DISTURBANCE OBSERVER AND OPTIMAL FUZZY CONTROLLER USED IN CONTROLLING OF CUTTING FORCE AND TORQUE IN HIGH PERFORMANCE OF DRILLING PROCESS FOR FERROUS AND NON-FERROUS INDUSTRIAL MATERIALS

Rajendra Singh
Assoc. Prof., Department of Mechanical Engineering,
Aryan Institute of Technology, Jindal Nagar, Ghaziabad (UP), India.

ABSTRACT

The automation of machining processes requires highly accurate process monitoring. However, the use of additional sensors leads to a significant increase in the cost and reduces the stiffness and reliability of mechanical systems. Hence, we propose a system called the cutting force and torque observer, which uses a sensor-less and real-time cutting force estimation methodology based on the disturbance observer theory. Monitoring methods using the cutting force and torque observer may enhance the productivity during drilling process in which one of the parameters that significantly affect the cutting process is the shear angle. The determination of the shear angle is very important as it can be used for identifying the machining conditions. In this study, an external sensor-less monitoring system of the shear angle during turning is developed, and its performance is evaluated. This paper deals with Proportional-Integral-Derivative (PID) controller used in a high performance drilling system for controlling the output obtained. The main objective is to obtain a stable, robust and controlled system by tuning, PID controller using minimization. The incurred value is compared with the traditional tuning techniques is improved better. Hence that drilling process results estimates the tuning in which PID controller using minimization technique gives less overshoot and better control performance with many advantages such as exibility, and reduced maintenance time and cost. In order to improve drilling efficiency while preserving tool life. , this study focuses on the design and implementation of an optimal fuzzy-control system for drilling force. This 49-rule controller is networked and operates on a computer numerical control (CNC) machine tool. It is optimally tuned using a known maximum allowable delay to deal with uncertainties in the drilling process and delays in the network-based application.

KEYWORDS: *Cutting force and torque, monitoring high-performance drilling process, shear angle, disturbance observer and Fuzzy control.*

I. INTRODUCTION

The cutting force is the most basic process information required for monitoring a machining process. The cutting force is monitored for detecting tool wear, tool breakage, and chatter vibration, which lead to low productivity. Generally, for monitoring the cutting force, additional sensors such as dynamometers are used. In order to achieve the transparency, and feel the sensation from the remote site, teleoperation architectures need properly measured force information. Up to date, however, many teleoperation systems have been using force sensors for haptic(force) feedback and control. To overcome the drawbacks of the force sensors, proposed works in this research work estimate the disturbance torque by using an input and an output signal of the motor installed on the each joint of the manipulator. As a result of the estimation, the estimated disturbance torque information, the angular position and the angular velocity of each joint will be transmitted to the opposite side without any force sensors. Thus, control designers will be able to apply many teleoperation architectures and their own control strategies with the haptic (force) feedback.

Recent rapid technological progress in machine tool performance is largely attributable to developments in feed drive and spindle motion control and machine and coolant temperature control [1]. Advances in numerically controlled machine tools have made it necessary to expert machine operators and parts-programmers to determine machining and operating parameters such as the selection of tools, feed rates, spindle speed, and depths of cut. In conventional numerically-controlled machining seen from process control, as shown in Fig. 1 [2], operators conduct process planning and programming using computer-aided manufacturing (CAM) software or an automatic programming system installed on CNC. On test cuts, operators observe the machining process through machining sound, vibration, chips, and spindle motor load. When abnormal processes such as chatter or overload arise, operators typically try overriding spindle speed or feed rate. They observe machining quality in surface finish and dimensional accuracy of machined work pieces, and if needed, change NC programs or adjust machining conditions to improve machining accuracy. This can be seen as a feedback control with a human operator's decision making included, as is illustrated in Fig. 1.

To support even a non-expert machine operator to perform high-productive and high-accurate machining processes, much research effort has gone into autonomously determining machining parameters to conduct feedback control while minimizing human intervention. Despite the necessity of such approaches widely recognized in manufacturing, their commercial implementation has remained limited, first of all due to sensor cost and reliability. Furthermore, in our view, most researches has focused on ways to control machining, without clearly presenting practical benefit of installing machining process control. This paper reviews monitoring and control schemes of cutting force or torque. Their practical implementation issues will be then discussed.

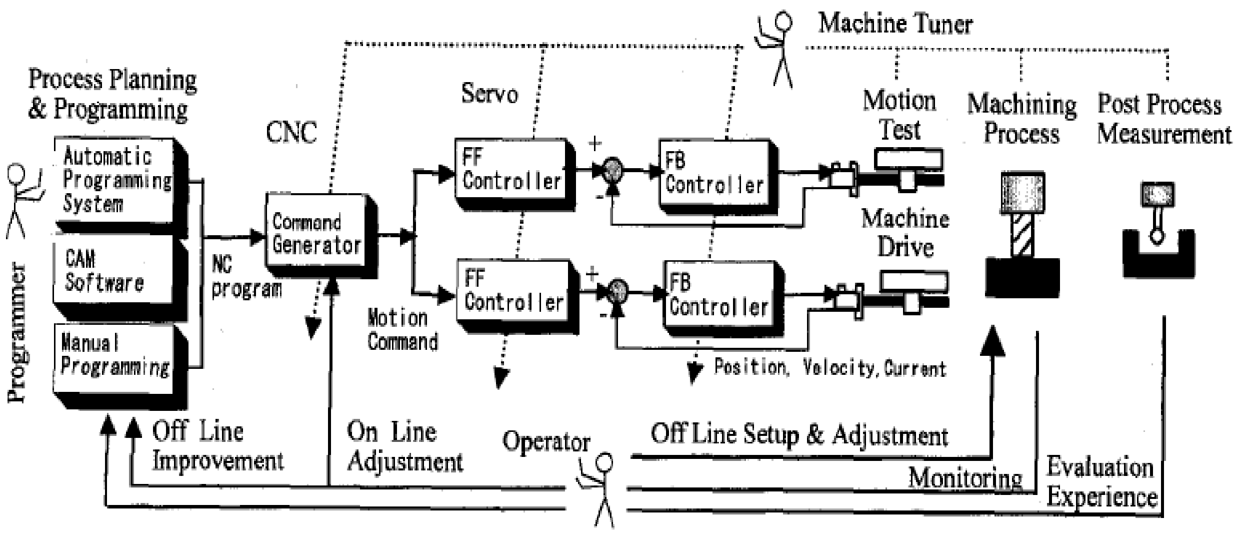


Fig. 1. Conventional machining configuration from the viewpoint of process control [2].

II. Literature Review

[1].Maeda proposed a method for preventing tool breakage and enhancing the productivity of drilling by using an in-process cutting torque monitoring method using dynamo meter. However, the use of additional sensor leads to a significant increase in the cost and a reduction in the mechanical stiffness. Recently, several methods for measuring the cutting force without the use of force sensors have been proposed.

[2]. Yoshioka et al. developed an in-process thermometry micro sensor mounted directly on the tool tip for ultra-precision turning.

[3].Altintas proposed the detection of tool breakage by monitoring the periodic cutting force using the feed motor current. Although these methods monitor the cutting force without the use of external sensor, the accuracy of these methods is not sufficiently high.

[4].Merchant's minimum energy method, the shear angle is approximated on the basis of the rate of the principle cutting force and thrust force. Therefore, monitoring these forces in real time will make it possible to monitor the shear angle. Because measurement of the shear angle takes time and is difficult, the above mentioned method is very effective. The purpose of this study is to develop a method for monitoring the shear angle without using external sensors.

[5].Piispanen, the card model, which is a method used for calculating the shear angle from the chip information, is used for evaluating the performance of the shear angle monitoring. Piezoelectric-based dynamometers are commercially available to measure cutting torques on a spindle.

[6].Ohzeki et al. studied the use of magneto strictive torque sensors in the spindle. A potentially critical issue with sensors integrated in spindles is the heat generated by the spindle motor.

[7].Jun et al. studied this, suggesting that temperature compensation was needed to reliably monitor torque. A torque or force sensor within the spindle may be difficult to install on many machines due to space restrictions. Alternatively, sensors are integrated into a tool holder, as is already commercially available.

[8].Artis, integrated strain gauges into a tool holder to measure torque, axial, and radial forces.

[9]. Montronix, commercialized small sensor-integrated plates or rings installed at different places on the machine, including the spindle head, affected by cutting force.

[10]. Kim et al. developed a cylindrical capacitance sensor installed near front spindle bearings to measure gap variation between the sensor head and the rotating spindle shaft under cutting load.

[11]. Albrecht et al. used a capacitance sensor to calculate cutting force, showing that bandwidth up to 1,000 Hz was obtained when spindle dynamics was compensated.

[12].Jeong et, all measured spindle displacement in turning using three capacitance displacement sensors similarly. The gap in a spindle supported by active magnetic bearings is calculated from command voltage to magnetic bearings , analogous to a capacitance sensor, and can be used to calculate cutting force . A high-speed spindle with sensors integrated to monitor spindle conditions such as vibration, run-out, and temperature, is gaining wider use in high-speed commercial machines .

III. THEORETICAL BACK GROUND

Drilling covers the methods of making cylindrical holes in a work piece with metal cutting tools. Drilling is associated with subsequent machining operations such as trepanning, counter boring, reaming and boring. Common to all these processes is a main rotating movement combined with a linear feed. There is a clear distinction between short hole and deep hole drilling, the latter being a specialist method for making holes that have depths of many times up to 150 times the diameter With the development of modern tools for short hole drilling, the need for preparatory and subsequent machining has changed drastically. Modern tools have led to solid drilling being carried out in a single operation, normally without any previous machining of centre and pilot holes. The hole quality is good, where subsequent machining to improve the measurement accuracy and surface texture is often unnecessary.

Figure: Drilling process during holes in work materials

MONITORING OF CUTTING FORCES AND TORQUES

Tool breakage is costly both in time lost and materials destroyed. Tool failure is estimated to account for 20%
of the downtime of an average modern machine tool. Tool breakage and severe tool wear may be avoided by using conservative machining conditions, which sacrifices machining efficiency. Many parts machining experts tend to choose heavy-cut machining rather than high-speed machining, which may require more frequent tool changes and higher tool cost. Accurate, reliable tool condition monitoring (TCM) could cut machining time by 10-50%, downtime reduction by scheduling it in advance, which has led to the active study of in-situ tool wear and breakage detection. This section reviews cutting force and torque monitoring.

Cutting Force Monitoring by External Sensors

Force Sensors

We collectively call sensors installed on machine tools to monitor cutting force “external” sensors . This is contrast to “internal” sensors – current sensors for servo and spindle motors installed on NC machine tools. Commercially available dynamometers measure cutting force using quartz piezoelectric transducers. Table and spindle dynamometers are commercially available. These dynamometers have sufficient resolution to be used in micro machining using a non rotating tool or a miniature rotating tool up to several dozen microns in the diameter. Despite the accuracy and reliability of commercial dynamometers, their high cost may limit their use in machining process control.

Torque Sensors

Piezoelectric-based dynamometers are commercially available to measure cutting torques on a spindle. Cutting torque was also calculated using strain gauges . Ohzeki et al. studied the use of magneto strictive torque sensors in the spindle. A potentially critical issue with sensors integrated in spindles is the heat generated by the spindle motor. Jun et al. studied this, suggesting that temperature compensation was needed to reliably monitor torque. A torque or force sensor within the spindle may be difficult to install on many machines due to space restrictions. Alternatively, sensors are integrated into a tool holder, as is already commercially available. Artis integrated strain gauges into a tool holder to measure torque, axial and radial forces.

Cutting Force Calculation by Spindle Displacement

Assessing force or torque using a sensor on a machine spindle may require a highly complex arrangement to ensure required resolution throughout the entire machine tool power range, and the measurement signal must be transmitted without contact from the rotating spindle. Non-contact measurement of displacement is easier than measuring force or torque. Calculating cutting force from spindle displacement has been also studied.

One example is the cutting force calculation that we developed using spindle-integrated displacement sensors, shown in Fig. 2. We used four inexpensive, contamination-resistant eddy-current displacement sensors (S1-S4). Calculating cutting force from spindle displacement, however, involves two major issues – thermal influence and spindle stiffness. Motor heat may critically deform or displace a rotating spindle, which must be separated from displacement caused by cutting force. In many commercial machining centers, the spindle is thermally controlled by circulating coolant through cooling jackets. In on-off temperature control, thermal deformation, is significantly influenced by its control period. In our study, multiple thermocouples are installed in the spindle to calculate thermal displacement. Many studies have reported thermal-mechanical spindle modeling. In addition to thermal influence, another critical issue is spindle stiffness, involving the entire spindle system, including a tool holder, a collet, and a tool. It must be calibrated accurately to estimate cutting force indirectly from spindle displacement. Spindle stiffness varies significantly with spindle speed. Dynamic stiffness may differ significantly from static stiffness. The measurement bandwidth is limited by natural modes of spindle structure. If cutting force frequency is within natural mode range or higher, measurement is distorted. To determine spindle dynamics, Tsuneyoshi used an axial force loader on a rotating spindle.

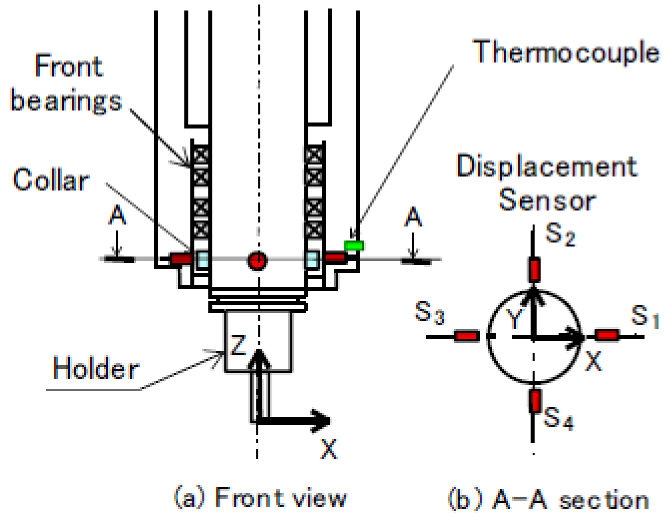


Figure: 2. Spindle-integrated displacement sensor configuration for determining cutting force.

Cutting Force Monitoring by Internal Sensors

Commercial numerically-controlled machine tools having servo motors in a feed drive or spindle motors have current sensors for motion control. When torque induces motor disturbance, armature current is modified by the servo controller to cancel its influence, so cutting torque or force is calculated from a motor's armature current – probably the cheapest way to monitor cutting loads because no extra sensors are needed. Altintas and Lee et al. discussed tool breakage detection based on cutting force calculation by servo motor current. A similar attempt was made observing spindle motor armature current. In many commercial CNCs, spindle load is displayed on a screen, seen as the simplest form of cutting torque calculation. Some CNCs digitally output calculated disturbance from servo motor currents. Commercial products to monitor spindle or servo motor current provide fault detection. Armature current is influenced by dynamic characteristics of the drive system. In a feed drive, particularly, compensating for the dynamics of the moving mass is important in separating out the influence of cutting force. A disturbance observer for a feed drive can be applied for this purpose. Algorithms to analyze and detect abnormal machining process, such as tool breakage, have been drawing attention in academia for years. A frequency domain analysis, statistic analysis, an artificial neural network , wavelet analysis and complexity analysis were applied in fault detection. We studied practical issues calculating cutting force using motor current on a small commercial machining center. Fig. 3 shows the armature current of a servo motor when the single linear axis is driven under a constant feed rate of 1,000 mm/min without a cutting load (ar-mature current is converted to drive force by torque coefficient and ball screw lead). Fig. 3 compares two feed drives – one driven by a rotary servo motor and a ball screw with roller bearings, and the other driven by a linear motor with hydrostatic guide ways. On a feed drive driven by a servo motor and roller or slide guide ways, commonly used in most commercial machining centers, the servo motor undergoes large friction imposed on guide ways or a ball screw. As shown in Fig. 3, the motor in the ball screw drive gives the driving force as 900 N even with no cutting load to overcome friction. Friction varies significantly with the location, or possibly other driving conditions. To separate out the influence of cutting force in motor current, this significant influence of friction

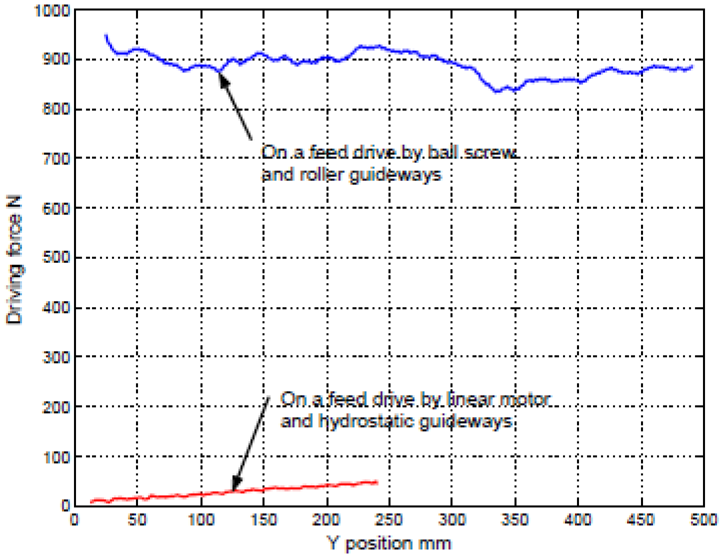


Fig. 3. Feed drive force during Y-axis movement at a constant non-cutting feed rate.

must be compensated for. This is particularly difficult when the drive is stationary, and subject to larger static friction and elastic force imposed by ball screw or nut deformation. Fig. 4 compares experimentally measured cutting force using a dynamometer (horizontal axis) and a disturbance observer based on servo motor current (vertical axis), when side cutting in the Y direction using a straight end mill at different depths of cut and feed rates. Error estimated in the stationary direction (X direction) is significant due to the unpredictability of static friction. We thus concluded that continuous in-process calculation of cutting force by servo motor current is difficult in many applications, and its application must be limited to discrete monitoring in specific locations where friction influence can be predicted sufficiently accurate (e.g. a line where both X and Y axes move). Cutting torque is calculated relatively easily from spindle motor armature current, because a spindle motor undergoes much lower friction, and typically operates at constant speed. Fig. 5 compares measured cutting force using a dynamometer (horizontal axis) and spindle motor current (vertical axis), under the same cutting tests as in Fig. 4. Linear error in Fig. 5 is caused by spindle motor torque coefficient miscalibration, and is easily compensated for. Note, however, that spindle torque shows only the cutting force component tangential to tool rotation. In high-speed machining of hard materials with higher feed rate and lower depth of cut, tool wear often greatly influences the cutting force component normal to the feed direction, making it difficult to observe this influence on spindle motor current. we proposed calculating cutting force components by geometrically combining force vectors from servo motor current on the moving axis and spindle motor current. Feed drives driven by linear motors with hydrostatic or aerostatic guide ways are widely used for ultra-precision and high-precision machine tools. As is shown in Fig. 3, such drives are subject to much lower friction than conventional ball screw drives, enabling cutting force to be calculated more accurately. Fig. 6 compares estimates of cutting force from rotary and linear motor current, under similar cutting tests as in Fig. 4. We are currently implementing machining process control in linear motor-driven machine tools. Machining Process Sensors High-frequency displacement or acceleration of a tool or a work piece may be measured directly instead of cutting forces. Accelerometers on tool holders or work pieces and laser interferometers on spindle shafts or directly on tools have been used to detect tool conditions such as wear, breakage, and chatter.

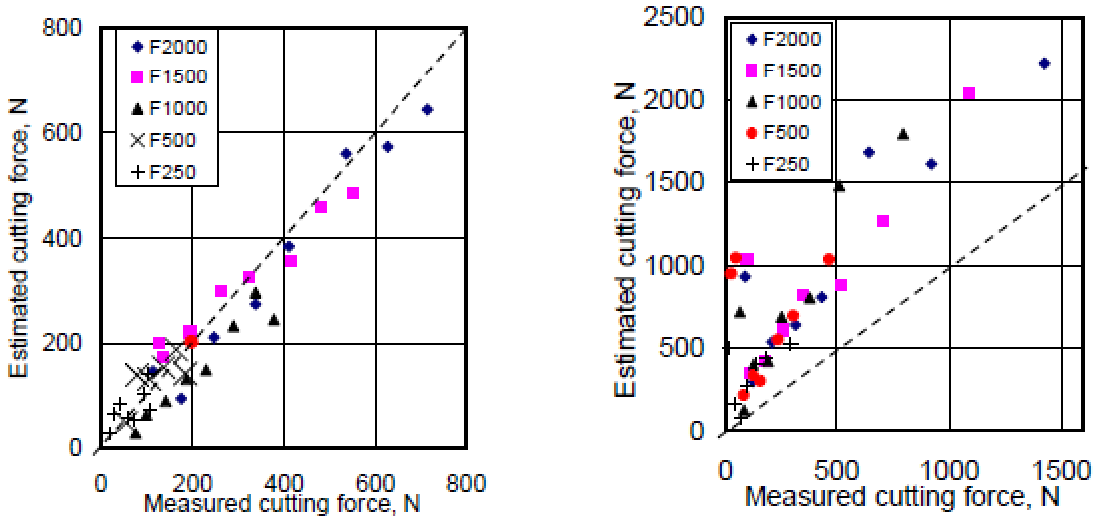


Fig. 4. Comparison of cutting force (horizontal axis) and estimates by monitoring servo motor current (vertical axis) under straight end mill side cutting.

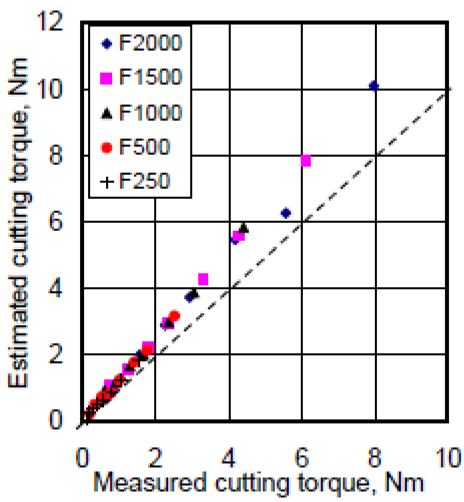


Fig. 5. Comparison of cutting torque by a dynamometer (horizontal axis) and estimates by monitoring spindle motor current (vertical axis) under straight end mill side cutting.

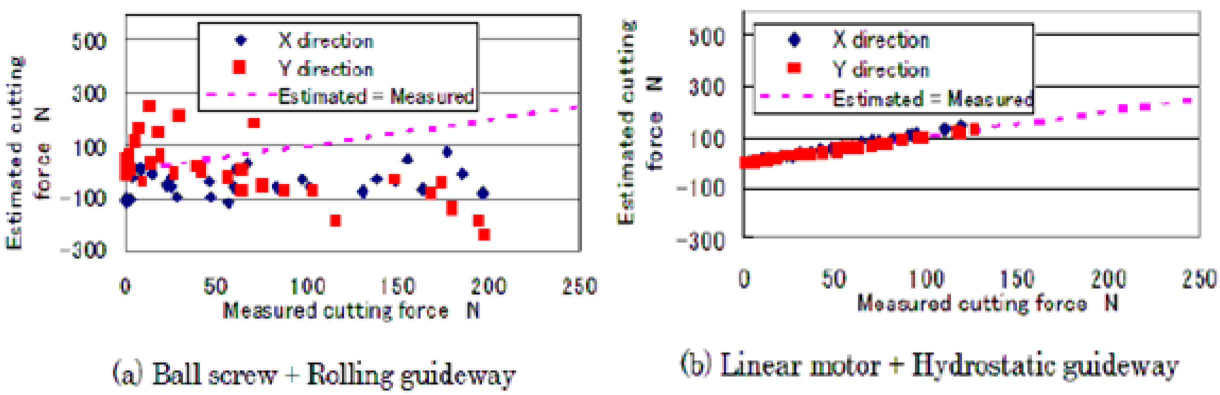


Fig. 6. Comparison of cutting torque by a dynamometer (horizontal axis) and estimates by monitoring (a) rotary motor current and (b) linear motor current (vertical axis) under straight end mill side cutting.

Cutting Force and Torque Control

Among machining process parameters, cutting force and torque are relatively easy to monitor quantitatively, and are directly connected to tool conditions. Most research has been related to their regulation, with objectives roughly categorized into (1) enhancing machining efficiency while avoiding tool damage, and (2) suppressing chatter. Abruptly increasing cutting force on a tool may damage it or cause unexpected wear. If cutting force is below an “appropriate” level, assumed to be known, machining efficiency is improved by raising it. This is a common control objective in many past researches. Chatter suppression, although widely researched, is beyond our scope here.

Feedback Control Approaches

Among in-process machining parameters, feed rate is the easiest to manage. Most commercial CNCs have dials for manually changing feed rate override, while some enable users to input a signal to continuously regulate it. Cutting force control is reviewed in the sections that follow, using feed rate as a control variable. Part of our reviews is included in machining control discussed by Liang et al. and Altintas. Cutting force control, taking feed rate as a control variable, is divided into (1) feedback control that continuously monitors cutting force and regulates the feed rate in real time and (2) model-based scheduling in which an NC program feed rate profile is optimized without real-time process monitoring. Model-based scheduling can be seen as a feed forward control approach. Early machining control work was classified into adaptive control with constraints (ACC), adaptive control with optimization (ACO), and geometric adaptive control (GAC). ACC was typically applied to roughing in which operation productivity was maximized by regulating cutting force at its allowable maximum level. A simple example can be found in its application to drilling processes. The principle involves increasing federate for higher productivity while keeping cutting torque below the maximum. Cutting torque is estimated from spindle motor current relatively accurately. Thrust force estimated from servo motor current is also reliable, unlike cutting force in milling. These were extended to tapping with adaptive “pecking” and were implemented in commercial CNC. Other cutting force and torque control applications have been made to drilling processes implemented in industry.

In any machining process, the force process may change dramatically during operation. Most research since the 1960s has been devoted to adaptive control, e.g. self-tuning regulation (Masory and Koren), model reference adaptive control (MRAC) (Tomizuka et al., Ulsoy and Koren, Landers and Ulsoy), MRAC extended by zero phase error tracking control (ZPETC) (Rober and Shin), direct adaptive control (Altintas), adaptive generalized predictive control (AGPC) (Altintas), adaptive pole placement control (APPC) (Elbestawi et al.), and robust adaptive control (Kooi). As nonlinear intelligent control such as neural networks and fuzzy logic matures, application to cutting force control has been actively studied, e.g. neural-network-based control by Tang et al. and fuzzy logic control by Kim et al. . Liu et al. compared the performance of these approaches. Limited commercial feedback control for end milling includes a milling process controller by Tu et al. implemented in high-speed machines for aircraft parts, using strain gauges attached to a spindle to estimate cutting force. An Omative Systems product monitors spindle motor current to regulate feed rate override, viewed as a simple ACC.

Real-Time Cutting Force and Torque Prediction During Turning

There are several parameters of machining that can be adjusted by installing cutting force observers in multiple axes to increase the productivity during turning. Shear angle is one of the parameters that significantly affect the cutting process. Hence, monitoring the shear angle is very important as this parameter can be used for identifying the machining conditions. This indicates that shear angle monitoring can be used for verifying cutting conditions. According to Merchant’s minimum energy method [7–9], the shear angle is approximated on the basis of the rate of the principle cutting force and thrust force. Therefore, monitoring these forces in real time will make it possible to monitor the shear angle. Because measurement of the shear angle takes time and is difficult, the above mentioned method is very effective. The purpose of this study is to develop a method for monitoring the shear angle without using external sensors. The validity of this method is verified through a lathe turning test with the developed turning machine. Further, the card model of Piispanen [10], which is a method used for calculating the shear angle from the chip information, is used for evaluating the performance of the shear angle monitoring.

Sensor-Less Shear Angle Monitoring Method

2.1. Cutting Force/Torque Observer

A schematic representation of the Cutting Force Observer (CFOB) which is developed on the basis of the disturbance observer theory [6] is shown in Fig. 1. The disturbance observer can estimate the disturbance force *Fl* [N] from the current *Ia* [A] and position information *x* [m]. The cutting force *Fcut* [N] is obtained by deducting the influence of the friction force *Ff ric* [N] from the estimated disturbance (Eq. (1)). The friction force *Ff ric* is identified from the experimental results in advance. A low-pass filter (cut off frequency: *gcut/trq* [rad/s]) is used for filtering out high-frequency noise. A Cutting Torque Observer (CTOB), shown in Fig. 1, can be designed in the same manner as the CFOB (Eq. (1)). In this case, the angle information θ [rad] is used instead of the position information.

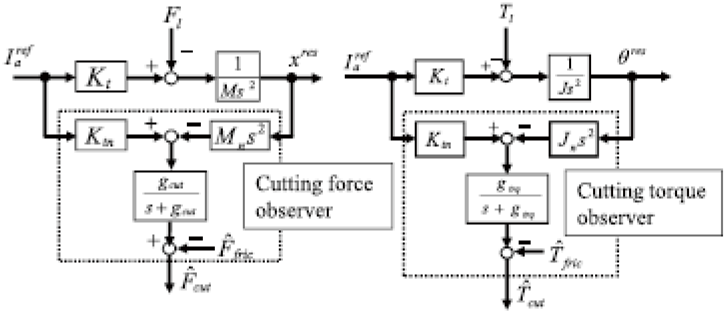


Fig. 1. Cutting Force Observer (CFOB) and Cutting Torque Observer (CTOB).

$$\hat{F}_{cut} = \frac{g_{cut}}{s+g_{cut}}(K_{tn}I_a^{ref} - M_n\ddot{x}^{res} - \hat{F}_{fric}) \quad . \; . \quad (1)$$

$$\hat{T}_{cut} = \frac{g_{trq}}{s+g_{trq}}(K_{tn}I_a^{ref} - J_n\ddot{\theta}^{res} - \hat{T}_{fric}) \quad . \; . \quad (2)$$

2.2. Shear Angle Monitoring Method

According to Merchant's minimum energy theory, when the principle cutting force *Fp*, thrust force *Ft* and the rake angle α are given, the cutting force along the rake face direction *Fv* and the cutting force of direction perpendicular to the rake surface direction *Ff* are obtained by using Eq. (3) (Figs. 2(a) and (b)).

$$\left.\begin{aligned} F_v &= F_p \sin\alpha + F_t \cos\alpha \\ F_f &= F_p \cos\alpha - F_t \sin\alpha \end{aligned}\right\} \quad . \; . \; . \; . \; . \; . \; . \quad (3)$$

The ratio of *Fv* and *Ff* is the friction angle β or the average coefficient of friction of the contact surface of the tool and the chips, μ (Eq. (4)).

$$\mu = \tan\beta = \frac{F_v}{F_f} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (4)$$

When considered separately, the cutting force along the shear plane *Fs* and that in the direction perpendicular to shear plane *Fn*, can be calculated using Eq. (5).

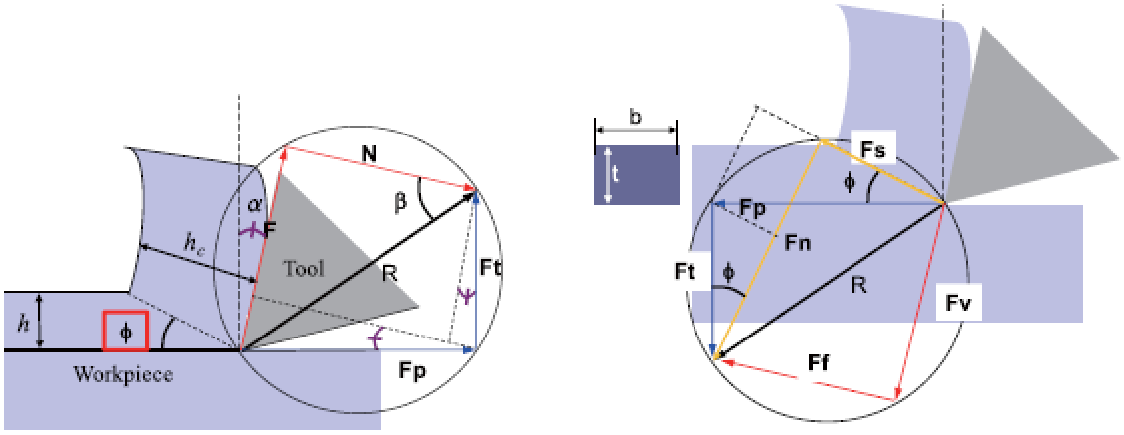
$$\left.\begin{aligned} F_s &= F_p \cos\alpha - F_t \sin\alpha \\ F_n &= F_p \sin\alpha - F_t \cos\alpha \end{aligned}\right\} \quad . \; . \; . \; . \; . \; . \; . \quad (5)$$

By dividing Eq. (5) with the area of shear plane *As*, we obtain the average shear cutting force τ*s* as obtained by follows (Eq. (6)):

$$\tau_s = \frac{F_s}{A_s} = \frac{(F_p\cos\phi - F_t\sin\phi)\sin\phi}{A} \quad . \; . \; . \quad (6)$$

Therefore, if the shear cutting force τs is given, the equation of the cutting force can be represented as Eq. (7).

$$\left.\begin{aligned} F_p &= \frac{\tau_s A\cos(\beta-\alpha)}{\sin\phi\cos(\phi+\beta-\alpha)} \\ F_t &= \frac{\tau_s A\sin(\beta-\alpha)}{\sin\phi\cos(\phi+\beta-\alpha)} \end{aligned}\right\} \quad \cdots\cdots \quad (7)$$



(a) Interactive force at tool side (b) Interactive force at workpiece side

Fig. 2. Schematic representation of orthogonal cutting.

The considered workpiece is regarded as a perfectly plastic body. Further, the shear angle is decided so as to be the criterion of minimization of the cutting energy required for the cutting (*Fp* is the minimum). When the derivative of *Fp* divided by shear angle is 0 (*dFp/d*φ = 0), the shear angle φ and the friction angle β are obtained using following equation:

$$\left.\begin{aligned} \phi &= \frac{\pi}{4}-\frac{1}{2}(\beta-\alpha) \\ \beta &= \tan^{-1}\frac{F_t+F_p\tan\alpha}{F_p-F_t\tan\alpha} \end{aligned}\right\} \quad \cdots\cdots\cdot \quad (8)$$

The shear angle is monitored by measuring the principle cutting force and the thrust force using the CFOB and CTOB, respectively. The principle cutting force is obtained from the work spindle, and the thrust force is caused by carriage; These forces are measured using the CTOB and CFOB, respectively. Figure 3 shows the proposed shear angle monitoring system, where *r* represents the radius of the workpiece. However, Merchant's minimum energy theory holds true when the orthogonal cutting that generates smooth shape chip without a built-up edge is the most simplified.

PID controller for a High performance Drilling Machine

In the control system, unknown disturbance detrimentally influences on not only stability but also performance. However, not all state variables and disturbance are available for feedback, i.e., some of them are not measurable. Thus, we need to estimate unmeasurable state variables and disturbance for disturbance compensation.

State observers

A device or program that estimates or observes state variables of a system is called a state observer[1]. A state observer utilizes measurements of the system inputs, outputs and a model of the system based on differential equations. In order to estimate unmeasurable state variables, many kinds of observer have been researched. In this subsection some of observers are introduced.

IV. LUENBERGER OBSERVER

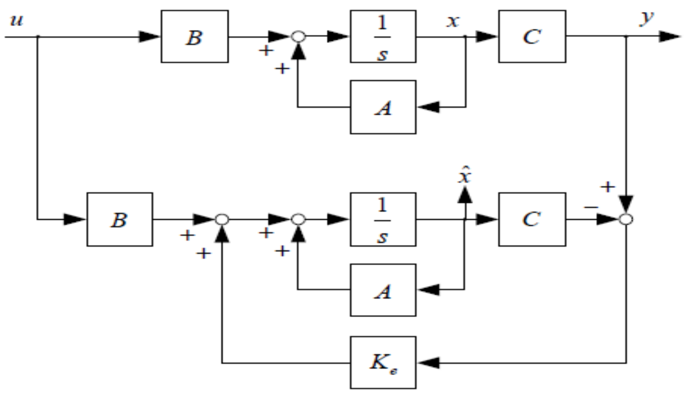


Figure 1.1: Block diagram of Luenberger observer

The Luenberger observer[2] estimates the state variables based on the measurements of the output, control variables and the system model. The Luenbergr observer is depicted in Fig. 1.1, where A, B, C and Ke represent characteristic matrix, input matrix, output matrix and observer gain matrix, respectively. In addition, u, x, ^x and y indicate control input, state variables, estimated state variables and output respectively.

The basic function of the controller is to execute an algorithm based on the control engineers input and hence to maintain the output at a level so that there is no difference between the process variable and the set point [1].

The popularity of PID controllers is due to their functional simplicity and reliability .They provide robust and reliable performance for most systems and the PID parameters are tuned to ensure a satisfactory closed loop performance [2].

A PID controller improves the transient response of a system by reducing the overshoot and by shortening the settling time of a system [3].

Standard methods for integer order tuning includes Ziegler-Nichols Ultimate-cycle tuning [4], Cohen-coons [6], Astrom and Hagglund [5] and many other techniques. In this paper we design fractional order PID controller for a High performance drilling machine. Fractional order PID controllers are variations of usual PID controllers:

$$C(s) = p + \frac{I}{s} + Ds \qquad (1)$$

where the (first-order) integral and the (first-order) derivative of (1) are replaced by fractional derivatives like this:

$$C(s) = p + \frac{I}{s^{\lambda}} + Ds^{\mu} \qquad (2)$$

(In principle, both λ and μ should be positive so that we still have an integration and a differentiation.) Fractional order PIDs have been increasingly used over the last years [7]. There are several analytical ways to tune them.

2. Dynamic model of a high-performance drilling process

The modeling of a high-performance drilling process [11] includes the modeling of the feed drive system, the spindle system and the cutting process. In this paper, the overall plant model is obtained by experimental identification using different step shaped disturbances in the command feed. The drilling force, F, is proportional to the machining feed, and the corresponding gain varies according to the work piece and drill diameter. The overall system of the feed drive, cutting process and dynamometric platform was modeled as a third-order system, and the experimental identification procedure yielded the transfer function as:

$$G(s) = \frac{1958}{s^3 + 17.89s^2 + 103.3s + 190.8} \qquad (3)$$

where s is the Laplace operator. The model does have certain limits in representing the complexity and uncertainty of the drilling process. However, it provides a rough description of the process behavior that is essential for designing a network- based PID control system.

3. A brief introduction to fractional order calculus

A commonly used definition of the fractional differo-integral is the Riemann-Liouville definition

$$ {}_aD_t^{\alpha} f(t) = \frac{1}{\Gamma(m-\alpha)} \left(\frac{d}{dt}\right)^m \int_a^t \frac{f(\tau)}{(t-\tau)^{1-(m-\alpha)}} dt \quad (4) $$

For $m-1 \prec \alpha \prec m$, where, $\Gamma(0)$ is the well-known Euler,s gamma function. An alternative definition, based on the concept of fractional differentiation, is the Grunwald-Letnikov definition given by

$$ {}_aD_t^{\alpha} f(t) = \lim \frac{1}{\Gamma(\alpha) h^{\alpha}} \sum_{k=0}^{(t-a)/h} \frac{\Gamma(\alpha+K)}{\Gamma(K+1)} f(t-kh) \qquad (5) $$

One can observe that by introducing the notion of fractional order operator ${}_aD_t^{\alpha} f(t)$ the differentiator and integrator can be unified. Another useful tool is the Laplace transform. It is shown in [12] that the Laplace transform of an n-th derivative $(n \in R_+)$ of a signal x(t) relaxed at t=0 is given by: $L\{D^n x(t)\} = s^n x(s)$ So, a fractional order differential equation, provided both the signals u(t) and y(t) are relaxed at, can be expressed in a transfer function form:

$$ G(s) = \frac{a_1 s^{\alpha_1} + a_2 s^{\alpha_2} + \ldots + a_{mA} s^{\alpha_{mA}}}{b_1 s^{\beta_1} + b_2 s^{\beta_2} + \ldots b_{mB} s^{\beta_{mA}}} \qquad (6) $$

Where $(a_m, b_m) \in R^2, (\alpha_m, \beta_m) \in R_+^2, \forall (m \in N)$

4. Tuning by minimization

In this tuning method for fractional PIDs by [13], we begin by devising a desirable behavior for our controlled system, described by five specifications (five, because the parameters to be tuned are five):

1. The open loop is to have some specified crossover frequency W_{cg} :

$$ |C(w_{cg})G(w_{cg})| = 0db \qquad (7) $$

2. The phase margin is to have some specified value:

$$ -\pi + \phi_m = \arg[c(w_{cg})G(w_{cg})] \qquad (8) $$

3. To reject high-frequency noise, the closed loop transfer function must have a small magnitude at high frequencies; hence, at some specified frequency W_h , its magnitude is to be less than some specified gain H

$$ \left| \frac{C(w_h)G(w_h)}{1+C(w_h)G(w_h)} \right| < H \qquad (9) $$

4. To reject output disturbances and closely follow references, the sensitivity function must have a small magnitude at low frequencies; hence, at some specified frequency W_l , its magnitude is to be less than some specified gain N :

$$ \left| \frac{1}{1+C(w_l)G(w_l)} \right| < N \qquad (10) $$

5. To be robust when gain variations of the plant occur, the phase of the open loop transfer function is to be (at least roughly) constant around the gain-crossover frequency:

$$\frac{d}{dw}\arg\left[C(w)G(w)\right]\Big|_{w=w_{cg}} = 0 \qquad (11)$$

Then the five parameters of the Fractional PID are to be chosen using the Nelder-Mead direct search simplex minimization method. This derivative free method is used to minimize the difference between the desired performance specified as above and the performance achieved by the controller. Of course this allows for local minima to be found: so it is always good to use several initial guesses and check all results (also because sometimes unfeasible solutions are found).

5. The set of s-shaped response based tuning

The set of rules proposed by Ziegler and Nichols apply to systems with an S- shaped unit-step response, such as the one seen in Fig 1. From the response an apparent delay L and a characteristic time – constant T may be determined (graphically, for instance). A simple plant with such a response is

$$G = \frac{k}{1+sT}e^{-Ls} \qquad (12)$$

The specifications used were

$$w_{cg} = 0.5 rad/s \qquad (13)$$

$$\phi_m = 2.3 rad \approx 38^0 \qquad (14)$$

$$w_h = 10 rad/s \qquad (15)$$

$$w_l = 0.01 rad/s \qquad (16)$$

$$H = -10 db \qquad (17)$$

$$N = 20 db \qquad (18)$$

Matlab,s implementation of the simplex search in function fmincon was used (7) was considered the function to minimize, and (8) to (11) accounted for as constraints.

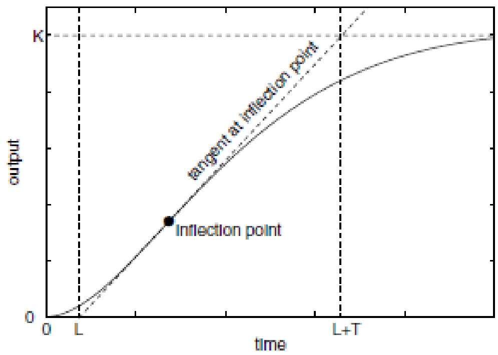
Obtained parameters P, I, λ, D and μ very regularly with L and T. using a least-squares fit, it was possible to adjust a polynomial to the data, allowing (approximate) values for the parameters to be found from a simple algebraic calculation [14.15]. The parameters of the polynomials involved are given in Table 1. This means that

$$\begin{aligned} P = & -0.0048 + 0.2664L + 0.4982T \\ & +9.0232L^2 - 0.0720T^2 - 0.0348TL \end{aligned} \qquad (19)$$

And so on. These rules may be used if

$$0.1 \le T \le 50 and L \le 2 \qquad (20)$$

International Journal of Engineering Sciences & Emerging Technologies, Oct. 2014.
ISSN: 22316604 Volume 7, Issue 2, pp: 578-593 ©IJESET



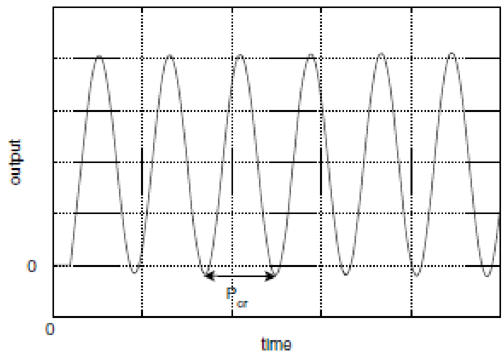


Table 1. Parameters for the first set of tuning rules for S-shaped response plants

	Parameters to use when $0.1 \leq T \leq 5$				
	P	I	λ	D	μ
1	−0.0048	0.3254	1.5766	0.0662	0.8736
L	0.2664	0.2478	−0.2098	−0.2528	0.2746
T	0.4982	0.1429	−0.1313	0.1081	0.1489
L^2	0.0232	−0.1330	0.0713	0.0702	−0.1557
T^2	−0.0720	0.0258	0.0016	0.0328	−0.0250
LT	−0.0348	−0.0171	0.0114	0.2202	−0.0323
	Parameters to use when $5 \leq T \leq 50$				
	P	I	λ	D	μ
1	2.1187	−0.5201	1.0645	1.1421	1.2902
L	−3.5207	2.6643	−0.3268	−1.3707	−0.5371
T	−0.1563	0.3453	−0.0229	0.0357	−0.0381
L^2	1.5827	−1.0944	0.2018	0.5552	0.2208
T^2	0.0025	0.0002	0.0003	−0.0002	0.0007
LT	0.1824	−0.1054	0.0028	0.2630	−0.0014

6. The set of critical gain based tuning rules

The second set of rules proposed by Ziegler and Nichols apply to systems that, inserted into a feedback control-loop with proportional gain, show, for a particular gain, sustained oscillations, that is, oscillations that do not decrease or increase with time, as shown in Fig1. The period of such oscillations is the critical period, and the gain causing them is the critical gain. Plants given by (12) have such a behavior. Reusing the data collected for finding the rules in section 5, obtained with specifications (13) to (18), it is seen that parameters P, I, λ, D and μ obtained vary regularly with and .The regularity was again translated into formulas (which are no longer polynomial) using a least- squares fit [16]. The parameters involved are given in Table 2. This means that

$$p = 0.4139 + 0.014sk_{cr} + 0.1584p_{cr} - \frac{0.4384}{K_{cr}} - \frac{0.0855}{P_{cr}} \qquad (21)$$

And so on. These rules may be used if

$$P_{cr} \leq 8 and K_{cr} p_{cr} \leq 640 \qquad (22)$$

Table 2. Parameters for the first set of tuning rules for plants with critical gain and period

	Parameters to use when $0.1 \le T \le 5$				
	P	I	λ	D	μ
1	0.4139	0.7067	1.3240	0.2293	0.8804
K_{cr}	0.0145	0.0101	−0.0081	0.0153	−0.0048
P_{cr}	0.1584	−0.0049	−0.0163	0.0936	0.0061
$1/K_{cr}$	−0.4384	−0.2951	0.1393	−0.5293	0.0749
$1/P_{cr}$	−0.0855	−0.1001	0.0791	−0.0440	0.0810
	Parameters to use when $5 \le T \le 50$				
	P	I	λ	D	μ
1	−1.4405	5.7800	0.4712	1.3190	0.5425
K_{cr}	0.0000	0.0238	−0.0003	−0.0024	−0.0023
P_{cr}	0.4795	0.2783	−0.0029	2.6251	−0.0281
$1/K_{cr}$	32.2516	−56.2373	7.0519	−138.9333	5.0073
$1/P_{cr}$	0.6893	−2.5917	0.1355	0.1941	0.2873

7. Fractional PID controller design for drilling machine

The model of the drilling machine is a third-order transfer function as:

$$G(s) = \frac{1958}{s^3 + 17.89s^2 + 103.3s + 190.8} \qquad (23)$$

The unit –step responses of the Drilling machine model is selected in Fig 2.To design on fractional PID controller, the model(23) should be approximated by a first order lag plus time delay system which is give in the following

$$G = \frac{10.3}{1 + 0.387s} e^{-0.197s} \qquad (24)$$

Then using tuning rules in the paper, obtained parameters and p, I, λ, D and μ :
P=0.2079, I= 0.4969, λ=1.4883, D= 0.08965, μ=0.9694

The transfer function for the fractional PID controller is:

$$c(s) = 0.2079 + \frac{0.4969}{s^{1.4883}} + 0.08965s^{0.9694} \qquad (25)$$

V. CONCLUSION

High machine tool controller flexibility is required to successfully develop and implement process monitoring and control. Since the 1990s, open-architecture computer numerically controlled (CNC) systems have been proposed. Based on open-architecture CNC systems, many attempts have been made to implement supervisory machining process control [108, 134–138], including our Intelligent Numerical Control (INC) project, shown in Fig. Despite extensive academic activity, few of these efforts have survived transfer to industry, with major CNC manufacturers hesitating to commercialize full open architecture CNC. We believe that applying process monitoring and control to specific machining problems has practical value, e.g. in micro-machining and the machining of new, difficult-to-cut materials – areas in which even expert human operators have difficulty in effective process planning. Conventional and microscopic machining processes often operates under radically different rules in dramatically different physical environments. Conventional CAM software tool path design raises many issues, as has been discussed, related to an almost exclusive consideration of machined-work piece geometries, to the detriment of the machining process itself. In the absence of greater tool path optimization, these gaps will no be spanned, and closer CNC and CAM software integration is one key to implementing practical approaches [139].

REFERENCES

[1] A. Matsubara, "Research and Development on Intelligent Control of Machine Tools," Proc. of 9th Int'l Conf. on Production Engineering, Design, and Control (Keynote speech), pp. 10-12, 2009.
[2] A. Matsubara, "Current Status and Trends of Monitoring and Control Control Technology in Machining Process," J. of the Society of Instrument and Control Engineers, 41-1, pp. 781-786, 2002 (in Japanese).
[3] S. Kurada and C. Bradley, "A review of machine vision sensors for tool condition monitoring," Computers in Industry, 34-1, pp. 55-72,1997.
[4] S. Ibaraki, A. Matsubara, and M. Morozumi, "Efficiency Comparison of Cutting Strategies for End Milling Processes under Feedrate Scheduling," Int'l J. of Automation Technology, 2-5, pp. 377-383, 2008.
[5] B. Najafi and H. Hakim, "A comparative study of non-parametric spectral estimators for application in machine vibration analysis,"Mechanical Systems and Signal Processing, 6-6, pp. 551-574, 1992.
[6] A. G. Rehorn, J. Jiang, P. E. Orban, and E. V. Bordatchev, "State-ofthe- art methods and results in tool condition monitoring: a review,"Int'l J. of Advanced Manufacturing Technology, 26, pp. 693-710, 2005.
[7] G. Byrne, D. Dornfeld, I. Inasaki, G. Ketteler, W. Konig, and R Teti, "Tool condition monitoring (TCM) – the status of research and industrial application," Annals of the CIRP, 44-2, pp. 541-567, 1995.
[8] P. W. Prickett and C. Johns, "An overview of approaches to end milling tool monitoring," Int'l J. of Machine Tools and Manufacture, 39, pp. 105-122, 1999.
[9] M. Shiraishi, "Scope of in-process measurement, monitoring and control techniques in machining processes Part 1: In-process techniques for tools," Precision Engineering, 10-4, pp. 179-189, 1988.
[10] S. Y. Liang, R. L. Hecker, and R. G. Landers, "Machining process monitoring and control: The state-of-the-art," Trans. of ASME, J. of Manufacturing Science and Engineering, 126-2, pp. 297-310, 2004.
[11] D. E. Dimla, "Sensor signals for tool-wear monitoring in metal cutting operations – a review of methods," Int'l J. of Machine Tools and Manufacture, 40-8, pp. 1073-1098, 2000.
[12] K. Jemielniak, "Commercial Tool Condition Monitoring Systems," Int'l J. of Advanced Manufacturing Technology, 15, pp. 711-721, 1999.
[13] K. Furutani, "Piezoelectric sensors," J. of the Society of Instrument and Control Engineers, 45-4, pp. 296-301, 2006 (in Japanese).
[15] D. Kono, A. Matsubara, I. Yamaji, and T. Fujita, "High-precision machining by measurement and compensation of motion error," Proc. of 4th Int'l Conf. on Leading Edge Manufacturing in 21st Century, pp. 809-812, 2007.