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Effects of helix angle, mechanical errors, and coefficient of friction on the time-varying tooth-root stress of helical gears

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ABSTRACT

Accurate estimation of tooth-root stress has been of great interest to researchers and engineers to prevent catastrophic damage of gear transmission system. However, analytical models in AGMA standard are not precise and FEM are mostly focused on the analysis of spur gear pairs. As a result, very little research has been conducted to investigate the time-varying tooth-root stress of helical gears. In this study, effects of helix angle, mechanical errors, and coefficient of friction on the time-varying tooth-root stress of helical gears has been rigorously investigated based on our previous proposed method. 10% tensile stress and compressive stress could be reduced with the increase of helical angle. Coefficient of friction has significant effects on the tensile stress of gear pairs. The peak value of time-varying tooth-root stress shifts from HPSTC to LPSTC due to its influence. The increase of parallel misalignment could reduce up to 18% tensile stress during approach process in double tooth contact condition.

1. Introduction

Gear sets, as one of the fundamental components of rotating machines, are widely used in numerous engineering applications due to the properties of compactness and high torque-to-weight ratios. Failure of gears not only results in the damage of equipment but also leads to potential risk to personal safety. There are two typical failures in gear system, namely pitting on gear surface and tooth breakage at gear root. Pitting depends on fatigue and so is a relatively slow process which in most cases stabilizes whereas tooth breakage at gear root is liable to be rapid and disastrous and is usually an indication of faulty design or faulty heat treatment [1]. Thus, an accurate estimation of tooth-root stress (TRS) in gear development process is of great importance in such cases.

The analytical models (AM) considered in AGMA [2,3] and ISO [4–6] gear rating standards are often used to estimate the TRS of gears prior to manufacturing. Although some enhancement has been provided in previous work based on these AM [7–9], these standards are not precise to perform the exact calculations due to the complex geometries of gear teeth. Furthermore, the use of empirical values for rating factors also decreased the computation accuracy of these models.

Therefore, a growing number of researchers start to examine the TRS by using FEM [10–22]. Aiming at studying the contact characteristics of spur gear pairs, a contact stress analysis of a pair of mating spur gears was conducted by using ten contact cases [10]. A similar method was used to analyze the fillet stress of one-sided involute asymmetric gear [15] and conjugated spur gears [14,20], the contact stress of high contact ratio spur gears [22], and the effects of tooth profile modifications on the bending stress of spur gears [21]. To investigate the crack initiation and bending fatigue of spur gears, the effect of dynamic meshing and contact loading on gear pairs was quantified in Ref. [13] and Ref. [16], respectively. Li presented a series of research to investigate the contact strength and bending strength of spur gears with machining errors, assembly errors, and tooth modifications [17–19]. As concluded in the Ref. [23], although some 3D analysis of helical gears were demonstrated to examine the meshing process [11,12], previous studies mostly focused on 2D analysis of spur gear pairs. The 3D analysis is relatively insufficient, especially the investigation concentrated on the time-varying tooth-root stress (TVTRS) of helical gear pairs.

The aim of this work is to investigate the effects of helix angle (HA), mechanical errors (ME), and coefficient of friction (COF) on the TVTRS of helical gears. This is achieved by using a 3D FEM which was proposed by our previous research [24]. The remainder of the paper is organized as follows: Section 2 gives an introduction of the analytical models of TRS based on AGMA standard, Section 3 explains the mathematical model used to the profile generation of gear pairs, Section 4 depicts the mathematical model of time-varying tooth-root stress, it is used for the calculation and comparison between FEM and AGMA standard, Section 5 elaborates the procedure of finite element analysis, Section 6 presents the comparison between FEM and AGMA standard and effects of HA, ME, and COF on TVTRS, Section 7 draws the conclusions.

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2. Tooth-root stress calculation

According to AGMA 2001-D04 the local TRS σ_F can be computed with [3]:

$$\sigma_F = F_t K_o K_{\vartheta} K_s \frac{1}{bm_t}\frac{K_H K_B}{Y_J} \tag{1}$$

where F_t-transverse load on gear teeth; b-face width; m_t-transverse module; K_o-overload factor; K_{ϑ}-dynamic factor; K_H-load distribution factor; K_s-size factor: considers influence of size of gearing on TRS; K_B-rim thickness factor.

For bending strength geometry factor Y_J, it is calculated from the equation

$$Y_J = \frac{YC_{\psi}}{K_f\, m_N} \tag{2}$$

where C_{ψ}-helical overlap factor (for spur and conventional helical transmissions $C_{\psi} = 1.0$; m_N-load sharing ratio (for spur gears $m_N = 1.0$; for helical gears $m_N = b/L_{min}$); b-effective face width; L_{min}-minimum length of contact lines.

For tooth form factor Y, this factor considers influence of shape of tooth at the TRS, as shown in Fig. 1. This shape is defined in computational procedure by the parameters of the critical section

$$Y = \frac{\cos\beta_w \cos\beta}{\frac{\cos\alpha_{Fen}}{\cos\alpha_{wn}}\left[\frac{6h_{Fe}}{s_{Fn}^2 C_h} - \frac{\tan\alpha_{Fen}}{s_{Fn}}\right]} \tag{3}$$

where α_{Fen}-load angle; α_{wn}-operating normal pressure angle; β-helix angle at the reference diameter; β_w-operating helix angle; C_h-helix factor.

The helix factor C_h is calculated in the following way:

– for spur gears $C_h = 1.0$
– for conventional helical gears

$$C_h = \frac{1}{1-\left[\frac{\omega}{100}\left(1-\frac{\omega}{100}\right)\right]^{0.5}} \tag{4}$$

where $\omega = \arctan(\tan\beta\sin\alpha_n)$.

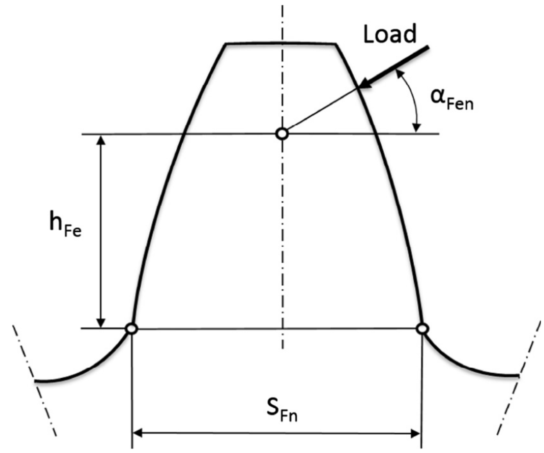

Fig. 1. Critical parameters used in the calculation of tooth form factor.

For stress correction factor K_f this factor considers complex stress state at tooth root and stress concentration caused by the fillet

$$K_f = H + \left(\frac{s_{Fn}}{\rho_F}\right)^L \left(\frac{s_{Fn}}{h_{Fe}}\right)^M \tag{5}$$

where $H = 0.331{-}0.436\alpha_n$;

$L = 0.324{-}0.492\alpha_n$

;

$M = 0.261 + 0.54\alpha_n$

.

3. Profile generation of gear pairs

For the conventional involute gear, the tooth surfaces can be generated by the screw motion of a straight line, as show in Fig. 2. The tooth flank of a left-hand helical gear and the unit normal to the surface can be determined as follows [25,26]

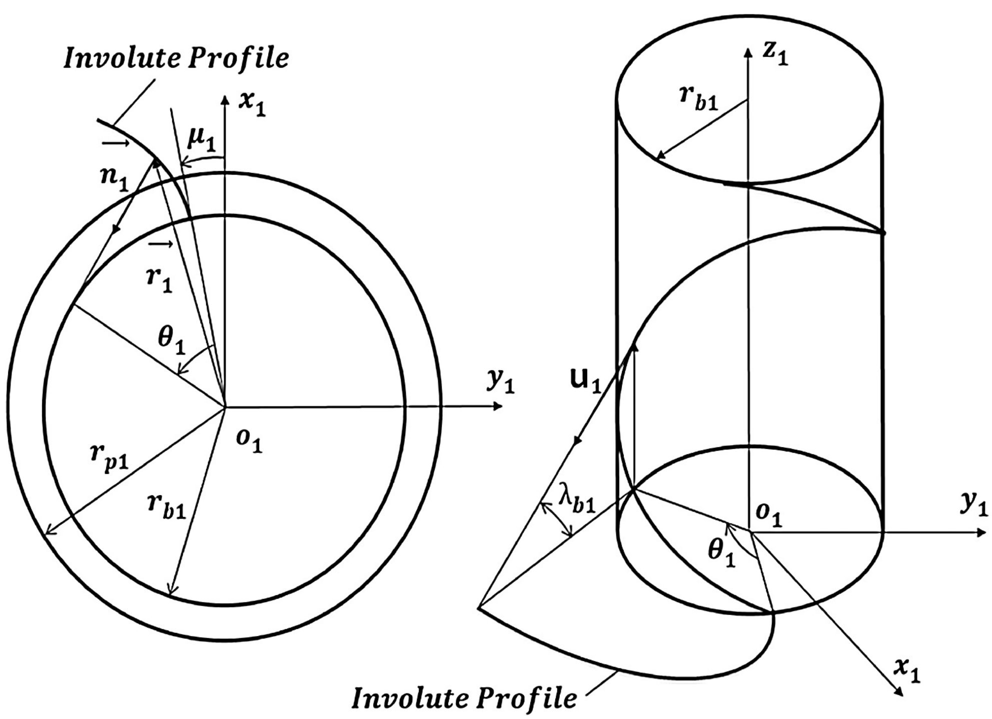

Fig. 2. Cross-section of a left-hand helical gear.