

Paper:

# Adaptive Cutting Force Prediction in Milling Processes

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**An adaptive force model is presented to predict the cutting force and the chip flow direction in milling. The chip flow model in the milling process is made by piling up the orthogonal cuttings in the planes containing the cutting velocities and the chip flow velocities. The chip flow direction is determined to minimize the cutting energy. The cutting force is predicted using the determined chip flow model. The force model requires the orthogonal cutting data, which associate the orthogonal cutting models with the cutting parameters. Basically, the required data for simulation can be measured in the orthogonal cutting tests. However, it is difficult to perform the cutting tests with specialized setups in the machine shops. The paper presents the adaptive model to accumulate and update the orthogonal cutting data with referring the measured cutting forces in milling. The orthogonal cutting data are identified to minimize the error between the predicted and the measured cutting forces. Then, the cutting forces can be predicted well in many cutting operations using the identified orthogonal cutting data. The adaptive is effective not only in extending the database but also in improving the quality of the database for the accurate predictions.**

**Keywords:** end mill, cutting force, chip flow, optimization

## 1. Introduction

Many milling operations have been performed to machine several parts in the manufacturing industries. The cutting operations have to be optimized for reducing the machining costs and times. The workers in the machine shops have found the applicable cutting parameters through trial and error in the cutting tests. However, the materials to be machined have been diversified with research and development of the material suppliers. The machine shops, therefore, do not have enough time to review the cutting processes with the cutting parameters.

Recently manufacturing industries have started using cutting simulations to review the cutting processes. Many researches have been made on the cutting simulation in the milling processes since Martellotti's work [1]. Smith and Tlusty reviewed many works on the modeling of the milling process [2]. Ehamann et al. also reviewed mech-

anistic models in milling [3]. Koenigsberger and Sabberwal developed a mechanistic model for slab milling and face milling operations based on the cutting force coefficients [4]. Kline et al. developed a prediction model of cutting force in end milling and introduced the effects tool runout and tool deflection on the machining accuracy [5]. Armarego et al. predicted cutting force in end milling based on the oblique cutting model [6, 7]. Then, Budak et al. studied the milling force coefficients using the orthogonal cutting data [8]. They discussed the edge force and the cutting components of the milling force coefficient in the predictive force model. Li et al. proposed a cutting force model of helical end milling based on a predictive machining theory proposed by Oxley [10]. The cutting force models have recently been applied to the cutting process with ball end mills. Yang and Park presented a force model in cutting with ball end mills using the orthogonal cutting data [11]. Yucesan and Altintas presented a semi-mechanistic analytical force model of ball end millings [12]. Bayoumi et al. analyzed the cutting force in cutting with profile milling cutters [13]. Feng and Menq presented the force model with analysis of the cutter runout [14, 15]. Lee and Altintas presented a predictive force model based on the oblique cutting [16]. They used the orthogonal cutting data associated with the shear plane cutting mechanism. Most of presented models based on the oblique cutting process predicted the milling force on the assumption that the chip flow direction was uniquely determined by Stabler's rule, in which the chip flow angle is associated with the edge inclination.

Usui et al. proposed a force model to predict not only the cutting force but also the chip flow direction [17]. Then, Hirota et al. extended this model to plane milling [18]. The model determined the chip flow direction to minimize the cutting energy in the chip flow model. Therefore, the model can be applied to simulation of the cutting process even if the local edge inclination angle of the cutting edge largely changes. Because the manufacturing industries have recently been performing the dry cutting operations from the environmental point of view, the model gives relevant information for the chip control with optimizing the cutting parameters and the tool geometry.

Recently finite element analysis has also been performed to simulate the cutting processes with the chip formations. Mackerle reviewed many literatures in FE analysis of the cutting processes [19]. Analyzing the stress

and the strain distribution in the material and the tool, FE analysis was used for evaluation of the affected layer with the residual stress [20].

Although many cutting force models have been presented, few researches have discussed to accumulate and improve the database for simulation. Basically, simulation cannot be executed without the database, which characterizes material deformation and friction between the tool and the workpiece. Because the simulation accuracy strongly depends on the quality of the database, the database should be accumulated and updated using the machining results to perform the practical and reliable cutting simulation.

The paper presents an adaptive cutting force model with identification of the required data for the prediction. The force model based on the minimum cutting energy is applied to prediction of the milling force. The prediction requires the orthogonal cutting data for characterizing the material properties and the friction on the tool face. Originally, the required data for simulation can be measured in the orthogonal cutting tests with the specialized setups. However, such experiments apart from the usual cutting operations cannot be performed easily in the machine shops. In the presented model, the orthogonal cutting data are identified by referring the measured cutting forces in the normal milling tests without the special operations. After the orthogonal cutting data are acquired, the cutting forces and the chip flow directions in many cutting operations can be predicted accurately to review the cutting parameters and the tool geometry. Although the presented model requires measurement of the milling forces, the prediction adapts the cutting operations performed in the machine shops well with identification and becomes more reliable. A case study is shown to verify the presented model with the identified orthogonal cutting data. Then, the cutting processes are discussed with the cutting force prediction.

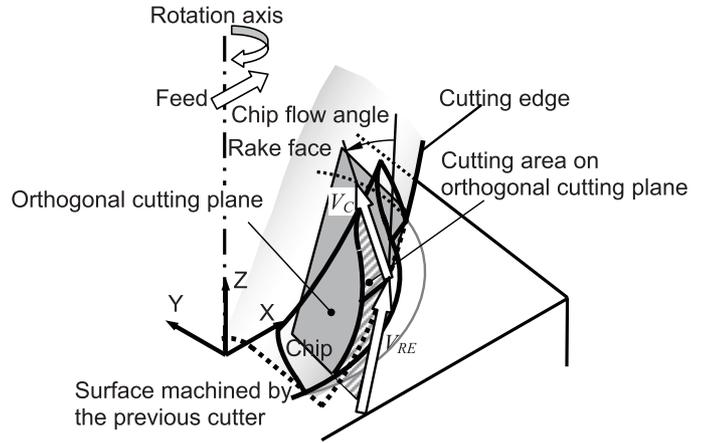
**2. Prediction Model of Milling Force**

The tool geometry of the milling tools associating with the cutting force can be defined as functions of the cutter height *h* as follows:

$$\left. \begin{aligned} R(h) &= F(h) \\ \alpha_R(h) &= G(h) \\ \alpha_A(h) &= H(h) \\ \gamma(h) &= J(h) \end{aligned} \right\} \dots \dots \dots (1)$$

where *R*,  $\alpha_R$ ,  $\alpha_A$  and  $\gamma$  are the radius, the radial rake angle, the axial rake angle and the delay angle of the cutting point with respect to the bottom of the edge, respectively.

**Fig. 1** shows an example of the chip flows with the general shaped end mills, which include the curved-edge end mills such as ball end mills. The cutting force components are predicted with the chip flow angle in the simulation. The chip flow model is made by pilling up the orthogonal cuttings in the planes containing the cutting velocities



**Fig. 1.** Chip flow in milling.

$V_{RE}$  and the chip flow velocities  $V_C$ . Although plastic deformation actually occurs in the chip flow, the interaction between each orthogonal cutting plane is ignored in the model. The cutting edge is divided into discrete segments to make the orthogonal cutting models using the following data:

$$\left. \begin{aligned} \phi &= \exp(A_{00}V + A_{01}t_1 + A_{02}\alpha + A_{03}) \\ \tau_s &= \exp(A_{10}V + A_{11}t_1 + A_{12}\alpha + A_{13}) \\ \beta &= \exp(A_{20}V + A_{21}t_1 + A_{22}\alpha + A_{23}) \end{aligned} \right\} \dots (2)$$

where  $\phi$ ,  $\tau_s$  and  $\beta$  are the shear angle, the shear stress on the shear plane and the friction angle.  $\alpha$ , *V* and  $t_1$  are the rake angle, the cutting velocity and the uncut chip thickness in the orthogonal cutting.  $A_{ij}$  ( $i = 0, 1, 2; j = 0, 1, 2, 3$ ) are parameters to be identified as described later. The cutting force should be regarded as the sum of the edge force component due to the rubbing or ploughing and the cutting component due to shearing in the shear zone and friction on the rake face. For the sake of simplicity in identification, this study employs the orthogonal cutting data expressed as Eq. (2) on the assumption that the cutting component is the major effect here. Therefore, the identified orthogonal cutting data would include the effect of the edge components.

**Figure 2** shows the coordinate systems used in the model. X-Y-Z is the reference system; and X'-Y'-Z' rotates with a cutting edge at the angular velocity  $\omega$ . X'-axis is defined in the direction of the cutter radius and Y'-axis is defined in the tangential direction of the cutter rotation. X''-Y''-Z'' is the coordinate system based on the direction of the cutting velocity. Y''-axis is defined in the velocity direction and the X''-axis is perpendicular to the Y''-axis. Because the cutting velocity  $V_{RE}$  at a cutting point P is the resultant of the circumferential velocity and the feed rate,  $V_{RE}$  and the wedge angle  $\Theta$  between X' and X'' are:

$$V_{RE} = \sqrt{f^2 \sin^2(\omega t - \gamma) + \{R_P \omega + f \cos(\omega t - \gamma)\}^2} \dots \dots \dots (3)$$

$$\Theta = \tan^{-1} \frac{f \sin(\omega t - \gamma)}{R_P \omega + f \cos(\omega t - \gamma)} \dots \dots \dots (4)$$