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Research paper

Optimal modification of tooth flank form error considering measurement and compensation of cutter geometric errors for spiral bevel and hypoid gears

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A B S T R A C T

In design and manufacturing for the spiral bevel and hypoid gear, the cutter geometric errors (CGEs) is one of main factors affecting tooth flan flank form error. To get an accurate and effective modification of tooth flank form error, a novel optimization and operation approach is proposed by correlating with measurement and compensation of CGEs. Firstly, an accurate modification model with optimal machine settings is developed as a nonlinear least square problem. Where, a small number of machine settings are selected as unknown optimal design variable by sensitivity analysis method. Then, CGEs are defined and their influences on the tooth flank form error are investigated for synthesis and analysis of the accurate higher-order modification. Finally, the optimal modification with small number of machine settings is performed based on measurement of the Doppler Laser interferometer MCV2002 following ISO 230-2(1997) standard and numerical control (NC) compensation of CGEs. In additional to the optimal design parameters is set to improve computational efficiency, the Levenberg–Marquardat (L–M) algorithm with trust-region strategy is applied to solve for the new machine settings with modification variations. A numerical application to a real case is designed to identify the validity of the proposed methodology.

1. Introduction

In design and manufacturing for the spiral bevel and hypoid gears, the relative kinematic position between the cutter and gear blank can directly be determined by the machine settings satisfying the theory of gearing [1,2]. More recently, the tooth flank form error modification is usually used as a main technique to design a sophisticated tooth flank by modifying the machine settings. Where, its target is to identify a set of accurate machine settings for infinitely matching a target flank whose tooth flank form error is prescribed by user [3]. With sate-of-the-art CNC technology [4], this modification technique has been being developed for satisfying the higher accuracy and efficiency of hypoid gear manufacturing.

First, with the proposed UMC [5], the universal machine tool settings which are used as the unknown design variable in modification have become a hotspot. It can provide more freedoms for generating tooth flank with the modified complex geometries for not only face-milling but also face-hobbing [6]. With the mathematical model using the universal machine settings, Astoul et al. [7] presented a simple and robust method to simulate the generating and tooth contact processes.

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Nomenclature

$\boldsymbol{\xi}$	vector of universal machine settings
n	order of the universal machine setting
R_a	ratio of generating roll
S_r	cutter radial setting
E_M	offset
X_B	sliding base
X_D	machine center to back
γ_m	root angle
σ	tilt angle
ζ	swivel angle
q	basic cradle angle
$\boldsymbol{r}_{\mathrm{b}}$	vector of tooth surface
$\boldsymbol{r}_{\mathrm{c}}$	vector of cutter
$\boldsymbol{v}_{\mathrm{bc}}$	relative velocity of cutter with respect to gear blank
μ	angle of cutter blade
θ	variable of blade edge
ϕ	rotation angle of the cradle
φ	rotation angle of blank axis
$\boldsymbol{r}_c$	represents the 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
$\mathbf{M}_{bf}$, $\mathbf{M}_{fc}$	rotation matrixes form cutter head to gear blank
$\boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}$	unit vectors in three-dimensional space
$\delta\boldsymbol{r}$	difference vector of tooth flank points
N	the number of optimal design parameters
M	the number of grid points
$\boldsymbol{S}_{ij}$	sensitivity coefficient matrix
$\boldsymbol{\xi}'$	the actual universal settings considering the CGEs
ϑ_i	ith cutter geometric error
K	represents the corresponding optimal design variable
$\boldsymbol{\xi}_K$, ξ_K	vector of optimal machine setting and its element
$\delta\boldsymbol{\xi}$, $\delta\xi$	the variation for modification and certain a element
$\delta\boldsymbol{\xi}'$, $\delta\boldsymbol{\xi}''$	variation of machine setting and CGEs
$\boldsymbol{g}_k$	gradient vector of the objective model
$\boldsymbol{G}_k$	Hessian matrix of the objective model
$\boldsymbol{x}_k$	machine tool settings after k iterations
$\boldsymbol{d}$, $\boldsymbol{d}_k$	the iteration step and the step at $\boldsymbol{x}_k$
$f(\delta\xi)$	objective function in modification model
f_k	quadratic Taylor expansion about $\boldsymbol{x}_k$ of the function $f(\boldsymbol{x})$
μ_k	damping coefficient
$\boldsymbol{I}$	the unit matrix in Levenberg–Marquardt (L–M) algorithm
$\boldsymbol{d}_k^{SD}$	iteration step in the steepest descent direction
$\boldsymbol{d}_k^{GN}$	Gauss–Newton (G–N) iteration step
$\boldsymbol{d}_k^{DL}$	iteration step of double Dogleg method
α	the coefficient for search path
Δ_k	radius of a spherical region
η_k	gain ratio of increments of function f and of function f_k
ε_1, ε_2, ε_3, k_{max}	the stopping criteria parameters
CGEs	cutter geometric errors
CMMs	coordinate measuring machines
NC, CNC	numerical control, computer numerical control
UMC	universal motion concept
TCA	tooth contact analysis
UGM	universal generation model
MRM	modified radial motion