Control of Machine Tools

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This paper reviews the progress in machine tool control during the last three decades. Three types of controls are discussed: (i) Servocontrol loops that control the individual axes of the machine, (ii) interpolators that coordinate the motion of several axes, and (iii) adaptive control that adjusts the cutting variables in real time to maximize system performance. We cover a selection of the most advanced techniques utilized in each of these types, and draw conclusions based on experimental results.

1 Introduction

Control of machine tools is a relatively new field that started in the early 1950s with the invention of the Numerically Controlled (NC) machine tool by John Parsons in Traverse City, MI, with subcontract to the MIT Servomechanism Laboratory [14]. Despite the importance of this invention, the rate of penetration of NC in the U.S. was very slow. The major advance in NC occurred in the early 1970's with the introduction of Computer Numerical Control (CNC) in which a dedicated computer replaced most of the digital hardware control boards of the NC. Approximately at the same time, a few companies (e.g., Bendix [54]) started to develop adaptive control (AC) systems for machine tools. One of the early CNC/AC machines, developed by J. Tlusty and Y. Koren in 1973 [63], utilized an HP-2100 computer as the controller that runs both the conventional CNC and the AC programs.

A typical control software of CNC systems has two major portions: the servo-control (Level I) and the interpolator (Level II) which coordinates the machine axial motions. The AC program along with other error compensation programs are located at a higher level (Level 3) of the control hierarchy. Level 4 is usually regarded as a supervisory level that receives feedback from measurements of the finished part or from other controllers. This general multi-level control architecture is depicted in Fig. 1. Accordingly, the following sections review the advances in servocontrol, interpolators, and adaptive control/compensation methods.

2 Servocontrol for Machine Tools

The task of the servocontroller is to reduce the axial position errors and the contour errors in machining operations [12, 13, 26]. The term ''contour error'' is used to denote the error component orthogonal to the desired trajectory (i.e., the deviation of the cutter location from the desired path). The contour error in machining a desired contour on a two-axis system is shown in Fig. 2. Reduction of contour errors can be performed by three basic approaches: (1) applying sophisticated axial controllers, (2) adding feedforward controllers, and (3) using a cross-coupling controller.

In the first approach, more comprehensive controllers than a simple P-controller are utilized (e.g., fuzzy logic, etc.), and consequently, a reduction in the position errors of each individual axis is achieved [2, 7, 9, 10, 22, 27–29, 35]. The second approach is based on adding a feedforward controller (e.g., ZPETC) to compensate for the axial position errors [8, 23, 30–32, 34]. The above two approaches intend to reduce the axial tracking errors (E_x and E_y in Fig. 2) and thereby reduce the resultant contour error.

By contrast, the philosophy of the cross-coupling control method [3, 6, 13, 15, 16, 19, 21, 29] is that the *elimination of the contour error* is the controller objective, rather than the reduction of the individual axial errors. Therefore, the cross-coupling concept calls for the construction of a contour-error model in real time and its utilization in the determination of a control law that reduces or eliminates the contour error.

2.1 PID Controller. In a PID controller, the correction signal is a combination of three components: a proportional, an integral, and a derivative of the position error. The task of the integral (I) controller is to eliminate the steady-error when position ramp inputs are the references, as in the case of linear cuts, and to reject the external disturbances. However, implementing an I-controller by itself will cause instability, and it must be combined with a proportional action to enable a stable system. The derivative (D) controller aids in shaping the dynamic response of the system. The combination is known as a PID controller.

The two main problems with PID controllers in contouring application are (1) poor tracking of corners and nonlinear contours and (2) significant overshoots. To reduce the effect of these problems, careful preprogramming of acceleration and deceleration periods is needed. A more effective method is the utilization of other types of controllers.

2.2 Fuzzy Logic Controllers. In precision machining, friction in the moving components (leadscrews, guideways, etc.) of machine tools can cause significant errors. However, it is very difficult to predict and model the characteristics of friction. At low velocities, friction may cause relatively large contour errors especially when a reverse in the direction of motion of an axis is required. Another problem appears in cases where the viscous friction is dominant (e.g., when hydrostatic guideways are used). In these cases, the friction becomes larger as the feedrate increases and results in large position or velocity errors. In general, the friction force has nonlinear characteristics, varies with the load on the machine, and is position-dependent as well as velocity-dependent [1].

Techniques such as adaptive controls [5, 33] and nonlinear controller [17] based on friction models have been applied in friction compensation of motor drives and robot arms. However, because of the reasons mentioned above, they are not applicable to machine tools. A different approach to address this problem is the use of a rule-based fuzzy-logic method rather than a model-based friction compensation strategy. Fuzzy logic control does not need an exact process model and is robust for disturbances, allowing large uncertainty and variation in the process behavior.

A fuzzy logic controller, composed of three main parts: a fuzzification process, an inference engine with a rule base, and a defuzzification process, is shown in Fig. 3 [9]. The controller has two inputs, the position error E and its digital derivative ΔE. Through the fuzzification process, these crisp, single-valued inputs are mapped to fuzzy sets. Each fuzzy set is characterized by a membership function (a triangular shape) which is assigned a linguistic value describing the input variable such as ''Positive Medium'', ''Negative Large'', ''Near Zero'', etc.

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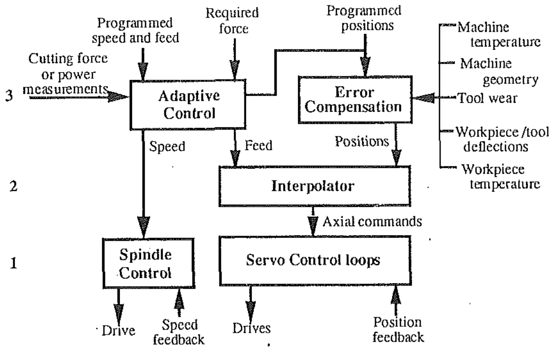

Fig. 1 Hierarchical levels in CNC controllers

In this controller, which is described in detail in [9], each input has seven fuzzy sets that transform the inputs to their fuzzy values. The fuzzy inputs are then transformed to a fuzzy output through fuzzy reasoning process aided by a control rule base. The fuzzy control rules are composed of fuzzy conditional statements and have the form of:

$$\text{If } E = \underset{\sim}{A}_i \quad \text{and} \quad \Delta E = \underset{\sim}{B}_j \quad \text{then} \quad U = \underset{\sim}{C}_{ij}, \quad i, j = 1, \ldots, 7.$$

Since there are two fuzzy inputs, each with seven sets, there are altogether 49 control rules that stored in the rule base. Finally, by the defuzzification process, a single-value output u_k, that drives the corresponding axial motor, is generated. The method was implemented on a machine tool with relatively large friction, and some results are shown at the end of this section.

2.3 Feedforward Controllers. To decrease the tracking errors, feedforward controllers might be added to the control loops (Fig. 4). The principle of the design in Fig. 4 is simple: implement in the control computer a transfer function $G_0^{-1}(z)$ that is the exact inverse of the one of the real control loop, $G(z)$, i.e., $G_0^{-1}(z)G(z) = 1$, and then the actual position becomes equal to the required position. This feedforward controller is the inverse of the feedback control loop, which consists of the controller and the drive, and therefore, it becomes more complicated if a more comprehensive controller rather than a PID controller is utilized.

However, if $G_0^{-1}(z)$ includes unstable poles (i.e., ''unacceptable'' closed-loop zeros) it cannot be implemented as a feedforward controller and must be modified. The ''acceptable'' zeros here mean the zeros that are located inside the unit circle and can be taken as the poles in the feedforward controller. Unacceptable zeros are located on or outside the unit circle and cannot be the poles of the feedforward controller since they will cause instability. To address this problem, a feedforward controller entitled ''Zero Phase Error Tracking Controller (ZPETC)'' was proposed by Tomizuka [31]. The concept of the ZPETC is based on pole/zero cancellation, i.e., $G_0^{-1}(z)G(z) = 1$. The ZPETC controller operates very well in tracking complex trajectories, but has a poor performance in machining systems with large disturbances, as shown on Section 2.5.

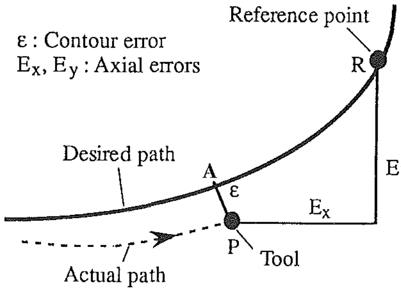

Fig. 2 Contour error in machining

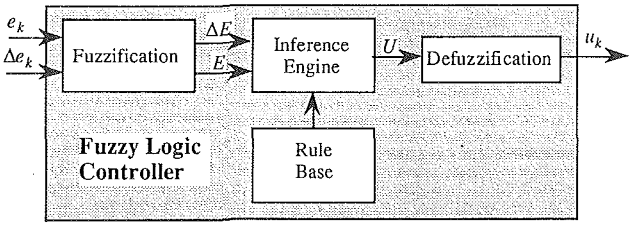

Fig. 3 Fuzzy logic controller

2.4 Cross-Coupling Controller. The cross-coupling control (CCC) architecture was first proposed by Koren [13]. The main idea of cross-coupling control is to build in real time a contour error model based on the feedback information from all the axes, to find an optimal compensating law, and then to feed back correction signals to the individual axes. The cross-coupling controller includes two major parts: (1) the contour error model, and (2) a control law. Consequently, the differences between the various CCCs that were proposed by many other researchers who followed the original work are in the contour error model or in the control law [3, 6, 15, 18, 19, 21, 24].

A recent version of the CCC, the variable-gain cross-coupling controller proposed by Koren and Lo [15], demonstrated excellent tracking ability on an experimental system and is summarized below. The contour error model is shown in Fig. 2. We see that the principle of the CCC is to place the tool P on the contour at point A rather than R, as done with feedback and feedforward controllers. The contour error mathematical model is given in the following equations:

$$\epsilon = -E_x C_x + E_y C_y \tag{1}$$

where C_x and C_y are

$$C_x = f(\sin\theta, E_x, \rho) \tag{2}$$

$$C_y = f(\cos\theta, E_y, \rho) \tag{3}$$

where θ is the angle between X-axis and the instantaneous tangent to the desired trajectory and ρ is the instantaneous radius of curvature (Note that ρ = constant for a circular contour and $\rho = \infty$ for a linear contour). The signals E_x and E_y are the axial position errors and are measured in real time; θ and ρ are calculated at each sampling period based on the interpolator data.

Based on the above contour error model, a cross-coupling controller with a PID control law $W(z) = W_P + W_I(T_z/z - 1) + W_D(z - 1/T_z)$ was implemented on a milling machine and gave error reduction of 5:1 compared with a system with axial controllers. The block diagram of a two-axis cross-coupling control system is shown in Fig. 5. Experimental results are shown below.

2.5 Experimental Analyses. The experimental tests were conducted on a 3 HP, 5-axis milling machine, that was interfaced with our computer, which allows us to write our own control software and test it on this real system [16]. The machine has large disturbances due to significant friction in the guides. As can be seen in Fig. 6, the ZPETC method results in the

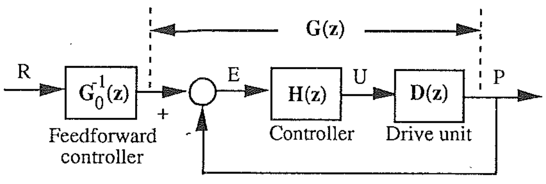

Fig. 4 Feedforward controller

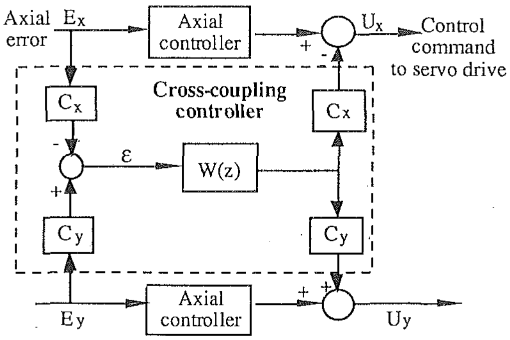

Fig. 5 The cross-coupling controller

worst performance in linear cuts. The ZPETC, as well as the P controller, cannot provide a good disturbance rejection ability. Moreover, the ZPETC results in an additional error due to the modeling error, which doesn't exist with a P controller. As expected, the advantage of the ZPETC is its ability in tracking nonlinear contours such as circles, rather than linear contours. The PID controller, as can be seen in Fig. 6, results in a significant overshoot at the transient state (without programmed acceleration). In addition, it also causes large overshoots at the end of the cuts (for both linear and circular cuts). To remedy this drawback, preprogramming of acceleration and deceleration periods is required, whereas they are not needed with CCC, P, and ZPETC methods. Adding acceleration and deceleration periods, however, increases the cutting time.

Circular motions with high feedrates make the contour error due to trajectory tracking more significant. We demonstrated experimentally [16] that at high feedrates, the PID controller failed since it cannot provide good tracking. The ZPETC method provides better tracking compared to the P and PID controllers. The CCC is the only method that provides a small contour error under such circumstances. Overall, the CCC method provides the best performance in both linear and circular cuts.

FLC—Experimental Results. Experimental results comparing contour errors in a circular motion with a 20 mm radius when using PID and fuzzy-logic controllers are shown in Fig. 7 (feedrate 0.96 m/min). The FLC outperformed the PID control. The large contour errors caused by friction at every quarter circle were reduced by a large factor by the FLC. The RMS error was reduced by a factor of 3.5, and the maximum contour error was reduced from 18 to 10 BLUs.

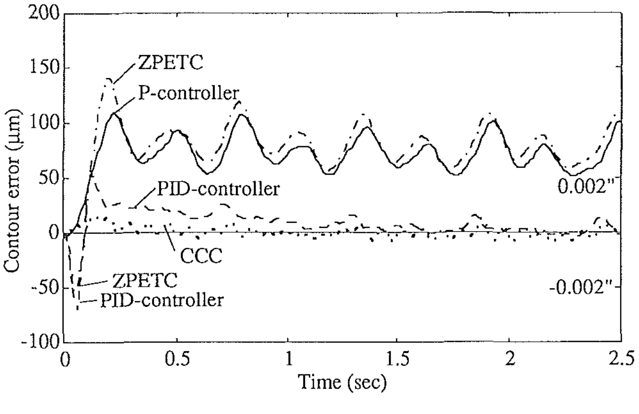

Fig. 6 Experimental results of a straight-line motion for different servo-controllers. [Feedrate = 1.2 m/min (47.2 ipm). Angle between straight line and the X-axis = 26.6 deg].

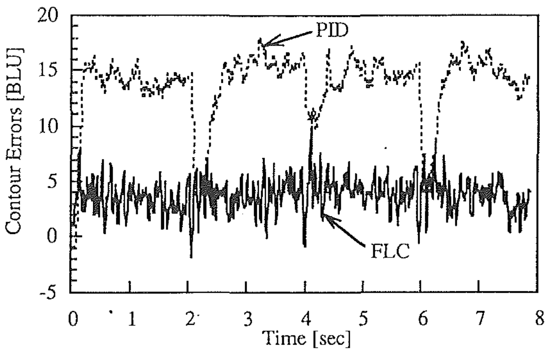

Fig. 7 Experimental results comparing the contour errors in a circular cut when applying FLC and PID controllers (radius = 20 mm; feedrate = 0.96 m/min)

3 Interpolators

A common requirement of all contouring systems (e.g., milling and turning) is to generate coordinated movement of the separately driven axes of motion in order to achieve the desired path of the tool. This involves the generation of signals prescribing the shape of the produced part by interpolators [42, 43]. Interpolation is performed by means of a special routine, located at Level 2 of Fig. 1, which generates command signals for each segment of the produced part based upon the initial and final points and the type of curvature of the segment. Typical interpolators are capable of generating linear, circular, and occasionally parabolic paths. Elliptic interpolation is inapplicable in CNC of machine tools but may be useful in other manufacturing systems such as laser-beam cutters. Recently, interpolators for complex-surfaces have been introduced.

3.1 Linear and Circular Interpolators. The linear interpolator is an iterative algorithm that is typically synchronized with the sampling time T of the control loop. Typical values of T are between 0.1 ms to 10 ms. At each iteration, the reference positions to X and Y are incremented by ΔX and ΔY, respectively, where

$$\Delta X = TV_x \quad \Delta Y = TV_y \tag{4}$$

The increments ΔX and ΔY are added up to obtain the reference positions. The calculation of the axial velocities V_x and V_y is based on the given incremental distances L_x and L_y, of the segment and the given desired velocity along the machined line, V:

$$V_x = V\frac{L_x}{L}; \quad V_y = V\frac{L_y}{L} \tag{5}$$

where L is the segment length.

Circular interpolation is based on dividing an arc into small angles α and calculating the minimum angle α [49]. The minimum α is the angle that the tool can traverse during one sampling period T (typical Ts are 0.1 ms to 10 ms), and is given by

$$\alpha = \frac{VT}{R} \tag{6}$$

In circular interpolator the tool moves between successive iterations, $(n - 1)$ and n, in short straight lines that their length is VT.

3.2 Complex-Surface Interpolators. Integrated Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) systems interfaced with Computer Numerical Controlled (CNC) enable the production of a part surface from geometric models [37, 45, 51]. In this process, the part geometric data have to be transferred from the CAD/CAM to the CNC.

In the conventional method, the surface is decomposed by the CAD/CAM system into a sequence of straight lines that approximate the desired part surface with a given tolerance. These straight lines are converted into the cutter location (CL) file. The CL file actually describes the cutter path in a sequence of tool positions. Using the post processor, the CL file is finally converted into *g*-code straight-line instructions that are downloaded into the CNC system [38, 40, 41, 44]. This approach is utilized since most conventional CNC machine tools provide only linear and circular interpolators, and the linear fitting is the simplest approximation. The drawbacks of this off-line approach are: (*i*) it requires acceleration and deceleration steps at each line of the CL file, thereby producing less smooth curves and substantially increasing the cutting time [52], (*ii*) tool orientations in 5-axis machining are interpolated inaccurately that sub-sequentially causes position errors and unsmooth surfaces [46], and (*iii*) the size of the CL file will be very large for complicated parts that causes memory shortage problems and data transmission errors.

Real-Time Curve Interpolator. Precision and productivity can be improved by the development of real-time interpolators for multi-axis CNC machine tools [50]. This real-time interpolator, which is contained in Level 2, calculates new commands for the control loops during a short time period (e.g., 1 to 10 ms). The successive commands are calculated during the execution time of the current commands. This approach produces smoother surfaces and requires substantially less machining time compared with the conventional off-line approach.

Figure 8 shows the scheme of a real-time surface interpolator [48]. This real-time interpolator consists of (*i*) tool-path planning, (*ii*) trajectory planning, and (*iii*) inverse kinematics. The input to the interpolator is a special *g*-code (i.e., NC instructions) of either a curve or a surface.

For surface machining, the interpolator begins with tool path planning, which generates curves as tool-paths, and subsequently executes the trajectory planning portion for the interpolation of each curve. When curve machining commands are specified, the interpolator starts with trajectory planning, which generates the cutter position (X, Y, Z) and orientation (O_x, O_y, O_z) of each interpolation step, for a constant feedrate. For 5-axis machines, the interpolator needs an additional portion, the inverse kinematics transformation, to generate the five axial reference positions (x, y, z, a, b), which, in turn, are transmitted to controllers for controlling the machine tool. For 3-axis machines, the inverse kinematics transformation is an identity matrix. The calculations for the tool positions orientations and the solution for the inverse kinematics have been presented in [47].

The proposed real-time surface interpolator generates the tool position and orientation (the latter in five-axis machining) in each sampling period, and sends the reference commands to the machine controller during cutting. Therefore, the proposed interpolator has the following advantages:

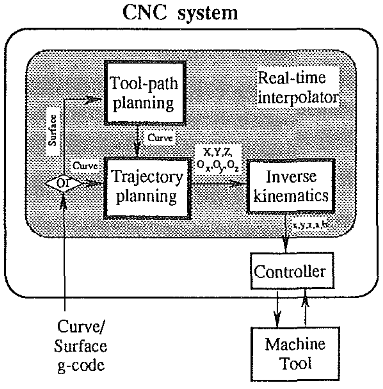

Fig. 8 The scheme of the proposed real-time interpolator

(i) Smoother surfaces and smaller machining time (the intermediate acceleration and deceleration steps are eliminated).
(ii) More accurate contour in 5-axis machining (achieved by accurately interpolating the tool positions and orientations [46]).
(iii) Smaller CNC memory is required.

Experimental CNC Systems. The surface/curve real-time interpolators were implemented on a 5-axis milling machine controlled by an Intel i486/33 MHz personal computer. In this system, the computation time needed for reading position/velocity feedback from five axes and executing the control algorithms is 1 ms. The computer was programmed to execute two types of interpolators: the conventional one and the curve interpolator described above. Tachometers were used to measure the velocity response in real time. Typical results, depicted in Figs. 9 and 10, show that the real-time curve interpolator reduced the time by a factor of 10:3 and enabled the machine to reach the programmed feedrate of 10 mm/s. The surface achieved by the curve interpolator was much smoother.

4 Adaptive Control and Compensation

As shown in Fig. 1, adaptive control & compensation (Level 3) includes two major functions:

(i) Enhanced productivity by applying adaptive control techniques such as Adaptive Control Optimization (ACO) and Adaptive Control Constraints (ACC). The adaptation strategy is used to vary the machining variables in real time as cutting progresses.
(ii) Enhanced part precision by applying real-time geometric error compensation techniques such as Geometric Adaptive Compensation (GAC) [62] for imprecision caused by the varying machine temperature, imprecise machine geometry, tool wear, etc. (see Fig. 1). The compensation strategy modifies the geometric data supplied by the part program (e.g., varies the depth of cut).

ACO refers to systems in which a given performance index (usually an economic function) is extremized subject to process and system constraints. With ACC, the machining variables are maximized within a prescribed region bounded by process and system constraints, such as maximum force or power. ACC systems, however, do not use a performance index and their operating point is always on the constraints. In GACs the part quality is maintained in real time by compensating for the machine tool temperature as well as for the deflection and wear of cutting tools. The purpose of the compensation may be to improve the part dimension precision or the surface finish. By their definitions ACC systems usually applied in rough cutting and GAC systems in finish operations.

4.1 Adaptive Control Optimization.

Although there has been considerable research on the development of ACO systems, few, if any, of these systems are used in practice. The most-known research for ACO systems for milling (turning is a similar problem) was conducted at Bendix during the years 1962 through 1964 under the technical supervision of the U.S. Air Force [54]. Despite the considerable resources spent on the Bendix project, it was not commercially accepted. The main problem with the Bendix system and such other systems is that they require on-line measurement of tool wear in production environment [56, 61, 65].

So far there have been no industrially acceptable methods developed for the direct measurement of tool wear. Indirect measurement assumes that tool wear is proportional to other

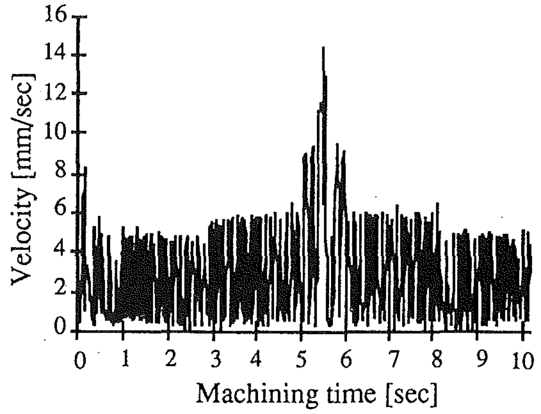

Fig. 9 Measured feedrate—the off-line approach and 92-line approximation

measurable variables such as cutting forces and temperatures [67]. The drawback of using these indirect measurements is that variations in their values can be caused by process variations other than tool wear, such as workpiece hardness or cutting conditions, thus making it difficult to identify the tool wear effect from the effect of the other parameter variations on the measurements. Therefore, ACO systems have been employed only on grinding machines [53] where tool wear measurements are not required.

4.1 Adaptive Control Constraints. The objective of most ACC types of systems is to increase the material removal rate (MRR) during rough cutting operations. This is achieved by maximizing one or more machining variables within a prescribed region bounded by process and system constraints [64]. The most commonly used constraints in ACC systems are the cutting force, the machining power, and the cutting torque [57]. The operating parameters are usually the feedrate velocity V (in millimeters per minute or inches per minute) and the spindle speed N (in revolutions per minute). One useful approach, for example, is to maximize the machining feedrate while maintaining a constant load on the cutter, despite variations in width and depth of the cut [55]. Such ACC system must therefore continuously check the radial cutting force and the cutting torque on the cutter, and vary the feedrate so as to keep both these variables below the permissible limit [39].

A typical computerized ACC system, which applies the concepts introduced in this section, is described for turning on a CNC lathe with a constant cutting force constraint [59]. The ACC system is basically a feedback loop where the feed adapts itself to the actual cutting force and varies according to changes in work conditions as cutting proceeds. The actual main cutting force F is sampled every T seconds (typically $T = 0.1$ s). The actual force representation F_c is immediately compared in the computer with a predetermined allowable reference force F_r. The difference between F_r and F_c, which is the force error E ($E = F_r - F_c$) is used as the input to the AC controller. The latter sends a correction signal to the interpolator routine (Level 2), which, in turn, produces the feedrate command signal. A positive error increases the feedrate and consequently increases the actual force, thereby decreasing the error E, and vice versa.

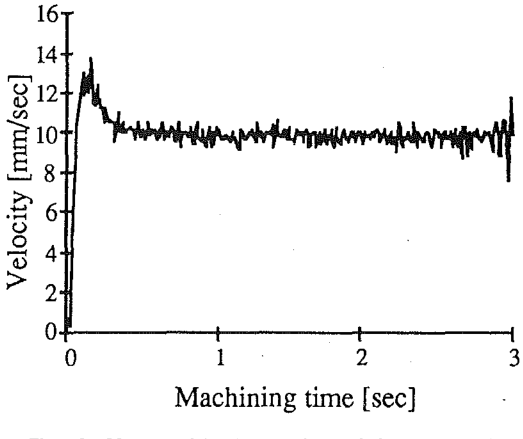

Fig. 10 Measured feedrate—the real-time approach

This strategy has been implemented on a high power CNC lathe [59]. A typical result for $K_c = 0.5$ is shown in Fig. 11. The feed before engagement was selected as 0.5 mm/r. At the start of cutting, the feed is automatically reduced to approximately 0.25 mm/r. The depth of cut is increased by increments of 2 mm, and each time, after a small transient, the force reaches the preselected reference value of $F_r = 1500$ N, and the corresponding feed is decreased.

If the gain K_c is not properly adjusted, the ACC system becomes unstable when wide variations in width or depth of cut are needed. To remedy this situation, a system that utilizes a variable-gain K_c may be employed. The objective of the variable-gain adaptive control algorithm is to maintain a constant open-loop gain despite variations in the cutting parameters [58, 60]. This system was successfully used in production environment.

4.3 Geometric Adaptive Compensation. The objectives of GAC are to achieve (1) the required dimensional accuracy and (2) a consistency of surface finish of machined parts. When large workpieces are machined, the dimension accuracy is mainly affected by the variations in the machine tool temperature (see article by Jun Ni in this issue). Both the dimensional accuracy and the surface finish are affected by the flank wear of the tools which deteriorate during cutting. The wear variable cannot be measured in real time; neither can it be accurately predicted from off-line tool testing. Therefore, the GAC approach usually taken is that the tool is assumed to worn out when the above criteria, (1) or (2), are no longer at acceptable values. This method has been found to correlate well in practice with actual tool deterioration [66].

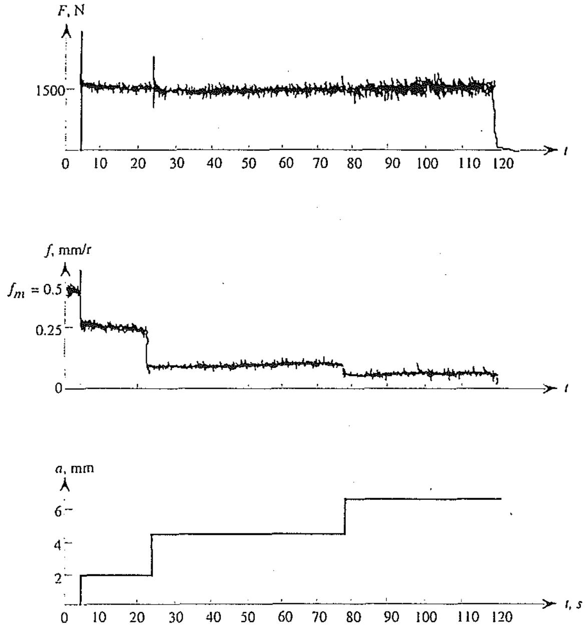

Fig. 11 A response of an ACC system to changes in depth of cut (*a*)

5 Conclusions

This paper reviewed the progress in machine tool control since the invention of the NC in the mid 1950s. The ASME Journal of Engineering for Industry played a major role in reporting research advances in this field over the last three decades.

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