Engineering Failure Analysis 60 (2016) 405–441

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Frequency spectrum and vibration analysis of high speed gear-rotor system with tooth root crack considering transmission error excitation

Zehua Hu, Jinyuan Tang, Jue Zhong, Siyu Chen *

State Key Laboratory of High Performance Complex Manufacturing, Central South University, Changsha, 410083, Hunan, China

A R T I C L E I N F O

Article history:
Received 24 July 2015
Received in revised form 21 September 2015
Accepted 6 November 2015
Available online 10 November 2015

Keyword:
Tooth root crack
Transmission error excitation
Frequency spectrum
Vibration analysis

A B S T R A C T

A finite element node dynamic model of gear-rotor-bearing system with different lengths of crack by taking the time-varying mesh stiffness, backlash, transmission error excitation, flexible shaft and supporting bearing into account is proposed. The time-varying mesh stiffness of gear-pair with cracked tooth is obtained by applying the improved potential energy method. Due to the periodic features of the dynamic responses of the system when the tooth is cracked, the short term component (tooth profile error and tooth pitch error) and long term component (accumulative pitch error) transmission error excitations are introduced, the RMS values, kurtosis values, and frequency spectrum diagrams of the dynamic response with respect to input speed considering different forms of transmission error excitation are gained. The influences of transmission error excitation and crack length on the dynamic responses are investigated. The effectiveness of the RMS value, kurtosis value and frequency spectrum in the judgment of the crack length is analyzed.

1. Introduction

Gear-rotor system is widely used in the transmission motion and power in transformation, industry and aerospace field. The various kinds of fatigue forms including crack, scuffing, wearing and pitting influence the transmission performance and life of the gear-rotor system a lot. Nowadays, the tooth root crack has become one of the hot issues of the gear fatigue research, focusing on the mechanism of the initiation and propagation of the tooth root crack [1–6], vibration and dynamic response analysis of cracked gear transmission system [7–17] and the diagnosis of the crack fault and prediction of the cracked gear's residual life [18–20]. Among these research contents, the study about the mechanism of crack fault's initiation and propagation is the initial point of the fundamental theoretical issue, the investigation of the fault diagnosis and life predicting focuses on the improvement of the transmission property and avoidance of the dangerous work condition in practical application. Between them, the analysis of the vibration and dynamic responses of the gear-rotor system with cracked tooth plays an important role that can connect the fundamental research and the practical usage. It cannot only deepen the understanding of the basic theory but also give some useful indicators and factors for fault diagnosis of cracked gear-rotor system.

In the analysis of the vibration and dynamic response of the gear-rotor system with tooth root crack, there exists three main contents, namely, the calculation and obtainment of the accurate time-varying mesh stiffness considering the cracked tooth, the development of the reasonable dynamic model of gear-rotor system, and the investigation method of the simulated results. The calculation of the mesh stiffness of the cracked gear pair is very mature and accurate after these years' research, giving some

* Corresponding author.
E-mail addresses: zhhucsu@csu.edu.cn (Z. Hu), jytangcsu_312@163.com (J. Tang), jzhong@csu.edu.cn (J. Zhong), chsy1324@csu.edu.cn (S. Chen).

http://dx.doi.org/10.1016/j.engfailanal.2015.11.021
1350-6307/

generalized methods, such like analytical method, FE methods, combined analytical-FE approaches and experiment approaches. Wu and Tian [7,8] took the Hertzian, bending, axial compressive, and shear energy into account and gained the analytical meshing stiffness with potential energy principle and verified its accuracy based on FE model. Based on the corrected tooth foundation deformation, Chaari et al. [9] introduced the fillet-foundation deflection into the computation of the meshing stiffness, obtained the reduced time-varying mesh stiffness caused by the tooth crack and compared the curves with the results obtained by finite element method (FEM). Chen et al. [13] proposed the meshing stiffness calculation method of a spur gear pair with tooth profile modification and cracked tooth, the tooth crack propagations along tooth width and crack depth were analyzed and mesh stiffness with different crack lengths and depths were gained. Considering the flexibility between the root circle and base circle, Wan et al. [21] talked about the relationship of the base circle radius and the root circle radius based on different number of gear teeth, and proposed an improved energy method to calculate the mesh stiffness. Considering the accurate transition curve, the misalignment of gear root circle and base circle, Ma et al. [16] developed an improved model to obtain the mesh stiffness of the perfect and cracked gear pair and validated the model by the finite element method.

Extensive investigations have been done about the development of the dynamic model of the gear-rotor transmission system with tooth crack. Zhou et al. [12] established a 16 DOF (degree-of-freedom) dynamic model of a spur gear system with different levels of crack and studied the dynamic response. Chen et al. [14] proposed a dynamic model of a one-stage planetary gear set with 21 DOF to investigate the internal gear tooth root crack and the influences of the crack on the system vibration. The former given dynamic models focused only on the gear transmission pair, ignoring the effects of other parts of the whole rotor system. However, the flexible shaft, supporting bearings and rotor element also influence the system vibration a lot, which can be taken into account in a finite element model of the gear-rotor-bearing system. In order to analyze the system vibration more reasonably, Ma et al. [22] proposed a finite element model of a spur gear with tip relief by applying ANSYS software, calculated the time-varying mesh stiffness under different amounts of tip relief and analyzed the effects of tip relief on lateral–torsional coupling vibration responses of the system. Ma et al. [17] gave a finite element model of a cracked gear-rotor system considering the effects of the extended tooth contact and crack on meshing stiffness and analyzed the simulated and measured signals by applying empirical mode decomposition. Considering the effects of geometric transmission error, bearing stiffness and the gear mesh stiffness, Wan et al. [21] developed a FE model considering the effect of the coupled lateral and torsional vibrations to analyze the vibration responses of a gear-rotor system with tooth root crack.

Many parameters and factors, such as RMS, kurtosis, and power spectrum, are used to diagnose and evaluate the gear crack fault based on the simulated vibration signals and validated very effective in the detection and evaluation of crack level. Mohammed et al. [19] presented an investigations of the performance of the statistical fault detection indicators (the RMS and kurtosis) for three different series of crack propagation scenarios, these indicators showed a significant change when the crack become deeper. Chen et al. [23] developed a coupled planetary gear dynamic model with crack model and investigated its dynamic features in time and frequency domains. The sidebands around the mesh frequency and its harmonics in the frequency spectrum were observed and studied. Ma et al. [24] investigated the dynamic behaviors of a perforated gear system considering effects of the gear crack propagation paths and focused on the frequency comparison of the vibration responses. Mohammed et al. [25] studied gear tooth crack detection by investigating the natural frequencies and by performing time-frequency analysis of a 6 DOF dynamic model, the relationship between the crack size and the mesh-stiffness-dependent frequency components was obtained. However, considering the periodic features of the impulse response caused by the cracked tooth in the vibration signal, the effects of the different periodic excitations caused by the tooth profile error, the base pitch spacing error, and the accumulative pitch error on the dynamic responses of the gear-rotor system with different lengths of crack are investigated rarely. Ma et al. [26] recently gave a comprehensive review on the dynamics of cracked gear systems, according to the conclusion, it is important to develop a reasonable dynamic model for numerical simulation.

Based on the analysis of the above-mentioned researches, the main objective of this paper is to develop a more accurate finite element model of cracked gear-rotor-bearing system and study the relationship between the dynamic responses and the periodic transmission error excitation. Section 2 gives out the time-varying mesh stiffness of the gear pair with different lengths of crack based on the improved potential energy principle. Section 3 develops a finite element node model of the gear-rotor system considering the flexible shafts, supporting bearing and meshing gear pair. The time-varying mesh stiffness, backlash and transmission error excitation are introduced in order to simulate the meshing gear pair more reasonably. Section 4 mainly focuses on the analysis of the dynamic responses of the gear-rotor system and the influences of different transmission error excitations on simulated signal, by applying the RMS, kurtosis, and frequency spectrum with respect to the input speed of pinion. Section 5 draws the main conclusions of the simulation results of the gear-rotor system with different lengths of crack.

2. Calculation of time-varying mesh stiffness

2.1. The improved energy method

For the gear-rotor-bearing system, the time-varying mesh stiffness is the main cause of the gear vibration, the calculation and analysis of the mesh stiffness is the basic issue of the vibration investigation.

Yang and Lin proposed a basic potential energy method to analytically model and calculate the mesh stiffness with perfect teeth, with only considering the engaged teeth and assuming all other elements to be perfectly rigid [27]. The total potential energy stored in the meshing gear system includes three components: Hertzian energy U_h, bending energy U_b, and axial compressive energy U_a. Tian took the shear energy U_s into account in 2004.