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Resultant vibration signal model based fault diagnosis of a single stage planetary gear train with an incipient tooth crack on the sun gear

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ABSTRACT

Planetary gear trains equipped in wind turbine often run under slow speed and non-stationary load condition. The incipient gear faults in a wind turbine gearbox can hardly be detected yet might cause tremendous loss. In order to detect the incipient faults, a resultant vibration signal model is proposed to characterize the faulty features of a single stage planetary gear train working under non-stationary load conditions. For this purpose, an analytical dynamic model is developed. By introducing the crack-induced mesh stiffness and varying load into the dynamic model, the vibration responses of the system are predicted. Based on this, a resultant vibration signal model is developed in the form of weighted summation of mesh vibration signals. With the resultant model, the vibration signals of an example system are simulated and analyzed. The simulation results indicate that varying load and tooth crack make the system's vibration signals become extremely complicated in both time and frequency domains. The incipient tooth crack induced impulse vibration signals are too weak to be identified in the time domain but can be detected from the order spectrum. The simulation results from the resultant signal model are verified by the test rig experimental measurements.

1. Introduction

As a sustainable renewable energy source, wind power generation has gained increasing attentions from industrial and academic societies in recent decades [1]. Wind energy is captured by rotating blades of wind turbine and then transformed into electric energy through a 'speed-up' gearbox. Such a 'speed-up' gearbox often contains a planetary gear train because of the advantages of compact structure, high power density and desirable transmission efficiency. As a typical rotating device operating at slow speed and non-stationary loading condition, wind turbine is vulnerable to gearbox faults. It is reported that the fault of planetary gear train is responsible for more than 21% of downtime of the wind turbine system [2]. Therefore, to prevent the malfunction of wind turbine system, the faults of the planetary gear train in a wind turbine gearbox must be diagnosed before it causes tremendous loss.

Though numerous investigations on fault diagnosis of wind turbines have been conducted in the past decades [3–11], only a few of them were focused on the diagnosis of planetary gearbox train in wind turbines [7–11]. Compared with its counterpart of fixed-shaft gear train, a planetary gear train claims more complicated structures, gear motions and operation conditions. As a result, the vibration signal features of a planetary gear train are much more complicated than those of a fixed-shaft gearbox. Because of the complicated vibration signal features, the fault diagnosis for planetary gear trains still remains as a challenging issue [4,12]. And it is more difficult to detect incipient faults in a planetary gear train due to their weak yet complex influences on the system's vibration characteristics [13]. Therefore, from the perspective of fault diagnosis, an in-depth understanding of the vibration mechanism of a planetary gear train with incipient faults is required in priority to characterize the faulty features.

In order to have an expert insight into the dynamics of wind turbine gearboxes, different dynamic models have been proposed, ranging from lumped parameter models to multi-body models. In these dynamic models, the wind turbine gearboxes were assumed to work under stationary load conditions [14–18]. Meanwhile, there are some investigations considered the influence of non-stationary load conditions on the dynamics of wind turbine gearboxes [19–24]. For example, Srikanth and Sekhar [22,23] described the dynamic characteristics of a wind turbine drive train by

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considering aerodynamic loads. Mabrouk [24] investigated the vibration responses of a wind turbine gear train under transient aerodynamic torque load conditions.

Compared with abundant studies that focused on the dynamics of healthy planetary gearboxes, the investigations on the vibration features of faulted planetary gearboxes are much less. For example, Kahraman and Chaari [25,26] investigated the effects of manufacturing errors on vibration characteristics of planetary gear trains. Kahraman and his co-workers also explored the influences of surface wear on planetary gear dynamics [27,28]. Cheng [29] proposed a pure-torsional model for a planetary gear train to study the influences of sun gear pitting on the system's dynamic responses. The effects of tooth crack on the vibration features of planetary gear trains are also explored based on different dynamic models [30–35]. There is common thread in these studies that the effects of tooth crack were introduced into dynamic models by modifying the meshing stiffness functions of the cracked gear pair.

However, it is worthy pointing out that establishing a dynamic model and carrying out dynamic analysis are not enough for fault diagnosis of wind turbine planetary gearboxes. In order to capture the faulty features of a planetary gearbox, one needs to establish a vibration signal model that considers the effect of transmission path of realistic vibration signals acquired by transducers installing on the gearbox housing [33–37]. For example, Parra and Vicuña [33] proposed an acceleration signal model to characterize the vibration features in frequency domain for a planetary gearbox working under healthy and faulty conditions. Inalpolat and Kahraman [36] developed a similar vibration signal model for a planetary gearbox. The simulation results obtained from this model were then verified by experimental tests. In these two vibration signal models [33,36], they only considered the mesh vibrations coming from ring-planet pairs while neglected the vibration effects of sun-planet pairs. Realizing this shortcoming, Inalpolat and Kahraman [25] included the dynamic forces of both sun-planet pairs and ring-planet pairs in their improved model. Liang and his co-workers [34,35] adopted a modified Hamming function in their vibration signal model to represent the effect of transmission path and diagnosed the tooth crack in a planetary gear train. They further developed a more comprehensive vibration signal model for the vibration features of a healthy planetary gear train, in which the effects of all vibration sources as well as corresponding transmission paths are included [37].

From the above literature review, it can be found that the previous studies on fault diagnosis of planetary gear trains in wind turbines can be roughly clarified into two groups: one group focused on the dynamic modeling and analyses of a planetary gear train working under varying load conditions without considering the effects of incipient faults; the other group focused on the dynamics-based vibration signal modeling of a planetary gear train having incipient faults without considering the effects of varying load conditions. The investigations on fault diagnosis of planetary gear trains that consider both varying load conditions and incipient faults are quite rare. In view of this, the present study aims to characterize the faulty features of a single stage planetary gear train with incipient tooth crack on the sun gear working under non-stationary load conditions. For this purpose, a lateral-torsional-coupled dynamic model is established to predict the dynamic responses of a single stage planetary gear train under healthy and faulty conditions. Based on the dynamic analyses, a resultant vibration signal model is developed as the summation of weighted vibration signals along the action lines of both sun-planet and ring-planet pairs by considering the effects of transmission paths. Then, a numerical example is used to demonstrate the vibration features of a single stage planetary gear train with incipient crack on the sun gear working under slow-speed and varying load condition in both time domain and frequency domain. In the last, an experimental test rig is set up to validate the simulations.

2. Resultant signal model of a single stage planetary gear train

2.1. Dynamic model of a single stage planetary gear train

A lateral-torsional-coupled dynamic model of a single stage planetary gear train is shown in Fig. 1. The system is composed of one sun gear '*s*', one ring gear '*r*', one carrier '*c*' and N identical planet gears denoted as p_n.

Herein, *Oxy* is defined as the general coordinate system rotating at the speed of the carrier ω_c with x axis passing through the center of the 1st planet. Each component i ($i = s,r,c,\ p_n$) has three degree of freedoms, i.e., two lateral motions (x_i, y_i) and one torsional motion (u_i). The supporting stiffness for each component is represented by a lumped virtual spring with constant stiffness k_{ij} ($j = x,y,u$). The internal and external meshing pairs are represented by virtual spring with time-varying stiffness (k_{rn}, k_{sn}) alone the line of action. The transmission errors of the nth ring-planet and sun-planet pairs are denoted as e_{rn} and e_{sn}. δ_{sn} and δ_{rn} denote the relative displacements along the action lines of sun-planet and ring-planet, respectively. And there are the follows

$$\delta_{sn} = -(x_s - x_{pn})\sin\psi_{sn} + \left(y_s - y_{pn}\right)\cos\psi_{sn} + u_s + u_{pn} - e_{sn} \tag{1}$$

$$\delta_{rn} = -(x_r - x_{pn})\sin\psi_{rn} + \left(y_r - y_{pn}\right)\cos\psi_{rn} + u_r - u_{pn} - e_{rn} \tag{2}$$

where $\psi_{sn} = \psi_n - \alpha_s$, $\psi_{rn} = \psi_n + \alpha_r$. α_s and α_r are the meshing angles of the external and internal gear meshes. $\psi_n = 2\pi(n-1)/N$ is the circumferential position angle of planet n around the sun, N is the total number of planets.

By using the 2nd Newtonian law, the differential equations of motion of the planetary gear system can be derived as the follows.

The equations of motion of the sun gear is

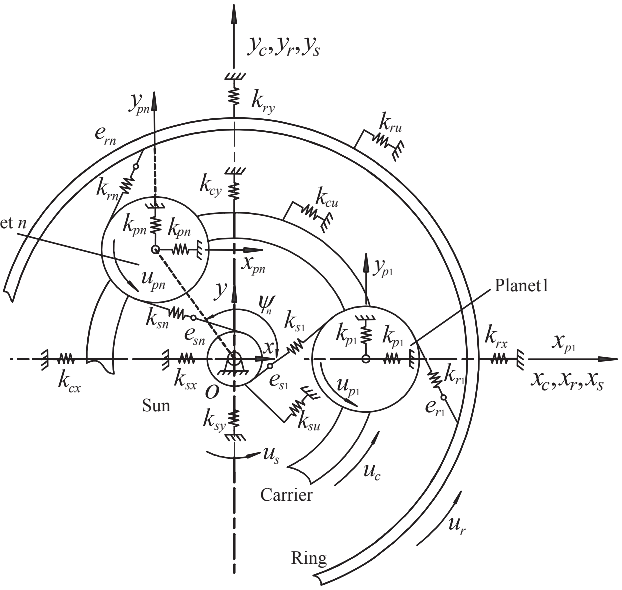

Fig. 1. Dynamic model of a single stage planetary gear train.