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An accurate prediction method of cutting forces in 5-axis flank milling of sculptured surface

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ABSTRACT

The instantaneous uncut chip thickness and entry/exit angle of cutter/workpiece engagement continuously vary with tool path and workpiece geometry in 5-axis flank milling of sculptured surface, which results in the obvious time-varying characteristic for consecutive cutting forces. An accurate prediction method for cutting force in 5-axis flank milling of sculptured surface is proposed in this paper. Comprehensively considering curved tool path and actual tool motion process with cutter runout (offset and inclination) effects, an accurate representation model for instantaneous uncut chip thickness during cutter/workpiece engaging in 5-axis flank milling is presented firstly, which can reach a higher accuracy and efficiency with the aid of linear iteration process than the methods published. Then, based on the thin plate milling experiments, an efficient calibration procedure for cutter runout parameters and specific cutting force coefficients is given and further verified in practice. Finally, a series of validation experiments are conducted under different cutting conditions, and the results reveal that there is a very good agreement between the experimental and simulation data both in shape and magnitude and prove the effectiveness and accuracy of the proposed method.

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1. Introduction

5-axis flank milling is suitable for complex sculptured surface machining with the help of increased tool orientation capability and has been widely used in the aerospace, automobile, textile machinery, and die/moud industries [1]. During machining process, cutting forces would excite tool system and workpiece system which would result in an undesirable dynamic displacement response between tool and workpiece and usually cause cutter deflections or even breakage, bad surface quality, and poor dimensional accuracy [2–3]. Hence, accurate prediction of instantaneous cutting force can provide important physical parameters for manufacturer to suppress chatter, improve surface quality and select reasonable cutting parameters [4–5]. Cutting forces, however, are dependent on the instantaneous machining condition. Complex tool path, mutative cutting parameters, non-ideal tool installation state and various workpiece geometry have important effects on the instantaneous uncut chip thickness and entry/exit angle of tool/workpiece engagement in 5-axis flank milling of sculptured surface. As a result, cutting forces in milling behave an obvious time-varying characteristic. At present, many scholars have conducted a lot of related research work about tool/workpiece engagement and specific cutting force coefficients calibration. Meanwhile, cuter runout including its offset and inclination is a commonly encountered phenomenon which increases the difficulty of the research.

The tool/workpiece engagement region in 5-axis flank milling is a complex irregular polyhedron, where the radial thickness corresponds to the instantaneous uncut chip thickness and the boundary decides the entry/exit angle. Martellotti [6–7] proposed an approximate circular arc model $h = f_t \sin\phi$ for uncut chip thickness in milling with straight line tool path. Based on this model, Wang et al. [8] considered the effects of cutter offset on instantaneous uncut chip thickness and developed an extra correction term. In addition to the studies of Martellotti [6–7] and Wang et al. [8], Wan et al. [9] presented an uncut chip thickness model with both consideration of cutter offset and cutter inclination. For peripheral milling of complex curved surface, tool position was always discretized into a series of intervals which is equal to feed per tooth when tool moves along a curved path. Zhang et al. [10] utilized equivalent feed per tooth to analyze the cutting forces during corner milling with constant curvature. Wei et al. [11] and Yang et al. [12] calculated cutting forces with equivalent feed per tooth during milling in a curved tool path. Desai and Rao [13–14] analyzed the effects of cutter offset on entry/exit angle and cutting forces. Recently, Han et al. [15] indicated that the actual chip thickness deviates greatly from

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Nomenclature

XYZ	global coordinate system
$\mathbf{X}_r\mathbf{Y}_r\mathbf{Z}_r$	tool rotation coordinate system
$\mathbf{X}_c\mathbf{Y}_c\mathbf{Z}_c$	tool geometry coordinate system
Rot*B*,RotC	rotation matrix for *B*-axis and *C*-axis
$h(i, j, t)$	instantaneous uncut chip thickness of jth cutting disk element on ith tooth at t moment
k_{ts}, k_{rs}, k_{as}	shearing specific cutting force coefficient in tangential, radial and axial direction
k_{tp}, k_{rp}, k_{ap}	plowing specific cutting force coefficient in tangential, radial and axial direction
$F_{w,x}(t)$, $F_{w,y}(t)$, $F_{w,z}(t)$	total cutting force components in **X**, **Y** and **Z** direction in workpiece coordinate system
ρ, λ, τ, η	cutter runout parameters: offset value, offset angle, inclination value and inclination angle
$\mathrm{P}(t)$	instantaneous tool point position
$\mathrm{S}(i, z_c, t)$	instantaneous tooth trajectory equation
$F_s(x, y, z)$	current workpiece surface
$\theta_{imme,i,j}$	nominal radial immersion angle of ith tooth
$\varphi_{i,i-1,j}$	nominal pitch angle between ith tooth and i-1th tooth
H	distance between tool tip and thin plate in **Z** direction
$r(u, v)$	ruled surface function

circular arc model in corner milling. For 5-axis flank milling, the actual tooth trajectory is a three dimensional trochoid motion. Zhu et al. [16] studied a method for cutting force modeling with ball end cutter in 5-axis milling, but did not provide detailed solution process for uncut chip thickness. Ferry and Altintas [17] projected tool feed velocity into horizontal component perpendicular to tool axis and vertical component coinciding with tool axis, and then gave an equivalent uncut chip thickness based on approximate circular arc model. Huang et al. [18] proposed an approach to analyze 5-axis flank milling process with fixed tool orientation using ball end cutter in which instantaneous uncut chip thickness was equivalent to the sum of two independent component caused by lead and tilt angle respectively. A major shortcoming of this method is that the model cannot be suitable for the case of tool orientation continuous change. Sun et al. [19] demonstrated a numerical calculation model for uncut chip thickness during 5-axis flank milling, but implicit equation is need to be numerically solved which is time-consuming. Azeem and Feng [20] employed this numerical model to emphatically analyze cutting forces in inclined plane milling with ball end cutter.

For the calibration of specific cutting force coefficients, the most commonly used method is the direct calibration approach in which the specific cutting force coefficients are determined by milling tests considering the cutter/workpiece combination. Literature review shows that there exist two specific cutting force coefficients models. The first one is a constant model both for shearing and ploughing specific cutting force coefficients. Yoon et al. [21] expressed the average cutting forces in one revolution as feed per tooth, and then fit the function through cutting force experimental data to obtain this constant model. Different from the calibration method in Ref. [21], Gonzalo et al. [22] adopted instantaneous cutting forces in one revolution to determine the constant model. On account of the simplification of mechanism and the ignorance of cutter runout, the cutting forces prediction error was inevitable in above researches. Edouard et al. [23] put forward an identification method for constant specific cutting force coefficients considering cutter offset and predicted cutting forces with improved accuracy. In another model only ploughing specific cutting force coefficients are treated as constant, while shearing specific cutting force coefficients are expressed as exponential function due to the size effects of uncut chip thickness. Yun et al. [24] studied an approach to identify specific cutting force coefficients using exponential model in which cutter runout is ignored. Wan et al. [25] presented a strategy to determine the specific cutting force coefficients from instantaneous value of the nominal component whereas the cutter offset parameters are identified using the perturbation component. After that, a numerical optimization method for specific cutting force coefficients and cutter offset parameters was carried out by Wan et al. [26], in which the results are not global optimal solution without consideration of the effects of cutter offset on the uncut chip thickness in specific cutting force coefficients exponential model. It is worth noting that both cutter offset and cutter inclination as important factors affecting the actual uncut chip thickness thus on specific cutting force coefficients identification in the milling process has not been synchronously focused on in these researches. It is known that in the case of large axial depth of cut in flank milling, not only cutter offset but also cutter inclination affects uncut chip thickness evidently and cannot be elided. Nevertheless, in the exponential model, the nonlinear coupling relationship among cutter runout, uncut chip thickness and specific cutting force coefficients increase the difficulties for identification process.

Based on the actual tooth motion process in 5-axis flank milling of sculptured surface, this paper overall considers the influences of complex tool path, workpiece geometry and cutter runout (offset and inclination) on instantaneous uncut chip thickness and entry/exit angle, presents a new calibration method for cutter runout parameters identification and specific cutting force coefficients, and predicts cutting forces and verifies the proposed method under different cutting conditions. The paper is organized as follows. Section 2 presents a total cutting force model in 5-axis flank milling of sculptured surface. Afterwards, Section 3 proposes an accurate model for instantaneous uncut chip thickness and entry/exit angle. Then, Section 4 gives the identification method for cutter runout parameters and specific cutting force coefficients with thin plate milling experiments. Finally, Section 5 details the verification process for theoretical studies followed by the conclusions in this paper.

2. Cutting force model in 5-axis flank milling

A general 5-axis flank milling process of complex curved surface is shown in Fig. 1. In order to describe the tool motion process, **XYZ** is defined as the global coordinate system attached to the worktable in which the workpiece geometry and tool path are described. $\mathbf{X}_r\mathbf{Y}_r\mathbf{Z}_r$ is created as the tool rotation coordinate system attached to the tool system with its origin at the tool center point. In the case of 5-axis machine tool with *B*-axis in headstock and *C*-axis in worktable, the transformation relationship between tool rotation coordinate system and global coordinate system is expressed as follows.

$$\begin{bmatrix}\mathbf{X} & \mathbf{Y} & \mathbf{Z}\end{bmatrix}^{\mathrm{T}} = \mathbf{O}_r + \mathrm{Rot}C\cdot\mathrm{Rot}B\begin{bmatrix}\mathbf{X}_r & \mathbf{Y}_r & \mathbf{Z}_r\end{bmatrix}^{\mathrm{T}} \quad (1)$$

where Rot*B* and are the rotation matrix about *B*-axis and *C*-axis, respectively.

When cutter moves along a complex tool path, the tool feed direction and workpiece geometry will change constantly, which

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