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Design and analysis of double-crowned high-contact-ratio cylindrical gears considering the load sharing of the multi-pair contact

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ABSTRACT

Tooth modification is widely used to reduce noise and vibration. However, the traditional middle-convex tooth modification is likely to cause excessive load concentration; therefore, the contact stress sharply increases. In this study, a new method is presented to reduce the amplitude of loaded transmission error and meanwhile significantly less increase of contact stress is caused. First, the pinion is double-crowned through the modified tooth profile of the rack-cutter and a predesigned transmission error. The novelty of the new method is that the transmission error is predesigned based on the theoretical contact ratio of the gears. Second, a multi-objective optimization model is established to minimize the amplitude of loaded transmission error and contact stress. Ultimately, two examples are presented to test the feasibility of this new method. The results show that the new method is more effective in reducing the amplitude of loaded transmission error and that the contact stress of the new method is much smaller than that of the traditional one. Moreover, the advantages of the new method are further confirmed by comparing the amplitudes of loaded transmission errors and contact stresses of the new and traditional method with the misalignment error.

1. Introduction

Tooth modification that removes small amounts of material from the flank of the gear teeth is commonly used in automotive, marine, aerospace and wind turbine gear transmission systems [1–4]. For the cylindrical gear drive, the pinion and gear tooth surfaces are in a line contact before the tooth modification; after the tooth modification, the line contact is replaced with the point contact. Therefore, the error-sensitivity of the gears can be reduced, and the noise and vibration can also decrease.

The typical tooth modification of cylindrical gears is the middle-convex modification. For example, a tooth is modified by using a predesigned second order parabolic function of the transmission error (TE) [5–8]. These typical methods are called the traditional tooth modification method herein. For low-contact-ratio (LCR) gears, mainly the spur gears, the gear tooth must experience a "double tooth – single tooth – double tooth" meshing process from the time when a tooth comes into

Abbreviations: ALTE, amplitude of loaded transmission error; FE, finite element; HCR, high-contact-ratio; LTE, loaded transmission error; LCR, low-contact-ratio; LSC, load-sharing coefficient; MPC, multi-pair contact; New-mod, new modification; Non-mod, non-modification; Tra-mod, traditional modification; TE, transmission error.

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Nomenclature

a, b	major and minor axes of contact ellipse
a_1	modification parameter for tooth profile modification
K	load-sharing coefficient
M	number of mesh positions in one mesh period
N_1, N_2	tooth numbers of pinion and gear
P	total external load
r_{b2}	radii of base cylinder of gear
S_i	coordinate system i
T_e, ΔT_e	loaded transmission error and amplitude of loaded transmission error
u_i, l_i	surface parameter of Σ_i
$[d]$	final tooth clearances
$[F]$	assembled flexibility matrix
$[M]_{i,j}$	coordinate transmission matrix (from S_j to S_i)
$[p]$	contact loads
$[w]$	initial tooth clearances
$[Z]$	tooth approach values
$\vec{r}_i$, $\vec{n}_i$	position vector and unit normal vector of surface Σ_i
β_b	base helix angle
ΔL_1	parameter of additional translation motion of rack-cutter
$\Delta\gamma$	misalignment angle error
$\Delta\varphi_1$	step of rotation angle of pinion
$\delta\varphi_2$	transmission error
θ_1	rotation angle of generated pinion
σ_H	maximum contact stress
φ_1, φ_2	rotation angle of pinion and gear
${\varphi^0}_1$, ${\varphi^0}_2$	initial rotation angle of pinion and gear

contact to the time when it leaves. The tooth deformation is smaller in the “double tooth” region than in the “single tooth” region. More modification mounts are required in the “double tooth” region to compensate the mounts of tooth deformation to reduce the amplitude of loaded transmission error (ALTE). The ALTE is considered as one important factor of the noise and vibrations of gear transmission systems [9–15]. Therefore, the traditional tooth modification methods are more suitable to LCR gears, mainly for spur gears. For the spur gears, the work of Ma et al. [16,17] was interesting. In these researches, a new mesh stiffness model of spur gears was developed and the evaluation of optimum profile modification curves of profile shifted spur gears had been finished based on the new model.

When the contact ratio increases, the shortcoming of the traditional tooth modification method appears. The middle-convex tooth modification cannot follow the variation of the numbers of the meshing tooth pairs in the meshing process; therefore, the effect of load-sharing of the multi-pair contact (MPC) cannot be involved by using the traditional method for high-contact-ratio (HCR) gears. However, there are many HCR gear drives in machines, mainly helical gears.

In addition, the traditional tooth modification may negatively affect the load-carrying capacity gears [18–21]. Before the tooth modification, the TE of standard involute gears is zero. After the tooth modification, TEs vary at different contact positions. The shared load on the tooth surface is transferred to the positions with small TEs, which likely amplifies the load concentration. Accordingly, the maximum contact stresses of gears increases due to the load concentration. The load-carrying capacity of the gear drive is strongly affected by the contact stresses of the gears [22]. Excessive contact stress can also exacerbate the surface wear, reduce the working life and decrease the gear drive efficiency [23].

The modern requirements of gears are to transmit a high power with comparatively smaller transmission systems and to run reasonably free of noise and vibration. Therefore, the designation of tooth modification need simultaneously reduce the ALTE and contact stress of gears. In the research of Harianto and Houser [24], the noise and the stress of the gears were reduced using the traditional tooth modification. Zhang et al. [25] proposed a new tooth modification approach to reduce the TE and maximum contact stress of double circular-arc helical gears. Artoni et al. [26] developed an optimization methodology to reduce the noise and improve the durability performances of cylindrical gears. Hotait and Kahraman [27] studied the relationships between the dynamic TE and the dynamic stress factor of the spur gear drive. Their studies provided helpful information to bridge the gap between the durability and the noise of cylindrical gear drives. Tesfahunegn et al. [28], Bruyère and Velex [29] studied the effect of the tooth modification on the TE and other criteria such as stress and meshing force. Ye and Tsai [30] proposed a method for loaded tooth contact analysis of HCR spur gears, and the loaded transmission error and the contact stress of the gears were calculated. Ren et al. [31] proposed a new method for cycloid disc tooth correction to improve the carrying capability and dynamic characteristics.