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Tool orientation optimization of 5-axis ball-end milling based on an accurate cutter/workpiece engagement model

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ABSTRACT

Tool orientation in 5-axis ball-end milling plays a significant role in machining efficiency and accuracy. The cutter/workpiece engagement varies with tool orientation continuously including lead and tilt angles during machining, which results in the obvious time-varying characteristic for consecutive cutting forces. Considering tool orientation, actual cutter runout and cutter motion process, an accurate calculation model for instantaneous cutter/workpiece engaging process in 5-axis ball-end milling is proposed based on an improved analytical method with high order Taylor formula, which can reach an excellent accuracy. Then base on the cutting force model, the tool orientation optimization strategies with a flexible cutter and rigid workpiece for roughing and finishing milling operation are further presented. For the three kinds of geometrical characteristic (plane, cylindrical and spherical surface), this study analyzes the influence of tool lead and tilt angles, and step over on the maximum cutting force and form error, and finally obtains an optimal tool orientation to realize a high efficiency and accuracy machining.

Introduction

As a result of increased tool orientation capability and adjustable cutting point, 5-axis ball-end milling is very suitable for complex sculptured surface machining and has been popularly used in many industries [1]. It's well known that cutting forces are greatly dependent on the transient machining condition. Especially during sculptured surface milling, various tool orientations (lead and tilt angles), nonideal tool installations and cruved tool paths have an important effect on the instantaneous cutter/workpiece engagement (CWE). Consequently, the milling process would behave an noticeable time-varying characteristic and thus affect machining efficiency and quality remarkably. Hence, research on 5-axis ball-end milling process can help manufacturer to choose an optimal tool orientation and improve milling efficiency and quality [2,3].

Cutting force is a primary factor to determine the tool orientation, and a precise description of CWE model is important for cutting forces prediction. The CWE region in 5-axis ball-end milling is an irregular polyhedrons, where the radial width corresponds to the uncut chip thickness and the engagement boundary determines the tooth entry/exit angle. At present, a number of studies [4–7] have been carried out on cutting force modeling with approximation uncut chip thickness model $h = f_t \sin \phi \sin \gamma$. But this model fails to describe the accurate uncut chip thickness in the case of cutter runout, moreover, in multi-axis milling process the true trajectory is a three dimensional trochoid motion where the approximation uncut ship thickness model have nonignorable calculation deviation. Accurate CWE model, therefore, has been a hot topic in the analysis of sculptured surface milling. Fontaine et al. [8,9] derived the uncut chip thickness and entry/exit angle and analyzed the effects of inclination angle on cutting forces based on the approximation model. Wojciechowski [10] further studied the influence of cutter runout and inclination angle on cutting forces and specific cutting force coefficients. All above research were conducted in the case of fixed tool orientation. When tool orientation changes constantly, Zhu et al. [11] proposed a method for cutting force prediction with ball end cutter in 5-axis milling, but the detailed solution for uncut chip thickness was not provided. Ferry and Altintas [12] separated tool feed velocity into horizontal component perpendicular to tool axis and vertical component coinciding with tool axis, and then gave a equivalent uncut chip thickness based on approximate circular arc model. Sun et al. [13] developed a numerical model for uncut chip thickness in 3-axis milling, but an implicit equation was necessary for numerical solution which is very time-consuming. Then, Sun

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Nomenclature

XYZ	Global coordinate system
$X_rY_rZ_r$	Tool rotation coordinate system
$X_{cp}Y_{cp}Z_{cp}$	Contact point coordinate system
$X_fY_fZ_f$	Tool feed coordinate system
$X_cY_cZ_c$	Tool geometry coordinate system
Rot_B,Rot_C	Rotation matrix for B-axis and C-axis
Rot_L,Rot_T	Rotation matrix for lead and tilt angle
Rot	Rotation matrix for the cutter
i, j	Number of tooth and cutting disk element
db	Thickness of cutting disk element
R_0,$R_{i,j}$	Nominal and actual radius of the cutter
$S(i, z_c, t)$	Instantaneous tooth trajectory
$h(i, j, t)$	Instantaneous uncut chip thickness of the jth cutting disk element on the ith tooth attmoment
$\theta_{s,i,j}$, $\theta_{e,i,j}$	Entry and exit angle for the jth cutting disk element on the ith tooth
k_{ts}, k_{rs}, k_{as}	Shearing specific cutting force coefficient in tangential, radial and axial direction
k_{tp}, k_{rp}, k_{ap}	Ploughing specific cutting force coefficient in tangential, radial and axial direction
$F_{w,x}$, $F_{w,y}$, $F_{w,z}$	Total cutting force components in X, Y and Z direction in workpiece coordinate system
ρ, λ	Cutter runout value and angle
L, T	Lead and tilt angle

and Guo [14] and Guo et al. [15] employed this method to predict cutting force considering cutter runout in 5-axis with flat and ball end cutters. Lazoglu et al. [16] developed a boundary representation based method to find the CWE in cutting force prediction of five-axis machining of parts with complex free form surfaces. Zhang [17] established a dexel process modeling for five-axis milling under the tool motion analysis which could extract the CWE regions for cutting forces prediction. Later, Azeem and Feng [18] employed this numerical model to emphatically analyze cutting forces in inclined plane milling with ball end cutter. Zhang et al. [19] proposed a linear numerical iteration method to calculate the instantaneous uncut chip thickness. Kiswanto et al. [20] presented an analytical method to define the CWE for toroidal and flat-end cutters during semi-finish milling of sculptured parts. Layegh et al. [21] employed a new and comprehensive mechanics-based strategy to investigate the effects of lead and tilt angles in 5-axis ball-end milling of flexible freeform aerospace parts.

In 5-axis machining, two additional rotations recognized by a lead angle and a tilt angle enable increased tool orientation capability and improved machining quality in less process time. The problem to select reasonable tool orientation during 5-axis machining is much complicated, which has been achieved a lot of attentions. The initial approach for tool orientation was to incline the tool at a fixed angle to minimize the scallops in the feed direction throughout the whole tool path, named as inclined tool method [22]. Then Rao et al. [23,24] presented the principal axis method where the the tool is inclined in the direction of minimum curvature instead of the feed direction. In the multi-point machining method [25], the tool is oriented to ensure multiple cutter contact points at each position along the path, which is time-consuming. Several other approaches were also proposed to improve the machining quality and computational efficiency including rolling ball method [26], faceted model method [27], configuration space method [28] and penetration-elimination method [29].

On the other hand, much work focused on the effect of tool orientation on cutting force, surface roughness, chatter and so on. Ko et al. [30] proposed an approach to analyze the effect of tool orientation on cutter wear and experimentally studied the optimization of tool orientation for high performance machining. Chen et al. [31] investigated the effects of tilt and lead angles on the scallop height, surface roughness, surface topography, and surface damages in 5-axis ball-end milling process. The effect of tool orientation on the final surface geometry and quality in 5-axis micro-milling of brass using ball-end mills was proposed by Fard and Bordatchev [32]. All above studies were performed dominantly by experiments. Ozturk and Budak [33,34] proposed a method to analyze the tool lead and tilt angles on CWE, cutting forces and machining error with fixed tool orientation based on approximation uncut ship thickness model, and optimized tool lead and tilt angles in a milling case. Geng et al. [35] proposed a simulation-based method to identify cutter postures that produce minimum deflection cutting force, which can greatly reduce the computational loads of cutting force calculation. Chao and Altintas [36] modeled the process mechanics and dynamics of ball end milling and then established an iteration using Nyquist criterion to search the chatter free tool axis orientations.

Literature reviews show that a lot of works have paid on the influence of tool orientation angle on CWE process, and thus on milling mechanics and dynamics. But what should by pointed out is that the most majority studies were conducted on plane surfac, which have not considered other complex geometrical charateristic of workpiece. Besides, a little attention has been focused on the description for an accurate CWE model with high calcualtion effciciency. What's more, during the whole machining process, roughing milling and finishing milling are the two main stages, which have different emphasis. Hence, the optimization for the tool orientation should take into account this kind of feature. In this study, a new CWE model based on an improved analytical method with high order Taylor formula is presented considering the tool orientation and cutter runout in 5-axis ball-end milling, and then a true tooth trajectory based cutting force prediction method is developed. The optimization strategies of tool orientation in both roughing and finishing milling are further developed for workpieces with different geometries.

Cutter/workpiece engaging process

Definition of coordinate system

Fig. 1 shows a general 5-axis ball-end milling process of complex curved surface. The global coordinate system XYZ is

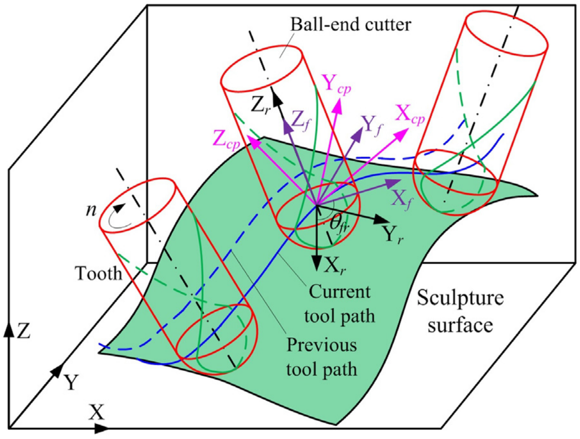

Fig. 1. General 5-axis ball-end milling process.

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