The Effect of Ball Waviness on Nonlinear Vibration Associated with Rolling Element Bearings

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(Received 13 January 2004; revised 19 October 2005; accepted 10 March 2006)

An analytical model was developed to investigate the nonlinear vibrations of a rotor bearing system due to ball waviness. In the analytical formulation the contacts between the balls and the races are modelled as nonlinear springs, whose stiffnesses are obtained by using Hertzian elastic contact deformation theory. The governing differential equations of motion are obtained by using Lagrange's equations. The implicit type of numerical integration technique Newmark-β with Newton-Raphson method is used to solve the nonlinear differential equations iteratively. A computer program was developed to simulate the effect of ball waviness. The formulation predicts the discrete spectra with specific frequency components for each order of ball waviness. Numerical results obtained from the simulation are compared with those of prior researchers.

Nomenclature

F_u	– unbalance force, N
I	– moment of inertia of each rolling element
I_{rotor}	– moment of inertia of the rotor
I_{in}	– moment of inertia of the inner race
I_{out}	– moment of inertia of the outer race
k	– waviness order
K	– constant of proportionality, N/mm$^{3/2}$
L	– arc length, mm
M_{rotor}	– mass of the rotor, kg
m_{in}	– mass of the inner race, kg
m_j	– mass of the rolling elements, kg
m_{out}	– mass of the outer race, kg
N_w	– number of wave lobes
N_b	– number of balls
p	– empirical constant for a particular geometry
q	– empirical constant for a particular geometry
R	– radius of outer race, mm
r	– radius of inner race, mm
r_{in}	– position of mass centre of inner race
r_{put}	– position of mass centre of outer race
T	– kinetic energy of the bearing system
T_{rotor}	– kinetic energy of the rotor
T_{i_race}	– kinetic energy of the inner race
T_{o_race}	– kinetic energy of the outer race
T_{roll_e}	– kinetic energy of the rolling elements
V	– potential energy of the bearing system
V_{shaft}	– potential energy of the shaft
V_{i_race}	– potential energy of the inner race
V_{o_race}	– potential energy of the outer race
V_{roll_e}	– potential energy of the rolling elements
V_{spring}	– potential energy of the springs
x_{in}, y_{in}	– centre of inner race
x_{out}, y_{out}	– centre of outer race
δ	– deformation at the point of contact at inner and outer race, mm
$(\dot{\phi})_{in}$	– angular velocity of inner race
$(\dot{\phi})_{out}$	– angular velocity of outer race
ω_{bp}	– ball passage frequency, Hz
ω_{wp}	– wave passage frequency, Hz
$(\Pi_i)_b$	– amplitude of the wave at ball, μm
ρ_j	– radial position of the rolling element
ρ_r	– radius of each rolling element
θ_j	– angular position of rolling element
χ_j	– position of j-th rolling element from the centre of inner race

FFT	– Fast Fourier Transformation
BPF	– Ball Passage Frequency, Hz
BPV	– Ball Passage Vibration, Hz
WPF	– Wave Passage Frequency, Hz

1. INTRODUCTION

Rolling bearings are the most used components in machinery and are employed in a wide variety of rotating machinery from small handheld devices to heavy duty industrial systems. It is generally known that ball bearings cause vibrations even under ideal conditions;[1,2] furthermore, in the presence of defects, which are naturally introduced due to manufacturing limitations and operational conditions, the vibrations and noise produced can be substantially complex and quite difficult to analyse.[3,4]

In addition to the fact that most machines are nonlinear devices with very complicated time signatures, these bearing defects tend to introduce strong nonlinearities. Hence, standard linear techniques that are employed widely in industry are incapable of predicting their response accurately. In addition, since the mathematical underpinnings of linear and non-