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Study of static and dynamic ploughing mechanisms by establishing generalized model with static milling forces

Min Wan*, Ying-Chao Ma, Jia Feng, Wei-Hong Zhang

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

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ABSTRACT

Studies on ploughing mechanism were separately treated for static and dynamic cutting processes in the literature. In this paper, a generalized method, which is suitable for exploring the ploughing mechanism of both static and dynamic cuts, is presented by only using the static milling forces. Whether for static or dynamic cutting processes, a unified proportional form is used to express ploughing forces as function of the volume of the materials extruded under the clearance face of the tool, and the corresponding proportional scale is named ploughing force coefficient. To facilitate identifying the ploughing force coefficient, the total static milling force is decomposed into two parts, i.e. the shearing force component and the ploughing force component, and then the ploughing force coefficient is identified using the ploughing force component. It is observed that the relative error between the determined ploughing force coefficient and the one obtained by using dynamic signals in existing method is less than two percent. Besides, determination procedure is also specially developed to calibrate shear angle, shear stress and friction constant based on the separated shearing force component. Both static and dynamic milling tests are used to validate the proposed model.

1. Introduction

Cutting forces occurring in machining processes are the main causes that may lead to many process defects such as deflection-based surface errors and regenerative chatter; hence, how to properly choose cutting conditions has been a vitally important issue to reduce or avoid these kinds of negative factors and thus to improve quality and productivity [1]. To achieve this aim, establishing reliable cutting force models which can predict the machining mechanics and then using these kinds of models to optimize and select cutting parameters ahead of the setup of actual machining have attracted the attention of scholars.

From the aspect of mechanism, cutting forces consist of shearing force on the rake face and ploughing force on the clearance face. The former component, which is generated by shearing effect, has been systematically modeled by previous researchers either using empirical approach from experimental measurements [2–5], analytical cutting mechanics supported by plasticity laws [1,6,7], or through numerical means with finite element techniques [8,9]. Kline et al. [2] used the average of sampled cutting forces while Larue and Anselmetti [3] adopted the measured cutter deflection to mechanistically develop cutting force models. Yun and Cho [4] and Cheng et al. [5] developed instantaneous cutting force models through developing the mathematical relationships between cutting force coefficients and the instantaneous uncut chip thickness. By adopting an orthogonal to oblique cutting transformation, Budak et al. [6] developed a unified static cutting force model that can be used for various cutting operations with cutters having arbitrary edge profiles, and identified the required shear angle, shear stress, and friction constants from abundant orthogonal cutting tests. Recently, Wan et al. [7] achieved efficient determination of these parameters by means of only a few milling tests rather than vast turning cuts. Strenkowski et al. [8] predicted tool forces and the chip flow angle by coupling an orthogonal finite element cutting model with an analytical model of three-dimensional cutting.

Ploughing force, which is associated with the indentation effect of clearance face of flank edge, is actually the so-called edge force in the study of static cutting forces and the damping forces in the analysis of cutting chatter stability. Budak et al. [6] assumed static ploughing force to be proportional to chip width, and empirically identified the proportion scale, i.e., edge force coefficient, by using linear regression method. Jin and Altintas [10] numerically determined the edge force from finite element analysis and slip-line theory.

Actually, the biggest impact of ploughing effect is on chatter stability [11–13]. At small spindle speeds, the time varying,

* Corresponding author.
E-mail addresses: m.wan@nwpu.edu.cn (M. Wan), zhangwh@nwpu.edu.cn (W.-H. Zhang).

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Nomenclature

i and j	index number of the tooth and the axial disk element
t	cutting instant time
$h_{ij}(t)$	instantaneous uncut chip thickness related to the jth axial disk element of the ith flute at cutting instant time t
z_{ij}	axial length of the jth axial disk element of the ith flute
ϕ	cutter rotation angle
Ω	spindle rotation speed, rev/min
$A_{ij}(t)$	chip load associated with the jth axial disk element of the ith flute at cutting instant time t
R	nominal radius of the cutter
$r_{i,j}$	cutter rotation radius related to the jth axial disk element of the ith flute
m	number means that the surface left by the jth axial disk element of the (i–m)th flute
ρ and λ	geometrical parameters in radial cutter runout model
τ_s	shear stress of the workpiece materials
ψ_n	shear angle defined as the angle between the shear plane and the cutting speed
β_n and η	friction angle and chip flow angle
β and α_n	helix and normal rake angles of the cutter
r_h	hone radius of cutting edge
β_s	separation angle, as defined in Fig. 1
h_p	penetration depth, as defined in Fig. 1
γ	clearance angle of cutting edge
a_p and a_e	axial and radial depths of cut
q=T or R	direction flags corresponding to tangential or radial directions
K_{qs}	shearing force coefficients
$K_{sp,q}$	ploughing force coefficients
N	total teeth number of the cutter
$\theta_{i,j}(t)$	cutter position angle related to the jth axial disk element of the ith flute at t
$\theta_{en,ij}$, $\theta_{ex,ij}$	entry and exit angles related to the jth axial disk element of the ith flute
$F_{q,ij}(t)$, $F_{qs,ij}(t)$ and $F_{qp,ij}(t)$	total, shearing and ploughing cutting forces related to the jth axial disk element of the ith flute at t
$\varphi(z)$	lag angle corresponding to axial coordinate z
$V_{ij}(t)$, $V_{s,ij}(t)$ and $V_{d,ij}(t)$	overall indented, statically indented, and dynamically indented volumes at cutting instant time t, respectively
$D_{s,ij}$	cross-section area of the statically indented volume
$F_X^M(t)$, $F_Y^M(t)$ and $F_Z^M(t)$	measured cutting force components in X-, Y- and Z-directions at cutting instant time t
W	tool wear land length
$v_{c,ij}$	cutting speed associated with the jth axial disk element of the ith tooth, m/min

periodic contact between the clearance face of the tool and relatively short undulation wavy surface generally leads to that more materials become ploughed [13–16], and the resulting higher process damping thereby improves the process stability. The underlying mechanism of this phenomenon has also been paid attention by many researchers. Wu [17] proposed that the dynamic ploughing force is linearly proportional to the interference volume between cutter clearance face and machined surface, and the proportion scale is generally named process damping force coefficients. Regarding this topic, research focuses are mainly on how to identify the process damping coefficients and how to accurately calculate the interference volume. The state of the art on this issue can be summarized as follows.

- While Wu [17] used the rules of contact mechanics to estimate process damping force coefficients, Altintas et al. [14] did this from the dynamic cutting tests in which the cutting tool is oscillated by a piezo-actuator driven fast tool servo at the desired frequency and amplitude. By inversely computing critical stability limits, Budak and Tunc [16] identified the indentation coefficients from chatter tests without using complicated measurement systems. Later, Budak and Tunc [18] proposed an alternative method to identify the indentation coefficients through energy balance formulation. Eynian and Altintas [19] designed static indentation tests to determine the contact force coefficient. Ahmadi and Altintas [13] estimated process damping coefficient from the frequency domain decomposition of the vibration signals measured at two locations of the tool during stable orthogonal turning tests.
- Chiou and Liang [20] expressed the interference volume as a closed function of extruded materials, cutting speed, vibration velocity, and wear land length. Ahmadi and Ismail [21] assumed the surface undulation as a sine wave, and analytically derived the computation procedure of indentation volume based on the assumption. It is important to note that the edge hone on the tool, cutting speed, and clearance angle are the most important factors for process damping [22]. Hence, Endres et al. [23,24] expressed the indentation volume as the function of honed cutting edge and clearance face edge, and then calibrated the specific indentation force coefficient from a ploughing force component decomposed from total orthogonal cutting forces. Recently, Ahmadi and Altintas [13] calculated wear land length as the summation of three segments by considering the effects of hone radius, separation angle and clearance angle. Tunc and Budak [18] comprehensively established theoretical expressions of indentation volume by including some important geometrical parameters such as tool hone radius, clearance angle, separation angle and geometry of clearance face.

In summary, all relevant researches mentioned above have the following typical characteristics.

- Prediction of static and dynamic ploughing cutting forces is in a separation state. As commented above, static ploughing cutting force coefficients obtained by traditional method were only used to predict total static cutting forces; at the same time, process damping induced by dynamic ploughing forces were estimated by the parameters generally calibrated from dynamic signals. In fact, in real cutting situation, the overall indented volume under clearance face consists of a statically indented volume and a dynamically indented one, respectively. Whether in static cutting or in dynamic cutting, the ploughing effect follows the same mechanism and should be studied in a unified way like one investigates shearing forces induced by static and dynamic uncut chip thickness. Although Endres et al. [23,24] made the first effort to express the ploughing cutting forces in a unified form for both static and dynamic ploughing cases, they did not extend to explore its influence on dynamic cuts.
- Determination of shear angle, shear stress, and friction constant in the unified static cutting force model, whether using the procedure proposed by Budak et al. [6] or the method by Wan et al. [7], did not plan to comprehensively establish a cutting