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Research paper

Geometric error analysis and compensation for multi-axis spiral bevel gears milling machine

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ABSTRACT

This article proposes a method to analyze and compensate geometric errors of six-axis CNC grinding machines for spiral bevel gears. Volumetric error prediction and compensation models are realized by the forward and inverse kinematics modeling via the screw theory. Key geometric error items of motion axes and their influences on gear tooth performance are modeled and analyzed. Advantages of the proposed compensation method for geometric errors over the machine settings modification method are demonstrated. The compensation strategy has been verified on a six-axis grinding machine controlled by a Siemens CNC. The pitch error and tooth form error of machined gears before and after compensation are compared to validate the effectivity of the proposed compensation method.

1. Introduction

Spiral bevel gears are of great significance to power transmission systems in modern industries.

At present, companies such as the United States' Gleason, Switzerland's Oerlikon and Germany's Klingelnberg, are in leading positions of the spiral bevel gear cutting technology. Because of extensive applications of spiral bevel gears, there is an increasing accuracy demand for both spiral bevel gears and grinding machines.

To further reduce noise, increase strength and accuracy of the gear transmission system, researchers did a lot of work to optimize the tooth form topography for spiral bevel and hypoid gears. Machine settings modification is the most common method to optimize the tooth form performance, such as minimize the tooth form error. Usually the machine settings modification process consists of three steps. First, the grinding machine is modeled by the universal motion concept [1], namely 6 machine settings S_r, E_m, X_D, X_B, γ_m and q. Then linear or nonlinear objective functions for tooth form error modifications are established. Finally, machine setting variations are obtained by solving the optimization problem. As an example, the ease-off topography method is adjusted to enhance strength and reduce noise of spiral bevel gears [2]. Term ease-off stands for the modification values of the tooth flank, namely the normal deviation between the ideal tooth flank and the actual one. Artoni [3, 4] established a least square model of target tooth flanks based on the ease-off topography, and the machine settings are identified by the trust-region Levenberg–Marquardt method. In Kolivand's research [5], the loaded tooth contact analysis is conducted based on the ease-off topography of hypoid gears. Shih [6] proposed a novel ease-off flank modifi-

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Nomenclature

e	space width
s	tooth thickness
p	pitch of the gear
α	gear rotation angle
ha^*	addendum coefficient
c^*	bottom clearance coefficient
m	module
h	tooth depth
S_r	grinding wheel radius
E_m	blank position including offset
X_D	machine center to back base
X_B	machine center to back base
γ_m	root angle
q	basic cradle angle
CCS	C-axis coordinate system
ACS	A-axis coordinate system
MCS	Machine coordinate system
ξ	twist (Basic operation unit of screw theory)
$e^{\xi\theta}$	Exponential product
$\mathbf{g}_{rw}$	Kinematic chain from workpiece to reference
$\mathbf{g}_{rt}$	Kinematic chain from tooltip to reference
$\mathbf{g}_{rw}(0)$	Initial position of the workpiece relative to MCS
$\mathbf{g}_{rt}(0)$	Initial position of the tool relative to MCS

cation method. Specifically, the desired ease-off topography is constructed from the ease-offs along the contact path and contact lines, which are calculated according to the predesigned transmission error and contact bearings, respectively.

Various linear and nonlinear identification methods are proposed by researchers to realize tooth form optimizations. For large-sized spiral bevel gears, Kawasaki [7, 8] proposed manufacturing methods in cyclopalloid system and remanufacturing techniques for pinion and gear member with the tooth optimization method. Simon did a lot of work on optimizing the tooth performance, such as analyzing the influence of shaft misalignments [9] and tooth modifications [10] on loaded tooth contact. Simon systematically defined the head-cutter geometry and machine tool settings to realize optimal tooth modification in face-hobbed hypoid gears [11]. Lin [12] investigated a linear regression method to minimize the tooth surface deviations. Corrective settings are calculated via the sensitivity matrix and the minimization problem is solved by the SVD method. However, SVD method sometimes may not have solutions, thus it cannot be applied to high-precision tooth surface applications. Shih [13] proposed a free-form flank topography correction method based on sensitivity analysis and corrections are solved by the least square method. As the number of tooth flank measurement points is much larger than the number of machine modification setting variables, as well as the coupling effects of the machine settings, the linear regression model often leads to ill conditions, thus scholars proposed nonlinear correction methods. Artoni [3] presented a new systematic method for identifying the machine tool settings via a nonlinear least-squares formulation, which is solved by the Levenberg–Marquardt method with a trust-region strategy. Lin [14] investigated the tooth surface sensitivity matrix to setting variations and proposed a nonlinear optimization procedure to minimize surface deviations of real cut pinion and tooth form. To ensure the stability of the setting modification algorithm, iterative methods are proposed. Gabiccini [15] compared the performance of three different types of algorithms for machine settings modification:(1) one step method, (2) iterative method, and (3) iterative method with step control. It shows that iterative approximations based algorithms with step length adaptively controlled turns to be the most effective solution. Considering material removal and discretized generating movements, Wang [16] built a roughness model which can precisely calculate the roughness distribution over the gear surface. Simon also [17] predicted the roughness based on determining instantaneous gear tooth surface point at each point on each active cutting edge. Alfonso [18] mathematically defined both the spherical involute and the octoidal bevel gears, and it shows that the spherical involute profile has the possibility to become the reference profile with the technique develop of additive manufacturing. Alfonso [19] also proposed a novel approach for setting determination of the rough-cutting process so as to reduce the manufacturing cycle and maximize the material removal rate.

However, the above researchers rarely considered the influence of geometric errors of motion drives on tooth form errors, such as positioning, straightness, angular errors, etc. Zhou [20] analyzed the effects of grinding wheel spindle eccentricity errors and perpendicularity errors on tooth surface errors, and the quantitative relationship between them is established. Ding [21] modified grinding machine settings for hypoid gears considering geometric errors. He first established relationships between 6 machine settings and more than 30 measured geometric errors, and then proposed a trust region algorithm with dogleg step to calculate setting modification variations.