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Nonlinear dynamics analysis of the spur gear system for railway locomotive

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ABSTRACT

Considering the factors such as the nonlinearity backlash, static transmission error and time-varying meshing stiffness, a three-degree-of-freedom torsional vibration model of spur gear transmission system for a typical locomotive is developed, in which the wheel/rail adhesion torque is considered as uncertain but bounded parameter. Meantime, the Ishikawa method is used for analysis and calculation of the time-varying mesh stiffness of the gear pair in meshing process. With the help of bifurcation diagrams, phase plane diagrams, Poincaré maps, time domain response diagrams and amplitude-frequency spectrums, the effects of the pinion speed and stiffness on the dynamic behavior of gear transmission system for locomotive are investigated in detail by using the numerical integration method. Numerical examples reveal various types of nonlinear phenomena and dynamic evolution mechanism involving one-period responses, multi-periodic responses, bifurcation and chaotic responses. Some research results present useful information to dynamic design and vibration control of the gear transmission system for railway locomotive.

1. Introduction

Gear transmission systems are one of key components in mechanical system for locomotive. Due to harsh operation environment including high speed, heavy load, high cold, heavy dust, etc, the gear systems of railway locomotive are prone to damage and hence are recognized as the most vulnerable part. It is therefore imperative to investigate gear failure mechanisms by developing reliable dynamic models of the gear transmission systems. Accordingly, dynamic behavior of the gear systems has been one of the main topics in rotary machinery and power transmission systems, both vibration health monitoring and fatigue life prediction of a gear set are often influenced by its dynamic behavior [1].

With the development of nonlinear dynamics theories, the nonlinear characteristics of the gear system have become the most interesting research areas. For instance, Kahraman and Singh [1,2] have researched nonlinear dynamics of a spur gear pair by harmonic balance method, where the backlash was represented by truncated series expansion. With consideration of the coupling effects between torsional, lateral and axial vibrations, Luo et al. [3] proposed a modal synthesis method of gear systems, which was demonstrated by analyzing the first 10 modes of vibration of an aero-engine helical gearbox with five shafts using FEM software. In Ref. [4], Amabili et al. studied the steady-state response and stability of the single degree of-freedom model of spur gear pairs, in which the gear errors, time-varying stiffness and damping proportional to the

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Nomenclature

b	half of total gear backlash
c_1	bearing damping of pinion
c_2	bearing damping of gear
c_m	damping coefficient of gear mesh
$e(t)$	static transmission error
T_1	drive torque acting on pinion
T_2	wheel/rail adhesion torque
$F_1(t)$	force transmitted through pinion
$F_2(t)$	force transmitted through gear
$F_k(t)$	elastic meshing force
$F_m(t)$	viscous meshing force
I_1	mass moment of inertia of pinion
I_2	mass moment of inertia of gear
k_1	bearing stiffness of pinion
k_2	bearing stiffness of gear
$k(t)$	time-varying mesh stiffness
m_1	mass of pinion
m_2	mass of gear
m_e	equivalent mass of the gear pair
$f()$	nonlinear displacement function
ω	angular velocity of gear pair
τ	non-dimensional time
R_1	base circle radius of pinion
R_2	base circle radius of gear
θ_1	rotational displacement of pinion
θ_2	rotational displacement of gear
y_1	translational displacement of pinion
y_2	translational displacement of gear
z	number of teeth
x	modification coefficient
r_b	base radius
r_f	root radius
r_{ff}	effective root radius
r_a	tip radius
r_x	distance of load and the center point
α	pressure angle
α'	meshing angle
b_m	tooth width
E	Young's modulus
V	Poisson's ratio
F_n	load in normal plane
Ω	rotating speed of pinion
ω_n	natural frequency, and $\omega_n=\sqrt{k_m/m_e}$

meshing stiffness were considered. Meantime, transition curves separating stable and unstable regions were computed by Hill infinite determinant. In a series of papers, Theodossiades and Natsiavas [5,6] studied the non-linear dynamics of a gear pair system with backlash, periodic mesh stiffness, static transmission error and external excitation, which were caused by torsional moments and gear geometry errors.

To illustrate the effect of the important parameters on the system response, some types of response diagrams were identified by employing suitable methodologies. Based on a finite element/contact mechanics model, Parker et al. [7] investigated dynamic response of a spur gear pair across a wide range of operating speeds and torques, and showed the ability of a two-dimensional finite element/contact mechanics formulation to accurately capture the strongly nonlinear dynamics of gear system. Considering the actual positions of the contacts and the actual deformations of the gear teeth, Andersson and Vedmar [8] presented a method to determine the dynamic load between two rotating elastic helical gears, and predict the dynamic behavior of a gear set. They also presented some figures to show the behavior of the dynamic transmission error as well as the variation of the contact pressure. Al-shyyab and Kahraman [9] developed a nonlinear time-varying dynamic model to investigate sub-harmonic and chaotic motions exhibited by a typical multi-mesh gear train. Effect of several system parameters such as alternating mesh stiffness amplitudes, gear mesh damping and static torque transmitted on sub-harmonic motions were described in the paper. In [10], the incremental harmonic balance method (IHBM) was applied by Shen et al to analyze the nonlinear dynamics of a single degree-of-freedom spur gear system with backlash, time-varying stiffness and static transmission error. Also, the chaotic response was investigated by using numerical simulation method.

In Ref. [11], Wang et al. developed a generalized dynamic model of hypoid gear pair in which time-varying mesh parameters and backlash nonlinearity was considered. The nonlinear phenomena such as periodic response, chaos and bifurcation in system were investigated. In addition, they [12] presented a nonlinear time-varying dynamic model of a hypoid gear pair system with time-dependent nonlinear mesh stiffness, mesh damping and backlash properties, formulated to study the effect of mesh stiffness asymmetry for drive and coast sides on dynamic response. Chang-Jian et al. [13] investigated dynamic responses of a single degree-of-freedom spur gear system with and without nonlinear suspension and found periodic and chaotic dynamics by means of the phase diagrams, power spectra, Poincaré maps, Lyapunov exponents and fractal dimension in this system. Fernandez del Rincon et al. [14] described an advanced model for the analysis of contact forces and deformations in spur gear transmissions. The model was validated through a quasi-static analysis of an example to visualize and assess how the magnitude of the transmitted torque, the friction and the modified center distance affect the resultant loaded transmission error, meshing stiffness and load sharing ratio. Wei et al. [15] developed a six-degree-of-freedom dynamic model with coupled flexional, torsional and axial motion of helical gear transmission system, which included time-varying mesh stiffness, bearing supporting stiffness, mesh damping and backlash. The effects on dynamic transmission errors and stabilities by contact ratio, support stiffness and mesh damping as well as backlash were analyzed.

In [16], Farshidianfar and Saghafi studied the global Homoclinic bifurcation and transition to chaotic behavior of a nonlinear gear system by means of Melnikov method. Additionally, the numerical bifurcation analysis and numerical simulation including bifurcation diagrams, phase plane portraits, time histories, power spectra, and Poincare sections were used to confirm the