MANUFACTURING PERSPECTIVE

Adaptive Control Systems for Machining

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This paper summarizes the major research efforts in the area of adaptive control for machining processes in the last 25 years. The objective of these adaptive control systems is to improve the production rate or the part quality by real-time setting of the optimal machining variables. In conventional CNC systems the machining variables are prescribed by part programmers, and therefore, their values depend on the experience and process-knowledge of these programmers. By contrast, the adaptive control system adjusts the variables in real time, based upon measurements of other process variables. Therefore, improvements in the performance of the overall system can be achieved by using adaptive control methods.

INTRODUCTION

During the past two decades the number of computerized numerical controlled (CNC) systems has grown tremendously in almost every field of manufacturing. A common drawback of these systems is that their machining control variables, such as speeds or feedrates, are prescribed by a part programmer and consequently depend on his or her experience and knowledge. In order to reduce the chance of a tool failure, the part programmer must consider the most adverse conditions (which in practice will seldom occur), and select conservative values for the machining variables. This practice consequently slows down the system's production [1].

The availability of a dedicated computer in the control system and the need for higher productivity has greatly accelerated the development of adaptive control (AC) systems for metal cutting [2]. These systems are based on real-time control of the cutting variables with reference to measurements of the machining process state-variables. The adaptive control is basically a feedback system that treats the CNC as an internal unit (see Fig. 1), and in which the machining variables automatically adapt themselves to the actual conditions of the machining process.

AC systems for machine tools can be classified into three categories [3, 4]: (1) adaptive control with optimization (ACO), (2) adaptive control with constraints (ACC), and (3) geometric adaptive control (GAC). 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 deflection and wear of cutting tools. By their definitions ACC systems usually applied in rough cutting and GAC systems in finish operations. In all systems an adaptation strategy is used to vary the machining variables in real time as cutting progresses.

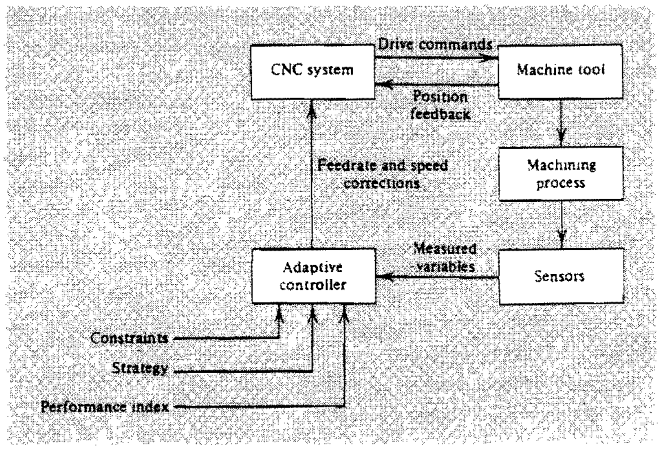

Fig. 1. Adaptive control system for machine tool.

Note that while this type of system is termed *adaptive* in the manufacturing literature, it is not an adaptive system in the sense defined in the control literature [5–8].

Although there has been considerable research on the development of ACO systems, few, if any, of these systems are used in practice [9]. The major problem with such systems has been the lack of suitable sensors which can reliably measure on-line the necessary process variables (e.g., tool wear) in a production environment. Most commercial AC metal-cutting systems which are used in industry today are of the ACC and GAC types, and seldom involve the control of more than one machining variable.

The objective of most ACC systems is improvement in productivity, which is achieved by increasing the metal removal rate (MRR) during rough cutting operations. Several studies have been published [3, 10–13] which present the productivity increase achieved with ACC system as compared to conventional machining. The increases in productivity range from approximately 20 to 80 percent and clearly depend on the material being machined and the complexity of the part to be produced. The AC systems show the most marked advantages in situations where there are wide variations in the depth of cut during machining.

The objective of GAC is to achieve (1) the required dimensional accuracy and (2) a consistency of surface finish of machined parts [14]. Both the dimensional accuracy and the surface finish are affected by the flank wear and the crater wear of the tools which deteriorate during cutting. These variables cannot be measured in real time; meither can they be accurately predicted from off-line tool testing. Therefore, the GAC approach usually taken is that the tool is assumed to be 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 [15].

Saving of time is achieved when applying AC systems in the programming stage. Since the machining variables, such as speeds and feedrates, are adjusted automatically by the system, the part programmer does not have to spend time and effort calculating their optimal values. Again, this time savings becomes significant in complex parts where wide variations in depth of cut must be accommodated. Other savings are associated with reduced tool wear [16] and the control of chatter [17–19].

ADAPATIVE CONTROL WITH OPTIMIZATION

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 [20]. The block diagram of the Bendix system is shown in Fig. 2. The sytem consists of a milling machine, NC controller, sensors unit, and adaptive controller. The sensors measure the cutting torque, tool temperature, and machine vibration. These measurements are used by the adaptive controller to obtain the optimal feedrate and spindle speed values as will be explained later.

The adaptive controller contains a data reduction subsystem (DRS) fed by the sensor measurements as well as by the calculated feedrate and spindle speed and a set of constraints. The DRS produces two signals: a metal removal rate (MMR) and a tool wear rate (TWR). The MRR is the product of the milling width (w), the depth of cut (a), and the milling feedrate (V) in inches per minute:

$$\text{MRR} = \text{waV} \tag{1}$$

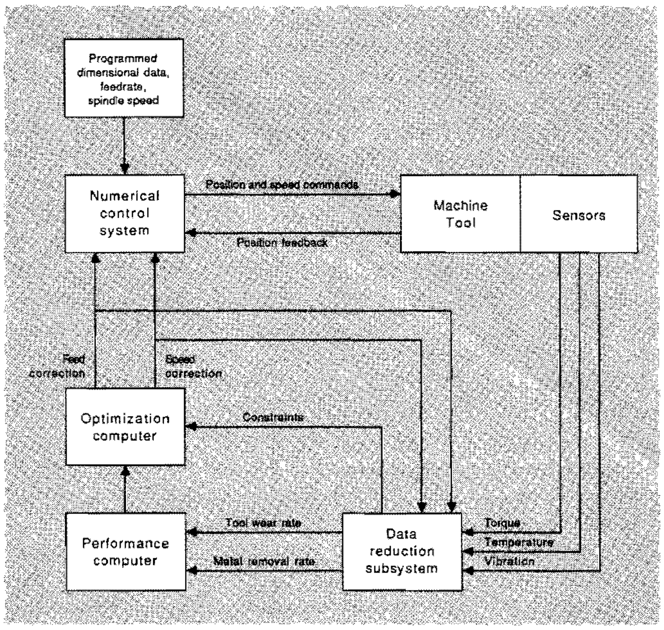

Fig. 2. ACO System for a milling machine.

The MRR is used in the calculation of the TWR value:

$$\text{TWR} = K_1\,(\text{MRR}) + K_2\theta + K_3\frac{dT}{dt} \tag{2}$$

where θ is the tool temperature, dT/dt is the time rate of change of the cutting torque, and K_1, K_2, and K_3 are constants which depend on the tool and workpiece material.

The *TWR* and *MRR* signals are fed into a performance computer which calculates the performance index ϕ as follows:

$$\phi = \text{MMR}/C_1 + (C_1t_1 + C_2\beta)(\text{TWR})/W_0 \tag{3}$$

where

C_1 = cost of machine and operator per unit time
C_2 = cost of tool and regrind per change
t_1 = tool changing time
W_0 = terminal allowable width of the tool's flank wear
β = adjustable parameter ($0 < \beta < 1$) which determines the type of performance index (PI):
If $\beta = 1$ the PI is the reciprocal cost per unit.
If $\beta = 0$ the PI is the production rate.
If $0 < \beta < 1$ the PI takes into account both the cost per part and the production rate.

The calculated index ϕ is fed into an optimization computer unit which contains the strategy according to which the optimization is performed. The objective of this unit is to continually maintain the value of ϕ at the highest possible value without causing any constraint violations. Examples of constraints are maximum and minimum spindle speed, maximum torque, maximum feed, maximum temperature, and maximum vibration amplitude.

Although considerable efforts were expended in the Bendix project, it was not commercially accepted. The main problem is that this, and other similar ACO systems for milling and turning, require on-line measurement of tool wear [21–25]. 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 measurable variables such as cutting forces and temperatures. 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. The Bendix researchers estimated the tool wear rate according to Eq. (2). However, since the constants K_1, K_2, and K_3 in Eq. (2) depend on the tool and workpiece material, to use the Bendix system the user needs to perform off-line experiments to determine the values of these constants for every combination of tool and workpiece material. The time and effort needed for these experiments may override the economic benefits of the AC system.

The lack of a reliable tool wear sensor is the main obstacle in developing industrial ACO systems for milling, drilling, and turning [26]. Although a few techniques were developed to measure the flank wear on turning tools in laboratories [27]—these methods cannot be utilized on the production floor. The problem in milling and drilling is even more difficult because of the complex geometry of milling cutters and twist drills [28]. Experimental ACO systems, however, have been implemented in grinding [29], in which a power or a force sensor can provide information about the wear of the grinding wheel.

ADAPTIVE CONTROL WITH CONSTRAINTS

We have seen that considerable research and development are required before ACO systems become practical for industrial use. Actually all the AC systems for rough turning and milling used in production today are of the ACC type and seldom involve control of more than one machining variable [30–31]. Unlike ACO, ACC systems do not utilize a performance index and are based on maximizing a machining variable (e.g., feedrate) subject to process and machine constraints (e.g., allowable cutting force on the tool, or maximum power of the machine).

The objective of most ACC types of systems is to increase the 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 [3, 32–34]. 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 cut [35–38]. This is illustrated in Fig. 3 for a slab milling operation. In a normal CNC system, the feedrate is programmed to accommodate the largest width and depth in a particular cut, and this small feedrate is maintained along the entire cut. As a result the machining rate is reduced. By contrast, with the ACC system, the maximum allowable load (e.g., cutting force) on the cutter is programmed. As a result, when the width or depth of cut are small the feedrate is high; when either the width or depth of cut (or both) are increased, the feedrate is automatically reduced, and consequently the allowable load on the cutter is not exceeded. The result is, the average feed with ACC is much larger than its programmed counterpart. Likewise, when the tool moves through air gaps in the workpiece, the feedrate reaches its maximum allowable value. Operating at the maximum allowable feedrate, maximizes the MRR (See Eq. 1). The ACC system guarantees maximum productivity while minimizing the probability of cutting tool breakage.

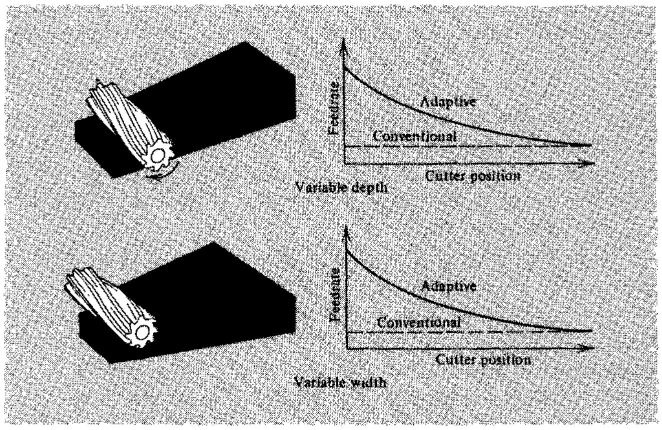

Fig. 3. The feedrate command in conventional and adaptive controlled CNC machine.

Commercial AC systems are available for end milling. An end milling cutter may break in bending or in torsion or a tooth may break away. An appropriate 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].

The most commonly used constraints in ACC systems are the cutting force, the machining power, and the cutting torque [27, 40]. 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); both can be easily manipulated under computer control. The machining feed f is defined by the ratio

$$f = V/pN \tag{4}$$

where p is the number of teeth in the cutter in the milling operation; in turning and drilling $p = 1$ is substituted in Eq. (4).

The main cutting force F is proportional to the depth of cut a and the feed:

$$F = K_s a f^u \tag{5}$$

where K_s is the specific cutting force, and u is a parameter in the range $0.6 < u < 1$. Both K_s and u depend on the workpiece and tool material. The cutting torque T is proportional to the force and the workpiece diameter in turning and the tool diameter in milling and drilling. The machining power P is proportional to the torque and the spindle speeds.

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 [36]. The ACC system shown in Fig. 4, 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 CNC computer executes the original control program and an additional AC routine, which is linked to the feedrate routine contained in the control program. The AC loop functions in a sampled-data mode. The actual main cut-

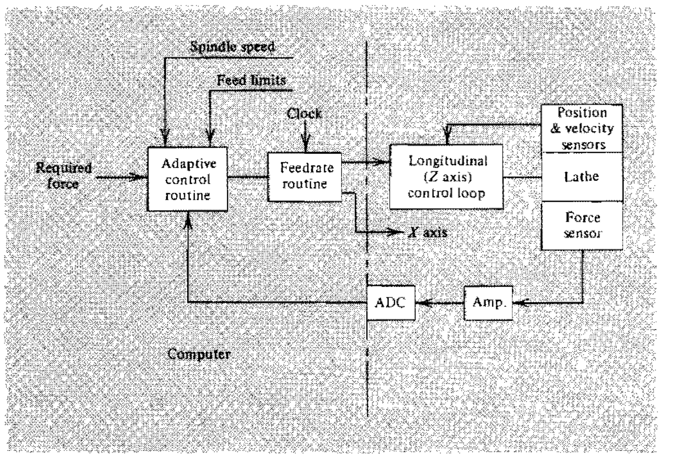

Fig. 4. Basic structure of ACC system.

ting force F is sampled every T seconds (typically $T = 0.1$ s), then converted to a digital signal F_c and sent to the computer. 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 feedrate routine, 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.

In order to eliminate completely the force error, the controller output command U should be proportional to the time integral of the force error W. The simplest structure for such an integral strategy can be written

$$W(i) = W(i-1) + TE(i) \tag{6}$$

and then the command signal U from the controller is

$$U(i) = K_c' W(i) \tag{7}$$

Equations (6) and (7) can be combined to give a more efficient form for programming:

$$U(i) = U(i-1) + K_c E(i) \tag{8}$$

where K_c, the controller gain, is proportional to the sampling period T, i.e., $K_c = TK_c'$. The resulting computer feedrate command V_f to the servoloops at the ith sampling (or to the interpolator in a multiaxial mode) is given by

$$V_f(i) = K_f U(i) \tag{9}$$

where K_f is a constant associated with the feedrate routine. The initial feedrate value $K_f U_0$ may be preselected so as to avoid tool breakage when the tool initially impacts the workpiece at the start of the cutting process. As long as there is an error, the command U varies the machine feedrate in a direction to correct this error. At the steady state, however, the error in the force is zero, causing the condition $U(i) = U(i-1)$, which means that the feedrate command is constant, maintaining the actual force equal to the required one.

This integral strategy has been implemented on a high-power CNC lathe [41]. A typical result for $K_c = 0.5$ is shown in Fig. 5. 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.

The selection of the gain K_c is critical to the operation of the AC system. It is known from control theory that the lower the gain K_c, the greater the tendency for stability. Although a small gain causes a sluggish response, the steady-state error always becomes zero.

SELF-TUNING AC SYSTEMS

Proper selection of the controller gain K_c in ACC systems is very critical if wide variations in width or depth of cut, feed, and spindle speed are permitted in the system [13, 42]. The reason is that in AC systems, the machining process itself is part of the control loop as is shown in Fig. 1. Therefore, variations in the process directly affect the control parameters of the loop, and consequently the AC system might become unstable.

The Stability Problem

The results of a turning experiment demonstrating the stability problem is given in Fig. 6. In this experiment the controller gain is $K_c = 0.6$ and the sampling period is $T = 0.1$ s. At the start of the cut the feed is automatically reduced and adapts itself to the programmed increase in the depth of cut. Note that the load force on the tool remains constant. However, the

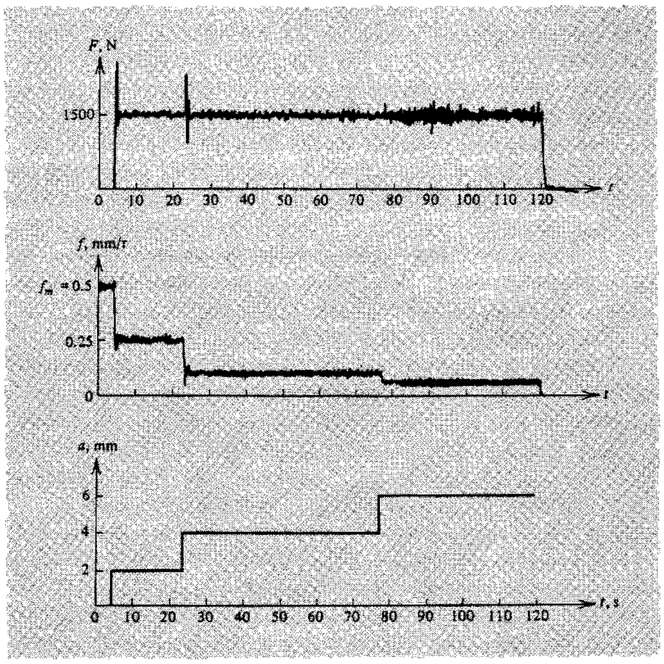

Fig. 5. Typical response of an ACC system.

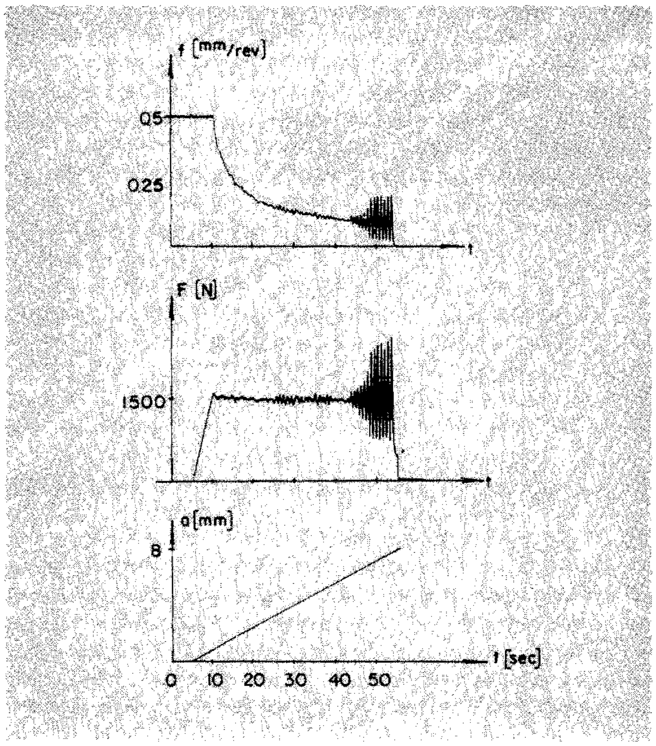

Fig. 6. Instability in ACC system.

system is stable as long as the depth of cut does not exceed 6 mm. At 6 mm, the system becomes unstable with oscillations of approximately 2 Hz. Furthermore, when running the system with different spindle speeds and constant depth of cut, the same phenomenon occurs. With a slower spindle speed, the system becomes unstable [36].

Instability in ACC systems has not been a familiar phenomenon to people on the shop floor in the 1980s, because most of them have not utilized AC systems in production. Users of AC production systems encountered this instability condition rather infrequently in practice, since their part programmers were experienced enough to avoid large changes in depth of cut and/or spindle speed. This, however, means that the production rate is decreased and that the objective of the ACC system is not fully achieved. Nevertheless, designers of ACC systems had experienced these instabilities and reported on them [43–44].

The reason for this type of instability prompts a more detailed study of the AC loop. First, the open-loop gain, which is the dominant parameter in determining system stability, must be calculated, as shown below.

The relationship between the actual feedrate, or longitudinal axis velocity, V, and the command V_f is given at steady state by

$$V = K_n V_f \tag{10}$$

where K_n is the gain of the CNC servosystem. The cutting force F is a function of the feed (f) and the depth of cut (a) and can be approximated by Eq. (5), which can be written as follows:

$$F = (K_s a f^{u-1}) f \tag{11}$$

The cutting force F is measured by a force sensor, then converted to a digital word F_c. The conversion factor between F_c and F, including the sensor electronics, is K_e:

$$F_c = K_e F \tag{12}$$

A steady-state block diagram representation of the whole system is shown in Fig. 7. Combining Eq. (4) with $p = 1$ and Eqs. (7) through (12) yields

$$F_c = KW \tag{13}$$

where K, the AC open-loop gain, is defined by

$$K = K_c' K_f K_n K_e K_s \left[\frac{a}{N}\right] f^{u-1} \tag{14}$$

and has the dimensions of s^{-1}.

Since the depth of cut and the spindle speed are contained in K, an increase of the first, or a decrease of the latter, can cause instability conditions, as seen in Fig. 6. One might think that a possible solution is the selection of a very small gain K_c' in Eq. (14) to decrease the open-loop gain under its stability limit even at the largest allowable depth of cut and a minimum permissible spindle speed. The result of this approach as demonstrated in [3] shows that if the chip load is too big, the recovery time from the initial impact is too long and the tool insert breaks.

We see that the selection of K_c is critical to the performance of the AC system. If K_c is too large, the entire CNC-AC system may become unstable. When K_c is too small, the transient behavior is very sluggish and, as a result, the tool insert may break at medium to large depths of cut. This calls for a different approach to AC system design. The system should operate with a variable-gain K_c which adapts itself to the cutting parameters. This involves an estimation in real time of the gain of the cutting process, and a subsequent self-tune of the AC controller gain (K_c) to the changing conditions of the cutting process.

The Estimator Algorithm

The cutting process estimator should measure in real time the quantity $K_s(a/N)f^{u-1}$ which affects the open-loop gain in Eq. (14). However, since a direct estimation of this quantity requires additional sensors and output channels to the computer, it is worthwhile to estimate the value of a process gain K_p, which contains the required quantity and is defined by

$$K_p = K_f K_n K_e K_s \left(\frac{a}{N}\right) f^{u-1}. \tag{15}$$

By definition, at steady state K_p is given by

$$K_p = F_c/U \tag{16}$$

Since the values of both F_c and U are available within the computer, the process gain can be calculated. Subsequently, the controller gain K_c (where $K_c = TK_c'$) could be adjusted in real time according to the equation

$$K_c = TK/K_p \tag{17}$$

where K is the desired open-loop gain.

Direct implementation of the algorithm based upon Eqs. (16) and (17) is not realistic because F_c is a noisy measurement and the resultant K_c will follow the noise signal rather than optimizing the process. Therefore, techniques used in estimation theory should be applied. One such technique is shown in Fig. 8. The estimated model block contains an estimated gain K_m, which is multiplied by the input U to generate an estimated force F_e. In general, $K_m = K_p$, and an error E_m is generated:

$$E_m = F_c - F_e = F_c - UK_m. \tag{18}$$

Since at steady state $F_c = UK_p$, the model estimation error is

$$E_m = U(K_p - K_m). \tag{19}$$

The estimated model gain K_m should be automatically adjusted to reduce this error. The simplest adjustment policy which guarantees a zero error is to apply an integration algorithm:

$$K_m = C\int E_m dt. \tag{20}$$

With this algorithm, when the error F_m is zero, K_m is a constant which satisfies $K_m = K_p$. In the computer program this estimator algorithm is given by the following equations:

$$F_m(i + 1) = F_c(i) - U(i)K_m(i) \tag{21}$$

$$K_m(i + 1) = K_m(i) + K_1E_m(i + 1). \tag{22}$$

The specific value of K_1 depends on the amount of noise in the measured force. In the presence of high-level noise, the estimator gain must be small in order to smooth the noise and estimate the process parameter K_m with good precision. This, however, causes the disadvantage of slower convergence to the steady-state value of K_m.

Variable-Gain Algorithm

The objective of the variable-gain adaptive control algorithm is to maintain a constant open-loop gain despite variations in the cutting parameters [3, 45]. By combining Eqs. (14) and (15) the open-loop gain is defined by

$$K = K_c'K_p \tag{23}$$

and substitution of the estimated value K_m for K_p yields

$$K = K_c'K_m = K_cK_m/T. \tag{24}$$

The constant open-loop gain can be obtained by adjusting the controller gain K_c according to variations of K_m. As in the

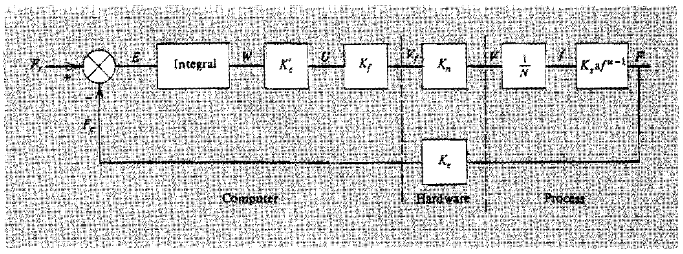

Fig. 7. Block diagram of an ACC system.

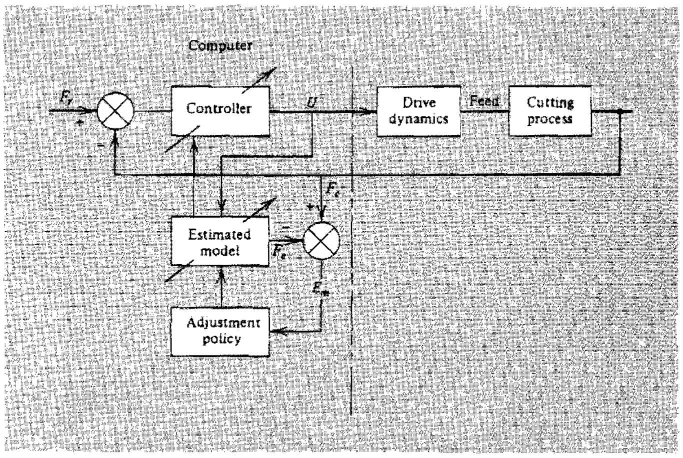

Fig. 8. Process estimation in a self-tuned ACC system.

case of the estimation algorithm, direct division is avoided and smoothing is achieved by using the following integration policy:

$$E_c(i + 1) = TK - K_c(i)K_m(i) \tag{25}$$

$$K_c(i + 1) = K_c(i) + K_2E_c(i + 1) \tag{26}$$

Again, the integration algorithm in Eq. (26) guarantees that $E_c = 0$ at the steady state, which means that the desired overall gain can be achieved.

We see that the solution to the original problem is in the form of a supplementary adaptation loop. In the main loop the machining feed is adapted to maintain a constant load on the cutting tool, and in the supplementary loop the controller gain is adapted, or self-tuned, to maintain a constant loop gain despite variations in the cutting condition.

A set of experiments was performed to compare the performance of a conventional AC system with the variable-gain AC system [46]. In these experiments the controller gain in the conventional AC was $K_c = 0.6$, the sampling period $T = 0.1$ s, and the integration constants in the variable-gain AC system were set to $K_1 = K_2 = 1/4$. The objective of the experiment shown in Fig. 9 was to remedy the unstable conditions obtained in Fig. 6 for the conventional AC system. In Fig. 6, it can be seen that the conventional AC system became unstable for a depth of cut of 6 mm. By contrast, as is seen in Fig. 9, the variable-gain AC system was always stable. The value of K_c was automatically reduced from 1.5 to 0.33 with the progressive increase in the depth of cut.

The self-tuned AC system provides a solution to the stability problem which arises in conventional ACC systems when wide variations in width or depth of cut are needed.

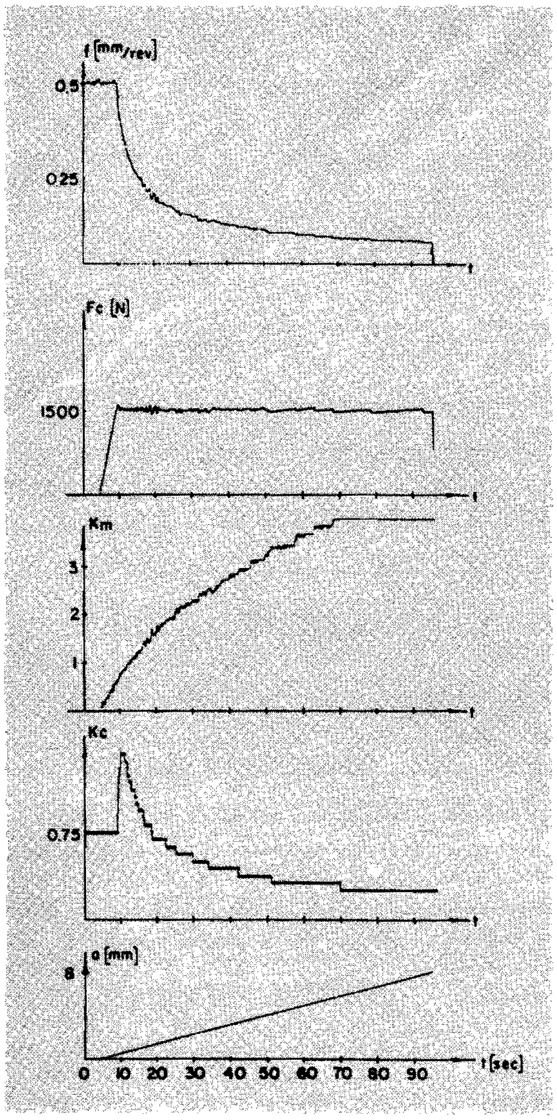

Fig. 9. Response of a variable-gain ACC system to a varied depth of cut.

The solution does not require any additional hardware, and all the modifications to the AC controller are implemented by software.

GEOMETRIC ADAPTIVE CONTROL

Geometric adaptive control systems (GAC) are typically used in finish machining operations, where the objective is to achieve a desired surface quality and/or accurate part dimensions despite tool wear or tool deflection. Most of the practical GAC systems are available for turning, but research is conducted also for milling [47] and grinding. From the point of view of surface finish, turning should be accomplished at as high a cutting speed as possible [48]. Therefore, in most GAC systems the cutting speed is constant and the machining feed is manipulated to achieve the desired surface quality. The dimensional precision in turning is usually achieved by measuring the part diameter at various points after the machining, and compensating for inaccuracies by adding an offset distance to the cross-axis position-command on a lathe.

The tool geometry has a significant role upon the theoretical surface finish of the machined parts. Two equations are used in the literature [48]. For a tool without nose radius the maximum amplitude of surface roughness, h, is given by

$$h = f/(cot_{\kappa r} + cot\kappa_e) \tag{27}$$

where κ_r, the tool cutting edge angle, has a typical value of 75°, and κ_e, the tool minor cutting edge angle, has a typical value of 15°. For a tool with a large nose radius r a good approximation of the surface roughness amplitude is

$$h = f^2/8r \tag{28}$$

As the tool wears, its nose geometry slightly changes, which, in turn, causes a change in the surface finish. From our experiences, the surface finish is usually improved during the first 10 to 20% of the tool life, then it stays at an almost steady level with a slight deterioration, and toward the end of the tool life it deteriorates very fast.

In a GAC system the surface roughness is measured on-line, either in-process or immediately at the end of the machining operations with the aid of a profilometer. The latter method fits turning on a lathe that typically has short machining time per part. For the purpose of GAC, Eqs. (27) and (28) may be combined to a model

$$h = c_1 f + c_2 f^2. \tag{29}$$

The coefficients c_1 and c_2 depend on the variations in the material and the change in tool wear and might be identified by using time-varying least-squares algorithms [49]. These estimated coefficients are subsequently used by the AC algorithm to determine the feed required to achieve a specific surface finish.

Alternatively, time series methodology might be applied for the identification process. Fig. 10 shows some results achieved by this method in turning [50]. The required surface finish is R_a = 1.5 μm (60 μinch), where R_a is the center-line average. The required finish is achieved with a new tool at f = 0.23 mm/rev (0.009 ipr) as shown in Fig. 10a. Without AC, the CNC system always uses the same feed and the resultant surface finish deteriorates to R_A = 3 μm with a worn tool (Fig. 10b). For the same worn tool, the GAC system automatically reduces the feed to 0.15 mm/rev (0.006 ipr), a value which maintains the required surface finish (Fig. 10c).

Figure 11 shows the surface finish and the adaptation of the feed (plotted versus workpiece number) on the same GAC system. The experiment was conducted on SAE 4140 steel with a carbide tool with r = 0.032″, cutting speed of 180 m/min (550 sfm), depth of cut 0.75 mm (0.03″), and an initial feed of 0.18 mm/rev (0.007 ipr). The surface finish is measured after the machining of a workpiece has been completed. As seen in the figure, the desired surface finish (60 μinch) is achieved after 10 parts, and then enters to a steady-state region in which the feed is held essentially constant. The tool actually failed in this experiment after 47 parts (the feed rapidly raised in the failure region).

The second criterion used in GAC systems is the dimensional accuracy of the produced part. In turning, the external diameters of the part increase as the tool wears. The reason is

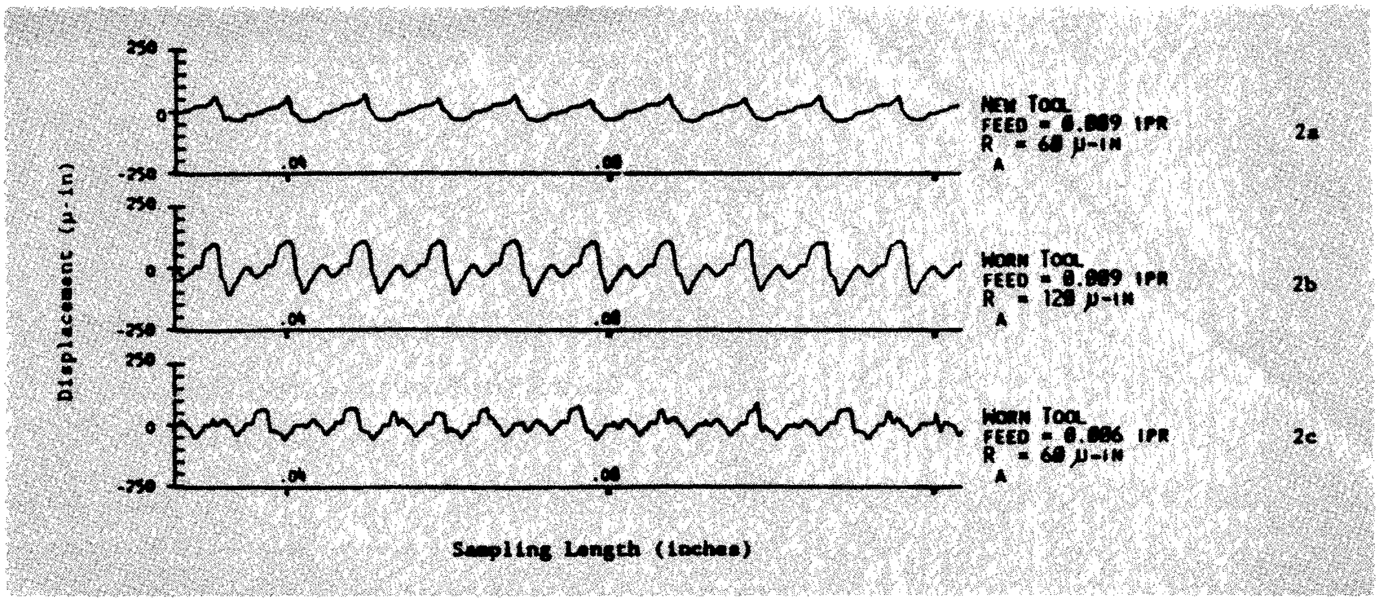

Fig. 10. Plots of surface roughness profile.

that the flank wear W at the tool nose reduces the effective tool length.

The principle of a GAC turning system that compensates for tool wear is simple. When the cut is completed, the system measures the external diameter of the part, and activates automatically the tool offset feature of the CNC system to compensate for the dimensional error. If the cycle time per part is short, the next part will be produced at the desired dimension.

GAC is also used in milling operations with end-miller cutters. Because of the cutting forces that operate at their end, these cutters deflect and consequently cause dimensional errors. Figure 12 [44] shows the bending-moment components in the feed direction and support direction (M_{BV} and M_{BSt}), that are generated at the point where the tool is clamped by the cutter-deflection force, F_A. The end of the milling cutter is deflected by an amount δ_v in the feed direction and δ_{St} in the support direction.

In the GAC system the machining operation is controlled in such a way that the maximum permitted cutter deflection δ_{max} and the given limit for the accuracy of the part δ_{St}, δ_{max} are not exceeded. The control is performed using the bending moments M_S, M_{BV}, and M_{St} as reference values with the feedrate as the control variable. A drawback of the system is that the function $\delta = f(F_A)$ must be determined experimentally in each case for the particular tool/chuck/machine combination. Therefore, this system is used only in research laboratories and not in production lines.

LIMITATIONS OF AC SYSTEMS

In spite of their economic advantages AC systems are not spread out in industry. A major reason for this situation is the unavailability of suitable sensors that have a reliable operation in a manufacturing environment [51–53]. The lack of a tool wear sensor is the major obstacle to the employment of ACO systems. Force and torque sensors for ACC systems are difficult to install. Cooperation with machine tool builders might facilitate the usage of sensors for AC systems [54]. For example, the tool-holder of a machine tool might be designed in such a way that a cutting force sensor could be easily installed. Or the spindle bearing might be designed to accommodate torque measurements. In GAC systems the bottle neck is the cost of the optical measuring devices and their inability to operate in a machining environment with chips and coolant fluids. The reliability of all these sensors is very important, since failure almost always leads to a machine damage.

The type of control variable employed might be another reason for the low penetration of AC systems. We have seen above that in most AC systems the machining feed is the natural control variable. It increases with the cutting depth decreases and vice versa. Decreasing the feed with increasing cutting depth, however, results in an unsuitable area of the chip section and might make the chip breakage impossible. A similar situation occurs with very small depth and large feed. Furthermore, in both cases the cutting tool is overloaded in a manner that might cause a high wear rate or breakage of the cutting edge [55]. To avoid these situations researchers have tried to design feed-limited ACC systems in which the depth of cut becomes the control variable when the feed limit is reached [55]. These AC systems, denoted as Automatic Cut Distribution (ACD) systems, must include real-time computation of the tool path. The economic advantage of these ACD systems is questionable because of the unpredictable tool path that might require very long machining time.

For operation of ACC systems, nominal values (e.g., forces) must be preset according to the properties of the tool and workpiece material, the performance of the machine, and the technology of the cutting process. For retrieving these nominal values, the corresponding data of the machine and of the workpiece material must be stored in the ACC computer or the CAD system, so that the nominal values can be computed from these data. This computing strategy has yet to be developed.

Another problem is the interface of an AC system with CNC units. As yet, manufacturers have not standardized interfaces. One might distinguish between implementing an AC system as a background processor supplementary to a CNC

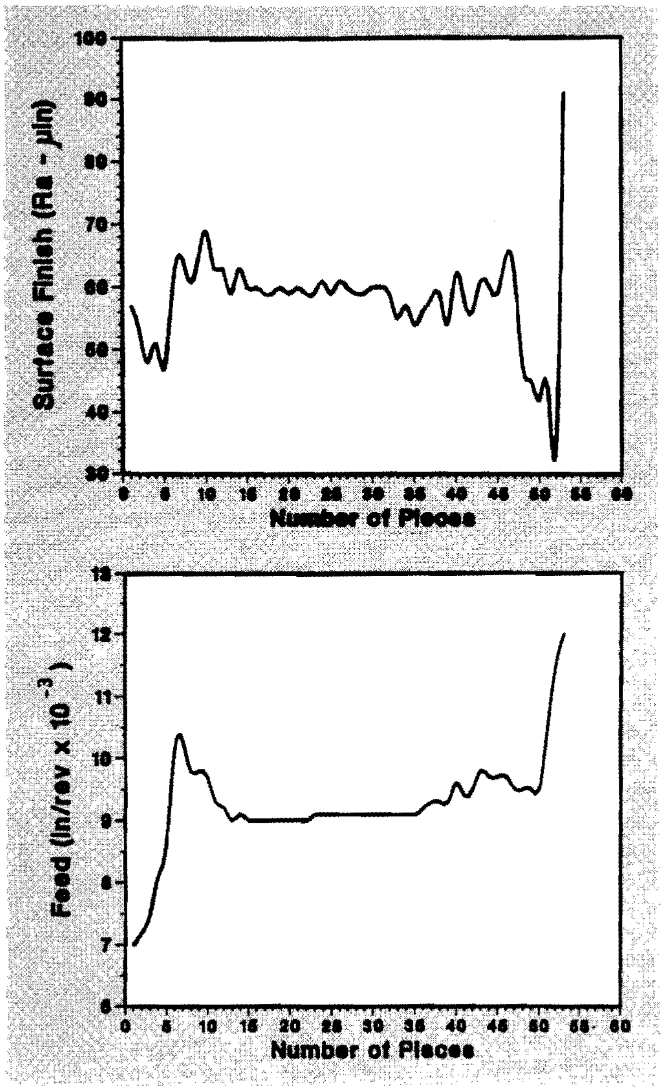

Fig. 11. The surface finish and feed in a GAC system.

system on the one hand, and systems in which the AC strategy is implemented within the CNC computer on the other. The effort required to define interfaces is certainly considerably greater in the second case, where it can not be performed by the customer, but only by the manufacturer of the control system.

Finally, it must be emphasized that most AC systems do not fit machining cell operation. In machining cells synchronization among the units in the cell is a prime requirement. Therefore the operation time of each machine must be predetermined and fixed. In most AC systems, however, the cutting variables (e.g., the feed) are changed in-process, and therefore the machining time is not predictable and varies from part to part. In these cases the AC might be implemented only in a background mode. That means that the AC is operated only once on a typical part and the corresponding feed is recorded [56]. This feed is then used in production without AC. Obviously by this method the full advantage of the AC system is not achieved, but it provides increased productivity over pure preprogrammed CNC systems.

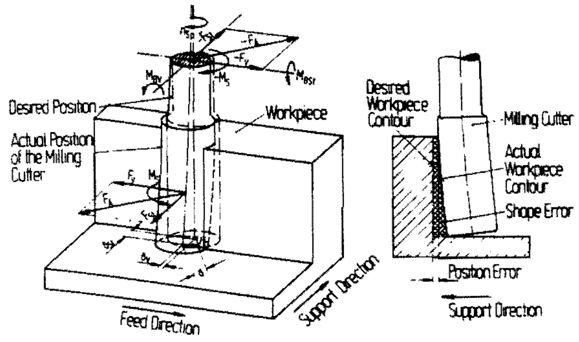

Fig. 12. Deflection of the end miller during machining.

CONCLUSIONS

The principal developments over the past 25 years in adaptive control of machining processes have been described. While AC systems offer a tremendous potential for improving metal removal rates, there are still some major theoretical and practical problems which must be solved before wide-spread industrial use can be expected. Progress in areas such as development of reliable sensors, machine tool design based on requirements of AC systems, and development of stable adaptive control strategies are required. These projects are underway in several research laboratories in Canada [57], in Japan [58], in Italy [59], and the USA at The University of Michigan—Ann Arbor [60], Texas A & M [61–62], University of California—Berkeley [63], Carnegie-Mellon University [64] and University of Southern California [65]. We hope that with these developments more AC systems will be utilized in the production plants. **MR**

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