	Coordinate perpendicular to x
Z	Number of balls
η	Absolute viscosity
ρ	Fluid density
ΔF	Offset force
δ	Displacement
$\dot{\delta}$	Velocity
θ	Angular displacement
α^0	Nominal contact angle
ψ	Azimuth angle
α	Contact angle
$\Re_I$	Distance between the geometric center of the bearing and the center of curvature of the raceways

Subscripts

i	Inner raceway
o	Outer raceway
r	Radial direction
a	Axial direction
x	x-direction
y	y-direction
z	z-direction
j	j-th ball
c	Central