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Deformation and meshing stiffness analysis of cracked helical gear pairs

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ABSTRACT

Based on the slice method, a new method is proposed for calculating the time-varying mesh stiffness (TVMS) of helical gears. The proposed method uses the idea of 'offset and superposition' to avoid the repetitive calculation of the TVMS of each sliced gear. Taking the TVMS obtained from the finite element (FE) method as a benchmark, the correction coefficient of the gear foundation stiffness is obtained by the optimization method. Four types of spatial crack are modeled, including addendum non-penetrating crack, addendum penetrating crack, end face non-penetrating crack and end face penetrating crack. The computational efficiency and accuracy are discussed under different crack parameters and crack types. Compared with the FE method and the traditional analytical method, the proposed method agrees well, and its efficiency is higher. For example, the proposed method costs 8 s to calculate the TVMS of helical gears with identical slice profile in one mesh period, while the traditional method and the FE method cost 2 min and 2.5 h, respectively. For the helical gears without identical slice profile, the proposed method is also applicable but the improvement of the calculation efficiency is not evident. The effects of extended tooth contact are ignored in the proposed analytical method, which leads to some errors between the TVMS of the cracked helical gears obtained from the proposed method and the FE method, but the change laws of the TVMS are in consistent.

1. Introduction

Time-varying mesh stiffness (TVMS) is the main excitation source of vibration for gear systems, and it will lead to more severe vibration under crack conditions. It is very important to accurately calculate the TVMS of cracked gear pairs for the vibration prediction and model-based crack fault diagnosis [1–3]. Most analytical methods for calculating TVMS of spur gears are based on the potential energy method in which the gear tooth is assumed as a non-uniform cantilever beam clamped on the base circle. In early studies, the mesh stiffness of the gear only involves the contact stiffness, the bending stiffness and the axial compressive stiffness [4]. In subsequent studies, the analytical method is improved by introducing the shear stiffness and the fillet-foundation stiffness [5–8]. Some other improvements related to the tooth stiffness [7,9,10], the extended tooth contact (known as corner contact) [11–14], the

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nonlinear Hertzian contact stiffness [11,15] and the revised foundation stiffness during double-tooth engagement [11,16] are also carried out. For example, the error between the assumptions of tooth clamped on the base circle (traditional analytical method) and the root circle (improved analytical method) is revised using the real transition curve between the involute starting point and the root circle [7], the circular arc [9], the extended involute [10].

Compared with spur gears, the total length of the contact line of helical gears changes smoothly, so the abrupt changeover of mesh stiffness can be avoided. More and more attentions are focused on the meshing characteristics of the helical gears. Cai [17] presented an empirical formula for calculating the TVMS of helical gears, but his method did not cover the influence of the gear foundation. The TVMS of helical gears is approximately proportional to the length of the contact line, and the TVMS of the helical gear can be acquired approximately by this characteristic [18,19]. The slice method, in which the helical gears are assumed as the superposition of sliced spur gears along the face width direction, is proposed to facilitate the calculation of the TVMS of helical gears [20–26]. It is pointed out that if the slice number is big enough, the slice method is enough accurate for the calculation of TVMS of helical gears [25]. Taking the elastic coupling between slices into account, Ajmi and Velex [21] proposed a method to make the slice method applicable to the helical gears with wide face width. Gu et al. [22] combined Fourier series and the slice method and proposed an analytical calculation method for calculating the TVMS of healthy helical gears. His method has a high efficiency but it can only be applicable to healthy gears. Wan et al. [24] combined the potential energy method and the slice method to calculate the TVMS of the helical gears with crack. But the correction of the foundation stiffness is not considered in Wan's method. Wang et al. [25] proposed an analytical method for calculating the TVMS of helical gears considering the tooth tip relief and lead crown, and the load distribution of helical gears was also analyzed. Feng et al. [26] improved Wang's method, considering the influences of the nonlinear Hertzian contact, the friction between tooth flanks and the addendum modification on TVMS.

Based on the TVMS model of healthy gear pairs, some researchers also studied the meshing characteristics under tooth cracks. In this field, the effects of different crack assumptions or crack types on TVMS are focused on, for instance, different tooth-crack types (crack propagation only along crack depth directions [7,27–35], crack propagation along the directions of crack depth and face width [8,24,36–38], crack propagation along the directions of crack depth, face width and tooth profile [39–42]), crack propagation path assumptions including straight lines [27–35] or multiple straight lines [43], plane parabolic curves [7] and spatial curves [38–42], different revisions for crack limiting line [44,45], gear-body cracks [46,47] and the revision of fillet-foundation stiffness with tooth root crack [48].

Above-mentioned studies mainly focus on TVMS of spur gear pairs with crack, and the adapted methods mainly include analytical method [1], finite element (FE) method [16,33,34] and analytical-FE method [15,32]. The analytical method has a high efficiency and a good accuracy and it is mostly used to calculate the TVMS of spur gear pairs. For helical gear pairs, the analytical method is based on the slice method and the related studies mainly focus on the TVMS of healthy gear pairs. The studies on TVMS of helical gear pairs with crack are insufficient [24], especially under complicated spatial crack conditions [49–51] (see Fig. 1). Aiming at this deficiency, this paper mainly focuses on two aspects: (1) a new calculation method is proposed in order to improve the traditional slice method proposed in our previous study [26], and the efficiency and accuracy of the proposed method are verified by comparing with traditional method and FE method. (2) The TVMS calculation method of the helical gears with crack is presented, and the influences of the four different types of the spatial crack on the TVMS are discussed.

The main structure of this paper is as follows: In Section 1, the research status is summarized. In Section 2, a new calculation method of the TVMS of helical gears is introduced and four different types of spatial cracks are involved in the calculation of the TVMS. In Section 3, the efficiency and accuracy of the proposed method are discussed under different crack types and crack parameters. Conclusions are given in Section 4.

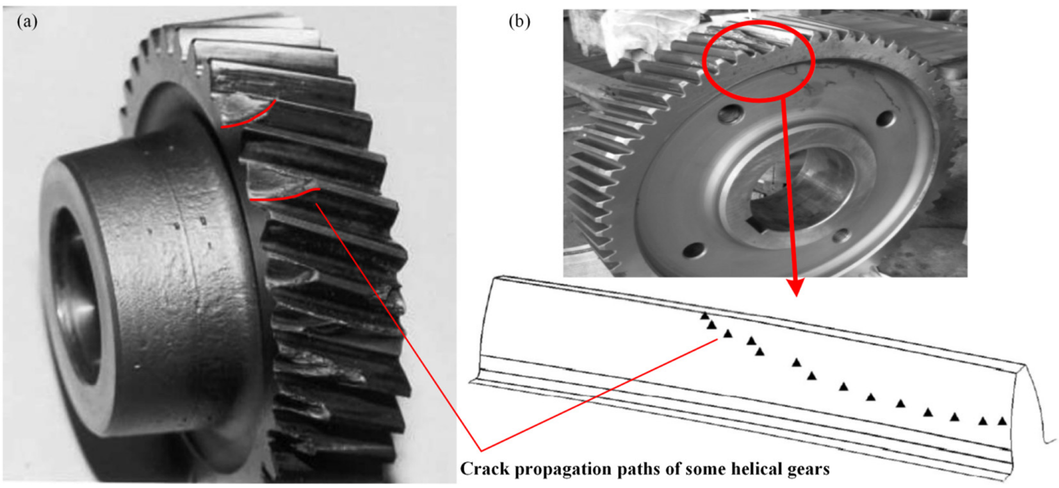

Fig. 1. Crack propagation paths of some helical gears: (a) gear crack in Ref. [49], (b) gear crack in Refs. [50, 51].