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Effects of gear crack propagation paths on vibration responses of the perforated gear system

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ABSTRACT

This paper investigates the dynamic behaviors of a perforated gear system considering effects of the gear crack propagation paths and this study focuses on the effects of a crack propagating through the rim on the time-varying mesh stiffness (TVMS) and vibration responses. Considering the effects of the extended tooth contact, a finite element (FE) model of a gear pair is established based on ANSYS software. TVMS of the perforated gear with crack propagating through tooth and rim are calculated by using the FE model. Furthermore, a lumped mass model is adopted to investigate the vibration responses of the perforated gear system. The results show that there exist three periods related to slots of the gear body in a rotating period of the perforated gear. Gear cracks propagating through tooth and rim both reduce the gear body stiffness and lead to reduction of TVMS besides the crack tooth contact moment, and the TVMS weakening for the former is less than that for the latter. Moreover, the results also show that the gear crack propagating through the rim (CPR) has a greater effect on vibration responses than the gear crack propagating through the tooth (CPT) under the same crack level. Vibration level increases with the increasing crack depth, especially for the gear with CPR.

1. Introduction

Gear pair is widely used in power transmission system and its vibration has a great influence on tooth fatigue failure. The gear vibration is closely related to the inherent periodic internal excitations stemming from time-varying mesh stiffness (TVMS) and transmission errors. Many researchers have paid their attention to calculate the TVMS. Analytical method [1–10], finite element (FE) method [11–16] and analytical-FE approach [17,18] have been widely used to obtain the TVMS. Analytical method generally simplifies the gear tooth as a cantilever beam and provides an efficient way to determine the TVMS. However, there exist some difficulties for analytical method to deal with the extended tooth contact problem under large torsion conditions and the weakening effect of crack on the stiffness of the foundation (gear body). In contrast with the analytical method, FE method is time consuming but is close to the actual condition.

Aiming the crack propagating through the tooth, based on the analytical method, many researches [1–10,19–23] studied the TVMS of cracked solid gear (gear without slots). In order to reduce the weight of the gear and improve transmission efficiency, thin rim is usually designed to meet this objective. However, too thin rim may lead to bending fatigue problems, which would be catastrophic for aircraft applications [24,25]. For the thin-rimmed gear, the effects of the crack propagation

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path and the rim thickness on crack paths have been performed [24–28]. The results of these studies can be used to simplify crack propagation paths, which provides some information to calculate TVMS under different crack levels. Lewicki and Ballarini [24] investigated the effect of rim thickness on gear tooth crack propagation and estimated stress intensity factors to determine crack propagation direction. Based on linear elastic fracture mechanics, Zouari et al. [25] investigated the crack propagation in the tooth foot of a spur gear and predicted catastrophic rim fracture failure modes. By using FE method and the boundary element method, Kramberger et al. [26] examined the bending fatigue life of thin-rimmed spur gears of truck gearboxes. Ševčík et al. [27] estimated the effect of a constraint on a predicted crack path. Aiming at spur gears with high contact ratio, Pandya et al. [28] carried out the researches on the crack propagation path, and analyzed the effects of the backup radio and pressure angle on the crack propagation path.

Quasi-static analysis were mainly performed for the gear with the crack propagating through the rim [24–28], and the loaded tooth contact analysis for the healthy gear system is carried out considering the flexibility effect of the gear body [29]. Moreover, vibration responses are also calculated by considering the effects of flexible gear or thin-rimmed gear in [30,31]. Aiming at a flexible gear system, Abbes et al. [30] proposed a novel approach to investigate the dynamics behaviors of the gear system by using the FE method combined with elastic foundation theory. Bettaieb et al. [31] compared the static and dynamic behavior of geared transmissions including flexible components. In their model, a hybrid method is adopted, which combines classical beam elements, elastic foundations for simulating tooth contacts, and substructures derived from 3D FE grids for thin-rimmed gears and their supporting shafts.

The above literatures indicate that the extensive attention has been focused on predicting the gear crack propagation path, estimating the stress intensity factors and calculating the TVMS of solid gear. However, for the perforated gear with crack propagating through the rim, the researches on TVMS and crack-induced vibration responses are still insufficient. Neglecting the effect of the dynamic flexibility of the gear body on the system vibration responses, the main objective of this research is to achieve TVMS of a perforated gear considering the effect of the gear body by FE method, and the system vibration responses are also evaluated by a lumped mass model. In addition, two groups of comparisons of TVMS and vibration responses are also carried out. The first group compares the healthy solid gear with healthy perforated gear, and the second group compares the perforated gears with cracks propagating through the tooth (CPT) and rim (CPR).

2. Time-varying mesh stiffness calculation

Assuming that the cracks appear in driving gear with backup ratio (rim thickness divided by tooth height) of 0.5, crack propagating through the tooth and rim are investigated in this section. The crack is simulated as a parabolic curve starting from the tooth root of driving gear (see Fig. 1). In Fig. 1, q denotes the crack depth, υ the crack propagation direction, subscripts 1 and 2 respectively denote cracks propagating through the tooth and rim, Ψ the crack initial position (in this paper $\upsilon_1=75^\circ$, $\Psi=35^\circ$ for gear with CPT, $\upsilon_2=70^\circ$, $\Psi=35^\circ$ for gear with CPR). The basic parameters of the gear pair are listed in Table 1.

By using Plane183 element based on the plane strain assumption in ANSYS software, a 2D FE model of the gear pair is established to calculate the TVMS. The driving gear is respectively modeled as a healthy solid gear, a healthy perforated gear and a cracked perforated gear. The driven gear is modeled as a solid gear. Here, singularity element is used to simulate the crack tip. In order to obtain TVMS accurately, all teeth are established, and the effect of the extended tooth contact is also taken into account. The accurate transition curve and involute are used for modeling the tooth geometry [22]. For the boundary conditions, the inner ring nodes of both gears are coupled with corresponding master nodes (the geometric center of gear, namely O_1 and O_2), respectively, which means the inner ring nodes have the same behavior with the master node.

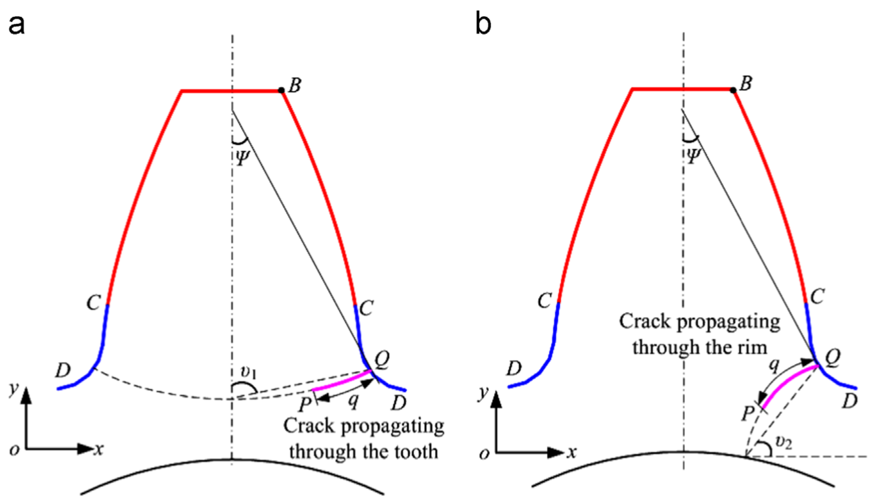

Fig. 1. Schematic of crack propagation path: (a) crack propagating through the tooth (CPT), (b) crack propagating through the rim (CPR).