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Dynamic modeling of spindle bearing system and vibration response investigation

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ABSTRACT

This paper presents a dynamic model of spindle bearing system combined both angular contact ball bearing (ACBB) and floating displacement bearing (FDB) with the consideration of the spindle housing. In the proposed dynamic model, the dynamic models of ACBB and FDB are developed by discrete element method with each bearing component owning 6 DOFs. The spindle shaft including the tool holder and cutter is modeled by finite element method based on Timoshenko beam theory, and spindle housing is modeled as rigid beam. The coupling restriction of the dynamic system model between dynamic models of bearings, spindle shaft and housing are the forces and response restriction at bearing installation nodes through bearing inner and outer races. Based on the developed spindle bearing system dynamic model, the dynamic frequency response functions (FRFs) of the system under different rotating speeds and time history responses of the system under different cutting forces are investigated and compared with the experimental measured results. The dynamic responses of the system with two different kinds of cutters under different cutting conditions are investigated. Simulated results agree well with the experimental results, and it indicates the effectiveness of the proposed dynamic model of spindle bearing system.

1. Introduction

The spindle bearing system is one of the most important parts of a machine tool, since its dynamic characteristics directly affect the performance of the machine tool. Therefore, a thorough understanding of the dynamic characteristic of a spindle bearing system is of great significance in making full use of the spindle system and in improving productivity [1,2]. The dynamic modeling of the spindle bearing system is an effective approach to investigate the dynamic property of the spindle bearing system of machine tools and has been widely used [1,3,4]. Moreover, the resulting dynamic can be applied in assessing the response of the system with respect to particular external loads. For example, in analyzing the chatter phenomenon in machining processes [5,6], the dynamic of the spindle-bearing system can be used to predict the system stability with respect to the cutting forces [7], nonlinear dynamic of the system [8], and virtual simulation of the cutting process and virtual design [7,9,10].

As Byrne et al. [4] has stated in the 2016 CIRP conference on High Performance Cutting (HPC), predictive capabilities will remain a critical component of the HPC technology roadmap. Modeling and simulation of machining operations have not yet

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Nomenclature

$\boldsymbol{a}^i_{bok}$	translational acceleration of the *k*th bearing outer race mass center
$\boldsymbol{a}^i_h$	translational acceleration of the rigid spindle housing mass center
A, B, C, D	coefficients for particular lubricant
c_{yh1}, c_{zh1}, $c_{\theta yh1}$, $c_{\theta zh1}$	equivalent connect damping between the spindle housing and the machine tool column at the first equivalent connect point along two orthometric radial directions.
d	diameter of the ball
d_m	pitch diameter of the bearing
f_i, f_o	groove curvature factor of the inner and outer raceway
$\boldsymbol{F}$	vector of total force
$\{F_{boyk}, F_{bozk}\}$	forces applied on the bearing outer race by balls in the *k*th bearing
$(F_{bx}, F_{br}, F_{b\theta})$	components of the total force vector applied on the ball by the cage and races in the inertial cylindrical frame
(I_1, I_2, I_3)	principal moments of inertial of the considered bearing component
k_{yh1}, k_{zh1}, $k_{\theta yh1}$, $k_{\theta zh1}$	the equivalent connect stiffness between the spindle housing and the machine tool column at the first equivalent connect point along two orthometric radial directions.
K_{bir}	Hertzian contact stiffness coefficients of ball-outer race and ball-inner race contact
l_{bk}	distance between the mass center of the *k*th bearing outer race and the rigid spindle housing along X axis with the consideration of the direction
l_{pg}	distance between the gth connect point and the mass center of the rigid spindle housing along X axis with the consideration of the direction
m_b	mass of the ball
m	mass of the considered component
m_h	mass of the spindle housing
(M_1, M_2, M_3)	components of the total moments vector applied on the considered bearing component
$\{M_{boyk}, M_{bozk}\}$	moments applied on the bearing outer race by balls in the *k*th bearing
Q_{bir}	ball-inner-raceway and ball-outer-raceway normal contact forces
r_{IRo}	outside radius of inner ring
r_{ORc}	orbit radius of center of the outer race groove curvature
r_{ORi}	radius of the bottom of the outer race groove
$r_{I1}, r_{I2}, r_{II1}, r_{II2}$	radii of curvatures of the outer raceway and ball in two main planes
$\mathbf{T}_{hi}$	transformation matrix from spindle housing fixed frame to the inertial frame
u_r	unilateral radial clearance of the FDB
$\boldsymbol{u}^{cor}_r, \boldsymbol{u}^{cor}_b$	velocity of the raceway and the ball at contacting point
$\boldsymbol{u}^{cor}_s$	slip velocity of the raceway relative to the ball at contacting point in the contact frame
$\boldsymbol{v}^i_h$	translational velocity of the rigid spindle housing mass center
$\boldsymbol{v}^i_{bok}$	translational velocity of the kth bearing outer race mass center
(x_b, r_b, θ_b)	components of the displacement vector in inertial cylindrical frame
(x^i, y^i, z^i)	global inertial frame
(x^r, y^r, z^r)	rotor fixed frame
(x^{r1}, y^{r1}, z^{r1})	inner race fixed frame of the 1st bearing
$(X^{air}, Y^{air}, Z^{air})$	azimuth-in-inner raceway frame
$(X^{aor}, Y^{aor}, Z^{aor})$	azimuth-in-outer raceway frame
(X^i, Y^i, Z^i)	bearing inertial frame,
(X^{or}, Y^{or}, Z^{or})	outer race fixed frame
$\boldsymbol{\alpha}^{bok}_{bok}$	rotational angular acceleration of the kth bearing outer race mass center
$\boldsymbol{\alpha}^h_h$	rotational angular acceleration of the rigid spindle housing mass center
α_{or}	actual contact angle between the ball and outer raceway
β	rotational angular displacement of inner ring around axis Y_i
δ_{bor}, δ_{bir}	contact deformation between the considered ball-outer raceway and ball-inner raceway
Δx	axial relative displacement motion of the bearing inner ring to the outer ring
(η, ξ, λ)	angular displacement of the considered frame relative to the reference frame
κ	traction coefficient
ρ	radius of curvature of the contact deformed pressured surface
$\ddot{\boldsymbol{v}}$	vector of acceleration
$\boldsymbol{\omega}^{bok}_{bok}$	rotational angular velocity of the kth bearing outer race mass center
$\boldsymbol{\omega}^h_h$	rotational angular velocity of the rigid spindle housing mass center