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Cutting force modeling for non-uniform helix tools based on compensated chip thickness in five-axis flank milling process☆

Qiang Guo[a,*], Bo Zhao[a], Yan Jiang[b], Wu Zhao[a]

[a] School of Mechanical and Power Engineering, Henan Polytechnic University, Jiaozuo 454000, China
[b] School of Survey & Land Information Engineering, Henan Polytechnic University, Jiaozuo 454000, China

A R T I C L E I N F O

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A B S T R A C T

Cutters with non-uniform helix and pitch angles are increasingly used in modern industries. However, few works have studied the cutting forces of this type of tool. Therefore, this study presents a compensated-chip thickness-based cutting force model for non-uniform helix tools in the five-axis milling process. First, the geometry of this special cutter is mathematically expressed. Based on this, the instantaneous uncut chip thickness (IUCT) model is established using error compensation theory combined with real trajectories of cutter edges. This model can overcome the disadvantages of numerical methods Subsequently, the cutting force coefficients are computed using the average IUCT. The engagement between the cutter and the workpiece is discussed. Finally, for verifying the validity and accuracy of the force model, the proposed IUCT, classical, vector-form and true models are compared for a traditional cutter and a cutter with variable helix and pitch angle. Two toolpaths including a line and a circle are selected to predict the IUCT values. The results show that the presented IUCT model exhibits the highest accuracy among the first three models. Additionally, some experiments are conducted. For the three-axis machining process, the toolpaths including a line and a circle are selected. The results show that the cutter with the variable helix angles can predict cutting forces with variable toolpaths. Using the same tool and for the five-axis machining process, a conical surface is selected as toolpath surface. The results show the validity of the cutting force model.

1. Introduction

Complex structures with sculptured surfaces are used more and more commonly in the modern industries such as automotive, aerospace and mold, among others. The five-axis machining process [1] with a flat-end mill is widely used in order to obtain higher accuracy, efficiency [2] and quality [3]. As one of the key and basic technologies that significantly influence the five-axis milling process, machining force prediction is vital for chatter study, deformation determination, fixture design, and so on. In particular, as one effective method to suppress chatter [4] and improve machining efficiency [5], the study of milling forces for milling tools [6] with variable helix and pitch angles has been gradually attracting greater attention. Therefore, the prediction of cutting forces in the five-axis machining process for a flat-end mill, including mills with non-uniform helix angles, is becoming a topic of active research.

With the five-axis milling process, the sculptured surfaces can be machined with high precision, owing to the fact that this process has two more degrees of freedom compared with normal three-axis machining tools [7]. However, simply by using two additional axes, the computation of the instantaneous uncut chip thickness (IUCT) [8] and cutter edges' cutting judgment [9] become difficult. Actually, there are numerous cutting force models for three-axes. Yun and Cho [10] predict three-dimensional forces using the ball-end mill. They consider that the force-coefficients are independent of the cutting conditions. Wei et al. [11] introduce a force model for a Z-level contouring tool path. They discretize the surface by a series of small segments using the feedrate per tooth. Wan et al. [12] predict the force coefficients in a three-axis machining process. The advantage of this model is to compute the cutter runout parameters. Feng and Menq [13] also introduce a force model. Their model has the ability to deal with many of the process variables, including changes in the axial and radial depths of cut and in the feed-rate. Zheng et al. [14] predict the cutting forces for the face milling. The action of a milling cutter is modeled as the simultaneous actions of a number of single-point cutting tools. Using orthogonal cutting data, Lee and Altintaş [15] predict the cutting force. This model is used more and more frequently. Gradišek et al. [16] predict the cutting forces for the general end mill. The cutting force-coefficients in

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* Corresponding author.
E-mail address: guoqiang@hpu.edu.cn (Q. Guo).

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Nomenclature

$\mathbf{P}(i,z)$ The point at the (i,z)
i, j The number
z The height along the cutter axis from the bottom
β_i The helix angle for the $i$the cutter edge
R The radius of the cutter
N The amount of the edges
$\varphi_{i,i+1}$ The pitch angle between ith and $(i+1)$th cutter edge
$df_t(\varphi(i, j, t))$ The tangent force
$df_r(\varphi(i, j, t))$ The radial force
$df_a(\varphi(i, j, t))$ The axial force
$K_t(h(i, j, t))$ The tangent force coefficients
$K_r(h(i, j, t))$ The radial force coefficients
$K_a(h(i, j, t))$ The axial force coefficients
$\varphi(i, j, t)$ The location angle
$h(i, j, t)$ The instantaneous uncut chip thickness (IUCT)
dz The height of the cutting element
$\{\mathbf{O}_c, \mathbf{X}_c\mathbf{Y}_c\mathbf{Z}_c\}$ The cutter coordinate system
$\{\mathbf{O}_w, \mathbf{X}_w\mathbf{Y}_w\mathbf{Z}_w\}$ The workpiece coordinate system
$f_{cx}(\varphi(i, j, t))$ The x cutting forces in the $\{\mathbf{O}_c, \mathbf{X}_c\mathbf{Y}_c\mathbf{Z}_c\}$
$f_{cy}(\varphi(i, j, t))$ The y cutting forces in the $\{\mathbf{O}_c, \mathbf{X}_c\mathbf{Y}_c\mathbf{Z}_c\}$
$f_{cz}(\varphi(i, j, t))$ The z cutting forces in the $\{\mathbf{O}_c, \mathbf{X}_c\mathbf{Y}_c\mathbf{Z}_c\}$
ϑ The included angle in the $\{\mathbf{O}_w, \mathbf{X}_w\mathbf{Y}_w\mathbf{Z}_w\}$
$Q(t)$ The tool position at t in the $\{\mathbf{O}_w, \mathbf{X}_w\mathbf{Y}_w\mathbf{Z}_w\}$
$a(t)$ The cutter axis vector at t in the $\{\mathbf{O}_w, \mathbf{X}_w\mathbf{Y}_w\mathbf{Z}_w\}$
$[x^w(t)\ y^w(t)\ z^w(t)]^T$ The components of $Q(t)$
$[a_x{}^w(t)\ a_y{}^w(t)\ a_z{}^w(t)]^T$ The components of $a(t)$
$f_{wx}(\varphi(i, j, t))$ The x cutting forces in the $\{\mathbf{O}_w, \mathbf{X}_w\mathbf{Y}_w\mathbf{Z}_w\}$
$f_{wy}(\varphi(i, j, t))$ The y cutting forces in the $\{\mathbf{O}_w, \mathbf{X}_w\mathbf{Y}_w\mathbf{Z}_w\}$
$f_{wz}(\varphi(i, j, t))$ The z cutting forces in the $\{\mathbf{O}_w, \mathbf{X}_w\mathbf{Y}_w\mathbf{Z}_w\}$
$B(\alpha(t))$ The rotational matrices about x axis in the $\{\mathbf{O}_w, \mathbf{X}_w\mathbf{Y}_w\mathbf{Z}_w\}$
$A(\gamma(t))$ The rotational matrices about z axis in the $\{\mathbf{O}_w, \mathbf{X}_w\mathbf{Y}_w\mathbf{Z}_w\}$
$\alpha(t)$ The rotational angles about x axis in the $\{\mathbf{O}_w, \mathbf{X}_w\mathbf{Y}_w\mathbf{Z}_w\}$
$\gamma(t)$ The rotational angles about z axis in the $\{\mathbf{O}_w, \mathbf{X}_w\mathbf{Y}_w\mathbf{Z}_w\}$
$P^w(i, z_j, t)$ The point on the current cutter edge at (i, z_j, t)
$\mathbf{Q}(t\text{-}\Delta t)$ The tool position at t-Δt in the $\{\mathbf{O}_w, \mathbf{X}_w\mathbf{Y}_w\mathbf{Z}_w\}$
$\mathbf{a}(t\text{-}\Delta t)$ The axis vector at t-Δt in the $\{\mathbf{O}_w, \mathbf{X}_w\mathbf{Y}_w\mathbf{Z}_w\}$
$\mathbf{S}_1$ The intersection point between the line $\mathbf{Q}(t)P^w(i, z_j, t)$ and the circle whose center is the $\mathbf{Q}(t\text{-}\Delta t)$
$\mathbf{S}_2$ The intersection point between the line $\mathbf{Q}(t)P^w(i, z_j, t)$ and the previous edge's trace
$\mathbf{S}_3$ The drop foot of the $\mathbf{L}^w(i, z_j, t, \nu)$ on the cutter axis $a(t)$
$\mathbf{S}_6$ The intersection point between a plane though the point $\mathbf{S}_1$ which is perpendicular to the axis $\mathbf{a}(t\text{-}\Delta t)$ and $\mathbf{a}(t\text{-}\Delta t)$
$\mathbf{S}_7$ The intersection point between the $(i\text{-}1)$th edge's trace and the circle whose center is the $\mathbf{Q}(t\text{-}\Delta t)$
$C(\omega(t))$ The rotational matrix about $\mathbf{Z}_c$ axis
ω The rotational speed
$\mathbf{L}^w(i, z_j, t, \nu)$ A straight line which is perpendicular to the cutter axis $a(t)$ at the tool position $Q(t)$
$\nu \in [0, 1]$ Parameter
$[s_3^x\ \ s_3^y\ \ s_3^z]^T$ The components of the $\mathbf{S}_3$
$\mathbf{Cyl}(\chi, z, t-\Delta t)$ The cylinder surface at $(t\text{-}\Delta t)$
χ, z The parameters of the $\mathbf{Cyl}(\chi, z, t-\Delta t)$
$T\kappa^{simple}(i, z_j, t)$ The simplification-form of the IUCT
$\boldsymbol{Tk}^{\mathrm{error}}(i,z,t)$ The simplification-error-form of the IUCT
D,E,F The parameters in the equation $D\cos(\chi) + E\sin(\chi) = F$
$d,e,f,d1,e1,f1$ The parameters in the equation $D\cos(\chi) + E\sin(\chi) = F$
$DF_{\max}$ The maximum tool deflection
$D1$ The edge diameter
$D2$ The shank diameter
$L1$ The flute length
$L2$ The overall length
C The constant
G The constant

their study are obtained using a mechanistic model of the process. Ranganath and Sutherland [17] model the runout in the peripheral milling. Their study is focused on a systematic modeling and measurement technique for cutter runout in peripheral milling. Azeem et al. [18] introduce a cutting force model for the ball-end mill. The cutting force-coefficients are mainly studied. Many researcher made great efforts in order to consider the two extra-degrees of freedom for a classical cutter in the five-axis machining process. Using traditional IUCT $= f\sin\theta$ or $f\cos\theta$, Ferry and Altintas [19] present a new method to predict the cutting forces for milling engine impellers. This method computes the total velocity using the horizontal and vertical feed components. Finally, the IUCT is calculated using the split velocity along the tool path. Budak predicts the cutting force model [20] in the five-axis machining process and simulates the machining process [21]. Li [22] utilizes the classical IUCT model to predict the cutting forces. Based on the modified model of the traditional IUCT, Wan and Zhang [23] study several existing methods, which are compared with each other for the five-axis machining process, and some important results are concluded. Fussell [24] transforms the classical IUCT model from a numerical-form to a vector-form. A milling force model for five-axis milling process is built based upon this vector-form IUCT model. It can be seen that, regardless of which of the above cutting force models is used, the IUCT models are the classical model or the modified-form of this model. When the tool path is a line of three-axis milling, this IUCT model can be used to predict the cutting forces with high accuracy or small theoretical error. However, when the tool path is not a line in three-axis machining process or the tool path is a surface that must be realized using a five-axis machine, the cutting force model based on this IUCT model cannot predict milling forces with better precision. In order to improve the prediction accuracy for the five-axis machining process, Sun [25] adopts a technology known as a triangle mesh of a tool path surface. Using the triangular mesh [26], the IUCT value can be calculated based upon the intersection point between the plane and line. Therefore, the accuracy of this method depends on the mesh density. For more mesh faces, the accuracy is higher, whereas for fewer triangle mesh faces, the accuracy is lower. Sun's further work [7] overcomes this disadvantage by computing the intersection point using the true tool path surface. Furthermore, using a numerical method, Zhang [27] presents a model for predicting the IUCT and cutting forces. However, the computation processes of Sun's and Zhang's theories are numerical and time-consuming.

As another important aspect, the determination of the force-coefficients is essential. Burdak et al. [28] present a new mechanical way to predict the cutting force coefficients using orthogonal cutting data. Using the method [28], Merdol and Altintas [29] predict the cutting forces for serrated cylindrical and tapered end mills and they [30] optimize the process. These take the form of a virtual milling system. In order to study the cutting forces, Wojciechowski [31] investigates the edge forces in the ball-end milling of inclined surfaces. He also [32] presents a method of determining force-coefficients considering