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Research paper

Study on interactions between tooth backlash and journal bearing clearance nonlinearity in spur gear pair system

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ABSTRACT

Gear transmissions with journal bearings are widely used in power machinery. The existences of the large bearing clearances and backlash lead to variations of tooth contact status under different operation conditions and assembly states (bearing center distance). The purpose of this paper is to examine the dynamic response of the spur gear–pair system and interactions between bearing clearance and the backlash. In the system dynamic model, the contact force on backside and journal bearing forces, where both clockwise and anticlockwise rotation of the gears exist, are considered simultaneously. Shift of the bearing position is also taken into account. In quasi-static analyses, equilibrium positions of shaft journals in bearing clearance are figured out by Newton iterations in a wide range of rotational speeds and input torques. In dynamic analyses, vibration responses are presented by frequency-amplitude curves, spectra, bifurcation and orbits, where oil whirl and tooth separation are observed. Finally, tooth wedging phenomena led by shift of bearing position are presented. The results show that the bearing clearances provide self-adaptive characteristics, both the shortening of bearings center distance and the input torque contribute to the occurrence of the tooth wedging.

1. Introduction

Geared rotor bearing systems are widely used as power transmission mechanism, among which oil journal bearings are usually adopted in high speed and heavy loaded applications. Tooth separation and tooth wedging, which lead to undesirable vibration or failures, should be avoided. With the increasing demand for quiet and reliable transmissions, mathematical modeling of dynamic analysis of gears has gained importance.

Numerous mathematical models were developed for different purposes in the past decades. These models evolved from single degree of freedom to multi degrees of freedom, adding variety of excitations and nonlinearity factors such as time-varying mesh force, unbalance, manufacture errors, bearing clearance, backlash, etc. Torsional motion was studied by single degree of freedom models in early studies [1]. Iida, Tamura et al. [2] investigated the coupled torsional-lateral vibrations of linear geared system theoretically and experimentally. Eritenel and Parker [3] studied the three-dimensional nonlinear vibration of gear pairs.

Based on these models, different excitation is added to obtain the dynamic response of systems. Lee and Ha [4] observed unbalance response characteristic of rotor-bearing system for turbo-chiller considering the coupling effect between the lateral and torsional dynamics due to gear meshing. Choi, Glienicke et al. [5] solved the eigenvalue problem to analyze the stability of the geared system and calculate the forced vibration under excitation of unbalances and static transmission errors. Theodossiades and Natsiavas [6] investigated dynamics of a gear-pair system involving time-dependent mesh stiffness and backlash, and illustrated the

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Nomenclature

x_i, y_i, θ_i	Translational and torsional displacements of the pinion or the gear
O_g, O_p	Origins of the reference frame for the gear and the pinion
b, b'	Real value and Design value of backlash
b_0, b_e	Initial value and the shift of backlash
f_d, f_b	Mesh forces on drive-side and the back-side
h_d, h_b	Switch function to track tooth contact
$\boldsymbol{e}_1^i$, $\boldsymbol{e}_2^i$, $\boldsymbol{e}_3^i$	Base vectors of the reference frame
$\boldsymbol{e}_d$, $\boldsymbol{e}_b$	Unit vector along the action line on the drive-side and the back-side
k_m	Mesh stiffness
l_0	Initial value of the bearing center distance
m_p, m_g, J_p, J_g	Mass and polar inertial moment
r_g^c, r_p^c	Radius of the reference circle
r_p^b, r_g^b	Radius of the base circle
s_x^p, s_y^p, s_x^g, s_y^g	Variation of the gear bearing position in x, $y$direction
α	Pressure angle
δ_d, δ_b	Deflections on drive-side and back-side
Δ_r, Δ'_r	Real value and Design value of the radial gap
Δ_0, Δ_e	Initial value and the shift of the radial gap
p, $\overline{p}$	Physical and dimensionless oil-film pressure
x, y, z	Coordinates of the shaft journal in a general bearing
$\overline{x}_p$, $\overline{y}_p$, $\dot{\overline{x}}_p$, $\dot{\overline{y}}_p$, $\overline{x}_g$, $\overline{y}_g$, $\dot{\overline{x}}_g$, $\dot{\overline{y}}_g$	Dimensionless positions and velocities in $\boldsymbol{e}_1$, $\boldsymbol{e}_2$ direction
$f_{b,x}^p$, $f_{b,y}^p$, $f_{b,x}^g$, $f_{b,y}^g$	Radial clearance of the bearing
C	Radial clearance of the bearing
L	Length of the bearing
R	Radius of shaft journal
β_b	Circumferential position where positive pressure area starts from
μ	Hydrodynamic viscosity coefficient of the lubricant media
θ_b	Circumferential coordinate start from ox direction
ω_p, ω_g	Rotational angular frequencies
ε_p, ε_g	Eccentricity of the mass center
f_{torq}^p, f_{torq}^g	Static torques
κ_i, ς_i	Torsional stiffness and damping coefficients
$\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$, $\mathbf{q}$	Global matrixes of mass, damping, stiffness and global displacement vector
$\mathbf{F}_m$, $\mathbf{F}_{be}$, $\mathbf{F}_u$, $\mathbf{F}_s$	Global vector of mesh force, bearing force, unbalance excitation and static load
β, γ, $c_i (i = 1, 2, \ldots, 7)$	Coefficients of the Newmark algorithm

effect of the mesh stiffness variation, the damping and the forcing parameters on the gear-pair periodic response. Cai [7] proposed a mesh stiffness function for helical gear pairs and simulated the vibration of a helical gear system. Velex and Ajmi [8] introduced an approach into the modeling of pinion–gear excitations by using a three-dimensional model of single-stage geared transmissions. In their model, shape deviations and errors on gears are considered.

Clearances including tooth backlashes and clearance of roller bearings provide nonlinearity for the geared system and makes contributions to the vibration and noise of the gear system. Kahraman and Singh [9] found a strong interaction between time-varying mesh stiffness and backlash by analyzing geared systems with single degree of freedom and multi degrees of freedom. They [10] made parametric study about bearing stiffness to mesh stiffness ratio, radial bearing preload to mean force ratio, etc. Sun and Hu [11] calculated the dynamic response of a planetary gear system considering multiple backlashes by harmonic balance method and compared with the numerical results. Gu¨rkan and O¨zgu¨ven [12] studied the interactions between backlash, bearing clearance and bearing flexibility in geared flexible rotors and presented the effect of the clearances and stiffness ratios on the bearing forces. Cai [7] analyzed a helical gear system with the effect of the tooth separation. Another important phenomenon due to multiple clearances is tooth wedging. Guo, Parker et al. [13–15] established dynamic models for the planetary gears with bearing clearance involving tooth wedging, and illustrated the effects of parameters such as backlash to bearing clearance ratio, mesh frequency and gravity. The results were presented with bearing forces and tooth force waves of drive-sides and back-sides.

Oil film bearings provide support in rotating systems, The nonlinearity in geared system had received more attentions. Sommerfeld deduced classical analytical expression of the hydrodynamic bearing force based on short bearing assumption [16]. Capone [17] improved this expression. The application in rotor systems is widely studied during past several decades and phenomenon such as oil whirl and oil whip were revealed [18,19]. For geared systems, Hamad and Seireg [20] calculated the whirl orbits and the stability of a pinion-gear system supported on oil film bearings with a linearized bearing force model. Kishor and Gupta [21,22] introduced the nonlinear hydrodynamic bearing force into rotor gear pair systems and presented the form of bearing force expression when rotation direction is opposite. Effects of parameters for gears and bearings were presented. Theodossiades and Natsiavas [23] analyzed the influences of system parameters and predicted the onset of oil whirl instability in the geared rotor system. Cui, Liu et al.[24] investigated the effect of oil film force, mesh force and subsynchronous forward precession theoretically and experimentally. Baud and Velex [25] made an experimental study about the static and dynamic tooth load in spur and helical geared systems supported on hydrodynamic and hydrostatic bearings. The results demonstrated the validation of their earlier simulation. Fargère and Velex [26] studied the dynamic interactions in gears-hydrodynamic journal bearing systems by a refined model and compared with experiment results. They found the factors including oil inlet location, oil temperature and coupling elasticity take effects by modifying the alignment of shafts.

Because of the complexity of nonlinearity of oil film force and mesh force with backlash, relative studies on geared rotor-hydrodynamic bearing systems are still insufficient. Interactions between clearance of journal bearings and backlash were seldom brought to the attention. The variation of bearing center distance due to bearings hole position errors or undesirable assembly states contributes to this interaction. The purpose of this paper is to propose a dynamic model for a gear-pair system involving nonlinear oil film bearing force and mesh force, further to investigate the dynamic response and variations of tooth contact status under