

Robust Cutting Force Control Using Indirect Force and Disturbance Estimators in the End Milling Process

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Abstract : In this paper, a robust cutting force control system using an indirect cutting force estimator and disturbance observer is studied in the end milling process. The indirect cutting force estimator is derived from the geometric cutting force model and the feed and spindle motor currents. In order to regulate the cutting force at a desired level during wide range of machining conditions, a robust control system with a disturbance observer is developed using a feedrate override function.

Keywords : Cutting force regulation, Cutting geometry, Disturbance observer, End milling force model, Indirect force sensor, Motor current, Robust real-time control, Unmodelled dynamics

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 in tool breakage, poor machined quality, and bad effects on the machine tool. Variation in cutting force may result in a variation of spindle or workpiece deflection, thus deteriorating resultant geometric accuracy. Nevertheless, variation of cutting force is often unavoidable due to factors such as a change in the depth of cut or workpiece geometry, hardness variation, and tool wear. One of the most straight-forward methods of improving productivity and quality in machining processes is real-time estimation and control of cutting forces during the machining process.[2] The purpose of such control is to maintain the cutting force at a prescribed level by adjusting cutting parameters. The adaptive cutting force control results in an increased metal removal rate while the machining system is protected against sudden failure due to overload. The part quality may be also improved.[3]

In this study, the robust cutting force control using indirect cutting force measurement is developed in the end milling process. This paper consists of two parts. One is an indirect cutting force estimator during the end milling process. The other is a robust adaptive cutting force controller. Cutting forces and torque models are derived from the cutting geometry in end milling processes. Relationships between motor currents and cutting forces are also developed from the proposed force models. Cutting forces are measured indirectly from the sensing currents of feed drive servo motors and the spindle motor through the estimator with the cutting geometry analyzer. Since the suggested method does not need an expensive sensor like a dynamometer,

the method is expected to be used practically. In order to maintain the cutting force at a desired level during the cutting process in spite of variation of machining conditions, a feedrate override robust adaptive control system is studied using the disturbance observer. Nominal models of the feed drive system and the cutting process are identified by experiments. To account for any unmodelled dynamics and parameter uncertainty of a time varying end milling process, a robust controller with an adaptive PI scheme based on real time process gain estimation is designed with the disturbance observer. By reducing the machining time resulting from making the actual cutting forces follow the reference force, the increase of productivity are also expected, and the quality of cutting surface has been improved due to the adjusted feedrate. The validity of the developed system is verified on a horizontal machining center through the experiments.

2. Indirect Normal Cutting Force Estimator

2.1 Force Modeling of End Milling

Cutting forces are described as functions of cutting pressures acting on the instantaneous chip load area [4-6]

$$dF_t = K_s dz h(\phi), \quad dF_r = r_t dF_t \quad (1)$$

where $dz = [R/\tan(\beta)]d\phi$ is thickness of the axial element of the cutting edge, $h(\phi) = l_f \sin(\phi)$ is instantaneous chip thickness, l_f is feed per 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

$$\begin{aligned} dF_x(\phi) &= dF_t \cos \phi + dF_r \sin \phi \\ dF_y(\phi) &= -dF_t \sin \phi + dF_r \cos \phi \end{aligned} \quad (2)$$

Integrating Eq. (2) within the contact range of a single tooth as shown in Fig. 1,

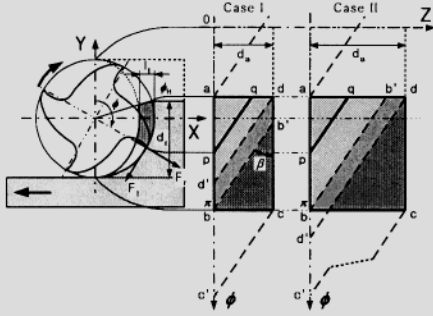


Fig. 1 Cutting mechanism of end milling process

$$\begin{aligned}
 F_x^i(\phi^i) &= K \int_{\phi_q}^{\phi_p} (\sin \tau \cos \tau + r_1 \sin^2 \tau) d\tau \\
 F_y^i(\phi^i) &= K \int_{\phi_q}^{\phi_p} (-\sin^2 \tau + r_1 \sin \tau \cos \tau) d\tau \\
 F_t^i(\phi^i) &= K \int_{\phi_q}^{\phi_p} \sin \tau d\tau
 \end{aligned} \quad (3)$$

For several teeth cutting,

$$\begin{aligned}
 F_x(\phi) &= K \sum_{i=1}^N (A^i(\phi^i) + r_1 B^i(\phi^i)) \\
 F_y(\phi) &= K \sum_{i=1}^N (-B^i(\phi^i) + r_1 A^i(\phi^i)) \\
 F_t(\phi) &= K \sum_{i=1}^N C^i(\phi^i)
 \end{aligned} \quad (4)$$

where, $A(\phi) = 0.25(\cos(2\phi_q) - \cos(2\phi_p))$,

$$B(\phi) = 0.5\{\phi_p - \phi_q - 0.5(\cos(2\phi_p) - \cos(2\phi_q))\},$$

$$C(\phi) = (\cos \phi_q - \cos \phi_p), \quad K = K_s R l_f / \tan \beta$$

Fig. 2 shows average cutting forces according to various axial and radial depth of cuts. Simulated average forces are compared to measured forces for various radial DOCs as shown in Fig. 3.

2.2 Cutting Force Estimation Using Motor Currents

Dynamics of feed drive and spindle systems are given by

$$K_t I_M = J \frac{d\omega}{dt} + B\omega + T_f + T_d \quad (5)$$

where, ω is the speed, I_M is the motor current, T_d is the disturbance torque due to cutting forces, and T_f is the coulomb friction torque.[2,3,6]

By using motor currents and identification procedures of [6], parameters of Eq. (5) can be extracted from a machining center. Fig. 4 shows measured and estimated results of average cutting forces through a dynamometer and motor currents, respectively.

2.3 Identification of Radial and Axial DOC

From cutting force models of section 2.1, radial and axial depth of cuts are able to be identified as shown in Fig. 5. The radial immersion ratio $R_r = d_r/R$ can be expressed by the force ratio of average feed force to average tangential force. And the axial immersion ratio $R_a = d_a/R$ can be derived from linear interpolation with

the average force change for a radial immersion. The estimated cutting forces using motor currents in Fig. 4 are applied to the estimator of radial and axial depth of cuts in Fig. 5. From these results, radial and axial DOCs and the normal force and measured motor currents, can be estimated as shown in Fig. 6.

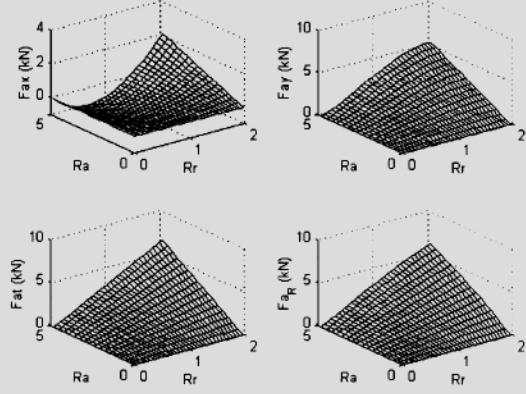


Fig. 2 Relationships between cutting forces and DOC

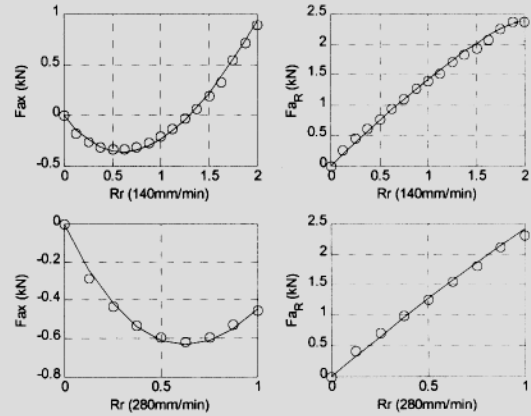
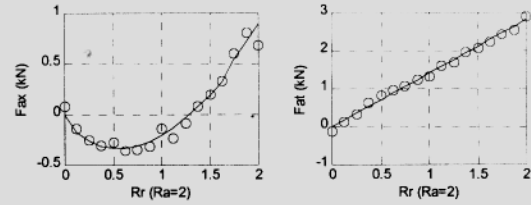
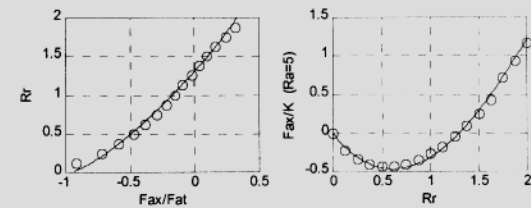


Fig. 3 Measured and simulated cutting forces (feedrate 140, 280 mm/min)



(a) Feed current (b) Spindle current
Fig. 4 Measured and estimated cutting forces



(a) Force ratio and Rr (b) Rr and force change for Ra
Fig. 5 Relationships between Rr, Ra and cutting forces

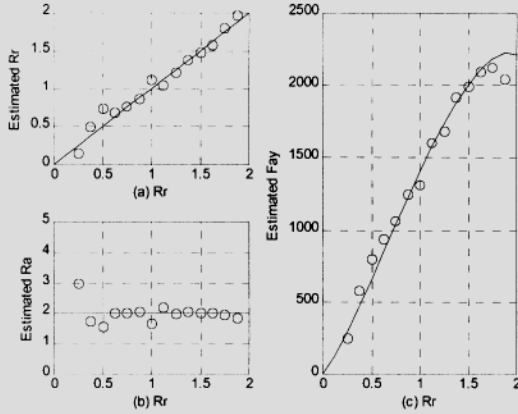


Fig. 6 Estimated radial and axial DOC, and normal force

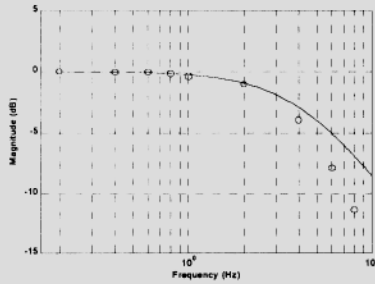


Fig. 7 Frequency response of the X-axis feed drive

Table 1 Cutting models for end milling processes (600rpm, 16mm dia., 4 teeth flat end milling)

Radial DOC (mm)	Gain (K_2)	Pole Location (p_2)
2	10.05	-2.35
3	12.57	-3.75
4	20.11	-5.35

3. Robust Cutting Force Control

3.1 Modeling of End Milling Process

To obtain a dynamic model of the end milling process, following identification procedures of the feed drive system are required. Sinusoidal inputs between 0.2Hz to 8Hz are used as excitation signals of feedrates. Feed velocities come from the encoder are measured as output signals. Fig. 7 shows the frequency response function between the input and the output signals of feedrates. From this frequency response function, a dynamic model of the feed drive is given by [7]

$$\frac{v(s)}{u(s)} = \frac{29.33e^{-0.1s}}{s + 29.33} \quad (6)$$

The cutting force can be derived as follows [7]

$$\frac{f(s)}{v(s)} = \frac{K_2}{s - p_2} \quad (7)$$

Combining Eq. (6) and (7), the end milling process model becomes

$$\frac{f(s)}{u(s)} = \frac{29.33K_2e^{-0.1s}}{(s + 29.33)(s - p_2)} \quad (8)$$

To account for any unmodeled dynamics and parameter uncertainty of the time varying end milling process, end milling experiments were conducted according to several values of cutting conditions. Table 1 shows cutting models obtained from some of end milling experiments. From this we can conclude that dynamics are varied during cutting. To follow up varying dynamics and design a cutting force controller, a robust controller is designed with the disturbance observer. In this case, the nominal model P_n of the plant P is chosen to be

$$P_n(s) = \frac{f(s)}{u(s)} = \frac{368.68e^{-0.1s}}{(s + 29.33)(s + 3.75)} \quad (9)$$

This model is based on 3mm radial depth of cut.

3.2 Design of Robust Controller

Fig. 8 shows a block diagram of the robust control system. The robust controller compensates for mechanical nonlinearities, parameter variation, and disturbances and lets the dynamic behavior of the actual feedback loop system stay close to the nominal plant. [8]

The disturbance observer is designed in the continuous time domain. The actual plant dynamics is $P(s) = P_n(s)[1 + \Delta(s)]$, where $\Delta(s)$ represents the variation of the plant from the nominal dynamics. $F(s)$ is derived as

$$F(s) = \frac{P_n(s)[1 + \Delta(s)]}{1 + \Delta(s)Q(s)} E'(s) + \frac{[1 - Q(s)]P_n(s)[1 + \Delta(s)]}{1 + \Delta(s)Q(s)} D(s) \quad (10)$$

Notice that $F(s) = P_n(s)[E'(s) + D(s)]$ for $Q(s) = 0$ and $F(s) = P_n(s)E'(s)$ for $Q(s) = 1$. By proper selection of $Q(s)$, we can let the actual plant behave like the nominal plant over a specified frequency region.

For internal stability $Q(s) \in RH_\infty$, and realizability $Q(s)/P_n \in RH_\infty$, $Q(s)$ is selected as the following form.

$$Q(s) = \frac{1}{(\tau s)^3 + 3(\tau s)^2 + 3(\tau s) + 1} \quad (11)$$

where τ is the response time.

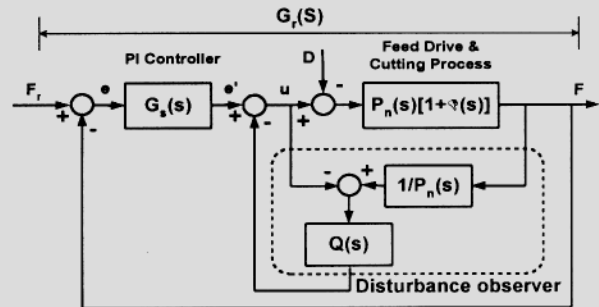


Fig. 8 Block diagram of a robust control system

4. Experiments

Combining the indirect force sensor and the robust adaptive controller, a robust adaptive cutting force control system is finally developed in the end milling process through the feedrate manipulation. An experimental setup was constructed for the commercial CNC machining center without major changes of the structure as shown in Fig. 9. The feedrate override function and PC/NC interface were accomplished by the programmable machine controller interface technique on a Fanuc 15MA NC controller.

Experiments are performed on-line to verify the robustness of the cutting force estimator and controller. Experimental results for 2 to 4 mm of DOC are shown in Fig. 10: (a) measured and estimated feed forces from feed current, (b) measured and estimated tangential forces from spindle current, (c) command feedrates, (d) estimated radial DOCs, (e) estimated axial DOCs, (f) measured and estimated normal forces.

5. Conclusion

The robust cutting force control using indirect cutting force estimators and the disturbance observer has been developed in the end milling process. Cutting force models are derived from the cutting geometry in end milling processes. Relationships between depth of cuts and cutting forces are also developed from the proposed force models. Cutting forces are measured indirectly from the observed currents of feed drive servo motors and the spindle motor through the mathematical estimator. In order to maintain the cutting force at a desired level during the cutting process in spite of variation of machining conditions, a feedrate override robust adaptive control system has been studied using the disturbance observer. Nominal models of the feed drive system and the cutting process were identified by experiments. The validity of the developed estimator and controller has been verified on a horizontal machining center through the experiments.

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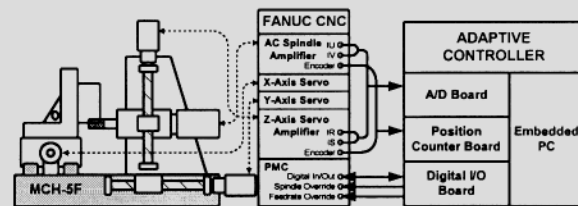


Fig. 9 Schematic diagram of experimental setup

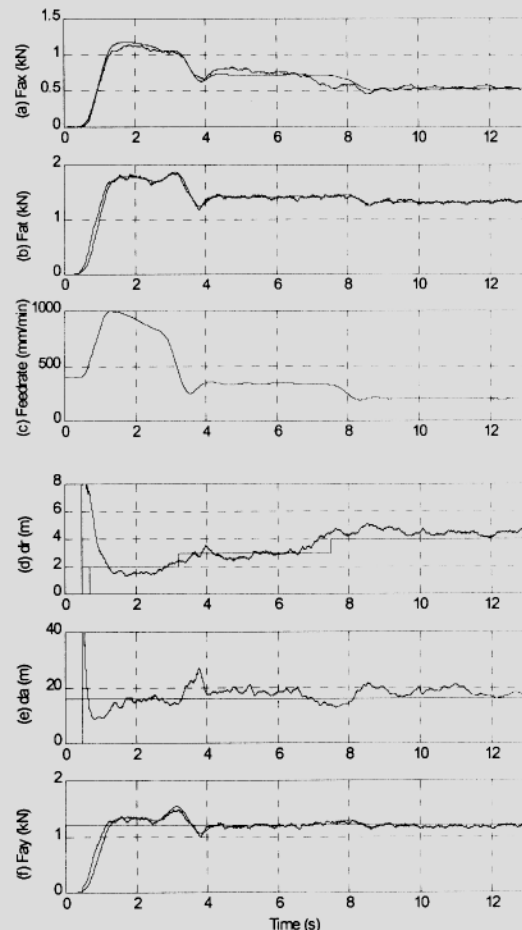


Fig. 10 Experiment results of robust control