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Research paper

Topography of modified surfaces based on compensated conjugation for the minimization of transmission errors of cylindrical gears

Chao Jia[a,*], Zongde Fang[a], Yongzhen Zhang[b]

[a] *School of Mechanical Engineering, Northwestern Polytechnical University, 127 West Youyi Road, Xi'an, 710072, China*
[b] *School of Materials Science and Engineering, Henan University of Science & Technology, 263, Kaiyuan Avenue, Luoyang, China*

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ABSTRACT

In order to reduce the peak to peak transmission error (PPTE) during the design of tooth surface modifications of cylindrical gears, a new approach is proposed based on compensated conjugation, and procedures for creating the mathematical models of the modified tooth surfaces are exhibited. The core principle is that conjugation impaired by the loading condition can be compensated by adjusting the intentional transmission function. Firstly, the controllable function of transmission error (TE) is predesigned based on the loaded transmission error (LTE) of standard involute gear pairs; then, the function of ideal TE is determined by optimizing PPTE. Secondly, if the gear-pair is under an unfavorable supported condition, a further longitudinal correction is still required to reduce the error sensitivity, improve the load distribution on tooth surfaces, and eliminate the harmful edge-loading. Ultimately, two examples are presented to test the feasibility of this new approach. The final results show that perfect transmission (PPTE $< 0.01''$) can be achieved by introducing the ideal TE, and reductions in PPTE are significant over a wide range of loads; after further longitudinal modification, the LTE can be still effectively compensated by the introduced TE.

1. Introduction

It is well accepted that one of the most important factors that influence gear vibrations and running noise is TE, which is defined as the deviation from perfect motion transfer between a driving (pinion) member and a driven (gear) one [1,2]. Tooth contact analysis (TCA) is a typical technique used to predict the shape of TE and the shift of contact pattern [3–5]. However, the influence of the load is ignored in TCA model. When the gear pairs are under a heavy load, the tooth deformation and load distribution on the gear tooth surfaces will affect the meshing characteristics. Consequently, the TE may differ from what is expected from TCA. Lately, loaded tooth contact analysis (LTCA) has been developed to simulate real properties of meshing tooth surfaces [6–11]. Based on finite elements and classical Hertz theory, the loaded TE (LTE) and load distribution on tooth surface is derived. The LTE is a periodic function, which fluctuates with time. The magnitude of LTE fluctuation is known as PPTE. For cylindrical gears, tooth modification is widely used to compensate the high PPTE. Over the last thirty years, a number of research works have been conducted in order to understand the role of tooth

* Corresponding author.
E-mail address: jiachao8507@163.com (C. Jia).

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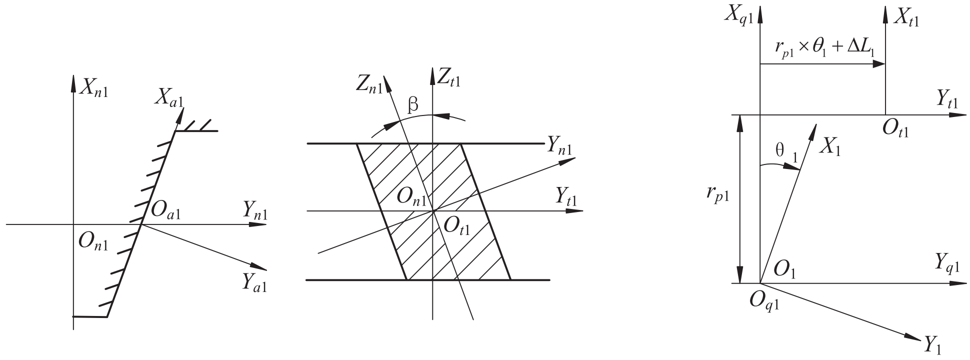

Fig. 1. The pinion generated by rack-cutter.

modifications in relation to reducing noise and vibrations. In 1982, Terauchi et al. [12] found that the dynamic load was decreased and noise was reduced after tooth modification. Tavakoli and Houser [13] in 1986 and Simon [14] in 1989 developed procedures to optimize profile modifications. Weck and Mauer [15] published their simulation results and pointed out that the gear characteristics could be improved by even simple geometric modifications of the tooth surface which didn't require advanced manufacturing methods. Maatar and Velex [16] analyzed the influence of tooth shape modifications on the dynamic behavior of single stage narrow-faced helical gears based on a 3D model with 36 degrees. Afterwards, the idea about perfect plane of action of helical gears was introduced by Rao and Yoon [17], and an approach of minimizing the TE was presented. In recent years the studies on tooth modification progressed further. Fonseca et al. [18] optimized the harmonics of the LTE using the model of Tavakoli and Houser [13] by introducing a genetic optimization algorithm. A methodology for obtaining optimum gear tooth micro-topographies was presented by Harianto and Houser [19] in 2007, Artoni et al. [20] in 2013 to minimize the PPTE and stress. Yu and Ting [21] presented a rigorous theory on compensated conjugation for a gear pair TE balance. And the tooth flank modification was derived from the modification of rack-cutter based on the screw theory and differential geometry. To minimize transmission error variations, Bruyere et al. [22–24] provided an analytical formulation for optimum profile modification including correction factors. The response surface methodology was used by Korta and Mundo [25] for gear optimization.

The methods of tooth modifications in above researches have been heavily focused on the material removal from tip or root, but without any change on the other regions of tooth surfaces, which are collectively called traditional methods herein. The corresponding TE function is always displayed as a convex curve by the tooth modification of the traditional methods. For standard involute gear pairs, if the gears contact ratio is less than two (usually for spur gears), one gear tooth need to go through a “two pairs - one pair - two pairs” meshing process. The tooth deformation in two-pair region is smaller than that in one-pair region. With the traditional methods, the values of tooth modification in two-pair region are more than that in one-pair one. Therefore, for low contact ratio gears, the PPTE can be effectively compensated by the traditional methods. Nevertheless, for the high contact ratio gears, for example, the contact ratio is greater than 2 and less than 3, one gear tooth need to go through a “three pairs - two pairs - three pairs - two pairs - three pairs” meshing process during the engagement. The LTE change its wave form according to the instantaneous number of meshing tooth pairs. In this case, the corresponding wavelike LTE is difficult to be compensated by the tooth modifications of the traditional methods.

In this paper, a new method is created using a controllable transmission function to guide the tooth surface modification. And the exact amounts of correction needed for a perfect transmission can be derived. An intentional TE will be the key point of tooth modifications. A deviation can be made between the ideal transmission and the original one by introducing an intentional ideal TE to the original conjugation, which will result in the ideal conjugation modification and consequently exert an influence on LTE. Then, the theory of compensated conjugation is established. Because the tooth modification is based on the transmission function rather than the specific geometry, the new method can be used for gears not only with a high contact ratio, but also with a low contact ratio. Based on the new method, the LTE in helical gears can almost have no variations, which has not been accomplished in most previous literatures. Moreover, after a further longitudinal modification, the PPTE could increase only slightly.

2. Tooth contact analysis and loaded tooth contact analysis

2.1. Generation of pinion tooth surface Σ_1

As depicted in Fig. 1, the rack-cutter Σ_{t1} generates the pinion. During the generation, the rack-cutter performs a translational motion while the pinion performs a rotational one. In this research, the pinion surface is a modified surface whose deviation from the standard involute tooth surface is controlled by the intentional designed TE and the further longitudinal modification (further details are given below in Section 3). Relations between the motion of the rack-cutter and pinion