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Fault feature analysis of planetary gear system with tooth root crack and flexible ring gear rim

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ABSTRACT

Planetary gear transmission has a wide application in different areas due to its advantages such as compactness, large torque-to-weight ratio, reduced noise and vibrations. However, its dynamic responses are much more complex due to the complicated structures and relative motions, which make it difficult in the fault feature extractions at the view point of fault detection. Better understanding on the dynamic features of a planetary gear transmission and the corresponding internal excitation sources will benefit the fault feature extractions. In this paper, an analytical model for mesh stiffness calculation is developed based on the potential energy principle and uniformly curved Timoshenko beam theory, which enables exploring the effects of the tooth root crack fault and the flexible ring gear rim on the dynamic responses. Based on the developed model, the frequency spectrum structures of the planetary gear transmission can be revealed and analyzed theoretically in the presence of tooth crack and flexible ring gear. A case study is performed to demonstrate the effectiveness of the developed model, where the tooth root cracks are seeded in a tooth of the sun, planet, and ring gears. The simulated results indicate that the complicated modulation phenomenon can be observed where the causes of different frequency components can be revealed. This study is expected to be able to give some theoretical guidance on the identification of vibration sources for planetary gear transmissions.

1. Introduction

Planetary gear transmission is a key element of many mechanical transmission systems for power delivery. It has been employed in a lot of industrial applications, such as wind turbine, mills, crushers, power plants, and aerospace field [1,2]. This is due to its advantages of compactness, large transmission ratios, high energy density, low noise and vibration level, as well as high efficiency and so forth [3,4]. As the increasing demand of weight reduction and cost saving, thickness of the ring gear rim of planetary gear set is always deliberately designed to be thin, which is also capable of improving the load sharing among planets and reducing the inaccuracies caused by errors of the internal gear and the carrier [3–5]. The flexible deformation of a thin-rimmed internal/ring gear is likely to alter the operation conditions of the whole power transmission system. Consequently, numerous works have been carried out to investigate the effect of thin-rimmed internal/ring gear on the performance of planetary gear systems.

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Hidaka et al. [6] did experiments to test the displacement away from the basic positions of the sun and the ring gears. Later, they [7] investigated the deflections of a ring gear by finite element (FE) method and theoretical approach, respectively. Satoshi ODA et al. [8] applied the FE method to study the root stress and the rim deformation of a thin-rimmed spur ring gear supported by pins. Abousleiman and Velex [9] developed a hybrid 3D finite element/lumped parameter model to analyze the quasi-static and dynamic properties of planetary/epicyclic gear sets, where the effect of a flexible ring gear was taken into account by using the beam elements for simple structures and the 3D brick elements for complex geometries. Wu and Parker [10] investigated the distinctive modal properties of equally-spaced planetary gear sets by perturbation analysis and a candidate mode method. In their studies, the ring gear was modeled as an elastic body and the other elements were regarded as rigid. Besides, the authors [11] also obtained the vibration modes of unequally-spaced planetary gear sets with an elastic internal gear rings mathematically, where the vibration modes were classified into two groups: one is the rotational mode and the other one the translational mode. Kahraman et al. [5] developed a deformable body dynamic model based on the near-field semi-analytical technique and the far-field finite element method, and then it was employed to reveal the dynamic effects of the gear rim thickness and the number of planets on the gear stresses. The more compliance resulted from the thin-rimmed ring gear will reduce intuitively the mesh stiffness of the internal/ring gear pair. In order to clarify how the internal/ring gear flexibility influences the mesh stiffness which is one of the most important excitations for geared transmission system, Chen et al. [3,4] proposed an analytical model to calculate the mesh stiffness of an internal/ring gear pair with flexible ring gear rim based on the uniformly curved Timoshenko beam theory. The results from these reviewed literatures reveal that the flexible deformation of the ring gear rim could introduce much more frequency component, thus complicating the frequency spectra structure, which makes it more difficult to detect the fault features of the planetary gear transmission set.

Planetary gear transmission set is always operating under harsh conditions such as being constantly subjected to cyclic stresses and external impulsive loads [2]. Occurrence of gear failures is likely to degrade the working performance of planetary gear transmissions, or even to cause catastrophes to the whole machine and the human life. What a pity, there are only few published papers concerning the gear teeth fault on the dynamics of planetary gear set due to its complicated structures.

Chaari et al. [12] applied a simplified square waveform mesh stiffness curve to simulate the effect of the tooth pitting and cracking faults by changing its phase and amplitude, and investigated the vibration features of a planetary gear transmission set. Dhanasekaran et al. [13] concluded that occurrence of a gear tooth crack is due to the fatigue based on the detailed analysis about a crack failure seeded in one tooth of the sun gear in a planetary gear train from the aspects of micro hardness, chemical properties, optical microscopy and scanning electron microscopy. Wu et al. [14] combined CAD models with ADAMS to study the dynamic responses of a differential planetary system with backlash and tooth defects. This method enables the interactions between the "chipped" sun gear tooth and backlash, and it could overcome the geometric simplifications. Chen and Shao [15,16] explored the vibration features of a planetary gear train with a tooth root crack, where a full consideration of tooth root crack seeded respectively in the sun gear, planet gear, and ring gear was made. Later, they [17] also investigated the effect of tooth plastically inclined deformation caused by a cracked tooth on the dynamic performance of a planetary gear transmission train.

In these published papers with respect to planetary gear failures, the internal/ring gear was assumed to be rigid indicating the effect of internal/ring gear flexibilities were ignored which is reasonable when the ring gear rim is thick. Research works about the dynamic fault feature of a planetary gear transmission train with thin-rimmed ring gear are hardly found. In this case, the flexible deformation of the ring gear rim cannot be neglected, which will alter the vibration responses of the planetary gear transmission obviously and complicate the frequency spectrum structure as aforementioned. Investigation on the effect of gear failures on the dynamic responses of planetary gear sets with flexible ring gear is helpful for obtaining deep insights into the identification of the vibration components and their excitation sources.

In this paper, an analytical model for mesh stiffness calculation of a planetary gear transmission set with flexible ring gear rim and cracked tooth is developed based on the uniformly curved Timoshenko beam theory and potential energy principle. Based on this model, how the ring gear flexible deformation and the tooth crack influence the dynamic features of the planetary gear transmission separately and together will be revealed by case studies where the flexible ring gear is supported by equally spaced fixed supports.

This paper is organized as follows: Reviews on the previous literatures about the research work on planetary gear transmission train with flexible ring gear and gear faults are carried out in the segment of introduction. Then, an analytical mesh stiffness formulation of an internal gear pair with deformable ring gear rim and a cracked gear tooth is introduced in Section 2 which is followed by a case study in Section 3 where the dynamic simulation results of a planetary gear transmission train are going to be discussed. Finally, conclusions will be drawn in Section 4.

2. Mesh stiffness of planetary gear with flexible ring gear and tooth root crack

A flexible ring gear will always deform under the action of mesh forces. For example, a schematic of a deformed and undeformed ring gear supported by six supports is shown in Fig. 1. In this figure, the solid circle denotes the ring gear with no load applied and the dashed curve represents the deformed ring gear under the action of mesh forces (F_1, F_2, and F_3). Here, the symbol w_c shows the rotational speed of the carrier loaded by a torque while the sun gear is driven by a driving torque. The compliance resulted from the ring gear rim deformation will soften the mesh stiffness of internal gear pairs, thus leading