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Vibration mechanisms of spur gear pair in healthy and fault states

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ABSTRACT

The vibration frequency components of gear system are complicated and changeful, some of those are even hard to explain. Based on the dynamic equations of a single-stage gear pair and some reasonable simplifications, frequency responses of the gear pair in healthy state and those suffering from different faults are analyzed, respectively. The excitation sources of vibration frequency components such as rotational frequency harmonics, mesh frequency harmonics, modulation sidebands and resonance frequency bands are investigated accordingly. The causes of the asymmetrical modulation sidebands around the mesh frequency harmonics, which are commonly appeared in the vibration spectrum of gear system, are explained. The effectiveness of the theoretical deductions is confirmed by dynamic simulations and experimental results.

1. Introduction

Gear system is one of the most common configurations for power transmission and is widely used in automobile, helicopter and industrial power trains. For the influences of the time-varying mesh stiffness and other nonlinear factors, the frequency components of gear vibration are complicated and changeful [1]. Even for a single-stage gear pair, the vibration signal picked up by transducers always contains the high order mesh frequency harmonics and modulation sidebands. In vibration signals of actual gearbox, many frequency components are hard to explain by existing theories, which cause many difficulties in the fault diagnosis. It has been an active research area to describe the gear failure mechanism precisely for many years.

Many works have been done on gear dynamic modeling to ascertain the effect of gear damages, which differ in terms of the excitation mechanisms and the solution technique applied. Since it's hard to solve the motion differential equations and obtain the vibration responses directly, the excitation sources of gear vibration are always transformed into the time-varying mesh stiffness in literatures, and the vibration responses are obtained by using finite element analysis (FEA) or other simulation software. In Ref. [2], the effect of tooth wear on the vibration spectrum variation of a rotating spur gear pair was studied by considering the changes of load, mesh stiffness, damping and friction coefficient in the mathematical model. In Ref. [3], the spur gear dynamic model with local tooth spall and time-varying mesh stiffness was established, and the vibration characteristic caused by spalling was evaluated by statistical indicators. In Ref. [4], the difference between the vibration signals with a tooth crack and spalling damage was discussed by utilizing a gear dynamic model. It was pointed out that the amplitude modulation caused by tooth spall can be ignored compared with that of tooth crack. In Ref. [5], an

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improved time-varying mesh stiffness algorithm was given, and it was found that the vibration response of gear-rotor system with a tooth crack was characterized by periodic impulse through simulation. In Ref. [6], an analytical method was proposed to quantify the reduction of gear mesh stiffness, and the dynamic response of a signal stage spur gear transmission was computed accordingly. But like other similar models, there was no clear explanation about the amplitude modulation of the defect signals.

On the other hand, the vibration based fault diagnostic technique is one of the most effective non-intrusive techniques available, whose diagnosis accuracy largely depends on the correct understanding of the fault vibration features. For examples, the narrow-band demodulation technique [7] is used to extract the fault feature when there is a potential modulation in vibration signal; wavelet analysis [8] can separate compound signal effectively only when the wavelet basis is properly selected; sparse representation [9] can reconstruct signal as sparsely as possible only when the sparse dictionary has similar structure with the analyzed signal.

Although many works have been focused on the gear vibration mechanism and vibration characteristics, the current understanding of gear vibration remains incomplete, and many frequency components are still hard to explain even when the gear system is working in healthy condition. In this study, based on the motion differential equation of a single-stage spur gear transmission and some reasonable simplifications, the dynamic responses of a single-stage spur gear transmission are investigated under different fault types, and the theoretical derivations and analysis results are confirmed by the finite element analysis and experimental methods. The causes of high-order mesh frequency harmonics and the asymmetrical modulation sidebands which commonly appear in the vibration spectrum of gear transmission are explained reasonably.

2. Vibration mechanism of spur gear transmission

In gear transmission, the gear system may suffer from different kinds of faults. For the sake of a convenient research, the faults of gear system are divided into steady-type, impact-type and compound-type faults according to the fault vibration characteristics in this paper. Steady-type fault, such as tooth profile error, run out error, mild wear and shaft mild misalignment, can be described by the displacement vibration excitation, whose spectrum is characterized by a subset of steady amplitude modulation sidebands. Impact-type fault, such as pitting corrosion, spalling damage and broken tooth, can be described by the impact vibration excitation, and whose spectrum is characterized by transient impact modulation. For the kind of fault, such as tooth crack, which can evoke both steady amplitude modulation and transient impact modulation, is classified into compound-type fault. It is worth noting that the steady-type fault may transform into compound-type fault with the degradation of fault level. For example, when shaft deflection or gear wear arrives at a certain degree, impact component may also be visible in the gear vibration signal. Therefore, during the fault diagnosis, impact component can be used as the main basis for judging whether a fault happens in the gear system. Based on the classification above, the vibration mechanisms of gear system suffering from different kinds of faults are discussed as follows.

2.1. Vibration mechanism of the healthy single-stage spur gear pair

The dynamic model of the engaged spur gear pair investigated in the present study is shown in Fig. 1, which has been employed in previous research work [1,10]. Here T_p and T_g denote the input and output torques respectively, R_p and R_g denote the radius of the base circles respectively. $e(t)$ is the relative displacement on the mesh point caused by the steady-type fault, and can be omitted for the perfect meshing gear. According to Lagrange theorem, the dynamic differential equation of the adopted system can be expressed by

$$M\ddot{x}(t) + C\dot{x}(t) + k(t)[x(t) + E] = W_0 \tag{1}$$

where $x(t)$ is the linear displacement along the action line, E is the average static elastic deformation of gear teeth after loading, C is the damping factor which has been simplified as a constant, $k(t)$ is the time-varying mesh stiffness, M is the equivalent inertia mass of the gear pair and $M = I_p I_g/(I_p R_p^2 + I_g R_g^2)$, $W_0 = T_p/R_p = T_g/R_g$, where W_0 is the static load.

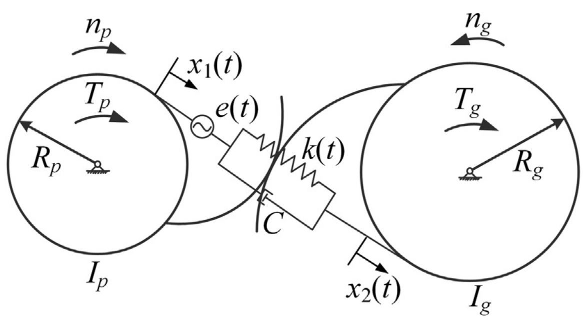

Fig. 1. Mechanical model of spur gear pair.