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An improved time-varying mesh stiffness model for helical gear pairs considering axial mesh force component

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ABSTRACT

An improved time-varying mesh stiffness (TVMS) model of a helical gear pair is proposed, in which the total mesh stiffness contains not only the common transverse tooth bending stiffness, transverse tooth shear stiffness, transverse tooth radial compressive stiffness, transverse gear foundation stiffness and Hertzian contact stiffness, but also the axial tooth bending stiffness, axial tooth torsional stiffness and axial gear foundation stiffness proposed in this paper. In addition, a rapid TVMS calculation method is proposed. Considering each stiffness component, the TVMS can be calculated by the integration along the tooth width direction. Then, three cases are applied to validate the developed model. The results demonstrate that the proposed analytical method is accurate, effective and efficient for helical gear pairs and the axial mesh stiffness should be taken into consideration in the TVMS of a helical gear pair. Finally, influences of the helix angle on TVMS are studied. The results show that the improved TVMS model is effective for any helix angle and the traditional TVMS model is only effective under a small helix angle.

1. Introduction

Gear transmission is one of the most widely used mechanical systems to transmit power and motion. Time-varying mesh stiffness (TVMS) is an important excitation of gear systems, which directly affects the vibration, noise and other dynamics of gear systems. Therefore, how to accurately and quickly calculate the TVMS has become a hotspot among many gear research fields.

Many works have been found on the TVMS analysis of gear pairs. The common methods include finite element (FE) method, analytical-FE method and analytical method [1,2]. FE method is the most popular tool and has a high accuracy to analyze TVMS of gear pairs, which can simulate the actual tooth profile and calculate automatically the contact position. Nevertheless, FE method needs mesh refinements and a large computing resource. Li [3,4] studied the mesh stiffness and stress of a spur gear by FE method, in which tooth profile modification, lead crown relief, manufacturing errors, misalignment error and other factors were considered. Pandya and Parey [5] and Raghuwanshi and Parey [6] analyzed the TVMS of spur gear pairs by FE method considering crack propagation and back-side contact. Wang and Howard [7] analyzed the

Abbreviations: TVMS, time-varying mesh stiffness; IMS, improved mesh stiffness; TMS, transverse mesh stiffness; AMS, axial mesh stiffness; FE, finite element.

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torsional stiffness of a spur gear by FE method. Adaptive meshing had been developed in the region of change. Wei et al. [8] studied the influences of tooth profile deviation on load distributions of helical gears using FE method. Mao [9] developed an accurate transmission error calculation method for a helical gear pair through an accurate nonlinear FE analysis. Micro-geometry modification was studied on the transmission error analysis. The common analytical-FE method includes integral equation method and FE flexibility coefficient method. For the integral equation method [10–13], the gear mesh stiffness was calculated by integrating the contact stiffness and bending stiffness along contact lines, in which the contact stiffness and bending stiffness were calculated by FE analysis. FE flexibility coefficient method is another analytical-FE method. Chang et al. [14] combined local contact analysis and FE method to calculate the TVMS of a gear pair. Effects of gear basic parameters and body parameters on TVMS were also studied.

The analytical method has faster computational efficiency than FE and analytical-FE methods. After many studies, analytical method can also offer accurate results in calculating gear mesh stiffness. In the analytical method, the tooth was simulated as a variable cross-section cantilever beam. The potential energy method was usually used, in which the total energy contains tooth bending energy, tooth radial compressive energy, tooth shear energy, Hertzian contact energy and gear foundation energy [15–32]. The mesh stiffness of a spur gear pair is composed of the tooth bending stiffness, tooth radial compressive stiffness, tooth shear stiffness, Hertzian contact stiffness and gear foundation stiffness. Effects of the tooth profile modification, crack, friction, spalling and other factors on TVMS were also studied in those studies.

In the conventional method of calculating the TVMS of a helical gear system, the slice theory was usually used, in which the helical gear was regarded as some sliced teeth along tooth width direction and the sliced tooth can be regarded as a spur tooth [33–37]. Wang and Zhang [35] developed a helical gear TVMS model by the slice method with tooth profile errors. TVMS, transmission error and stress were studied considering tooth profile errors. Wan et al. [36] calculated the TVMS of helical gears by the accumulated integral method. Effects of the crack, helix angle and normal module on TVMS were analyzed. Based on the previous studies, Feng et al. [37] presented an improved TVMS model of a helical gear pair, in which fillet-foundation coefficient, nonlinear Hertzian contact, modification coefficients and friction coefficients were taken into consideration. An FE model was developed for the model validation, in which the axial degrees of freedom of all nodes were restrained. In the above helical gear mesh stiffness researches, the helical gear was regarded as a series of spur tooth pairs and effects of the axial mesh force on TVMS had not been taken into account. In fact, the axial vibration had been included in most of the studies on dynamic analysis of helical gear systems [38–45]. It revealed that axial vibration should be considered in the vibration analysis of helical systems.

Therefore, this paper focuses on TVMS calculation method for helical gears with axial mesh force component. At first, transverse tooth bending, transverse tooth shear, transverse tooth radial compressive, transverse gear foundation, Hertzian contact, axial tooth bending, axial tooth torsional and axial gear foundation stiffness models are presented, respectively. Then, considering those stiffness components, a rapid TVMS calculation method is established. Finally, the TVMS model of a helical gear pair is validated using three cases and influences of the helix angle on TVMS are studied.

Four sections are concluded in this paper. The TVMS calculation of gear pairs is reviewed in this section. In Section 2, the improved TVMS theory of a helical gear pair is presented. Then, three cases are used to validate the improved mesh stiffness (IMS) model in Section 3. Effects of the helix angle on TVMS are also studied. At last, some conclusions are given in Section 4.

2. Theory

For a helical gear, it has a non-zero angle between the contact line and axial line. As shown in Fig. 1, the mesh force direction is perpendicular to the tooth face. Therefore, the mesh force F of a helical gear can be resolved into the transverse mesh force F_t and the axial mesh force F_a. The transverse mesh force F_t brings the transverse mesh stiffness (TMS), which can be calculated by the "slice method" [33,35,37]. The axial mesh force F_a brings the axial mesh stiffness (AMS), which will be

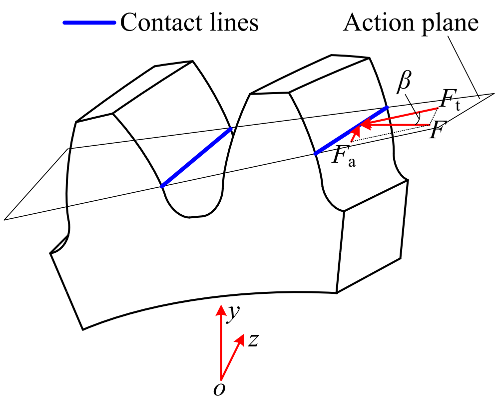

Fig. 1. The mesh force sketch of a helical gear.