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Fault feature analysis of cracked gear based on LOD and analytical-FE method

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ABSTRACT

At present, there are two main ideas for gear fault diagnosis. One is the model-based gear dynamic analysis; the other is signal-based gear vibration diagnosis. In this paper, a method for fault feature analysis of gear crack is presented, which combines the advantages of dynamic modeling and signal processing. Firstly, a new time-frequency analysis method called local oscillatory-characteristic decomposition (LOD) is proposed, which has the attractive feature of extracting fault characteristic efficiently and accurately. Secondly, an analytical-finite element (analytical-FE) method which is called assist-stress intensity factor (assist-SIF) gear contact model, is put forward to calculate the time-varying mesh stiffness (TVMS) under different crack states. Based on the dynamic model of the gear system with 6 degrees of freedom, the dynamic simulation response was obtained for different tooth crack depths. For the dynamic model, the corresponding relation between the characteristic parameters and the degree of the tooth crack is established under a specific condition. On the basis of the methods mentioned above, a novel gear tooth root crack diagnosis method which combines the LOD with the analytical-FE is proposed. Furthermore, empirical mode decomposition (EMD) and ensemble empirical mode decomposition (EEMD) are contrasted with the LOD by gear crack fault vibration signals. The analysis results indicate that the proposed method performs effectively and feasibility for the tooth crack stiffness calculation and the gear tooth crack fault diagnosis.

0. Introduction

As the most important mechanical components, gears are widely used in industry mechanical equipment, such as aviation, automotive, power machinery. With the rapid development of production technology, due to their growing applications, the gear vibration monitoring for fault detection and diagnosis has been increasingly investigated. As is known to us all, many researchers are investigating the use of dynamic modeling of gearbox vibration to ascertain the effect of different types of gear train damages on the resultant gear case vibration [1]. The reason is that fault severity of gear tooth is usually related to dynamic parameters. A lot of research work of gear fault has been done by establishing dynamical simulation model [2].

According to the dynamic model, as an important vibration motivation in the gear system, the time-varying mesh stiffness (TVMS) directly affects the dynamic behavior of the gear [3,4]. Therefore, the calculation method of gear mesh stiffness

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has profound significance on failure mechanism of gear. With the development of the gear failure mechanism theory, a lot of calculation methods for gear mesh stiffness, such as finite element model (FEM) [5], analytical method (AM) [6] have been applied to the gear failure mechanism field. Sirichai et al. [7] used FEM in order to quantify the gear mesh stiffness reduction due to the presence of tooth crack fault. Xue et al. [8] presented an improved FEM method for calculating gear mesh stiffness with varying gear centre distance. FEM is an efficient tool for calculating mesh stiffness, the calculation result is more close to the actual situation, because it not only handles complex gear load cases and boundary conditions, but also takes into consideration the tooth profile error caused by manufacturing and assembly errors, deviation of tooth profile [9]. However, it also has a problem of computation complexity, especially in cases where require mesh refinement and accurate modeling [10]. Compared with the FEM, many research studies have been performed to develop AMs for investigating the TVMS of faulty gears. These AMs can offer a simple and effective way to evaluate the TVMS. Therefore, in recent years, AM has been often used to calculate the gear mesh stiffness, especially under tooth damage conditions such as crack and spalling. Yang and Lin presented an analytical model for calculating TVMS by adding bending deflection, axial compression with Hertzian contact [11]. Wu et al. [12] presented a refined model for calculating the total accuracy mesh stiffness based on bending, axial, Hertzian and shear mesh stiffness values for a pair of spur gears which contains a healthy gear and a pinion with cracked tooth. The crack levels were established from 0% to 80% of the theoretical cross-tooth crack size. Chaari et al. [13] proposed a novel AM for calculating the gear mesh stiffness reduction due to the presence of tooth crack depth propagation. This model was further improved by Chen et al. [14] and they proposed an improved AM by considering the fact that crack propagates along tooth width and depth for calculating TVMS. Ma et al. [15] presented an AM for establishing fault model with nonlinear contact stiffness and tooth spalling defect, and then studied the effect of this model on the TVMS and dynamic response.

However, their analytical equations are inconvenient to use. Their methods were based on the assumption that a gear tooth is a non-uniform cantilever beam. In this case, for TVMS calculation, it is very difficult to accurately reflect local tiny transformation, and it is hard to consider the factors such as assembly and installation errors [3]. In this paper, an analytical-FE approach is proposed which retains all advantages of the FEM and AM and overcomes their drawbacks as well. In this approach, the stress intensity factor (SIF) is introduced to assist the calculation of tooth crack mesh stiffness. As an important characteristic parameter in linear elastic fracture mechanics, SIF is used to determine stress distribution intensity near the crack tip and it can also reflect the effect of crack shape, loading, crack size and geometry on severity of crack. On the one hand, it has a very significant effect on calculating the TVMS of faulty gear, on the other hand, it can offer a simple and effective way to calculate the TVMS under most conditions.

In the research field of gear fault diagnosis, vibration analysis method serves as an important part in gear fault diagnosis technologies. It can be summarized as three steps: acquisition and preprocessing of vibration signal, fault feature extraction [16], and fault pattern recognition [17]. When a pair of gears operate with faults, its dynamic behavior always appears to be non-stationary and nonlinear, and the vibration signals will also present the same characteristics. Therefore, a signal decomposition method is employed to deal with signals before extracting feature parameters. By decomposing the original vibration signal into several components, which contain different characteristic information of the original vibration signal with different bands, the interference or coupling of the signal characteristic information can be reduced, and the effective separations of fault features of the signal can also reflect the essence of fault information better.

The mainly used signal decomposition methods include wavelet analysis [18], empirical mode decomposition (EMD) [19], ensemble empirical mode decomposition (EEMD) [20]. However, these method have some drawbacks. Firstly, the wavelet transform is a non-adaptive signal processing method, which requires to preset decomposing layers and wavelet basis. Secondly, the EMD has frequency or scale mixing, boundary effects and other problems [21]. In 2005, a new time-frequency analysis method, which was called local mean decomposition (LMD), was put forward and applied to process non-stationary and nonlinear signal by Smith [22]. In 2006, intrinsic time-scale decomposition (ITD) was proposed [23]. In 2013, another novel signal decomposition approach called local characteristic-scale decomposition (LCD) was proposed [24]. As an improvement of EMD, LMD, or ITD, or LCD, it also has the problem of mixing-mode [25], distorted components and time-consuming calculation [26].

Based on the concept of Intrinsic Mode Function (IMF) [19] as well, a novel signal decomposition approach called local oscillatory-characteristic decomposition (LOD) is proposed in this paper. Similar to the EMD, a complex signal can be decomposed into several Mono-oscillation components (MOCs) and a residue signal by using the LOD. Because of three special decomposition algorithms, LOD has the ability to overcome the time-consuming problem and iterative problem. Therefore, the LOD method will be superior to EMD and its modified methods.

In summary, the new fault feature analysis approach of gear tooth crack which incorporates the LOD and analytical-FE is put forward as follows. Firstly, the tooth crack mesh stiffness is calculated by using the analytical-FE method. Then, a 6 degree-of-freedom (DOF) dynamic model of a gear system with tooth root crack is established and it demonstrates the major effects of different tooth crack levels on the system vibration responses. Based on the result of dynamic simulation, the relationship between the characteristic parameters and the tooth crack level can be obtained. But, these parameters are based on the assumption of stationary and linearity of the signal generation process. In order to deal with non-stationary and nonlinear vibration signals, the LOD method is applied to analyze the experimental data of a pair of gears with crack fault. Firstly, each fault vibration signal is decomposed into several MOCs by using the LOD method. Then the characteristic parameters of the first few MOCs which contain the main failure information are extracted. Finally, the gear tooth crack level can be