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Data-driven operation and compensation approaches to tooth flank form error measurement for spiral bevel and hypoid gears

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ABSTRACT

In the actual design and manufacturing of spiral bevel and hypoid gears, the real tooth flank form geometry inevitably deviate from their theoretical or master target one, due to machine tolerances and systematic flexibility, heat treatment distortions, variation of cuttings forces and other noise factors. This deviation in normal direction is tooth flank form error which can cause some detrimental effects on tooth contact performances. Particularly, once the edge contact or highly concentrated stresses occurs, it will result in noisy operation and premature failure. This paper presents an accurate systematic CMM measurement method to prescribe and data-driven control the tooth flank form error. Firstly, the accurate measurement positioning is developed as an important step in whole measurement. And then, a data-driven programming is performed to prescribe a flank grid in CMM measurement. Where, this programming includes: (i) UMC machine settings are used to establish a universal tooth flank model, (ii) NURBS fitting and stitching approach is employed to accurate explicit flank expression, and (iii) flank parameterization using the steepest descent method with Newton step is proposed to identify flank grid points. Moreover, to distinguish with the conventional methods, a high-order machine setting modification considering residual tooth flank form error is proposed to get a flexible compensation of tooth flank form error. Given numerical test can verify the proposed methods.

1. Introduction

1.1. Motivation

Spiral bevel and hypoid gears are widely applied in aircraft engine and automotive reducer for transformation of the rotation and torque between intersected axes. In their actual design and manufacturing, the real tooth flank form geometry inevitably deviate from their theoretical or master target one, due to machine tolerances and systematic flexibility, heat treatment distortions, variation of cuttings forces and dynamic effect from high speed cutting or grinding [1]. This tooth flank form error can cause some detrimental effects on tooth contact performances that unfavorable displacement of tooth contact pattern, increase of transmission error amplitude. Particularly, once the edge contact or highly concentrated stresses occurs, it will result in noisy operation and premature failure [2]. In the development process of spiral bevel and hypoid gear technology, a machine setting modification technique was usually employed to improve manufacture accuracy. Actually, the modification is a flexible compensation to tooth flank form error, in form of approximation to match a target flank which is predesigned tooth flank form error by applying measurement of CMM [3]. Its final target is the accurate determination of a set of machine settings which can be provided for the actual industrial manufacturing. More recently, with state-of-the-art CNC technology, UMC has been applied by establishing additional freedoms for modifying tooth form error flank in modern gear industry [4,5]. Machine settings modification technique [6] considering the mathematical relationships between their components and universal machine settings [7,8] has become an active topic in design and manufacturing. They focus on not only the pursuit of geometric properties but also physical properties [9,10]. Where, some technical aspects such as the prescribing tooth form error flank and the optimal selection of a small amount of machine settings can make this machine setting modification become more versatility, efficiency and flexibility [11].

Undeniably, the accuracy requirement on both design and manufacturing has always played an important role in the machine settings modification. In recent literature, gear designers mainly focus on numerical algorithm of identifying the accurate machine settings [12]. However, there are some aspects affecting modification accuracy has not been paid enough attention. Where, establishment of modification model, modification evaluation criterion setup and optimal selection of design variable are also indispensable to ensure accuracy. In the present

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Nomenclature

CMMs	coordinate measuring machines
CNC	computer numerically controlled
UMC	universal motion concept
TCA	tooth contact analysis
NTCA	numerical tooth contact analysis
NURBS	non-uniform rational B-spline
RMSE	root mean-squared error
SQP	sequential quadratic programming
TR	trust region
SGEs	spatial geometric error
μ	rotation angle of the cutter
θ	variable of the blade edge
q	basic cradle rotation angle
$\boldsymbol{p}_i^{(0)}$	i-th grid data point on basic tooth flank
$\boldsymbol{p}_i^*$	i-th grid data point on target flank
$\boldsymbol{h}^{(0)}$, $(h_1^{(0)}, \dots, h_m^{(0)})$	tooth flank form error vector and numerical items
VR	virtual reality
UGM	universal generation model
$\boldsymbol{r}_c$	tool blade with edge geometry
R_c	cutter point radius
α_c	blade pressure angle
ρ_f	edge radius of the cutter head
λ_f	angle of the circular arc
ζ	cutter swivel angle
σ	cutter tilt angle
S_r	cutter radial setting
R_a	ratio of generating roll
E_M	blank offset
X_B	sliding base setting
γ_m	machine root angle
X_D	machine center to back base
$\mathbf{M}_{bf}$, $\mathbf{M}_{fc}$	transformation matrices from the cutter to the blank
$\boldsymbol{n}_b$	normal vector at work gear blank
$\boldsymbol{v}_{bc}$	relative velocity of gear blank and the cutter
$\boldsymbol{x}$	design variable, namely selected machine setting
$\boldsymbol{x}_0$	the initial basic machine settings
$\boldsymbol{x}^*$	new machine settings
m	number of flank data points
n	number of the selected variables
$h_i^{(0)}$	prescribed tooth flank form error value of the target flank
$\wp$	prescribed tooth flank form error threshold
$\boldsymbol{h}$, $(h_1, \dots, h_m)$	residual tooth flank form error vector and numerical items
$\mathbf{U}$, U	grid node vector and its element
$\mathbf{V}$, V	control vector and its element
$\mathbf{W}$, w	weighting factor vector and element
$\boldsymbol{N}_{i,3}$(U)	cubic B-spline base function
$\boldsymbol{J}$	Jacobian matrix
$\mathbf{R}^{m\times m}$, $\mathbf{R}^{n\times n}$	m × m and n × n dimensional spaces
λ	threshold value of the optimized tooth flank error
FW	face width
TH	tooth height

paper, some data-drive operation methods are proposed for flexible design of tooth flank micro-geometry topography with higher accuracy.

Firstly, CMM measurement is proposed to prescribe tooth flank form error by investigating the components of tooth form error flank. Where, NURBS fitting in piecewise and G^1 stitching are used to determine a prescribed tooth flank grid for CMM measurement, and to identify the prescribe tooth form error flank as a target flank [13]. They can provide an accurate input for the whole modification according to user's requirements. Here, the operation and identification of the tooth flank form error can make the machine setting modification get a higher precision and validity [5]. Then, a more accurate machine setting modification method is proposed to obtain an accurate data-drive compensation of tooth flank form error measurement. Where, in order to distinguish with the first or second-order characteristic in the conventional modification [6,12], the high-order characteristics [13] of tooth form error flank is developed by applying universal machine settings with high-order characteristics which are set as the optimal variables [8,9]. Meanwhile, it is different that it only considers tooth flank form error in traditional modification, residual tooth flank form error as new evaluation criterion and tooth flank form error as a design tolerance, which make modification become more flexible and practical for the actual manufacturing.

1.2. Related works

In recent literature, there is only a small number of researchers have occasionally mentioned flank topography design and optimization in machine settings modification. Firstly, bi-cubic interpolation was employed for tooth flank fitting. Zhang et al. [14] established tooth flank model by applying bi-cubic interpolation method in proposed NTCA. Litivin et al. [15] also employed bi-cubic interpolation to construct tooth flank geometry for simulation of gear meshing. Then, B-spline interpolation became a main flank topography fitting method. It was used by Artoni et al. [16] and Gabiccini et al. [17] to obtain accurate tooth flank in optimization of the loaded contact pattern, considering the explicit expression for tooth flank as well as a simple form in addition to some advantages of this method itself. Fong [18] utilized this method to reconstruct tooth flank as a B-spline free form surface for analyzing toot contact performances, according to measured tooth geometry data. Actually, in the machine setting modification, in additional to tooth flank topography, it is needed to pay more attention on the tooth flank form error topography. As a result, its aim is to minimize the tooth flank form error or residual tooth flank form error for approximation of the prescribed target flank as much as possible [19] by solving the objective function of whole modification having a strong nonlinearity problem [20]. Ding [21] proposed the accurate NURBS fittings for the tooth flank after simulation process modeling of the spiral bevel and hypoid gears, and provided some optimization methods after accurate fitting for getting a higher accuracy. Furthermore, in whole modification process, the tooth form error flank especially the residual tooth form error flank was needed to get higher accuracy. In Ref. [18] by Fong, the tooth flank error was reduce from original 3 mm to 100 μm when control data points were increased from 5 × 8 to 37 × 37 points, and then reduced to less than 0.2 μm by B-spline interpolation. In a study by Fan at Gleason Works [13], RMSE of tooth form error flank on tooth convex flank after high-order tooth flank form error modification was significantly reduced from the 33.8 μm to 1.8 μm. In Ref. [12] published by Artoni et al., with the predesigned optimal tooth form error flank with maximum-to-minimum error value was 60 to −60 μm, the maximum residual tooth flank form error was finally determined as 0.004 μm, while the modification with 17 machine setting parameters was solved successfully. It can indicate that the numerical scope of precision evaluation is very small and the accuracy of flank topography including the tooth flank, tooth flank form error and residual tooth flank form error can deeply affect the numerical result of machine settings modification.

In past decades, to compensate tooth flank form error, machine setting modification technique has always been developed and improved. Firstly, Krenzer [22] of The Gleason Works described a corrective machine setting method by using a linear regression. He