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Fault mode analysis and detection for gear tooth crack during its propagating process based on dynamic simulation method

Liming Wang, Yimin Shao *

State Key Laboratory of Mechanical Transmission, Chongqing University, PR China

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ABSTRACT

Gearbox is one of the most important parts of rotating machinery, therefore, it is vital to carry out health monitoring for gearboxes. However, it is still an unsolved problem to disclose the impact of gear tooth crack fault on gear system vibration features during the crack propagating process, besides effective crack fault mode detection methods are lacked. In this study, an analytical model is proposed to calculate the time varying mesh stiffness of the meshing gear pair, and in this model the tooth bending stiffness, shear stiffness, axial compressive stiffness, Hertzian contact stiffness and fillet-foundation stiffness are taken into consideration. Afterwards, the vibration mechanism and effects of different levels of gear tooth crack on the gear system dynamics are investigated based on a 6 DOF dynamic model. Then, the crack fault vibration mode is studied, and a parametrical-Laplace wavelet method is presented to describe the crack fault mode. Furthermore, based on the maximum correlation coefficient (MCC) criterion, the optimized Laplace wavelet base is determined, which is then designed as a health indicator to detect the crack fault. The results show that the proposed method is effective in fault diagnosis of severe tooth crack as well as the early stage tooth crack.

1. Introduction

As one of the most important parts of rotating machinery, gearboxes are widely used in the fields of industrial application, petrification and transportation [1]. It is, therefore, of significant to carry out health monitoring for gearboxes.

Unfortunately, due to tough working environment or improper gear design, unexpected gear failures may occur, i.e. tooth crack, tooth pitting even tooth broken, which seriously reduce the reliability of the whole equipment and may cause significant economic losses, even catastrophes [2,3]. Among the common gear faults, tooth crack is usually observed at the tooth root because of excessive loads transmitted and the material fatigue especially, which can reduce transmission accuracy and cause removal and/or plastic deformations on the contacting tooth surfaces [1,4,5].

The occurrences of gear crack will directly weaken the gear mesh stiffness, which has a bad influence on dynamic responses of the gearbox, higher vibration and acoustic emissions are observed. So lots of researchers have been studying the dynamic modeling of gear vibration in order to understand the vibration generation mechanisms and the relationship between crack faults and the changes in the generated signals [6]. Randall [7,8] reported the advantages of simulating faults in machine such as producing sufficient representative signals to train automated fault recognition algorithms, generating signals for faults with different sizes and locations in order to test and compare diagnostic algorithms, and in his work, gear tooth crack and spalling were involved.

* Corresponding author.
E-mail address: ymshao@cqu.edu.cn (Y. Shao).

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Chaari et al. [4,5] proposed an analytical method to quantify the reduction of gear mesh stiffness due to crack, spalling and breakage, and identified the vibration signatures of each tooth fault. Zhou et al. [9] improved potential energy method to calculate the time-varying meshing stiffness, and developed a modified mathematical model for simulating gear crack from root with linear growth path in a pinion. Yang et al. [10] presented an analytical model to study the dynamics of meshing gears with the consideration of gear tooth bending deflection, axial compression, Hertzian contact and Coulomb friction. Tian et al. [11] investigated the steady-state vibration response of a gearbox with gear tooth faults, the relationship between the waveforms of the vibration and the types of local faults of the gear are analyzed. Du et al. [12] introduced a modified transmission error (TE) model to study the effects on the transmission error of variation of tooth body stiffness based on FEM. Howard et al. [13] proposed a simplified gear dynamic model to explore the effect of friction and gear tooth torsional mesh stiffness on the resultant gear case vibration, where the mesh stiffness are derived by FEM. Kiekbusch et al. [14] developed a two- and a three-dimensional FEMs to calculate the torsional mesh stiffness, the results from the 3D model show a good agreement with the results obtained by analytical equations. Pandya et al. [15] pointed out that crack grew following a curved trajectory, and the TVMS in different crack length was calculated based on variable crack intersection angles which are measured between the line joining the crack initiation point to the end point of different crack length and tooth central line. Ma et al. [16] and Mohammed et al. [17] presented several methods to calculate the TVMS for cracked spur gear and compared with FEM, the results show that parabolic curve as a limiting line has a better agreement with the FEM simulations especially for large crack size. In conclusion, the former studies have done a lot of works on analytically modeling of gear tooth crack, however, according to the observation reported by Lewicki [2,18], the location of the initial crack varies in the tooth fillet region and root region, the paths of the crack depth propagation tend to be straight with a slight curvature, as shown in Fig.2(a), most of the aforementioned crack path models degrade when describing these kinds of cracks. Therefore, a new mathematic model is proposed to describe different initial crack locations and crack intersection angles, based on which the gear mesh stiffness affected by the different crack propagating process will be investigated. It is noted in the current study only the location of the initial crack varies in the root region are studied.

The main objective of this paper is to investigate the relationship between different crack propagating level and gear mesh stiffness, and then the influences of gear tooth crack fault on vibration features and vibration mode will be studied, moreover, an new indicator for gear root tooth crack during its propagation process especially at early stage is proposed base on dynamic simulation method. To realize the objective, firstly an analytical model for time-varying mesh stiffness (TVMS) is established with tooth bending stiffness, shear stiffness, compressive stiffness, Hertzian contact stiffness and fillet-foundation stiffness taken into consideration, based on this model the influences of crack fault on TVMS are studied, and stiffness change percentage method is proposed to evaluate the reduction of TVMS as the crack propagating. Then, a 6 degree of freedom (DOF) lumped parameter model for the gear pair is engaged to investigate the influence of the gear mesh stiffness on dynamic responses, in addition, the relationship between the gear mesh stiffness and vibration features in time domain and frequency domain is analyzed. After that, the crack fault vibration mode is studied, based on which a parametrical-Laplace wavelet is chosen to describe the crack fault mode. While, the optimized Laplace wavelet base is derived by the application of maximum correlation coefficient (MCC) criterion. The results show that the proposed method is useful in gear crack fault detection, particularly for the tooth root crack at early stage.

The rest of the paper is organized as follows. Section 2 introduces the tooth crack model, and the time varying mesh stiffness influenced by the crack propagation is studied in this part. Section 3 analyzes the effects of the gear tooth crack on dynamic responses, besides, the relationship between the gear mesh stiffness and dynamic responses in time domain and frequency domain

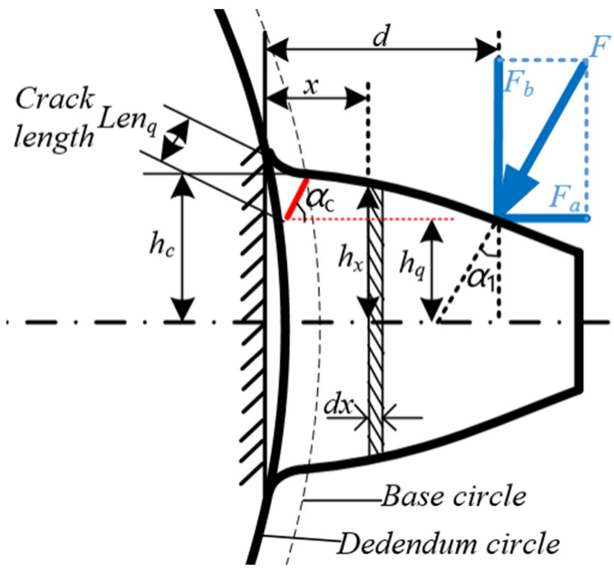

Fig. 1. Sketch of a spur gear tooth.