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A unified instantaneous cutting force model for flat end mills with variable geometries

Min Wan, Wen-Jie Pan, Wei-Hong Zhang*, Ying-Chao Ma, Yun Yang

School of Mechanical Engineering, Northwestern Polytechnical University, 710072 Xi'an, Shaanxi, People's Republic of China

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ABSTRACT

A new and unified instantaneous cutting force model is developed to predict cutting forces for flat end mills with variable geometries. This model can routinely and efficiently determine the cutting properties such as shear stress, shear and normal friction angles (SSSNFAs) involved in the cutting force coefficients by means of only a few milling tests rather than existing abundant orthogonal turning tests. Novel algorithms are developed to characterize these properties using following steps: transformation of cutting forces measured in Cartesian coordinate system into a local system on the normal plane, establishment of explicit equations to bridge SSSNFAs and the transformed cutting forces, determination of SSSNFAs by solving the equations and fitting SSSNFAs as functions of process geometries. Results definitely show that shear stress can be treated as a constant whereas shear and normal friction angles should be characterized by Weibull functions of instantaneous uncut chip thickness. Experiments verify that the proposed unified model is effective to predict the cutting forces in flat end milling in spite of cutter geometries and cutting conditions.

1. Introduction

In the past decades, the rapid boom of milling process has been witnessed in die/mold, aerospace and automobile industries for roughing and finishing components. Behind these applications, one of the challenging problems concerns the machining accuracy that was however found to be disturbed in some cases by the process defects, such as deflections of cutter and workpiece as well as regenerative chatter induced by cutting forces. Much effort has been made to predict and optimize milling operations ahead of the setup of actual machining. Among these, one of the essential topics is to develop effective cutting force models.

Existing models can be classified into three categories: lumped-mechanism model, dual-mechanism model and ternary-mechanism model. Koenigsberger and Sabberwal (1961) developed the first kind of model by which the entire cutting process was treated as an equivalent shearing mechanism and cutting forces were assumed to be a function proportional to chip load with a scaling factor named cutting force coefficient. However, Thomsen (1966) found later that the cutting forces do not converge to zero as the chip load approaches zero. Endres et al. (1995) attributed this phenomenon to the rubbing effect of the clearance face of the flank edge and proposed a dual-mechanism model in which shearing and rubbing effects are separately considered by two cutting force coefficients related to chip load and chip width, respectively. Regarding flat end milling, Wan et al. (2012a) recognized that flank shearing, flank rubbing and bottom cutting effects have all their contributions to total cutting forces and can separately be revealed in a ternary-mechanism model by using three coefficients linearly bridging chip load, chip width and bottom contact width together.

In fact, above models indicate that cutting force coefficients act as an important bridge or bond to relate cutting forces to process geometries. The second concern in cutting force modeling is to establish mathematical expressions of cutting force coefficients. Reliable algorithms are further developed to determine their values. The most widely used concept is to assume the cutting force coefficients as constants. For instance, Kline et al. (1982) treated the cutting force coefficients as constants in lumped-mechanism models, while Gradisek et al. (2004) treated the cutting force coefficients as constants in dual-mechanism models. Some researches also attempted to express the cutting force coefficients as improved formats of constant model, i.e., nonlinear function of average uncut chip thickness. Altintas and Spence (1991) expressed the cutting force coefficients as exponential function of average uncut chip thickness. Shi and Tobias (1984) treated the cutting force coefficients as cubic polynomial of average uncut chip thickness.

Nevertheless, Melkote and Endres (1998) found that the usage of constant cutting force coefficients might lose prediction accuracies at peak values of the instantaneous uncut chip thickness, during tool entry and exit periods. Thus, the concept of instantaneous cutting force coefficients was introduced to characterize the

* Corresponding author. Tel.: +86 029 88495774; fax: +86 029 88495774.
E-mail addresses: m.wan@nwpu.edu.cn (M. Wan), zhangwh@nwpu.edu.cn (W.-H. Zhang).

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Nomenclature

β	helix angle of the flank edge
R	ideal cutter radius
N	tooth number of the cutter
S	spindle rotation speed of the machine
f	feed per tooth
a_p,a_e	axial and radial depths of cut
ϕ	cutter rotation angle
$\theta_{i,j}(\phi)$	angular position related to the jth disk element of the ith flute at ϕ, as shown in Fig. 1
$h_{i,j}(\theta_{i,j}(\phi))$	instantaneous uncut chip thickness corresponding to $\theta_{i,j}(\phi)$, as shown in Fig. 1
P_n	normal plane which is vertical to the cutting edge of the cutter, as shown in Fig. 2
P_s	shear plane which is vertical to normal plane P_n, as shown in Fig. 2
P_R	rake face, as shown in Fig. 2
$z_{i,j}$	axial length of the jth disk element of the ith flute
$K_{T,i,j}(\phi)$, $K_{R,i,j}(\phi)$, $K_{A,i,j}(\phi)$	tangential, radial and axial cutting force coefficients for the jth disk element of the ith flute at ϕ
$F_{T,i,j}(\phi)$, $F_{R,i,j}(\phi)$, $F_{A,i,j}(\phi)$	tangential, radial and axial cutting forces related to the jth disk element of the ith flute at ϕ
$F_{X,i,j}(\phi)$, $F_{Y,i,j}(\phi)$, $F_{Z,i,j}(\phi)$	cutting forces in the Cartesian coordinate system related to the jth disk element of the ith flute at ϕ
$F_{Tn,i,j}(\phi)$, $F_{Rn,i,j}(\phi)$, $F_{An,i,j}(\phi)$	projections of $F_{T,i,j}(\phi)$, $F_{R,i,j}(\phi)$, $F_{A,i,j}(\phi)$ on P_n, as shown in Figs. 1 and 2
$F_{fn,i,j}(\phi)$	friction force on P_n, which is related to the jth disk element of the ith flute at ϕ
$F_{nn,i,j}(\phi)$	normal force to P_R, which is related to the jth disk element of the ith flute at ϕ
$F_{sn,i,j}(\phi)$	projection of shear force on P_n, which is related to the jth disk element of the ith flute at ϕ
$F_{i,j}(\phi)$	resultant force related to the jth disk element of the ith flute at ϕ
$F_{n,i,j}(\phi)$	projection of $F_{i,j}(\phi)$ on P_n, which is related to the jth disk element of the ith flute at ϕ
ρ, λ	runout offset and its orientation angle
θ_{en}, θ_{ex}	entry and exit angles
$R_{i,j}$	actual cutting radius related to the jth axial disk element of the ith flute
$m(i)$	index number denoting that the current tooth i is to remove the materials left by its $m(i)$th previous tooth
τ_s	shear stress at the shear plane
α_r, α_n	radial and normal rake angles of a cutter
β_a	actual firction angle on the rake face
ψ_n, β_n	normal shear and friction angles in oblique cutting
η	chip flow angle in the rake face

instantaneous influences of process geometries. In the representative work of Cheng et al. (1997), it was shown that instantaneous cutting force coefficients in face milling can be expressed as power functions of instantaneous uncut chip thickness, cutting speed and cutting edge length. Ko and Cho (2005) expressed coefficients as Weilbull functions, whereas Wan et al. (2007) developed exponential function for cutting force coefficients.

In all the work mentioned above, it is important to notice that cutting force coefficients have to be determined in advance for each specific cutter and then used under different cutting conditions. In other words, cutting force coefficients have to be renewed whenever the cutter's geometry is changed. In order to establish a unified model for cutters with arbitrary process geometry, Budak et al. (1996) attempted to employ the classical oblique theory proposed by Armarego and Whitfield (1985) to express the cutting force coefficients as nonlinear functions of shear stress, shear angle, friction angle, chip flow angle, cutter's helix and rake angles. At the same time, Budak et al. (1996) also proposed a practical approach to determine the values of shear stress, shear angle and friction angle from orthogonal turning tests, and indicated that an orthogonal to oblique cutting transformation approach (OOCTA) can be used to predict milling forces. Later, unified geometric and kinematic models were also developed by Engin and Altintas (2001) for general solid end mills and the OOCTA was extended to different machining operations. Kaymakci et al. (2012) established unified geometric and kinematic models for general inserted tools used in turning, milling, boring and drilling processes. The state of the art on this topic is as follows.

(1) The determination of shear stress, shear angle and friction angle involved in the cutting force model still resorted to abundant orthogonal cutting tests. For example, more than 180 turning experiments were even needed in the determination procedure of Altintas (2000). Thus, how to develop simple methods using only a few milling tests is still an untouched territory.
(2) Although great successes have been made in unifying geometric and kinematic models for general cutters, studies about the influence of instantaneous process geometry of milling itself on shear stress, shear angle and friction angle have seldom been carried out.

The motivation of this paper is to develop a new and straightforward method for establishing a unified instantaneous cutting force model suitable to flat end mills with different geometries. Novelties are highlighted as follows.

(1) Instead of orthogonal turning, milling experiments and relevant new algorithms are directly designed to determine shear stress, shear angle and friction angle.
(2) Only a few milling tests are required for the determination procedure. This can greatly reduce the burden of abundant orthogonal experiments for different cutters and cutting conditions in the existing methods as used in Altintas (2000).
(3) It is observed that the uncut chip thickness has clearly an instantaneous effect on the crucial parameters such as shear angle and friction angle. This is the so-called size effect that can be modeled by treating concerned parameters as a Weibull function of the instantaneous uncut chip thickness.
(4) The advantage of the new method is demonstrated by comparing the predicted cutting forces with the measured ones for flat end mills with different geometric parameters of cutters such as diameter, tooth number, rake angle and helix angle under a wide range of cutting conditions.

2. Basic mechanical model

Fig. 1 shows a general flat end milling process, in which the cutting edges are discretized into a finite number of axial disk elements with equivalent axial length $z_{i,j}$. Tangential, radial and axial cutting forces related to the jth disk element of the ith flute can thus be expressed as

$$
\begin{aligned}
F_{T,i,j}(\phi) &= g(\theta_{i,j}(\phi))K_{T,i,j}(\phi)h_{i,j}(\theta_{i,j}(\phi))z_{i,j} \\
F_{R,i,j}(\phi) &= g(\theta_{i,j}(\phi))K_{R,i,j}(\phi)h_{i,j}(\theta_{i,j}(\phi))z_{i,j} \\
F_{A,i,j}(\phi) &= g(\theta_{i,j}(\phi))K_{A,i,j}(\phi)h_{i,j}(\theta_{i,j}(\phi))z_{i,j}
\end{aligned}
\quad (1)
$$