Review:

Monitoring and Control of Cutting Forces in Machining Processes: A Review

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Much research has gone into machining process monitoring and control. This paper reviews monitoring and control schemes of cutting force and torque. Sensors to measure cutting force and torque, as well as their indirect estimation, are reviewed. Feedback control schemes and model-based feedforward scheduling schemes of cutting forces, as well as tool path optimization schemes for cutting force regulation, are reviewed. The authors' works are also briefly presented.

Keywords: milling, cutting force, machining process monitoring, machining process control

1. Introduction

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, feedrates, 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 feedrate. They observe machining quality in surface finish and dimensional accuracy of machined workpieces, 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.

2. Monitoring of Cutting Forces/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 [3]. 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 [4], 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 [5], which has led to the active study of in-situ tool wear and breakage detection.

This section reviews cutting force and torque monitoring. A part of our review is included in past literature reviews on TCM in [6–12].

2.1. Cutting Force Monitoring by External Sensors

2.1.1. Force Sensors

We collectively call sensors installed on machine tools to monitor cutting force "external" sensors [2]. 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 [13] (e.g. [14]). 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 [15]. Despite the accuracy and reliability of commercial dynamometers, their high cost may limit their use in machining process control [12].

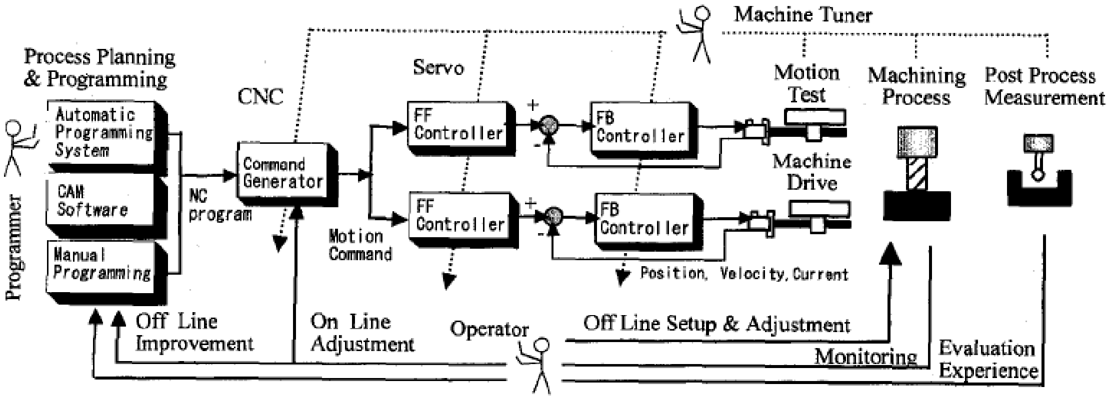


Fig. 1. Conventional machining configuration from the viewpoint of process control [2].

Notable unique approaches include the installation of force sensors in tools. Yoshioka et al. [16] developed an in-process thermometry microsensor mounted directly on the tool tip for ultra-precision turning.

2.1.2. Torque Sensors

Piezoelectric-based dynamometers are commercially available to measure cutting torques on a spindle [14]. Cutting torque was also calculated using strain gauges early on [17]. Ohzeki et al. [18] studied the use of magnetostrictive 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. [19] 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 [20] integrated strain gauges into a tool holder to measure torque, axial, and radial forces. Montronix [21] commercialized small sensor-integrated plates or rings installed at different places on the machine, including the spindle head, affected by cutting force.

2.1.3. 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.

Kim et al. [22] 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. Albrecht et al. [23] used a capacitance sensor to calculate cutting force, showing

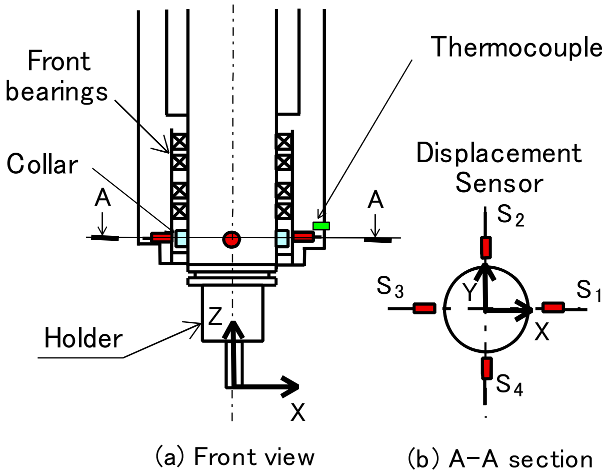


Fig. 2. Spindle-integrated displacement sensor configuration for determining cutting force [28].

that bandwidth up to 1,000 Hz was obtained when spindle dynamics was compensated for. Jeong et al. [24] 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 [25], analogous to a capacitance sensor, and can be used to calculate cutting force [26]. 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 [27].

One example is the cutting force calculation that we developed using spindle-integrated displacement sensors [28, 29], 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 [29]. In our study, multiple thermocouples are installed in the spindle to calculate thermal displacement. Many studies have reported thermal-mechanical spindle modeling [30, 31].

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 [32–34]. 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 [32] used an axial force loader on a rotating spindle. Rantatalo et al. [35] developed a magnetic exciter to laterally vibrate a spindle to measure its dynamic response, so that it can be compensated for by model-based signal processing such as the Kalman filter [23, 36, 37]. We studied spindle-integrated displacement sensor use for evaluating dynamic rotating spindle characteristics [38].

2.2. 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 [39] and Lee et al. [40] discussed tool breakage detection based on cutting force calculation by servo motor current. A similar attempt was made observing spindle motor armature current [41]. 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 (e.g. [42]). Commercial products to monitor spindle or servo motor current provide fault detection [21, 43, 44].

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 [45–47]. Algorithms to analyze and detect abnormal machining process, such as tool breakage, have been drawing attention in academia for years. A frequency-domain analysis [48], statistic analysis [49], an artificial neural network [50], wavelet analysis [51], and complexity analysis [52], were applied in fault detection.

We studied [53] 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 feedrate of 1,000 mm/min without a cutting load (armature 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 guideways. On a feed drive driven by a servo motor and roller or slide guideways, commonly used in most commercial machining centers, the servo motor undergoes large friction imposed on guideways 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.

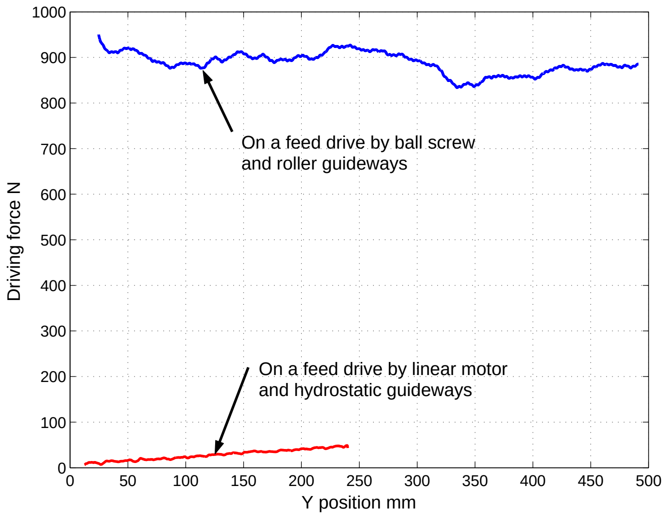
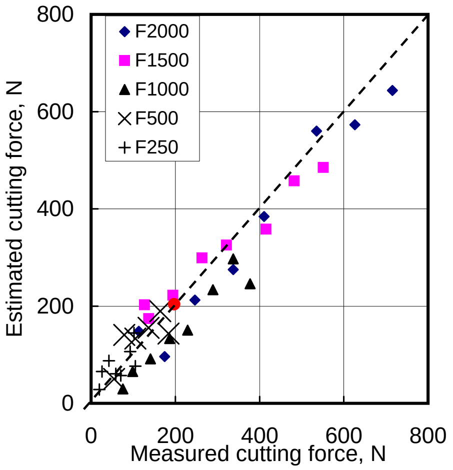


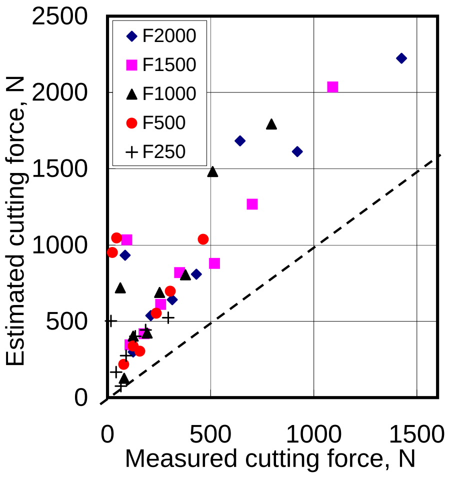
Fig. 3. Feed drive force during Y-axis movementat at a constant non-cutting feedrate [59].

To separate out the influence of cutting force in motor current, this significant influence of friction 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 [54]. **Fig. 4** [53] 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 feedrates. 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) [55].

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 [56]. **Fig. 5** [53] 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



(a) Y direction (moving direction)



(b) X direction (stationary direction)

Fig. 4. Comparison of cutting force (horizontal axis) and estimates by monitoring servo motor current (vertical axis) under straight end mill side cutting [53].

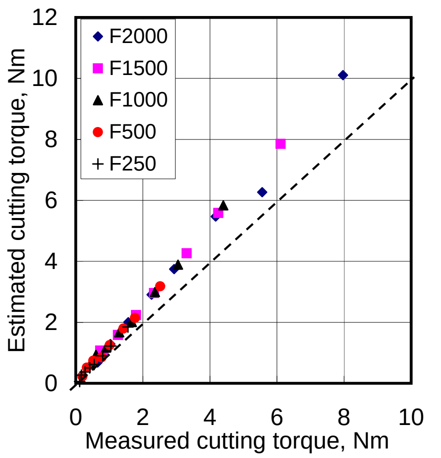
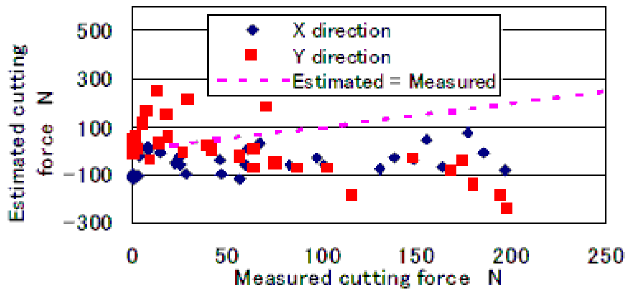
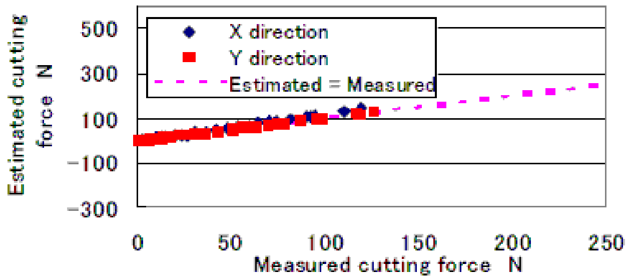


Fig. 5. Comparison of cutting torque by a dynamometer (horizontal axis) and estimates by monitoring spindle motor current (vertical axis) under straight end mill side cutting [53].



(a) Ball screw + Rolling guideway



(b) Linear motor + Hydrostatic guideway

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 [59].

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 feedrate 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. In [53, 56], 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 guideways are widely used for ultra-precision and high-precision machine tools [57, 58]. 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 [59, 60]. **Fig. 6** [59] 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 [105].

2.3. Machining Process Sensors

High-frequency displacement or acceleration of a tool or a workpiece may be measured directly instead of cutting forces. Accelerometers on tool holders [61] or workpieces [62], and laser interferometers on spindle shafts [63] or directly on tools [64], have been used to detect tool conditions such as wear, breakage, and chatter.

Acoustic emission (AE) analysis of machining processes has been long studied (e.g. [65–67]). More thorough review can be found in [6–8]. Except for a few commercially successful products, few implementations exist in current practical machining.

Since we focus mainly on cutting force and torque measurement, these and other TCM are not covered here.

3. 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, but is well reviewed in [10, 68, 69].

3.1. Feedback Control Approaches

Among in-process machining parameters, feedrate is the easiest to manage. Most commercial CNCs have dials for manually changing feedrate override, while some enable users to input a signal to continuously regulate it. Cutting force control is reviewed in the sections that follow, using feedrate as a control variable. Part of our reviews is included in machining control discussed by Liang et al. [10] and Altintas [70].

Cutting force control, taking feedrate as a control variable, is divided into (1) feedback control that continuously monitors cutting force and regulates the feedrate in real time and (2) model-based scheduling in which an NC program feedrate profile is optimized without real-time process monitoring. Model-based scheduling can be seen as a feedforward 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 [71–73]. The principle involves increasing feedrate for higher productivity while keeping cutting torque below the maximum. As has been discussed in Section 2.2, 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" [74, 75] and were implemented in commercial CNC. Other cutting force and torque control applications have been made to drilling processes implemented in industry [76].

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 [77]), model reference adaptive control (MRAC) (Tomizuka et al. [78], Ulsoy and Koren [79], Landers and Ulsoy [80]), MRAC extended by zero phase error tracking control (ZPETC) (Rober and Shin [81]), direct adaptive control (Altintas [82]), adaptive generalized predictive control (AGPC) (Altintas [70]), adaptive pole placement control (APPC) (Elbestawi et al. [83]), and robust adaptive control (Kooi [84]).

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. [85] and fuzzy logic control by Kim et al. [86]. Liu et al. [87] compared the performance of these approaches.

Limited commercial feedback control for end milling includes a milling process controller by Tu et al. [88], implemented in high-speed machines for aircraft parts, using strain gauges attached to a spindle to estimate cutting force. An Omative Systems product [43] monitors spindle motor current to regulate feedrate override, viewed as a simple ACC.

3.2. Model-Based Feedrate Scheduling Approaches

In simpler cutting force regulation, model-based feedrate pre-scheduling was widely studied. If an exact process model for predicting cutting force from machining conditions could be found, machining conditions could be optimized a priori to regulate cutting force as required. In practice, many consider this model-based approach more feasible and practical than feedback control.

Feedforward control performance depends on process model accuracy. The simplest cutting force model, assuming that cutting force is proportional to the material removal rate (MRR), calculates from three-dimensional geometric interference of a tool and workpiece. In an early work [89], Wang used Z-buffer representation of workpiece and a simple volumetric model to relate cutting force and MRR. Yamazaki et al. [90] analogously simulated geometrical interaction between a workpiece and tool, optimizing the feedrate to maximize MRR. Some commercial CAD/CAM software (e.g. [91]) use a simple process simulator to optimize NC program feedrate. Commercial software to perform this feedrate scheduling for constant-feedrate NC programs are also available (e.g. [92]). Simple MRR-based models may cause a significant estimation error due to lower material removal, especially in high-speed milling of harder materials at higher feedrates and lower depths of cut. Kakino et al. [93, 94] presented a second-order response surface model [95], experimentally showing its better accuracy in estimating cutting force in high-speed pre-hardened steel cutting.

Coefficients of such a process model must be identified a priori by cutting experiments or from the database.

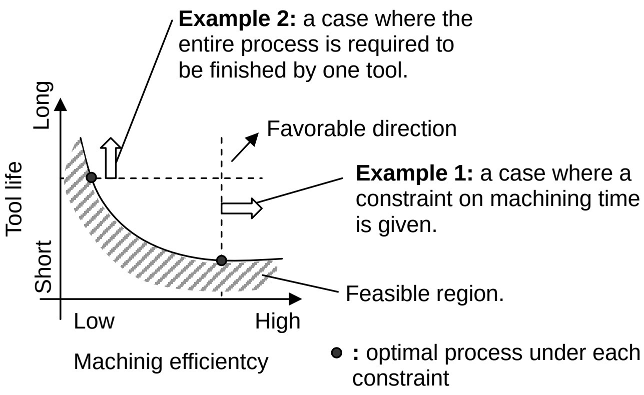


Fig. 7. Trade-off between machining efficiency and tool life.

Mechanistic models of cutting force generation in turning, drilling, and milling, have been actively studied. Budak [96] used a nonlinear mechanistic model proposed by Altintas and Spence [97] to regulate peak cutting force, and showed that the model-based approach exhibited control performance similar to adaptive feedback control. Teramoto et al. [98] proposed on-line identification for a mechanistic process model, on which the cutting force regulation is based. Spence and Altintas [99] used model-based cutting force prediction with adaptive feedback control, such that a priori information of milling process can be utilized to avoid large overshoot due to feedback control time delay. Similarly, Richards et al. [100] combined on-line adaptive force control and off-line feedrate optimization based on the mechanistic model proposed by Fussell et al. [101]. We also tested analogous combination of model-based feedrate scheduling and its feedback adaptation [102, 103].

3.3. Feedback Control Implementation Issues

Despite significant research on feedback process control reviewed in Section 3.1, its impact on the industry has been limited. Ulsoy and Koren [69] in 1993 and Liang et al. [10] in 2004 came to similar remarks.

From the authors' view, three major reasons are, first, the difficulty of systematically integrating machining control in machine tools [10]; second, the cost of installing reliable sensors to monitor cutting forces; and third, insufficient user understanding of a benefit of installing real-time feedback control. Feedback control generally requires that cutting force be continuously monitored. Guaranteeing sensor-less estimation reliability based on motor current is difficult in commercial implementation, especially in milling (Section 2). Reliable sensors such as piezoelectric dynamometers are considered expensive for general use by many machine tool manufacturers and users.

We consider that another critical reason is that many users do not understand a practical advantage of installing real-time feedback control with such an extra cost. Off-line feedrate scheduling may provide sufficient control when the process model is sufficiently accurate (Section 3.2). Feedback control is clearly advantageous in

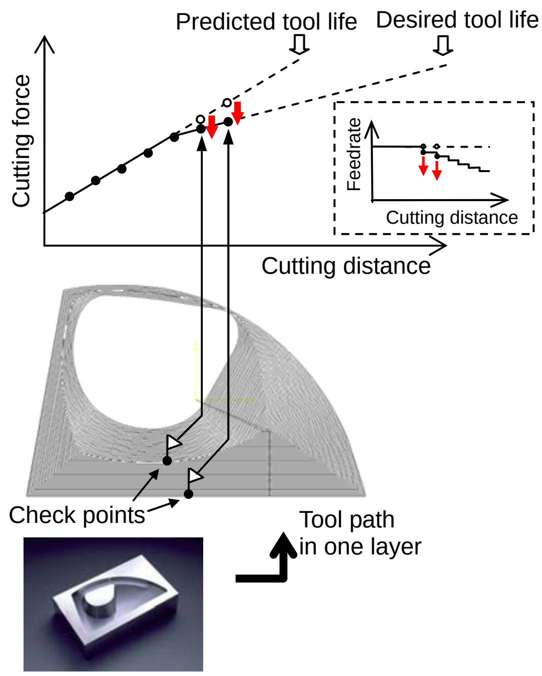


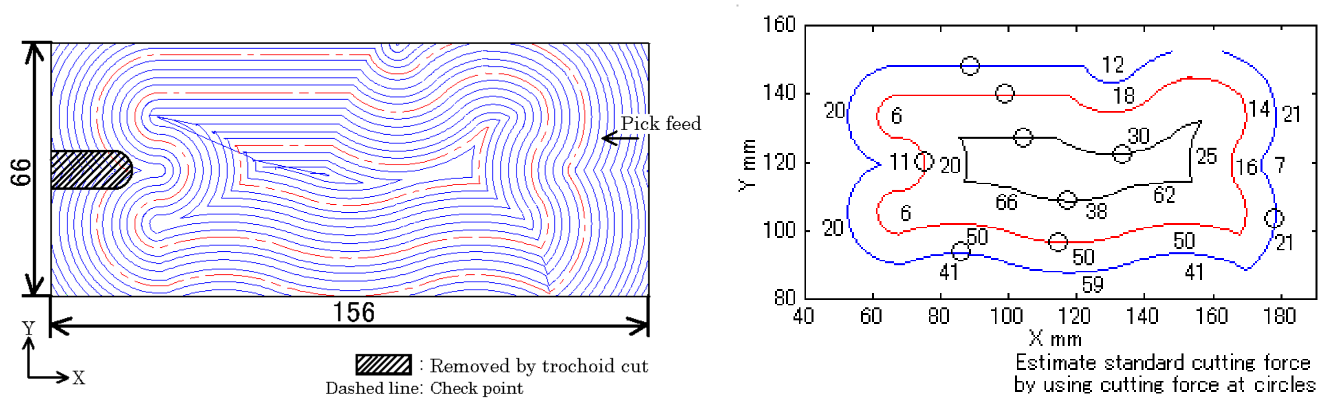
Fig. 8. Concept of tool life control through cutting force control [104].

adaptability to unmodeled machining processes. In many practical applications, however, even the simplest MRR-based feedrate scheduling, implemented in much CAM software, effectively suppresses cutting force changes. In such cases, the necessity of installing feedback control is not clear.

This section presents our attempt to propose feedback control practically motivated to monitor machining process [104, 105].

A basic problem with model-based feedrate scheduling is its poor adaptability to machining process changes. The most important process change is, in our opinion, the progress of tool wear. We implemented feedback control focusing on tool wear control. **Fig. 7** shows the trade-off between machining efficiency and tool life. Generally, speeding up material removal to enhance machining efficiency often shortens tool life, increasing tool cost, meaning efficiency is often sacrificed for tool life. Practical machining places various constraints on this relationship, for example, on machining time to meet the manufacturing deadline. Another example is where machining is required to be finished using a single tool only, often done in die and mold machining. Our proposal [104] autonomously conduct "optimal" processing (● in **Fig. 7**) under the given constraint by explicitly controlling tool life. Our scheme features the following:

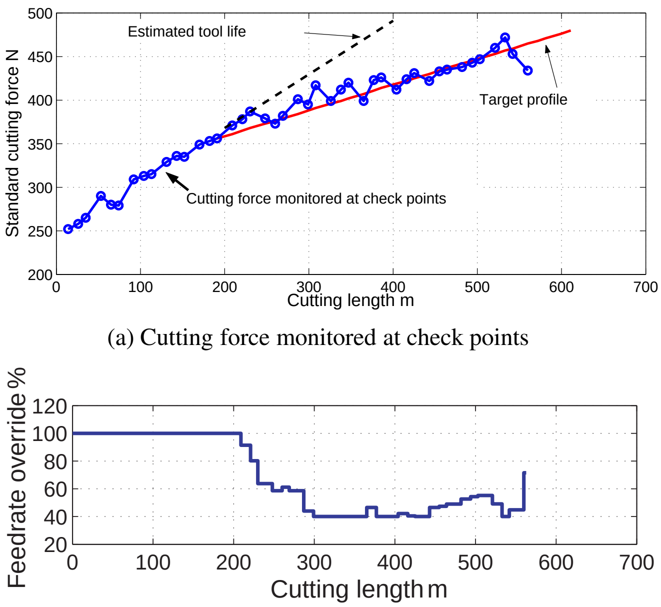
1. Cutting force changes quickly occurring due to tool path geometry are suppressed using model-based feedrate scheduling [93, 94].
2. Cutting force is monitored only at tool path check points, set typically at intervals of several dozen meters. Estimates using internal sensors (Section 2.2) are more feasible in such an application.



(a) Tool path

(b) Check points

Fig. 9. Tool path and check points in experiments [105].



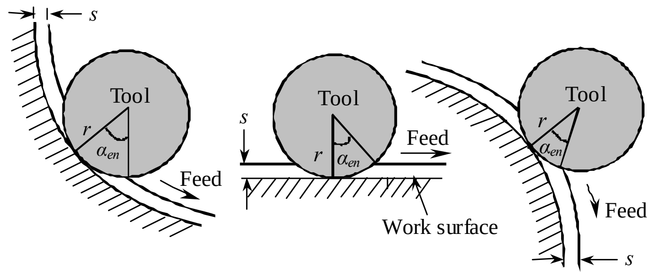
(a) Cutting force monitored at check points

(b) Feedrate override

Fig. 10. Experimental results under proposed tool life control [105].

3. In the proposed control concept illustrated in **Fig. 8**, cutting force increases with tool wear, with control targeting tool life providing cutting for the given desired distance. The feedrate profile is updated at each check point to achieve the target.

In an experimental application, our proposed scheme was applied to contour-parallel tool paths shown in **Fig. 9(a)** [105]. **Fig. 9(b)** shows check points. A hardened steel workpiece (JIS SKD61, HRC53), is repeatedly machined from outermost to innermost path until the tool breaks or wears beyond use. In cutting force at each check point shown in **Fig. 10(a)**, the feedrate profile was modified by simply changing feedrate override at check points, as shown in **Fig. 10(b)**. This simple feedback control extended tool life to 570 m – sufficiently close to the targeted 600 m.



(a) Concave arc

(b) Linear

(c) Convex arc

Fig. 11. Variation in cutting engagement for different tool path geometries in 2D end milling. r: tool radius, α_{en}: engagement angle, s: step-over distance [128].

4. Tool Path Modification Regulating Cutting Force

Depth of cut is considered a control variable for cutting force regulation in turning or surface grinding (e.g. [107]). Particularly in 2-1/2- or 3-dimensional milling using contour-parallel or direction parallel tool paths, depth of cut is extremely difficult to modify in-process, because it requires that tool paths be modified in-process on a CNC. Real-time tool path modification was tested on the "NC program less" control architecture [108, 109].

Purely geometric approach of typical conventional tool path planning [110], e.g. contour- or direction-parallel offsetting, inevitably generates significantly varied cutting engagement, adversely affecting cutter load and tool deflection, making the machine surface geometrically inaccurate [111–113], as suggested in **Fig. 11**.

Regulating feedrate to suppress cutting force variation may not effectively avoid tool damage, especially in high-speed milling. Yamaji [114] experimentally verified cutting heat as a major tool-damage cause at high-engagement regions – a problem that regulating feedrate cannot solve. Feedrate scheduling also raises another potentially critical issue – the limitation on feedrate control accuracy in commercial CNCs. Feedrate adaptation is often difficult to apply to a finishing path, where rough or abrupt transient changes easily deteriorate the surface finish.

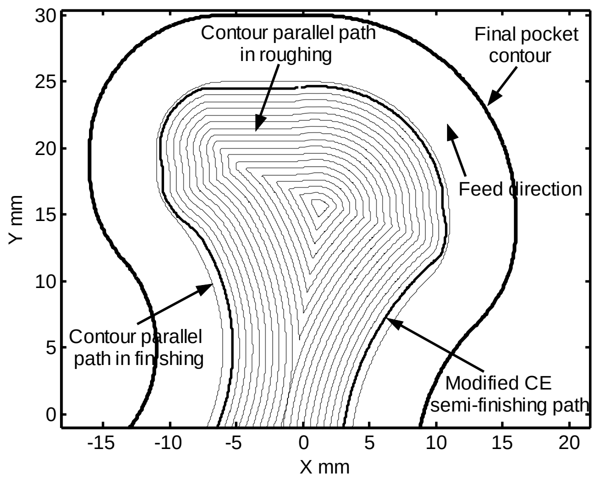


Fig. 12. Modified constant-engagement semi-finishing path within contour-parallel paths [128].

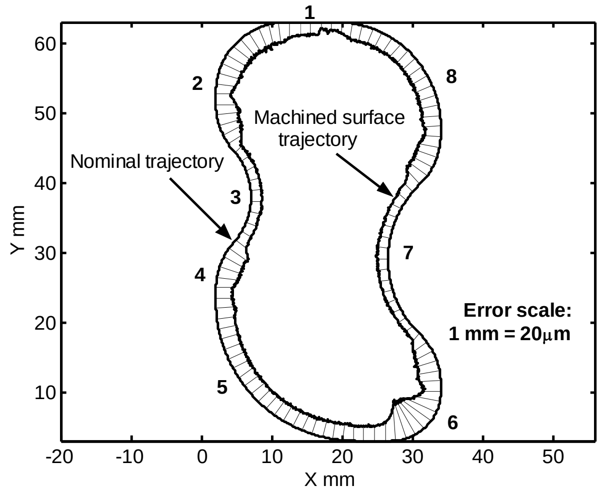
Compared to feedrate scheduling, tool path modification approaches to regulate cutting force have been less explored. Iwabe et al. [115] proposed adding circular arcs to regulate prescribed cutting engagement in convex corner cutting. Tsai and Takata [116] built on this by removing excess material in cornering while coping with complex corner shapes. Its application to pocket milling was presented by Choy and Chan [117]. Kim et al. [118] optimized the tool path using a pixel-based simulation to regulate constant corner-cutting MRR by inserting additional looping paths. An analogous algorithm inserting loops to sharp corners has been implemented in some commercial and add-on software (e.g. [119]).

Trochoidal grooving [120] extends corner loops to remove greater region. We [114, 121, 122] inserted trochoidal grooving to "critical cutting regions" subject to higher machining loads in die and mold machining. Trochoidal milling strategies were geometrically analyzed [123]. Trochoidal grooving insertion has been implemented in some CAM software (e.g. [124]).

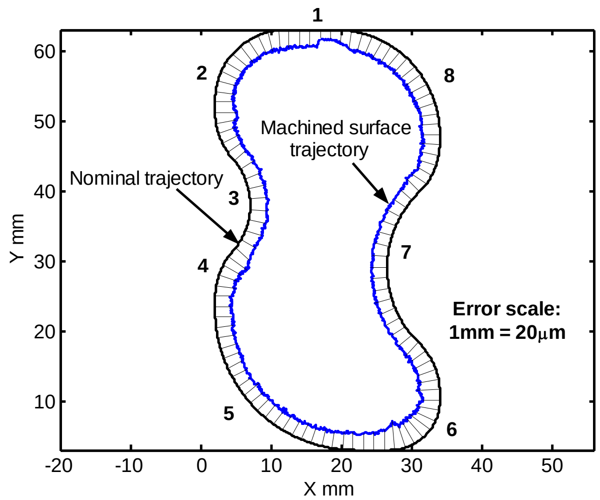
Stori and Wright's [125] approach modifies the offset tool path by maintaining constant cutting engagement on a convex geometry, i.e. basically modifying the tool path by shifting the tool center normal to the original path and regulating the desired cutting engagement. Wang et al. [126], in a quantifiable metric-based approach to 2D tool-path optimization, considered instantaneous path curvature and cutter engagement. We [127] extended the Stori and Wright algorithm to apply it to arbitrary paths.

We [128, 129] extended this idea further to a finishing path application. Unlike the approach of Stori and Wright [125], we proposed modifying the previous semi-finishing tool path trajectory to regulate the desired cutting engagement angle while preserving the geometry of the final path itself. While the approach [125] focused on mostly stable roughing, we have dealt mainly with efficient finishing to improve the final machined contour's geometric accuracy and surface quality. Moon [130, 131] presented an analytical solution to this approach.

Figure 12 shows an example of the modified tool path.



(a) Original contour-parallel path



(b) Modified constant-engagement semi-finishing path

Fig. 13. Comparison of machined surface trajectories for nominal trajectory [128].

Fig. 13(a) shows the machined surface trajectory for the nominal trajectory measured by a coordinate measuring machine (CMM) using original contour parallel paths. **Fig. 13(b)** shows the error trajectory under the modified constant-engagement semi-finishing path. Note that significantly reduced variation in machine surface error is attributable to reduced cutting force variation in finishing path.

5. 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 [132–134] 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 [139], shown in **Fig. 14**.

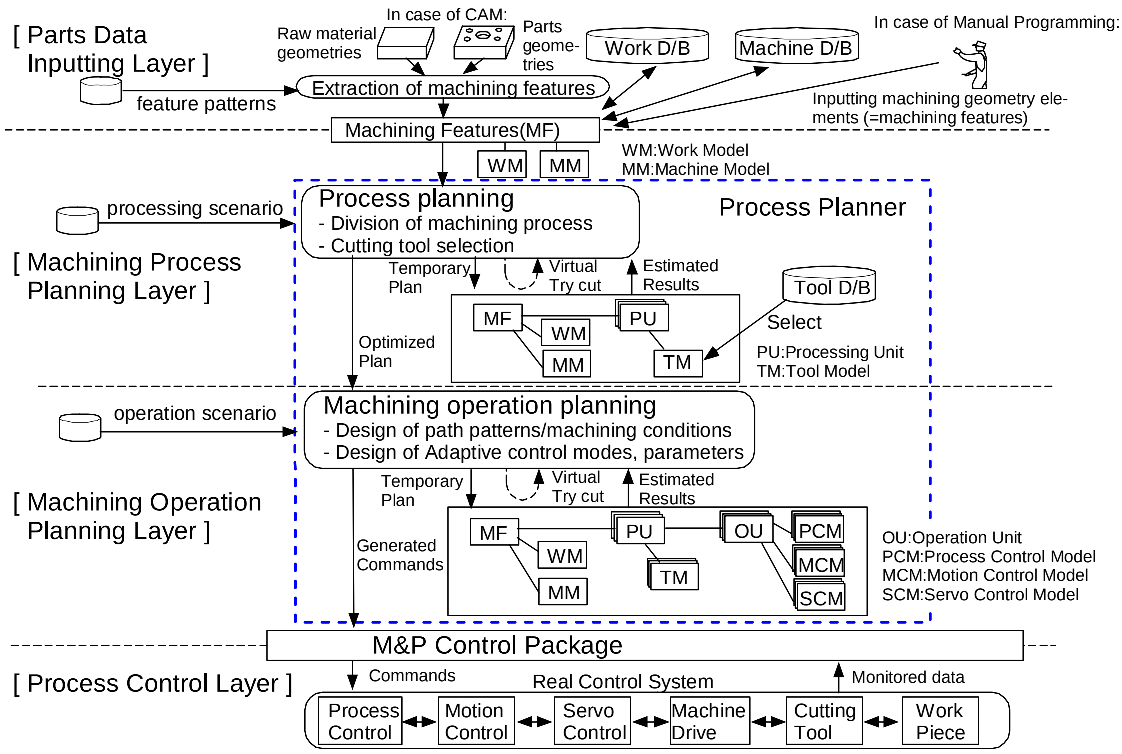


Fig. 14. INC System configuration [139].

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 [140–143].

Conventional CAM software tool path design raises many issues, as has been discussed in Section 4, related to an almost exclusive consideration of machined-workpiece 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].

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