Rapid Calibration of Cutting Force Control System Using Motor Currents in End Milling Processes

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Abstract : In this paper, an easy and rapid calibration method of a cutting force estimator with motor currents is proposed for end milling machines. The rapid calibration method consists of following three steps: selection of standard cutting conditions for the end-mill and the workpiece, calibration of drive systems, and calibration of cutting force coefficients. The proposed method makes cutting force estimator calibrated easily and rapidly without additional cutting force measurement system, so that it is possible to raise practicality of the cutting force control system.

Keywords : Cutting force coefficients, Cutting force estimator, End milling process, Motor current, Rapid calibration, Standard cutting condition

1. Introduction

In modern manufacturing processes, there is an ever-increasing demand for higher productivity by reducing machining time with the increase of cutting force and material removal rate.[1] However, the excessive increase of cutting force results tool breakage, poor machined quality, and bad effects on the machine tool. One of the most straight-forward methods of improving productivity and quality in machining processes is real-time estimation and control of cutting forces.[2] If we develop a cutting force estimator through the measurement of motor currents in end milling processes, we should calibrate the motor currents according to cutting force values as quickly as possible. In this case, the easy and rapid calibration method is required for initial set up of the cutting force estimator on the milling machine.

In this study, an easy and rapid calibration method of a cutting force estimator with motor currents is proposed for end milling machines. The rapid calibration method consists of following three steps: (1) selection of standard cutting conditions for the end-mill and the workpiece, (2) calibration of drive systems, and (3) calibration of cutting force coefficients. In the first step, general end-mill and workpiece are selected standards for measuring cutting forces without an expensive dynamometer. And construct database of cutting forces as motor currents according to the standard cutting conditions. The calibration of drive systems means identification of relationships between motor currents and cutting forces without dynamometers through the measured currents and already known cutting forces obtained from standard cutting conditions. From this result, system parameters of the drive systems, and relationships between currents and cutting forces can be calibrated. The last step is to identify cutting coefficients for an end-mill and a workpiece. Through experiments with the standard cutting conditions for a new end-mill and a workpiece, the cutting coefficients can be identified with estimated cutting forces from the calibrated cutting force estimation system. The calibrated cutting coefficients become important parameters of an analytical model that estimate axial and radial depth of cuts and various cutting forces using estimated feed cutting force and cutting torque obtained from motor currents.

For various end-mills and workpieces, the validity of the developed rapid calibration method is verified on a horizontal machining center through experiments of the cutting force control.

2. Cutting Force

2.1 Force Modeling of End Milling

Cutting forces are described as functions of cutting pressures acting on the instantaneous chip load area [3-6] as shown in Fig. 1,

$$dF_t = K_s\, dz\, h(f)\,, \quad dF_r = r_1 dF_t \tag{1}$$

where $dz = [R/\tan(b)]df$ is thickness of the axial element of the cutting edge, $h(f) = t_c \sin(f)$ is instantaneous chip thickness, t_c is feed per a tooth. The cutting pressure K_s can be expressed as a function of the average chip thickness. In the peripheral down-milling process instantaneous forces in the X and Y directions along the chip load of a single flute are given by

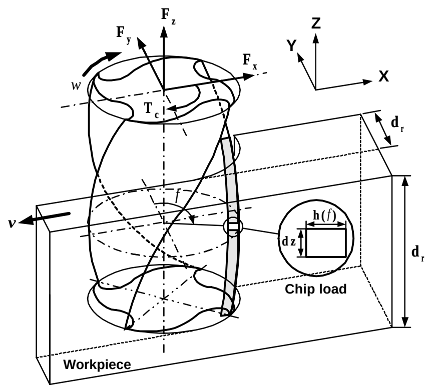

Fig. 1 Cutting forces in peripheral end milling process

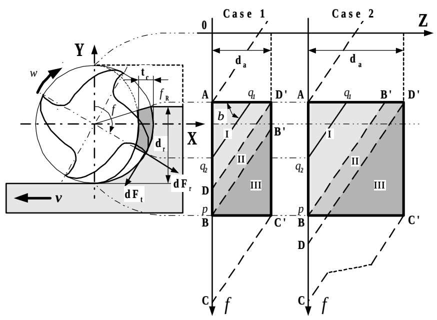

Fig. 2 Cutting mechanism of end milling process

$$dF_x(f) = \quad dF_t \cos f + dF_r \sin f$$
$$dF_y(f) = -dF_t \sin f + dF_r \cos f \tag{2}$$

Integrating Eq. (2) within the contact range of a single tooth as shown in Fig. 2,

$$F_{ti}(f) = K\int_{q_1}^{q_2} \sin t \, dt$$
$$F_{xi}(f) = K\int_{q_1}^{q_2} (\sin t \cos t + r_1 \sin^2 t)dt$$
$$F_{yi}(f) = K\int_{q_1}^{q_2} (-\sin^2 t + r_1 \sin t \cos t)dt \tag{3}$$

The average forces per a tooth can be obtained to divide total cutting forces through cutting range $[f_A, f_C]$ by period of tooth $f_N = 2p/N$. Average cutting forces for several teeth cutting are

$$F_{at} = KR_a C_r$$
$$F_{ax} = KR_r\left(A_r + r_1 B_r\right) \tag{4}$$
$$F_{ay} = KR_r\left(-B_r + r_1 A_r\right)$$

where, $A_r = \dfrac{\tan b}{2f_N}\left(R_r^2 - 2R_r\right)$,

$$B_r = \frac{\tan b}{2f_N}\left\{\left(R_r - 1\right)\sqrt{2R_r - R_r^2} - f_N + p\right\},$$

$$C_r = \frac{\tan b}{f_N} R_r \quad , \quad K = K_s R t_c / \tan b$$

Generally, cutting force coefficients in Eq. (4) are function of average chip thickness $t_a = t_c R_r / (p - f_r)$,

$$K_s = k_s t_a^{p_s}, \quad r_1 = k_1 t_a^{p_1} \tag{5}$$

2.2 Identification of Radial and Axial DOC

The radial immersion ratio $R_r = d_r/R$ can be expressed by the force ratio of average feed force to average tangential force, derived from linear interpolation.[7]

$$\frac{F_{ax}}{F_{at}} = \frac{A_r + r_1 B_r}{C_r} \tag{6}$$

And the axial immersion ratio $R_a = d_a/R$ can be derived from the estimated radial immersion and average cutting force

$$R_a = \frac{F_{ax}}{K\left(A_r + r_1 B_r\right)} \tag{7}$$

3. Rapid Calibration of Cutting Force Estimator

3.1 Selection of Standard Cutting Condition

Standard cutting conditions are firstly determined by the cutting conditions recommended by the tool makers. Then, in order to obtain the expected data during cutting, the cutting experiments are performed within the boundaries that do not exceed the limit.

In this study, carbide 4-flute flat end mills ($f = 8mm$) and SM45C for workpiece are used. And Table 1 shows the standard cutting conditions based on the recommendation of the tool maker.

The feedrate (100~700mm/min) that is designed for the average cutting force not to be over 1000N, and the radial depth of cuts (0.1~2.0mm) are adopted in the experiments. The major factor to analyze the cutting characteristics of tools and workpieces, the cutting force coefficients, are shown in Table 2 and Table 3. The cutting forces are estimated through the cutting force coefficients, and then the current stage of the cutting process can be determined.

Table 1 Standard cutting conditions

Spindle speed (rpm)	1260	Cutting speed (m/min)	31.6673
Feedrate (mm/min)	250	Chip thickness (mm/tooth)	0.0496
Radial DOC	0.1D	Removal Volume (mm^3/tooth)	0.4762
Axial DOC	1.5D		

Table 2 Parameters of cutting force coefficients for carbide

	K_s	r_1
k	1007.59	0.2242
p	-0.2557	-0.1546

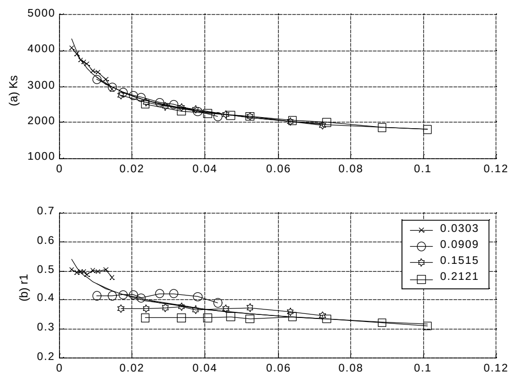

Fig. 3 Cutting force coefficients for average chip thickness

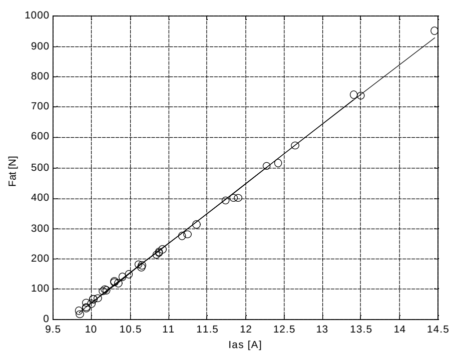

Fig. 4 Spindle system modeling for Eq. (8)

3.2 Calibration of Drive System

Spindle system : When spindle speed is constant, dynamics of spindle systems are given by [2]

$$F_{at} = K_{t1} I_{as} + K_{t2} \quad (8)$$

where, $K_{t1} = 196.61$, $K_{t2} = -1911.0$

Feeddrive system : Dynamics of feed drive systems are given by

$$I_{axf} = K_{x1} w^2 + K_{x2} w + K_{x3} \quad (9)$$

$$\begin{aligned} F_{ax} &= K_{x4}\left(I_{ax} - I_{axf}\right) + K_{x5}/w \\ &= K_{x4} I_{dx} + K_{x5}/w \end{aligned} \quad (10)$$

where, w is the federate(m/min), I_{ax} is the measured average motor current, I_{axf} is the motor current due to nonlinear friction torque disturbance torque.

The variables in Eq. (9) are evaluated by measuring the feeddrive motor currents according to the unloaded feedrate. Fig. 5 shows the experiment results and the evaluated values of variables are presented in Table 3. The relationship between feeddrive motor currents and cutting forces are expressed by Eq. (10). The model is established with the considerations of the feeddrive motor currents subtracted from the currents due to friction and the forces inversely proportional to the feedrate. Fig. 6 shows the experiment results to evaluate variables of the model and the values of them is shown in Table 3.

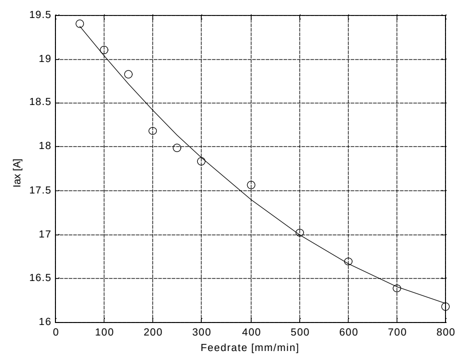

Fig. 5 Feedrate vs. feeddrive motor current for Eq. (9)

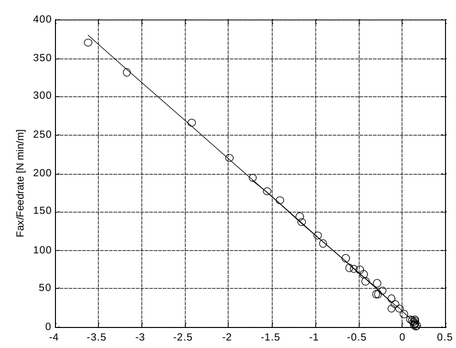

Fig. 6 Feeddrive motor current vs. feed force for Eq. (10)

Table 3 Parameters of feeddrive system

K_{x1}	3.5788	K_{x4}	196.61
K_{x2}	-7.2469	K_{x5}	-1911.00
K_{x3}	19.7252		

3.3 Calibration of Cutting Force Coefficients

In order to verify the rapid calibration of the cutting force estimator, the estimated values and the experiment results, which are performed with the HSS 4-flute flat end mill, are compared each other. Before the calibration by the currents, the specific cutting force coefficients that are evaluated from the cutting forces are presented in Table 3 and Table 4.

From the results of section 3.1 and 3.2, the cutting forces can be determined through the estimation of feed forces from the current in the feed drive motor and the estimation of tangential cutting force. And, based on the standard cutting condition, the cutting experiments are carried out with the unknown tool and workpiece, and then the specific cutting force can be evaluated by the equation (4) without the tool dynamometer. In Table 5 and Fig. 8, the cutting pressures calculated from the estimated cutting forces are compared. The cutting pressures are estimated well, but the coefficient r_1 shows relatively large errors due to the non-linearity of the feeddrive motor currents and the large friction effect in small radial DOC.

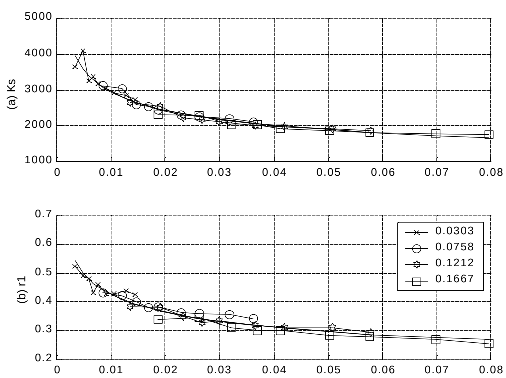

Fig. 7 Cutting force coefficients for HSS flat end mill

Table 4 Parameters of cutting force coefficients for HSS

	K_s	r_1
k	831.16	0.1526
p	-0.2749	-0.2227

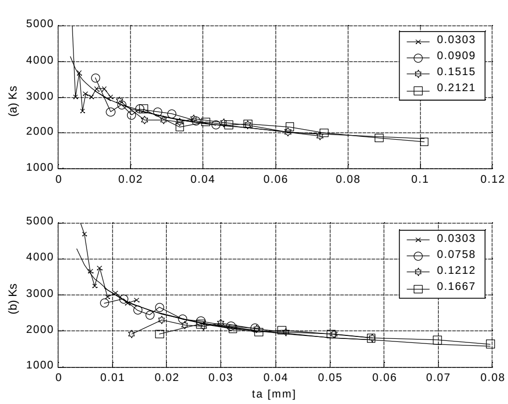

Fig. 8 Cutting force coefficients with motor currents

Table 5 Parameters of cutting pressure by motor currents

	(a) Carbide	(b) HSS
k	1052.96	703.26
p	-0.2403	-0.3176

4. Conclusion

An easy and rapid calibration method of a cutting force estimator with motor currents is proposed for end milling machines. With the general end-mill and workpiece, the database of cutting forces and motor currents is constructed according to the standard cutting conditions. Relationships between currents and cutting forces are calibrated through cutting forces obtained from the constructed database and the measured currents really, and then cutting force coefficients are identified with only motor currents.

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