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Propagation path and failure behavior analysis of cracked gears under different initial angles

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ABSTRACT

Modeling of tooth root crack propagation is one of the research hotspots for gear systems. But the effect of crack initial angle on the crack propagation still requires further analysis. Moreover, the degradation modeling of gears using a realistic crack propagation path is rarely studied. A realistic crack propagation path is essential for the development of gear failure criterion and the accurate lifetime prediction. In this study, a two-dimensional finite element (FE) model of the cracked gear is built through FRANC 2D software, which is used to evaluate the effect of crack initial angle on the crack propagation path. Then, the time varying mesh stiffness (TVMS) of gears is calculated by an improved mesh stiffness model for different propagation paths. After that, vibration responses of gears are simulated using a lumped mass model. By examining the characteristic of the abnormal vibration signals, a degradation model is established to link the crack propagation process and the degradation level. A fracture failure criterion is established based on this degradation model that can represent the gear's functional abnormality at the system level, which is more suitable than the traditional fracture toughness based criterion. The proposed criterion can provide a theoretical and methodological reference for lifetime prediction and the optimization design of the gear system.

1. Introduction

A gear pair as a critical component in machine systems is widely used to transmit power and change velocity. It may suffer from various degradation and failure modes, such as crack, surface wear and corrosion [1,2]. The crack at gear tooth root is the one of the most common failure modes which may be caused by inappropriate operating conditions, materials defects, and manufacturing errors [3].

Crack propagation path directly affects gear lifetime. Ma et al. [3] reviewed the dynamics of cracked gear systems and tooth crack propagation modeling. Lewicki and Ballarini [4] estimated the crack tip stress intensity factor to determine crack propagation direction, and investigated the effect of rim thicknesses on crack propagation path. They pointed out that tooth crack might propagate through the tooth (CPT) or rim (CPR) (see Fig. 1) depending on gear geometry and applied torque on the gear. Lewicki [5] also studied the influence of initial locations on the crack propagation path. The occurrence of rim fractures increased as the initial crack location moved down the tooth root. Ševčík [6] analyzed the effect of constraints on the

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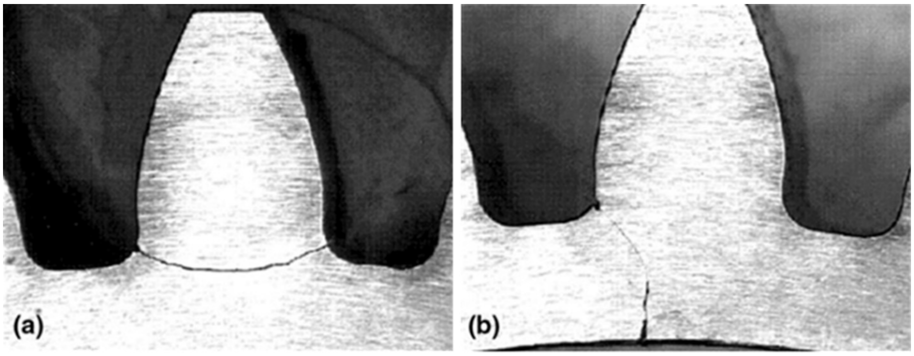

Fig. 1. Schematic of crack propagation along root and rim [4].

predicted crack path, and concluded that the crack propagation direction was affected by the backup ratio which is the ratio of the rim thickness to the tooth height. Pandya et al. [7] analyzed the effect of backup radio and pressure angle on the crack propagation path. The above-mentioned studies did some research on gear tooth crack propagation, but ignored the influence of the initial angle. The effect of gear tooth crack with different inclination angles on the vibration responses was performed in Refs. [8,9]. However, in their studies, the gear crack path was assumed to be a straight line. With this assumption, these studies do not really reflect the crack propagation process. In this paper, the crack propagation paths under different initial angles are investigated without the straight line assumption, and its influence on the lifetime of cracked gears is also studied.

Fig. 1 shows two scenarios of crack propagation paths. The left one propagates through the tooth eventually leading to the tooth fracture. The right one propagates through the rim, which may result in the collapse of the entire gear. The right scenario may lead to more serious catastrophe in aircraft applications [5,10]. Some studies estimated the fatigue fracture time using the stress intensity factor and the Paris' law in the design phase [1,11] or established the relationship between the remaining life and condition monitoring data in the use phase [12–14]. But the degradation modeling of gears using a real crack propagation path is rarely studied, especially considering that the crack propagation path may be heavily affected by crack initial angles. By investigating the crack propagation process, a degradation model is developed in this study to represent gears' degradation with time.

For the tooth root crack fracture, the existing failure thresholds are determined using fracture toughness of the material or empirical crack critical length. Glodež [11] used the fracture toughness of the material as the gear fracture failure criterion to predict the fatigue life of the gear. Zhao [1] assumed that the failure threshold of the cracked gear is the critical crack length which is 80% of the full length. These experience-based failure thresholds were determined ignoring the differences of gear structures and working conditions which may seriously affect the gear's predicted lifetime. Thus, a new failure criterion should be established based on a degradation model which can represent the gear's functional abnormality at the system level. This shortcoming will be addressed in this study.

Many works have been carried out to investigate the dynamics of a gear system with tooth crack. Liang et al. [15] reviewed the dynamic modeling of gearbox faults, and listed four methods for evaluation of TVMS: FE method [16,17], analytical method [18–20], experimental method [21] and square waveform method [22,23]. FE method can model a system closer to real situation because more accurate deformation of gear tooth and fillet foundation can be obtained [24]. In contrast with the FE method, analytical method generally simplifies the gear tooth as a cantilever beam and has a higher computational efficiency to determine the TVMS [25,26]. The limiting line between the crack tip and tooth profile has been modeled as either a straight line [1,20] or a parabolic curve [19,24]. Ma et al. [24] proposed the mesh stiffness model in which a parabolic curve is chosen as limiting line is more accurate compared with the traditional mesh stiffness model in which a straight line is selected as limiting line. Many studies have been conducted to evaluate the TVMS of gears with tooth crack. However, there is no available method to evaluate the TVMS of gears with the crack propagating through the rim. We will propose a model to evaluate the TVMS of gears with crack propagating to the rim.

Lumped parameter dynamic models have been used by many researchers to simulate the vibration signals of a gearbox. Wu et al. [20] adopted a six degree of freedom (DOF) gear model to analyze the effect of tooth crack on the system's vibration. They introduced several statistical indicators to reflect the crack growth level and found the RMS and Kurtosis were good indicators to reflect the change in the vibration response caused by the tooth crack. Hu et al. [27] focused on the analysis of the dynamic responses of a gear-rotor system and the influence of transmission error on simulated signals. Ma et al. [28] investigated the dynamic behaviors of a perforated gear system considering the effects of crack propagating through the tooth and rim, respectively. However, the crack propagation path was simplified as a parabolic curve. Liang et al. [29] simulated vibration signals of a planetary gearbox with considering the effect of transmission path. In this study, the model reported in Ref. [20] will be adopted directly to investigate the crack propagation effect on gear vibration and performance loss.