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Effects of gear center distance variation on time varying mesh stiffness of a spur gear pair

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ABSTRACT

Gear center distance variation is one of the most common defects of gear transmission systems. The changes in the gear center distance as well as other faults (e.g. tooth crack, pitting) have a direct influence on the Time Varying Mesh Stiffness (TVMS) which further modifies gear vibration behaviors. Accurately estimating gear TVMS under fault conditions is crucial in gear vibration dynamic simulation. Common methods used to evaluate TVMS are generally based on the assumption that the gear pair is perfectly mounted and that all mesh points are at their theoretical positions. This assumption prevents these methods from modeling deviations in gear center distance. To address this shortcoming, this paper proposes a new gear mesh kinematic model that can evaluate the actual contact positions of tooth engagement with time varying gear mesh center distance. With the proposed kinematic model, the actual TVMS of both healthy and cracked gear teeth are computed under conditions of perfect mounting, constant gear center distance deviation, and also time-varying gear center distance. Numerical simulations indicate that gear center distance variation has a significant effect on gear TVMS. Comparison between the effect of multiple faults and summed individual effects on TVMS indicates that the TVMS modification due to multiple-faults do not appear to combine in a linear manner. The proposed model for actual TVMS enables gear system dynamic models to be used to study the effects of assembly errors, gear run-out errors, shaft bending, and bearing deformation on the vibration behavior of gear transmission systems.

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1. Introduction

Time Varying Mesh Stiffness (TVMS) has received much attention in recent years due to its importance on gear dynamic analysis and fault diagnosis. As is known, the TVMS is a major excitation source of the gear system and its value is modified when a gear fault develops and/or propagates. Therefore, the TVMS provides important information about the instantaneous conditions of gear tooth engagement [1,2]. Changes in the TVMS have a direct influence on the dynamic response of the gear system, and accordingly cause different system vibration behaviors. The characterization of this changed vibration behavior is crucial in transmission optimization during the design stage, as well as detection and diagnosis of gear faults [3,4].

Much research has been carried out to investigate TVMS with or without gear faults. Methods such as the Finite Element method (FE), Analytical Method (AM), AM-FE hybrid method, and experimental methods have been developed and/or validated [5]. The FE method has been widely used to calculate the TVMS of both healthy and cracked gear tooth cases, because of its high

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accuracy and the ability to simulate complex gear tooth geometry[5,6]. Sirichai, et al. evaluated the torsional mesh stiffness of a spur gear pair by a two-dimensional FE method [7]. Ma et al. applied the FE method to simulate the TVMS of spur gears with tooth spalling defects [8]. Zouari et al. predicted the effects of crack size, position, and direction on the behavior of the gear meshing using a three-dimensional FE model [9]. The analysis of successive discrete TVMS values needs to redefine loads and boundary conditions for each contact point. This is not an onerous work if the gears are perfectly mounted, where the gear center distance always equals its theoretical value. However, if the actual center distance differs from the theoretical value because of gear assembly errors, run-out errors, shaft bending, or simply bearing deformation caused by heavy loads, then the actual tooth contact points will be modified. Under this condition, the corresponding evaluation process will need a different finite element model for every modified contact point, which could be difficult and very time consuming to perform [3,6].

Analytical methods (AMs) have been considered to be the most promising approach to evaluating TVMS, and some studies, e.g., those reported in [8,10,11], show that very accurate TVMS values can be obtained using AMs with reduced computation time compared with FE methods. Yang and Lin modeled the gear tooth as a cantilever of variable cross-section starting from the base circle, and then utilized the Potential Energy method (PE), with consideration of Hertzian contact stiffness, bending stiffness and axial compressive stiffness, to calculate the TVMS of spur gear pairs [12]. This work was further improved by Tian et al. [13] and Wu et al. [10] through considering shear stiffness. Later, Zhou et al. [14] and Wan et al. [15] pointed out that the deformation of the gear body should also be taken into consideration. Soon after, Ma et al. [16] and Liang et al. [17] indicated that ignoring the misalignment between the base circle and root circle led to significant deviation from the actual TVMS. This observation prompted them to propose a more advanced PE method based on the gear root circle instead of the base circle. Recently, Ma et al. [5] revised the calculation error of the fillet foundation stiffness during double-tooth engagement, and investigated the effect of extended tooth contact on TVMS [18]. Saxena et al. [19] modified the PE model and studied the effect of angular shaft misalignment and friction on TVMS of spur gear pair. The continuous improvement of the PE method has made it a more accurate analytical tool for evaluating TVMS of spur gear pairs compared with the FE method.

In addition to these methods, Rincon et al. considered the advantages of both AM and FE methods and proposed a hybrid AM-FE method to evaluate TVMS of spur gear pairs [3,6,20]. In this method, the deformations of the mating teeth were resolved into global and local terms and evaluated using the FE method and Hertzian contact theory, respectively. Eritenel and Parker proposed a lumped-parameter model to evaluate the TVMS, which captures partial contact-loss and nonlinear load distribution caused by tooth surface modifications, misalignments, and elastic deflections [21]. Yu and Mechefske [22] proposed an analytical method to study the effects of corner contact (contact outside the normal path of contact) on gear mesh stiffness. Moreover, some experimental methods such as the photo-elasticity technique [23,24] and strain gauge technique [25] were used to measure the actual TVMS in real applications.

Although the aforementioned studies have improved the accuracy in assessing the TVMS of a spur gear pair, most focused on a tooth crack fault and its propagation [26]. For example, the crack path was treated as linear (e.g. [13,27]), curved (e.g. [16,28]), constant depth along the tooth width (e.g. [1,2,5,16]), inconstant depth along the tooth width (e.g. [29–31]), or a more complicated spatial crack where the tooth crack path propagates along both tooth width and profile direction with a non-uniform crack depth, e.g. [32–34]. Few studies have investigated the effect of eccentric errors on the TVMS of spur gear pairs because most of them were based on the assumption that the gear pair is perfectly mounted and that all mesh points are at their theoretical positions. However, ignoring the center distance variation caused by gear faults such as assembly errors, gear run-out errors (also called eccentric errors), shaft bending, bearing stiffness et al. may lead to large deviations between the theoretical and actual tooth contact positions, and thus lead to inaccurate TVMS evaluations. To evaluate the actual TVMS with time varying center distance, a new kinematic model is highly desirable.

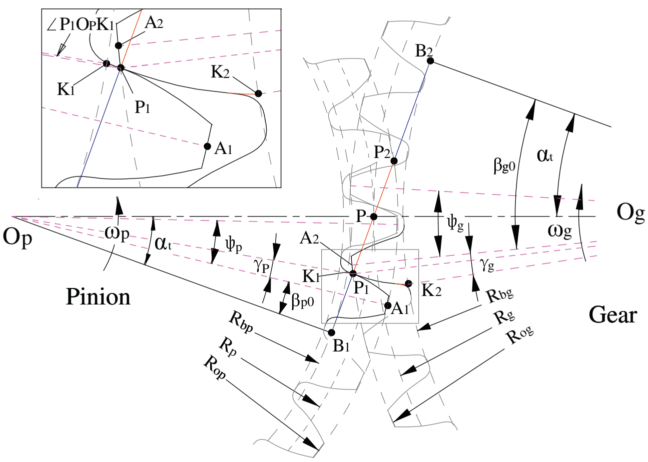

Fig. 1. Meshing process of a spur gear pair (initial position).

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