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Research on the dynamic mechanism of the gear system with local crack and spalling failure

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ABSTRACT

This study focuses on the dynamic and vibration characteristics of a four-degree of freedom gear system with local defects to explore the failure mechanism. The dynamic models of the gear system with tooth crack and spalling failure are respectively established to investigate the effect of the failures on mesh stiffness and dynamic response by numerical simulation. The differences and comparisons between the vibration signals with the tooth crack and spalling failure are discussed by using time history, phase contrail, Poincaré section, spectrum analysis and fractal dimension, which shows the different dynamic characteristics between the tooth crack and spalling failure. An experimental gearbox with tooth crack and spalling failure was designed and experiments was carried out to determine the dynamic characteristics of the faulty vibration signals. The results obtained herein show good agreement qualitatively with the theoretical analysis, which provides a theoretical basis for the fault diagnosis of gearboxes.

1. Introduction

Gearboxes are widely used to transmit power and change speed or direction in many mechanical systems. The smooth operation and high efficiency of gears are necessary for the normal running of machinery. Therefore gear fault detection is a main topic in the field of condition monitoring and fault diagnosis.

Failures in gearboxes can be tooth-related such as pitting, spalling, crack and broken tooth, which can take place frequently and lead to a complete failure of the gearbox. At the present time, the work on gear fault diagnosis is focused on two aspects: signal processing and dynamic analysis. A variety of signal-processing techniques which can be classified as time domain, frequency domain, time–frequency domain and intelligent diagnosis methods are available for the fault detection of real gear vibration signals [1–4].

To improve the current techniques of gearbox vibration monitoring and diagnosis, many researchers worked on the gear dynamic modeling to ascertain the effect of different types of gear damage on the gear vibration. Local crack and spalling failure represent typical types of damage, so different dynamic model with the two defects were established. The dynamic models of gear with tooth crack usually took into account the effect of the crack on mesh stiffness, and considered the variant stiffness as internal defect excitation [5–8]. In addition, some researchers established the models of gear system using finite element method, which showed the effect of crack propagation on the dynamic behavior of the system by modal analysis [9,10]. An acceptable dynamic model considering the local spalling defect as a defect excitation was proposed by Badaoui et al. [11,12], but didn't consider the variant mesh stiffness in the presence of the defect. Parey et al. [13] proposed the model with spalling in which the severity, extent and age were represented by a decaying sinusoidal pulse, which was reasonable

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when considering the typical impulsive nature of the fault signal. Jia and Howard [14] considered the spalling error as a combination of three harmonic terms and discussed the difference between tooth crack and spalling damage by amplitude spectra and phase modulation. Endo et al. [15] presented a diagnosis technique to differentially diagnose spalling and crack failure, where the effect of the spall was predominantly determined by the geometry of the fault. The simulation signals obtained from the dynamic models were frequently diagnosed by spectrum analysis and statistical techniques [5,7–9,11–15]. Therefore few researchers focused on the dynamic mechanism of gear system with failures, however the research on crack and spalling dynamic mechanism of gear system in this paper combining with experimental gearbox can supply a theoretical basis to fault diagnosis of gearbox.

In this paper, the models of gear system with failures are established. The variant stiffness is only considered as the effect of crack, while the effect of spall is determined by both the variant stiffness and defect excitation function. The effects of the two failures on mesh stiffness and dynamic mechanism are analyzed by numerical simulation. Finally, theoretical results are qualitatively validated by the vibration characteristics of the fault signals measured on an experimental gearbox.

2. Generation of the dynamic model with failures

2.1. Mechanical model of the gear system

The geared rotor-bearing model investigated in the present study is shown in Fig. 1. In this model, friction forces at the mesh point are assumed to be negligible. Because of this the transverse vibrations along the directions of the line of action and the vibrations along the direction perpendicular to the line of action are uncoupled. Bearings and shafts that support the gears are represented by equivalent damping and stiffness elements as shown in Fig. 1. The damping elements are characterized by linear viscous damp coefficients c_1 and c_2, and the stiffness elements are defined by k_1 and k_2. F_1 and F_2 are the excitation of bearings applied to the gears. The model takes into account the so-called static transmission error, and both the stiffness $k_g(t)$ and the static transmission error $e(t)$ can approximately be considered as time–periodic functions, and the fundamental frequency of both of the quantities equals the gear mesh frequency.

$$e(t) = f_m + f_1 \cos(\omega_e t) \tag{1}$$

where $\omega_e = z_1\omega_1 = z_2\omega_2$ is the mesh frequency, the integers z_1 and z_2 stand for the tooth number of each gear, ω_1 and ω_2 are the constant angular velocity components of the gears, f_m is the mean static transmission error, f_1 is the harmonic coefficient.

Under these assumptions, the equations of coupled transverse-torsional motion of the geared rotor-bearing system with time-variant mesh stiffness can be expressed as

$$\begin{aligned} m_1\ddot{y}_1 + c_1\dot{y}_1 + k_1y_1 - c_gy - k_g(t)y &= F_1 \\ m_2\ddot{y}_2 + c_2\dot{y}_2 + k_2y_2 + c_gy + k_g(t)y &= F_2 \\ I_1\ddot{\theta}_1 + r_1c_gy + r_1k_g(t)y &= M_1 \\ I_2\ddot{\theta}_2 - r_2c_gy - r_2k_g(t)y &= -M_2 \end{aligned} \tag{2}$$

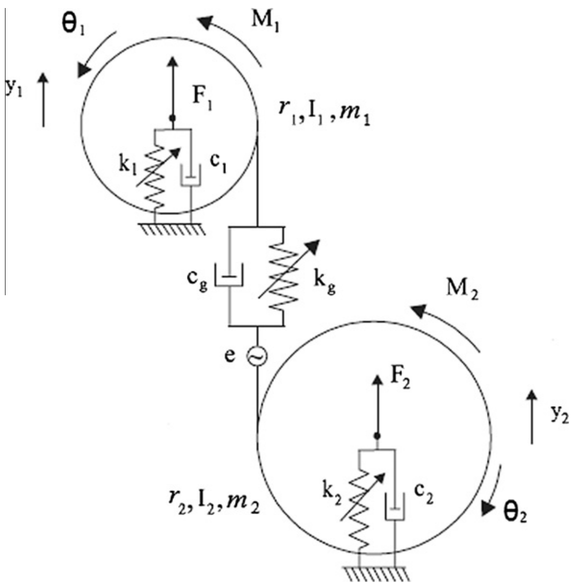

Fig. 1. Mechanical model of a gear-pair system on deformable bearings.