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Mechanistic modeling of five-axis machining with a general end mill considering cutter runout

Zhou-Long Li, Jin-Bo Niu, Xin-Zhi Wang, Li-Min Zhu*

State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China

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ABSTRACT

The accurate and fast prediction of cutting forces in five-axis milling of free-form surfaces remains a challenge due to difficulties in determining the varying cutter-workpiece engagement (CWE) boundaries and the instantaneous uncut chip thickness (IUCT) along the tool path. This paper proposes an approach to predict the cutting forces in five-axis milling process with a general end mill considering the cutter runout effect that is inevitable in the practical machining operations. Based on the analytical model of cutting edge combined with runout parameters, the expression of the rotary surface formed by each cutting edge undergoing general spatial motion is firstly derived. Then by extracting the feasible contact arc along the tool axis, a new arc-surface intersection method is developed to determine the CWE boundaries fast and precisely. Next, the circular tooth trajectory (CTT) model is developed for the calculation of the IUCT with a slight sacrifice of accuracy. In comparison with the true IUCT calculated by the trochoidal tooth trajectory model, the approximation error introduced by the circular assumption is negligible while the computational efficiency improves a lot. Finally, combining with the calibrated cutting coefficients and runout parameters, comprehensive formulation of the cutting force system is set up. Simulations and experimental validations of a five-axis flank milling process show that the novel CTT model possesses obvious advantages in computing efficiency and accuracy over the existing approaches. Rough machining of a turbo impeller is further carried out to test the practicability and effectiveness of the proposed mechanistic model.

1. Introduction

Five-axis milling has been widely applied in the production of complex parts such as die-molds, turbines, impellers and various aerospace components. Compared with the traditional three-axis milling, five-axis milling brings huge advantages owing to the two additional degrees of freedom, including better tool accessibility, higher production rate, fewer set-ups, better surface quality, etc. However, due to the complicated process geometry and mechanics, it remains a challenge to select optimal process parameters. In order to ensure high machining accuracy and avoid undesirable results such as excessive tool deflection or even tool breakage, conservative process parameters are usually adopted at the sacrifice of machining efficiency. Since the cutting force is one of the most critical constraints in the machining parameter optimization, the force prediction plays a vital role for five-axis milling operations.

There have been numerous studies on two-dimensional (2D) milling force modeling for flat-end mills [1–3], ball-end mills [4–6] and general end mills [7–9]. Nevertheless, in the field of five-axis milling, most researches focused on the computer-aided manufacturing (CAM) aspect such as tool path planning and collision detection, while few involved the physics of the milling process such as cutting forces. Due to the complicated tool path and workpiece geometry in five-axis milling, the cutter-workpiece engagement (CWE) boundaries are quite difficult to be determined, which instead are normally obtained using non-analytical methods including discrete and solid modeling methodologies. Discrete modeling methods, such as Z-map [10], Z-buffer [11,12], Dexel [13] and Octree [14], calculate the CWE boundaries by dividing the workpiece into finite units. Zhu et al. [10] utilized the Z-map method to develop a mechanistic modeling approach to predict the five-axis cutting forces with ball end mills. Fussell et al. [11] integrated an extended Z-buffer model of the workpiece with the cutter swept envelope to locate the tool-workpiece contact area for cutting force prediction in five-axis milling. Recently, Zhang [15] presented a dexel approach to extract CWE regions for

* Corresponding author.
E-mail address: zhulm@sjtu.edu.cn (L.-M. Zhu).

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Nomenclature

D, R, R_r, R_z parametric radial dimensions of the end mill
α, β parametric angles of the end mill
H usable cutting edge length from tool tip
M_r, N_r radial offsets of the end mill profile
M_z, N_z axial offsets of the end mill profile
$R(z)$ radial coordinate of a cutting edge point at z
$\kappa(z)$ axial immersion angle of a cutting edge point at z
$\psi(z)$ radial lag angle of a cutting edge point at z
i_0 flute helix angle
N tooth number of the cutter
ρ, λ runout offset and its orientation angle
τ, ϕ runout tilt angle and its orientation angle
$\mathbf{o}_s - x_s y_s z_s$ spindle coordinate system
$\mathbf{o}_o - x_o y_o z_o$ offset coordinate system
$\mathbf{o}_t - x_t y_t z_t$ cutter coordinate system
$\mathbf{o}_f - x_f y_f z_f$ moving feed coordinate system
$\mathbf{o}_W - x_W y_W z_W$ global workpiece coordinate system
$\mathbf{o}_D - x_D y_D z_D$ rotary dynamometer coordinate system
$\mathbf{p}_{j,q}(z)(q = t, o, s, f, w)$ coordinate of a cutting point on the jth cutting edge at z expressed in cutter, offset, spindle, feed and workpiece coordinate system
$\varphi_j(z)$ position angle measured clockwise from the y_t-axis to the point $\mathbf{p}_{j,t}(z)$
L cutter overhang length
$\mathbf{P}(t)$, $\mathbf{Q}(t)$ two guiding curves of the tool motion
$\mathbf{A}(t)$ tool axis orientation at time t
$\mathbf{S}_j$ rotary surface of the jth cutting edge
$\mathbf{c}_j$ center of the section circle corresponding to the jth cutting edge
$\mathbf{q}_j$ intersection point of the tool axis and the rotary surface normal
$\mathbf{n}_j$ unit normal of the jth rotary surface
$\mathbf{v}_{axis,j}$ velocity of point $\mathbf{q}_j$
$\mathbf{m}_j$ feasible contact arc corresponding to the jth cutting edge
$\theta_{en,j}$,$\theta_{ex,j}$ entry and exit angels corresponding to the jth cutting edge
$\mathbf{E}_j$ swept envelope surface generated by the jth cutting edge
$\mathbf{E}_j^-$ ingress surface at the initial cutter location
$\mathbf{E}_j^+$ egress surface at the final cutter location
$\mathbf{V}_j$ swept volume generated by the jth cutting edge
$\mathbf{V}$ valid cutter swept volume
$\mathbf{p}^*_{m,w}$ intersection point of the normal line along vector $\mathbf{n}_j$ and the preceding swept surface of the mth cutting edge
$h_{ij}(t)$ instantaneous uncut chip thickness related to the ith disk element of the jth cutting edge at time t
$K_{qc,i}$ $(q = r, t, a)$ tangential, radial and axial cutting force coefficients corresponding to the ith disk element
$K_{qe,i}$ $(q = r, t, a)$ tangential, radial and axial edge force coefficients corresponding to the ith disk element
a_i height of the ith disk element
s_i,b_i cuttting edge length of the ith disk element and its chip width
$F_{q,ij}(t)(q = r, t, a)$ tangential, radial and axial cutting force components related to the ith disk element of the jth cutting edge at time t
$F_{s,ij}(t)(s = x, y, z)$ x-, y-, z- components of the cutting forces related to the ith disk element of the jth cutting edge at time t
$F_s(t)(s = x, y, z)$ x-, y-, z- components of the total cutting forces at time t
Ω_R reference rotation angle between the direction of y_D-axis and the nearest tooth
CWE cutter-workpiece engagement
IUCT instantaneous uncut chip thickness
FCA feasible contact arc
CTT circular tooth trajectory
TTT trochoidal tooth trajectory

five-axis milling force prediction. However, these discrete modeling methods cannot achieve highly accurate CWE boundaries. Comparatively, solid modeling methods can improve the calculation accuracy. Spence et al. [16] identified CWE boundaries using a CSG based process simulation system to predict cutting forces. Larue and Altintas [17] extracted the cutter immersion angles for flank milling by intersecting the cutting tool with the workpiece in ACIS solid modeling environment. Recently, Lazoglu et al. [18] proposed a novel B-Rep based method to determine the complex CWEs in five-axis milling of free-form surfaces. In spite of high accuracy, the solid modeling methods suffer from the problem of low computational efficiency and inferior robustness.

The instantaneous uncut chip thickness (IUCT) is another fundamental parameter for five-axis cutting force prediction. In 2D milling, the IUCT is simplified as $h = f_t \sin\theta sin\kappa$, where f_t is the feed per tooth, θ is the radial immersion angle of the cutting tooth and κ is the axial immersion angle. It is a widely used model which is referred as the classical IUCT model hereafter in this paper. Unlike the 2D milling process, the five-axis motion of the cutter complicates the calculation of IUCT which is unevenly distributed along the cutter axis. Imani et al. [19] developed a modified chip model considering the vertical feed component for 3D ball-end milling. Ferry and Altintas [20] extended the classical IUCT simplification formula to five-axis milling by attaching each differential cutting element along the tool axis to its own feed-coordinate system. However, due to the continuous variations of the tool axis orientation, the curved shape of tool paths and the feedrate, the true trace of the cutting edge in five-axis milling becomes complicated. Thus, the above simplification in the classical model will bring big errors in calculating the IUCT which consequently leads to inaccurate cutting force prediction. Bouzakis et al. [21] developed a “BallMILL” algorithm to determine the undeformed chip geometry considering the milling kinematics. Guo et al. [22] presented an improved chip thickness model based on the real kinematic trajectories of the cutting edges with varying tool orientations.

All the above works did not consider the influence of cutter runout on cutting forces. In fact, cutter runout, which consists of cutter offset and cutter tilt, is common and unavoidable in machining operations with rotary cutting tools. When cutter runout occurs, the rotating radius of each cutting edge differs from its nominal value and is also different with each other. Hence, both the CWE boundaries and the IUCT deviate from their nominal values. Nevertheless, few works have integrated cutter runout effect into the mechanistic model of five-axis milling process. Liang and Yao [23] combined a three-dimensional trochoidal tooth trajectory model and the engagement-boundary chip model to determine the IUCT in five-axis ball-end finish milling, which is able to handle cases with various feedrate, tool-workpiece inclination and cutter runout. Sun et al. [24] established an approach