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Parametric chip thickness model based cutting forces estimation considering cutter runout of five-axis general end milling

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ABSTRACT

In the process of sculpture surfaces machining, due to the changes of the cutter orientation and the inevitable eccentricity between tool and spindle, machining parameters optimization based on five-axis cutting force is quite a challenge. To solve this problem, this study proposes a new method, cutting edge element moving(CEEM) method, to calculate instantaneous undeformed chip thickness(IUCT), to distinguish cutter/workpiece engagement(CWE) area and to simulate five-axis machining cutting force considering runout for general end mills. On the basis of upper work, the parameter representation of IUCT is deduced by the parametric expression of coordinate transformation matrix and feed vector, and resolved to three sub models about tool orientation, tool orientation change and cutter runout. At last, cutting force coefficients and cutter runout parameters are calibrated by cutting test and dial gauge testing. And inclined axis cutting test for bull nose mill, cylinder face-milling test for ball end mill and conical surface flank milling test for flat end mill are carried out to verify the effectiveness of the proposed model and related decomposition model. Combined with the specific test, some analysis about peak values, mean values and peak to peak difference values of cutting forces in various tool orientations are conducted, and the effect to cutting force from the changes of lead and tilt angles are evaluated. Some conclusions obtained and the methods utilized can be used to optimize tool orientation and feed rate etc.

1. Introduction

Machining of sculpture surface, such as turbine blades, propeller blades and cavity mold, are widely used in automotive, aerospace, marine and mold industry. In order to avoid interference of the tool and the workpiece, and to obtain better surface quality, higher processing efficiency and accuracy, five-axis machining method of general end mills is applied more frequently. In the process, cutting forces have a great effect on heating and deformation of the cutter, chatter of the cutting system, and the quality of the machined surface. So five-axis cutting force simulation is a hot research topic in the field of metal cutting, and tool orientation optimization and machining parameters optimization based on cutting force become a new urgent needs.

For five-axis cutting force modeling, as the five-axis machining of sculpture surfaces increases the rotational degree of freedom than the ordinary tool axis machining, but for the coefficients calibration model for flat end mill [1,2], ball end mill [3,4] and general mill [5], the model of calculating instantaneous undeformed chip thickness(IUCT) and the model of determining the cutter/workpiece engagement(CWE) area applying for common axis machining [5–9] or three-axis machining free-form surfaces [10–16], cannot meet the needs of five-axis machining. In order to model IUCT and CWE which reflected the changes of the orientation angle in five-axis machining, Ferry and Altintas [17] proposed a method of cutting force prediction for the five-axis flank milling of jet engine impellers. For each cutting edge differential element, the total velocity due to translation and angular motion is split into horizontal and vertical feed components, which are used to calculate total chip thickness along the cutting edge. Larue and Altintas [18] used a commercial ACIS modeler solid modeling environment to determine the engagement region for force simulations of flank milling. Kim et al. [19] determined the cutter contact area from the Z-map of the surface geometry and current cutter location. Budak et al. [20] and Ozturk and Budak

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Nomenclature

CCS	cutter coordinate system
WCS	workpiece coordinate system
WLCS	workpiece local coordinate system
IUCT	instantaneous undeformed chip thickness
CWE	cutter/workpiece engagement
CEE	cutting edge element
CEEM	cutting edge element moving
M_z, N_z	axial offsets of the end mill profile
ψ,ψ_t	spindle rotation angle at time t
N	number of cutter flutes
φ	radial contact angle of CEE
κ	axial contact angle of CEE
$\psi(z)$	radial lag angle of CEE
$r(z)$	radius of CEE at z
$n(z)$	unit normal of the cutter envelop surface at CEE
${}_C C$	coordinate position of CEE in CCS
${}_W C_t$	coordinate position of CEE in WCS at time t
${}_W C_{t-\Delta t}$	coordinate position of CEE in WCS at time $t-\Delta t$
${}_W\boldsymbol{F}$	feed vector of CEE at WCS
${}_T\boldsymbol{F}$	feed vector of CEE at CCS
Δt	unit cutting flute machining time
$\boldsymbol{CL}_n$, $\boldsymbol{Z}_n$	the *n-th* cutter location point and cutter axis vector in CL file
$\boldsymbol{CL}_{n+1}$, $\boldsymbol{Z}_{n+1}$	the *(n+1)-th* cutter location point and cutter axis vector in CL file
$\boldsymbol{CL}_t$, $\boldsymbol{Z}_t$	cutter location point and cutter axis vector interpolated at time t
$\boldsymbol{CL}_t'$, $\boldsymbol{Z}_t'$	cutter location point and cutter axis vector considering cutter runout at time t
$\boldsymbol{FV}$	cutter moving vector at time t
$\boldsymbol{FV}'$	cutter moving vector considering cutter runout at time t
$\boldsymbol{x}_t \cdot \boldsymbol{y}_t \cdot \boldsymbol{z}_t$	unit vector of the cutter axis of CCS expressed in WCS at time t
$\boldsymbol{x}_t' \cdot \boldsymbol{y}_t' \cdot \boldsymbol{z}_t'$	unit vector of the cutter axis of CCS expressed in WCS at time t considering cutter runout
${}_W^C\boldsymbol{R}_t$	rotation transformation matrix from CCS to WCS at time t
${}_W^C\boldsymbol{R}_t'$	rotation transformation matrix from CCS to WCS considering cutter runout at time t
${}_W^C\boldsymbol{T}_t'$	coordinate transformation matrix from CCS to WCS considering cutter runout at time t
${}_W^C\boldsymbol{T}_{t-\Delta t}'$	coordinate transformation matrix from CCS to WCS considering cutter runout at time $t-\Delta t$
${}_{t-\Delta t}^{t}\boldsymbol{T}_C'$	coordinate transformation matrix from CCS at time t to CCS at time $t-\Delta t$ considering cutter runout
α, β, and γ	parametric angle of cutter orientation in WCS
ω_α, ω_β, and ω_γ	angular velocity of parametric angle of cutter orientation in WCS
ρ, λ	cutter runout parameters
h and $h(\alpha, \beta, \gamma, \omega_\alpha, \omega_\beta, \omega_\gamma, \rho, \lambda, n, F)$	lump IUCT of CEE
$h(lead, tilt, n, F)$	IUCT related to fixed cutter orientation translation feed mode
$h(lead, tilt, \omega_{lead}, \omega_{tilt})$	IUCT related to cutter orientation change feed mode
$h(\rho, \tau)$	IUCT related to cutter runout
$db(z)$	instantaneous uncut chip width
$K_q(q=r, t, a)$	radial, tangential and axial cutting force coefficient
$dF_{q,j}(z)(q=r, t, a)$	radial, tangential and axial components differential cutting force of CEE at z of *j-th* flute.
$F_{x,y,z}(\varphi)$	*x*-,*y*-,*z*- components of the total cutting forces at spindle rotation φ

[21] presented a complete geometry and force model for 5-axis milling operations using ball-end mills, and analyzed the effect of lead and tilt angles on the condition for engagement in detail, but which just suit for monotonic surfaces and ball end mill. Zhu et al. [22] presented a geometrical analysis method to calculate IUCT and detected the CWE area through z-map method. Guo et al. [23] established an analytical model to describe the sweep surface of cutting edge during the five axis ball-end milling process of curved geometries, and calculated the IUCT according to the real kinematic trajectory of cutting edges under continuous change of the cutter axis orientation. On the basis of work in Guo et al. [23], Sun [24] established the five-axis cutting force considering cutter runout. Recently, Li and Zhu et al. [25] modeled five-axis machining cutting force IUCT considering cutter runout for general end mills and improved the simulation efficiency through the method of the approximately circular cutter edge trajectory. Summary, five-axis cutting force IUCT model of upper works could be divided two categories: one is the vector projection method [17,20,21] from the total feed vector including linear and angular feed mode to the unit vector on the tool envelope surface normal direction, the other is geometrical calculation method [22–25] of calculating the segment length on the IUCT defined line between the cutting edge element(CEE) and the cutter edge trajectory sweeping surface of the front cutting edge. And the two models calculate the IUCT in a lump mode including all the cutting parameters, and could not characterize the effect from the specific cutting parameters directly.

Based on the cutting forces models, the effects on cutting force of cutting parameters such as the tool orientations, the feed directions, and the feed rate and so on, were studied to improve the accuracy, the quality and the efficiency of the multi-axis machining. Lopez de Lacalle et al. [26] determined preferable tool orientation and local machining directions with respect to minimizes the mean value of the tool deflection force in finishing operations. Ozturk and Budak [27] investigated the effects of lead and tilt angles on cutting forces, torque, form errors and stability, and shown that the cutting geometry, mechanics and dynamics vary drastically and non-linearly with these angles. Yusuke Koike and Atsushi Matsubara [28] designed the material removal sequence, feed direction and tool orientation by minimizing the workpiece static displacements at cutting points, and the static components of the cutting force were used for the calculation. Salami et al. [29] and Merdol and Altintas [30] optimized feed rate in three-axis milling by calculating maximum threshold value about cutting force and improved the productivity of CNC machine tools. Overall, the past works just pay attention to the lump and resultant cutting forces, such as studying the static value [28] and the mean value [26,27] of the tool deflection forces to optimize the feed direction and tool orientation, studying the peak cutting forces and the threshold value to maximize the feed rate [29–31], etc. Meanwhile, unlike feed rate optimization in three-axis milling only considering the translation feed, the cutter orientation angle change have huge effect on cutting forces in five-axis machining. In addition, the cutting edge is the main cutting body and affects the machined surface directly, and different feed modes in multi-axis machining, such as translation feed, lead angle and tilt angle feed mode, and cutter runout have enormous different influence on CEE load. But rarely seen the research describing the