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Principal Developments in the Adaptive Control of Machine Tools

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Although adaptive control (AC) systems for machine tools have a tremendous potential for improving productivity in manufacturing, their acceptance by industry has been slow. This paper identifies the major research and development areas for AC machine tools, and summarizes the principal developments of the last two decades. Current research at The University of Michigan, which is aimed at the development of stable yet high performance AC systems for turning and milling, is also described.

Introduction

During the past decade there has been a steady increase in the number of computer numerically controlled (CNC) machine tools. A common drawback of these systems is that their operating parameters, such as speeds and feedrates, are prescribed by a part-programmer and consequently depend on his experience and knowledge. To prevent tool breakage, part-programmers tend to select conservative values for the operating parameters, thus reducing the production rate. Adaptive control (AC) systems have been developed to address this problem. AC systems provide for automatic manipulation of the operating parameters based on measurements of the actual machining process characteristics. Typically AC systems for machine tools are classified into two types [1-4]:

1) Those using adaptive control for optimization (ACO) extremize a performance index (usually an economic function) subject to process and system constraints.

2) Those using adaptive control with constraints (ACC) maximize machining parameters (e.g., feedrate or cutting speed) subject to process and system constraints (e.g., allowable cutting force).

Due to difficulties in formulating realistic performance indices and in measuring required variables in a process environment, ACO applications have been limited mainly to grinding. Most of the systems used in practice for milling, turning, and drilling are of the ACC type.

A conventional ACC system, as shown in Fig. 1 for a CNC lathe, is a feedback control system where the feed (f) is manipulated to maintain a required value (F_R) of the cutting force (F_c). The process block in Fig. 1(*a*) contains the control loops of the CNC controller, the cutting process, and the force transducer, as illustrated in Fig. 1(*b*). The cutting process itself is part of the control loop, and variations in the parameters of the cutting process affect the performance of the AC system. 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]. An adaptive system in this latter sense, in addition to adapting the feed to the cutting force, must also adapt the AC controller to the changing parameters of the cutting process. Here we refer to such systems as "parameter adaptive systems," and they are discussed in detail in a subsequent section.

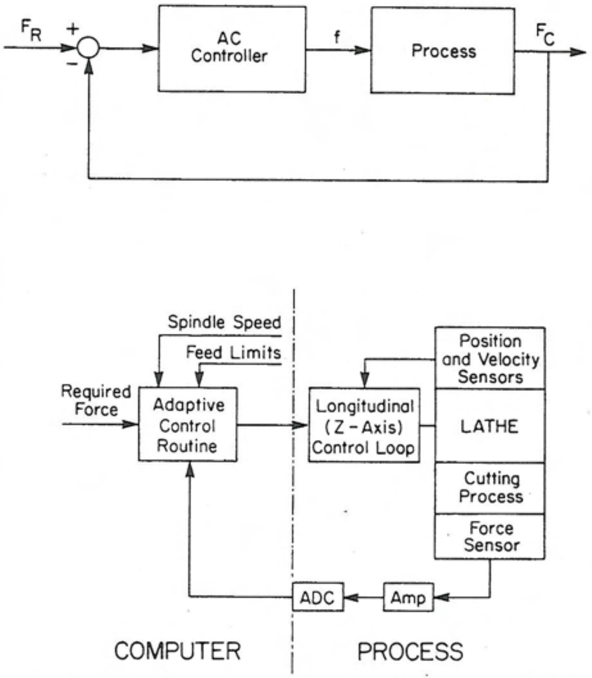

Fig. 1 Typical adaptive control system for turning. (*a*) The structure of the AC loop; (*b*) Hardware configuration.

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The most common applications of AC systems are for grinding, drilling, and milling [9–18]. There are numerous studies which have shown that AC systems can increase metal removal rates by 20–80 percent, as well as providing other benefits [9–23]. Despite their potential for improving productivity, and considerable research and development effort during the past 20 years, AC systems have not been widely accepted by industry [9–13]. Early AC systems, based on analog or hybrid technology, were costly and this initially hindered industrial acceptance. With the advent of CNC systems, AC can be implemented in software and sophisticated algorithms can be utilized. There are still, however, some impediments to the widespread use of AC systems in industry:

1) Studies indicate that for current industrial practice actual machining time comprises about 5–10 percent of the total production time [24]. Thus even significant reductions in machining time with AC systems have a minor impact on total production time.

2) There is a need for developments in sensor technology, so that accurate and reliable on-line measurement of a wide range of machining parameters is possible [9, 12–14, 25]. Particularly significant is the problem of tool wear and tool breakage detection.

3) Due to the variable nature of the machining process, there is a need to develop parameter adaptive systems which are stable and have good performance characteristics over the full range of operating conditions [26–33].

All three of these areas are currently receiving attention from researchers at universities and in industry. The purpose of this paper is to highlight some of the contributions to adaptive control during the past 20 years, focusing mainly on the third area cited above, and to briefly describe our current research program in this area at The University of Michigan.

Previous Research

Research and development efforts for adaptive control of machine tools have been underway since the early 1960's [4, 12, 37–40]. These research efforts were primarily concentrated in the U.S., West Germany, Italy, and more recently Japan and Israel [11, 26, 27, 40–47]. Early AC systems were implemented using hardware and many different approaches and strategies were developed [11, 12, 19, 40–43, 46, 48–54]. These efforts began bearing fruit in the late 1960's and early 1970's with the development of several commercial systems [4, 10–12, 19–21, 40, 55, 56].

While these early AC systems, which were used primarily in grinding, drilling, and milling operations [13–18], demonstrated significant increases in productivity, there were also many practical problems which discouraged industrial users [4, 10, 13, 55]. In particular, there were reliability problems, especially with sensors [12, 13, 19, 25, 30, 40]. Further, in any control application a good understanding of the controlled system is essential, and as Colwell and his colleagues point out [38], there is a lack of basic understanding of the cutting process itself. Recent advances in this area are reported in [57], particularly with regard to tool wear.

Attempts to mathematically define an economic performance index, and to optimize the machining process online met with limited success [38, 44, 58]. In light of the difficulties in formulating an index of performance and measuring all the required variables, perhaps these early ACO systems were too ambitious. Many types of AC systems have been proposed and tested, including dimensional correction loops based on inspection of the finished part [63, 64] and systems for controlling the tool wear rate [9, 38, 44, 53, 54, 59–62], minimizing tool-workpiece impact [31, 53, 62], and detecting and correcting for chatter [41, 42, 46, 65], etc. Successful AC applications in drilling and milling are mainly of the ACC type [4, 10, 13, 14], and in grinding of the ACO type [14, 15].

With the widespread acceptance of CNC systems during the past decade, the implementation of ACC systems has become more reliable and economical. For CNC drilling or milling systems the implementation of ACC requires only a torque or cutting force sensor and additional software. The low cost and reliability of microprocessors [64], and advances in sensing technology in recent years [25, 66] has made these systems much more attractive. Even with CNC systems it is not an easy task to incorporate an AC controller. It is desirable that CNC machine tools be designed to accomodate the possibility of adding sensors and modifying software for AC [13]. The main problem with the CNC/AC systems is with performance and stability. Since the cutting process is part of the control loop (as shown in Fig. 1), variations in the process parameters can lead to poor performance or even instability [26–31]. This problem is discussed further in the next section.

There is currently renewed interest in more complex AC systems using a hierarchical computer control structure [1, 30, 60, 61, 67]. This trend is in keeping with the general goals of integrating and automating design and manufacturing through the use of computer systems [64]. One can envision a computer controlled machine tool in the future with several levels of control, including the position and velocity control loops; ACC loops which maintain cutting forces and torque at desired levels; and additional control loops for tool wear rates, dimensional corrections, chatter, etc. Such complex hierarchical computer control systems can be implemented in a modular manner as our basic understanding of the machining process improves. These systems will be part of an even more complex automated system, which will include tool changing, parts handling, inspection, etc.

Parameter Adaptive Systems

Feedback control systems are intended to eliminate the effects of external disturbances acting on the controlled system or process. The term "adaptive control" in the control literature refers to the systems that attempt to eliminate the effects of changes in the controlled system itself, in addition to the effects of external disturbances acting on the system. An adaptive control system modifies the parameters of the controller, or generates an auxilliary control signal, in order to maintain some index of performance at a desired level despite changes in the controlled system (e.g., [5–8]). In the manufacturing literature, the term "adaptive control" is used in a much more general context and feedback control systems, such as shown in Fig. 1, are also termed adaptive. Groover [5] has discussed the differences between feedback and adaptive control systems and proposed a classification scheme for machine tool control systems. As stated previously, we refer to systems which adapt the AC controller to changes in the process parameters as parameter adaptive control systems.

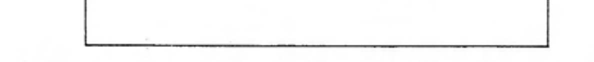

Fig. 2 Structure of a variable-gain AC system with explicit parameter estimation

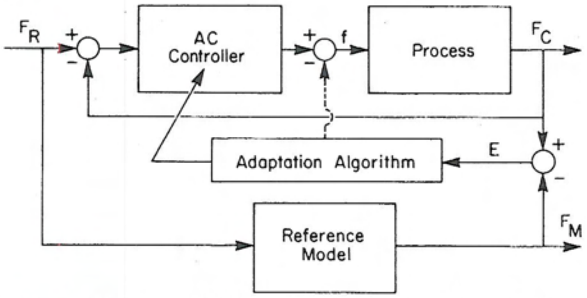

Fig. 3 Structure of an adaptive model following control system

Many researchers have recognized the need for parameter adaptive control systems, in order to achieve stability and good performance over a wide range of operating conditions [26-33]. During the past five years several researchers have reported various schemes for the implementation of parameter adaptive control systems for machine tools. Mathias [33] described a commercial AC system with "automatic gain control," where "the controller gain is automatically reduced at the onset of feedrate oscillations." Gieseke [32] reported an AC system with a PI controller where the P and I action gains are functions of the spindle speed. Weck [30] has described an AC system which uses digital logic to switch the controller gains based on the operating conditions. Stute [28, 29] has described two alternative schemes for controller gain adjustment. One uses a cutting process model to estimate the process gain and adjust the controller gain accordingly (see Fig. 2). The second scheme uses a digital PID algorithm whose gains are a function of the manipulated variable (feedrate). These parameter adaptive systems, however, all represent preliminary attempts at a practical solution and not a theoretically based design.

The most advanced work to date on parameter adaptive control systems for machine tools has been conducted by Masory and Koren [26, 27]. They have developed a variable-gain AC system for turning based on cutting force measurement and manipulation of the feedrate. Figure 2 shows the structure of their variable-gain system. By comparing this structure to that shown in Fig. 1 for a conventional AC system, we note that a parameter estimation block [34, 35] and a controller adaptation block have been added. The parameter estimation block provides estimates of the cutting process parameters which vary with depth-of-cut and spindle speed. The controller adaptation block uses the estimated parameter values to adjust the controller gain such that a desired constant value of the open-loop gain is maintained [26, 27]. Masory and Koren have theoretically and experimentally (using a 70HP CNC/AC lathe) verified the feasibility of a variable-gain AC system for turning. However, their work has also indicated the need for further studies. Specifically research is needed to:

1) Determine the best strategies and structure for parameter adaptive control.

2) Develop practical methods for the selection of adaptation parameters and sampling periods.

3) Evaluate selected designs (from #1 above) through actual machining tests.

Current Research

Our current research at The University of Michigan is aimed at the three tasks listed above. At present our research concentrates on the first task which requires the investigation of controller algorithms, parameter estimation algorithms, and controller adaptation algorithms for a variable-gain system such as shown in Fig. 2. Furthermore, other structures for parameter adaptive control, such as the Adaptive Model Following Control (AMFC) system shown in Fig. 3, will also be investigated. AMFC systems do not require explicit parameter estimation and use a reference model to specify the desired closed loop system characteristics [7, 8]. Such systems have been successfully applied to certain industrial problems, and extensive theoretical developments are available [7, 8, 36].

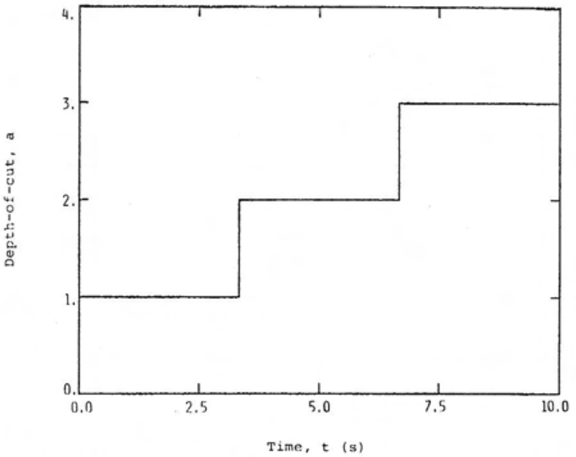

Fig. 4 Depth-of-cut versus time for simulation results in Figs. 6-12

The comparison of different candidate structures and algorithms, as well as methods for the selection of adaptation parameters and the sampling period, are best achieved through digital simulation and analytical methods. We are currently carrying out digital simulation studies of the variable-gain system in Fig. 2. Digital simulation and analytical studies will then be extended to other structures for parameter adaptive systems. Based on these studies, the most promising structures and strategies will be selected and studied in further detail. Finally, machining tests on an NC lathe and a CNC milling machine will be conducted for final evaluation of the selected design. These tests will utilize cutting force measurements and manipulation of the feedrates.

Digital simulation studies for the structure shown in Fig. 2 have shown excellent qualitative agreement with the experimental results in [26, 27]. Thus, these studies can be expected to provide useful information for evaluation and design. The simulation is based on the following equations for the turning process [26, 27],

$$\tau \dot{F}_c + F_c = K_p f \tag{1}$$

where F_c is the product of the actual cutting force and the sensor gain and the A/D converter gain; f is the feed; K_p is the process gain and depends on the depth-of-cut, the spindle speed, properties of the tool and workpiece, and the feed itself; and τ is the process time constant. The feed is related to the digital command signal (u) from the computer,

$$\ddot{f} + 2\xi\omega_n \dot{f} + \omega_n^2 f = K_s u \tag{2}$$

where ξ is the damping ratio, and ω_n is the natural frequency of the CNC servo-loop dynamics. K_s is the servo-loop gain. The adaptive controller uses an integral policy,

$$u = K_c \int_0^t (F_R - F_c)\, dt = K_c \int_0^t E\, dt \tag{3}$$

The process estimation is also based on an integral policy,

$$K_m = c_1 \int_0^t (F_c - uK_m)\, dt \tag{4}$$

where K_m is the model gain corresponding to K_p in equation (1). Finally, an integral policy is used for the controller gain adaptation,

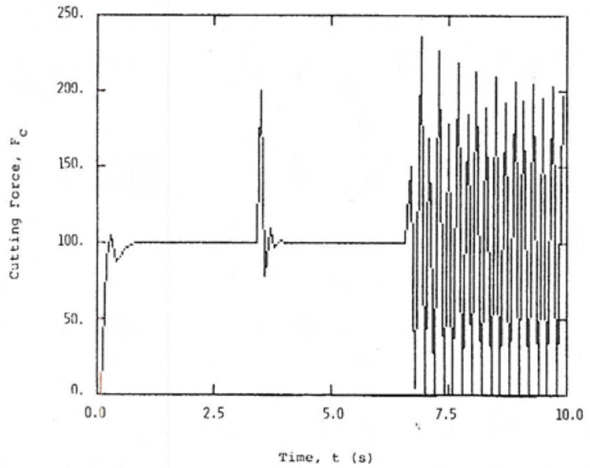

Fig. 5 Simulated force versus time for conventional AC system ($c_1 = 0.0, c_2 = 0.0$)

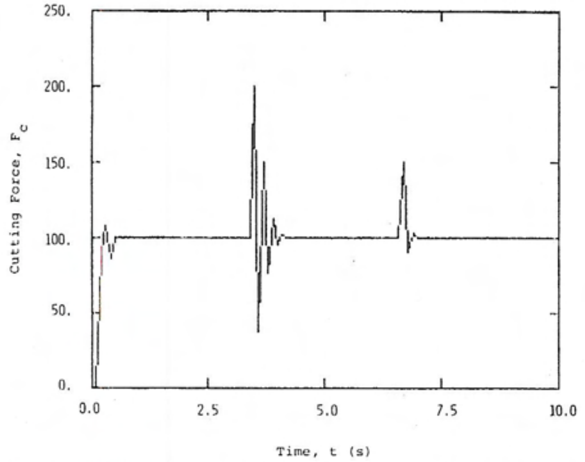

Fig. 6 Simulated force versus time for a variable-gain AC system with $c_1 = 0.001$ and $c_2 = 0.5$

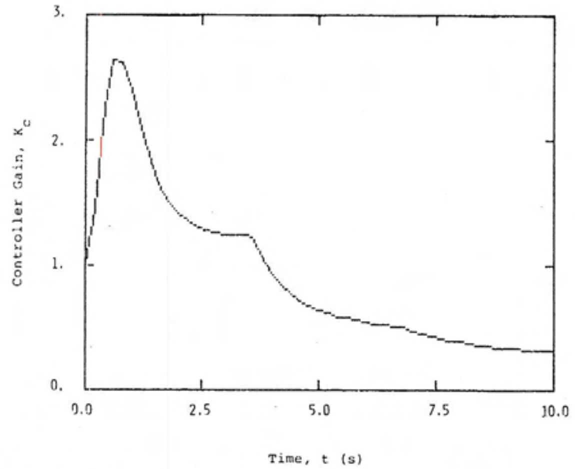

Fig. 7 Simulated controller gain versus time for a variable-gain AC system with $c_1 = 0.001$ and $c_2 = 0.5$

$$K_c = c_2 \int_0^t (K - K_o K_m)\,dt \tag{5}$$

where K is the desired value of the system open-loop gain which is selected based on stability and performance considerations. Although the simplest strategies have been employed, equations (1)–(5) lead to a sixth-order system of nonlinear equations, the analysis of which is not trivial. The effect of sampling is then accounted for to derive the corresponding difference equations on which the simulation results presented below are based. It should be noted that the cutting process model in equation (1) is intended for control system analysis and design, and does not attempt to describe the fundamental physical processes of a machining operation.

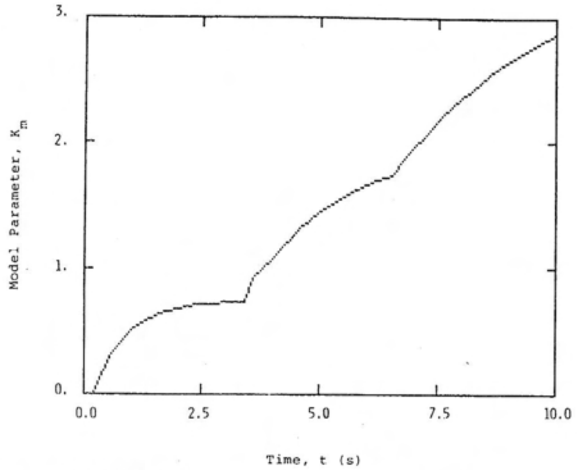

Fig. 8 Simulated model gain versus time for a variable-gain AC system with $c_1 = 0.001$ and $c_2 = 0.5$

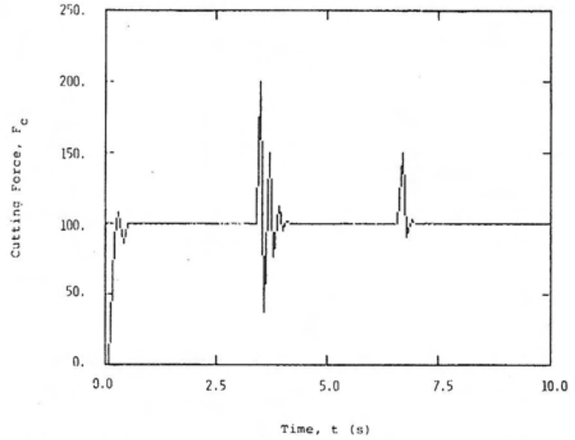

Fig. 9 Simulated force versus time for a variable-gain AC system with $c_1 = 0.015$ and $c_2 = 0.1$

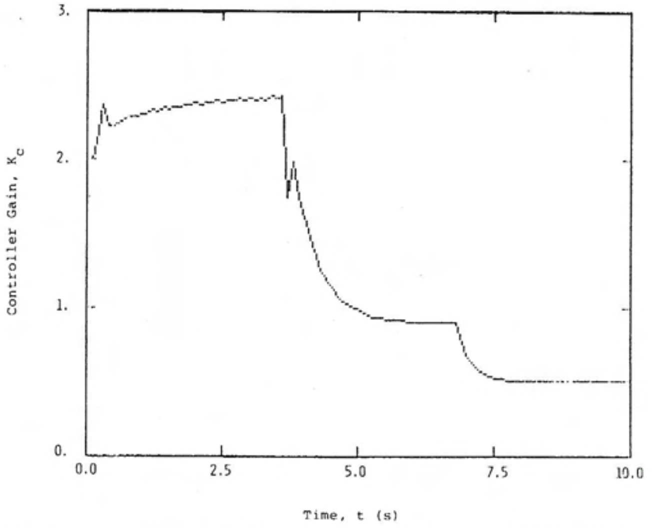

Fig. 10 Simulated controller gain versus time for a variable-gain AC system with $c_1 = 0.015$ and $c_2 = 0.1$

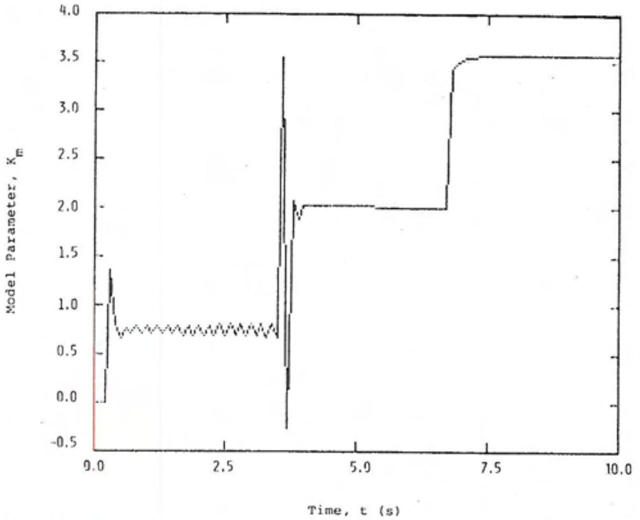

Fig. 11 Simulated model gain versus time for a variable-gain AC system with $c_1 = 0.015$ and $c_2 = 0.1$

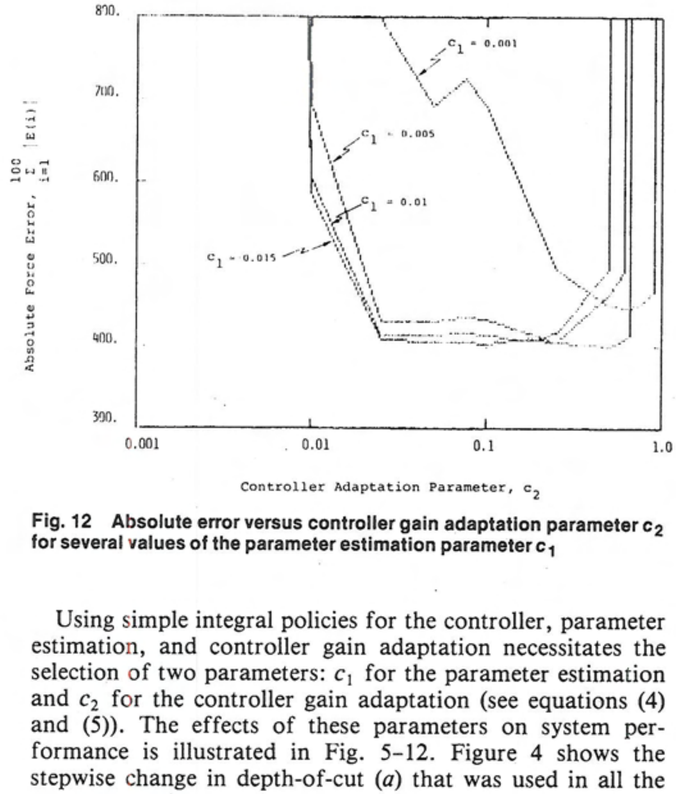

Fig. 12 Absolute error versus controller gain adaptation parameter c_2 for several values of the parameter estimation parameter c_1

Using simple integral policies for the controller, parameter estimation, and controller gain adaptation necessitates the selection of two parameters: c_1 for the parameter estimation and c_2 for the controller gain adaptation (see equations (4) and (5)). The effects of these parameters on system performance is illustrated in Fig. 5–12. Figure 4 shows the stepwise change in depth-of-cut (a) that was used in all the simulation results presented in Figs. 5–12. The sampling period used was $\Delta t = 0.1$ second in all cases. Figure 5 shows the cutting force response for the conventional AC System in Fig. 1 (i.e., $c_1 = c_2 = 0$). The system is seen to be unstable at large depths-of-cut. This instability is remedied by using the variable-gain approach. Figure 6 shows the cutting force response with $c_1 = 0.001$ and $c_2 = 0.5$. The system is now stable, and Figs. 7 and 8 show how the controller gain (K_c) and estimated process gain (K_m) are varied to achieve this improved performance. Another simulation with a larger c_1 and smaller c_2 is also presented in Figs. 9–11. Figure 9 shows the cutting force response with $c_1 = 0.015$ and $c_2 = 0.1$. The cutting force response is again stable and, as shown in Fig. 10, the controller gain (K_c) is adapted to the changing depth-of-cut in the process. Figure 11, however, shows that the estimation of the model gain (K_m) is beginning to exhibit instability at low depths-of-cut.

The effects of the parameters c_1 and c_2 on system performance is illustrated in Fig. 12, where the absolute force error criterion is plotted versus c_2 for several values of c_1. Small values of c_1 and c_2 lead to poor performance and instability. This is to be expected since the variable-gain nature of the system is lost and the system behavior approaches that shown in Fig. 5. Poor performance and instability also results with large c_1 and c_2 values. There is, however, a region of c_1 and c_2 values for which good performance is obtained. The designer of the AC system must select the c_1 and c_2 values within this region in order to ensure stability and satisfactory performance of the entire AC/CNC system. It is clear that practical methods for the selection of adaptation parameters and sampling period must be established if parameter adaptive AC/CNC systems are to find widespread industrial acceptance.

Summary and Conclusions

We have described the principal developments over the past two decades in adaptive control of machine tools. 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 parameter adaptive control strategies are required. These developments must be complemented by progress in more efficient methods for part handling, tool changing, etc. We have highlighted our current research on the development of truly adaptive control systems for machine tools.

In conclusion, we note that:

1) AC systems can have a major impact on productivity, particularly in conjunction with developments in the non-machining parts of the production cycle.

2) AC systems must be reliable and easy to implement if they are to achieve industrial acceptance. Thus the requirements of AC systems must be considered in the design of the machine tool and the CNC controller.

3) Reliable sensors, particularly for the state of wear of the tool, must be developed for the hostile machining environment.

4) AC systems can have many objectives, such as increasing metal removal rates, maintaining a desired tool wear rate, or detecting and eliminating chatter, and these can involve several levels of control. Simple and effective strategies should be applied initially and more advanced schemes incorporated in a modular manner as they are tested and proven.

5) The design of parameter adaptive systems is complex. Even simple strategies, such as described here, require the solution of a high-order system of nonlinear difference equations. The investigation of more comprehensive strategies and methods are required to obtain good performance over a wide range of cutting conditions.

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