VARIABLE GAIN ADAPTIVE CONTROL SYSTEMS FOR MACHINE TOOLS

by

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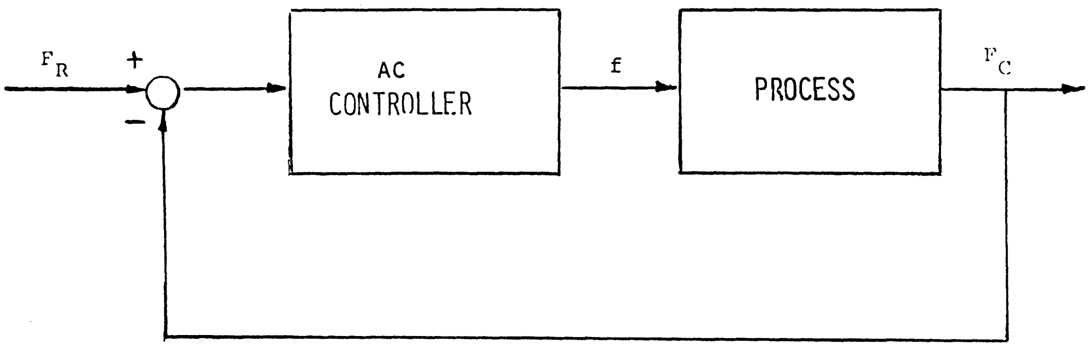
PROGRAM OBJECTIVES: Computer Numerically Controlled (CNC) machine tools are gaining widespread acceptance in industry. With CNC machine tools the specification of the operating parameters (i.e., feeds and speeds) is left to the experience and judgement of the part programmer, who tends to select conservative values, and consequently reduce production rates. Adaptive control (AC) systems are aimed at providing an additional level of control to automatically adjust operating parameters on-line so as to maximize metal removal rates (MRR). AC systems, however, are not widely used in practise due to the following factors:

(i) A lack of detailed understanding of the machining process.
(ii) Reliability problems with sensors and other hardware associated with AC systems.
(iii) Machining time may comprise as little as 5% of the total production time, thus, increases in MRR do not have a significant impact on production rates without significant improvement in tool changing, parts handling, etc.
(iv) Performance and stability problems associated with AC systems due to the variable nature of the machining process.

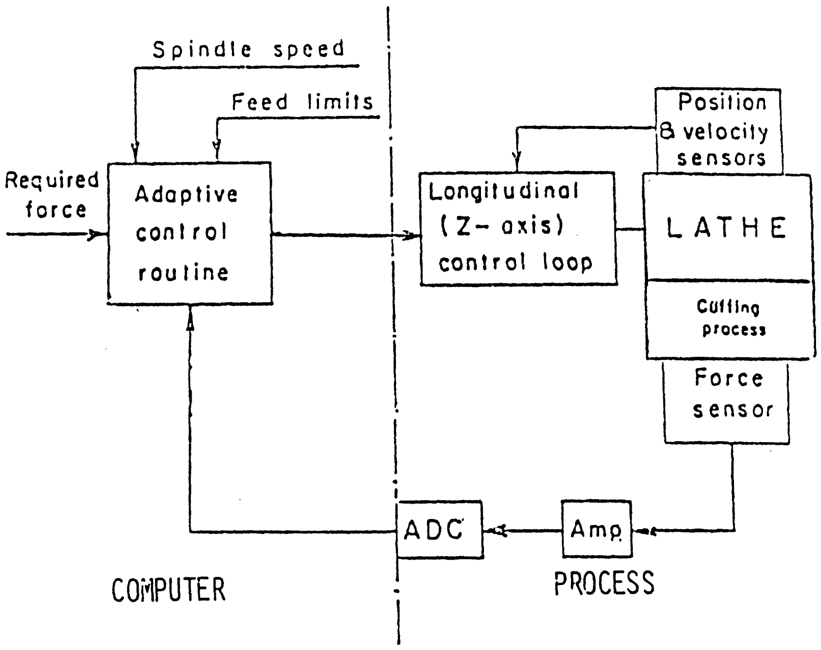
The objective of our program is to address the last problem through the development of high performance, stable AC systems. Specifically our goals are:

(i) To design a variable-gain or parameter adaptive AC system which will adapt the AC controller to the changing process parameters and ensure stability and good performance over the full range of machining operations.
(ii) To develop a laboratory system to evaluate the variable-gain AC controller through machining tests on an NC lathe and CNC milling machine.

PROGRAM ACHIEVEMENTS (9/81 to 8/82): During the first year of our program, we have made progress in both the theoretical and experimental studies required to achieve the above stated goals.



(a) The Structure of the AC Loop



(b) Hardware Configuration

Figure 1. Conventional Adaptive Control System for Turning.

Theoretical Studies: We began our theoretical investigation by reviewing the literature pertinent to AC systems for machine tools, and through digital simulation studies of a candidate Variable-gain AC system. These studies have been presented in the two papers listed in the "Documents" section and are summarized below.

Typically AC systems for machine tools are classified into two types [1-3]:

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., cutting speed or feedrate) subject to process and system constraints (e.g., allowable cutting force). ACC Systems do not use a performance index.

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 [4-7]. 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."

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 [23-29]. Mathias [29] described a commercial AC system with "automatic gain control", where "the controller gain is automatically reduced at the onset of feedrate oscillations." Gieseke [28] reported an AC system with a PI controller where the P and I action gains are functions of the spindle speed. Weck [26] has described an AC system which uses digital logic to switch the controller gains based on the operating conditions.

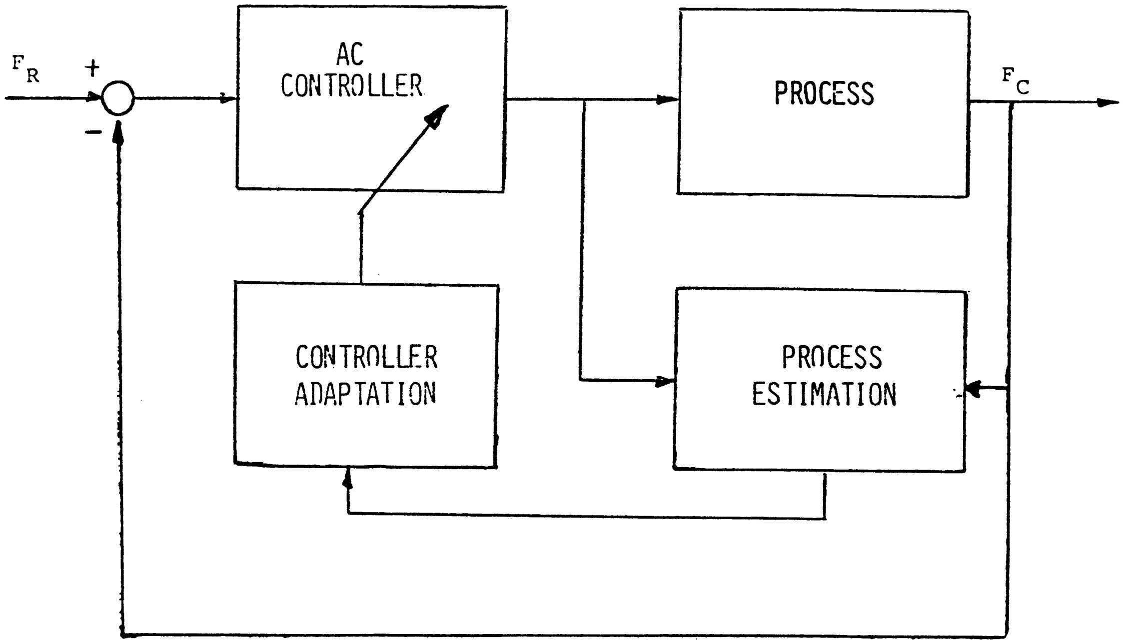


Figure 2 Structure of a Variable-Gain AC System with Explicit Parameter Estimation

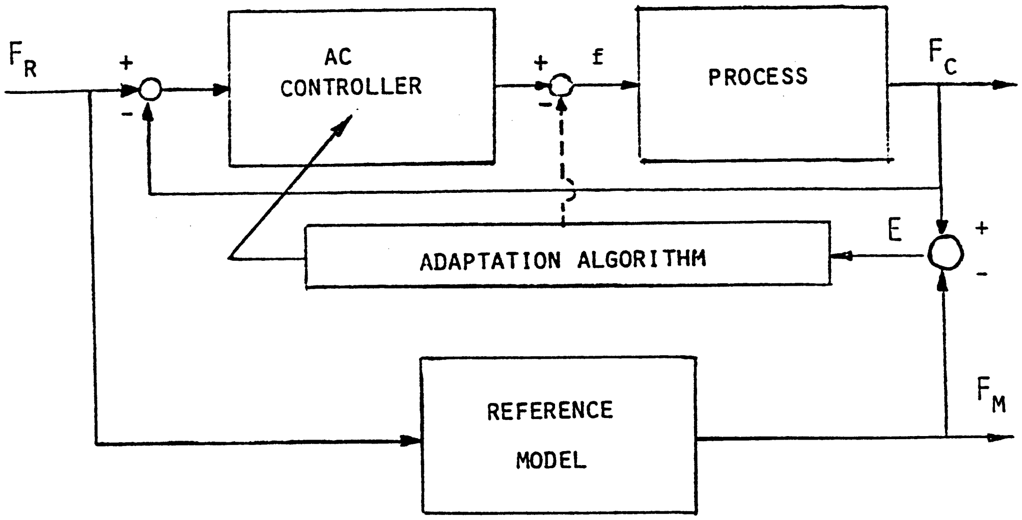


Figure 3 Structure of an Adaptive Model Following Control System

Stute [25] 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 reported by Masory and Koren [23,24]. They have developed a variable-gain AC system for turning based on cutting force measurement and manipulation of the feedrate. Fig. 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 [30,31] 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 [23,24]. Masory and Koren have theoretically and experimentallly (using a 70HP CNC/AC lathe) verified the feasibility of a veriable-gain AC system for turning.

Our current project is aimed at extending the work of Masory and Koren by conducting further studies 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.

To date we have concentrated on the first task which requires the investigation of controller algorithms, parameter estimation algorithms, and controller adaption algorithms for a variable-gain system such as shown in Fig. 2 Other structures for parameter adaptive control, such as the Adaptive Model Following Control (AMFC) system shown in Fig. 3, will be investigated in the near future [6,7,32].

Digital simulation studies for the structure shown in Fig. 2 have shown excellent qualitative agreement with the experimental results in [23,24]. 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 [23,24],

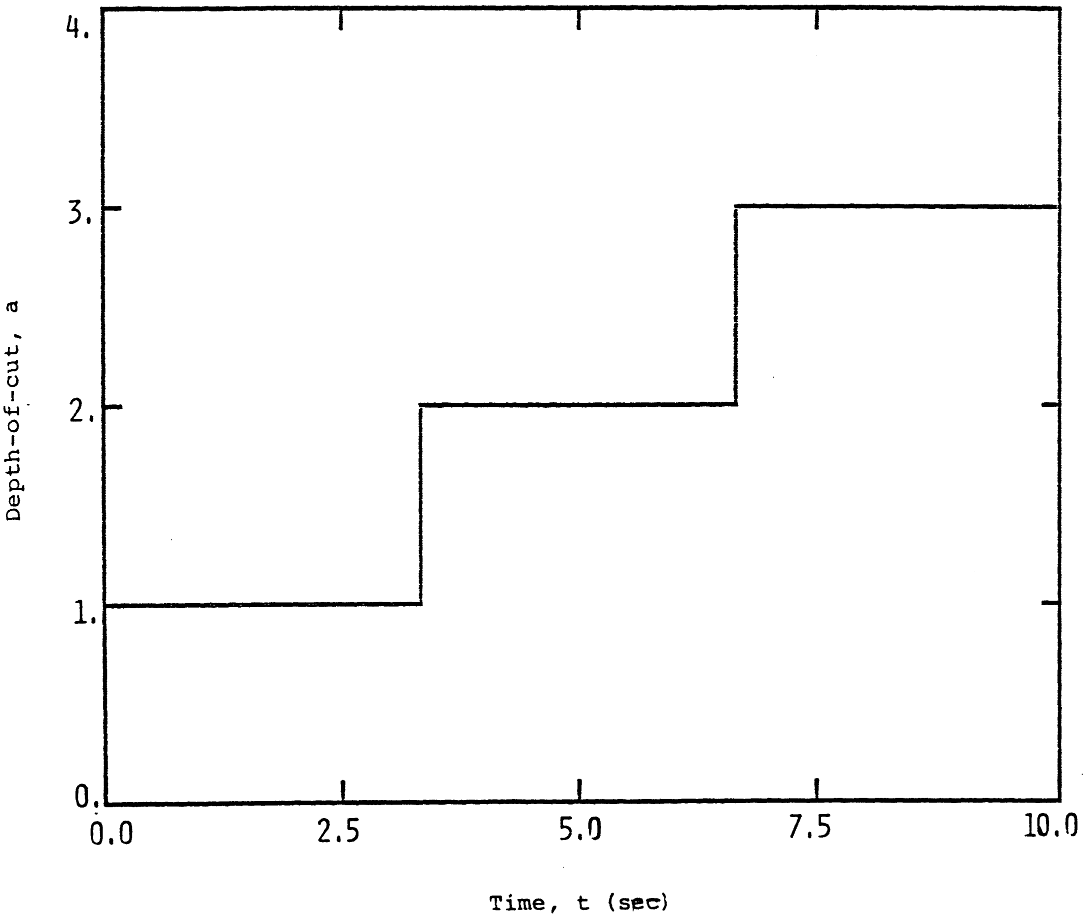


Figure 4 Depth-of-Cut versus Time for Simulation Results in Figs. 6-12

$$\tau\dot{F}_c + F_c = K_p f \qquad (1)$$

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,

$$\ddot{f} + 2\xi w_n\dot{f} + w_n^2 f = K_s u \qquad (2)$$

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

$$u = K_c \int_0^t (F_R-F_c)dt = K_c \int_0^t E\ dt \qquad (3)$$

The process estimation is also based on an integral policy,

$$K_m = c_1 \int_0^t (F_c-uK_m)dt \qquad (4)$$

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

$$K_c = c_2 \int_0^t (K-K_cK_m)dt \qquad (5)$$

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 Eq. (1) is intended for control system analysis and design, and does not attempt to describe the fundamental physical processes of a machining operation.

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 Eqs. (4) and (5)). The effects of these parameters on system performance is illustrated in Fig. 5-12. Fig. 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

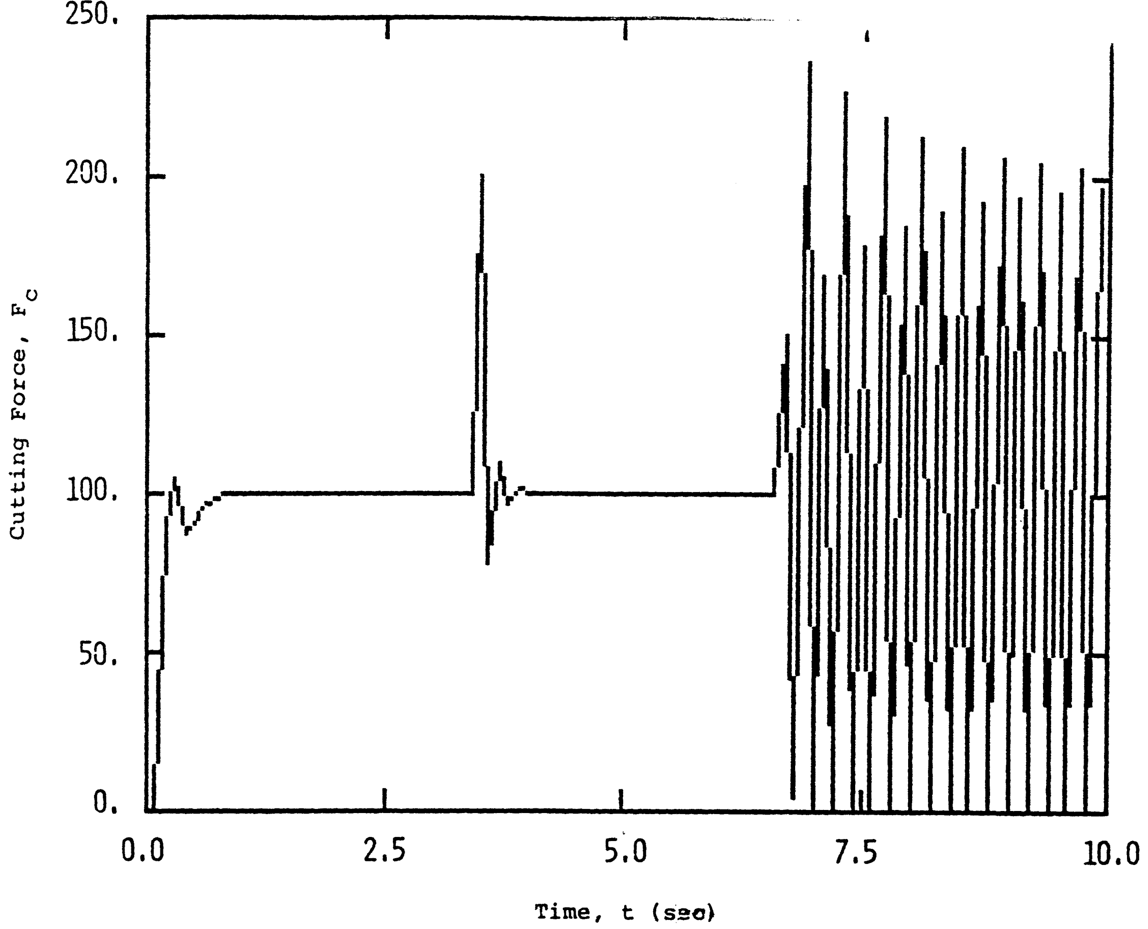


Figure 5 Simulated Force versus Time for Conventional AC System (c_1 = 0.0, c_2 = 0.0)

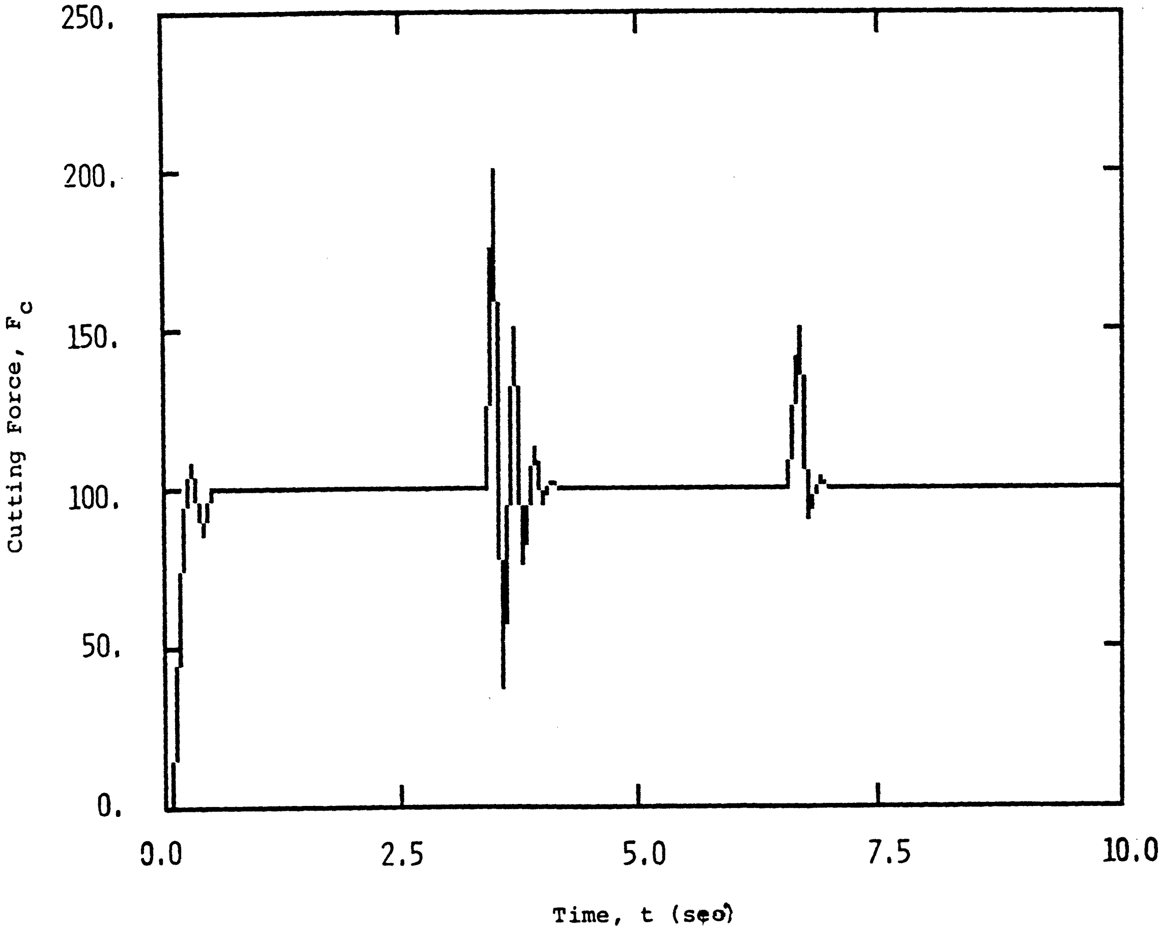


Figure 6 Simulated Force versus Time for a Variable-Gain AC System with c_1 = 0.001 and c_2 = 0.5

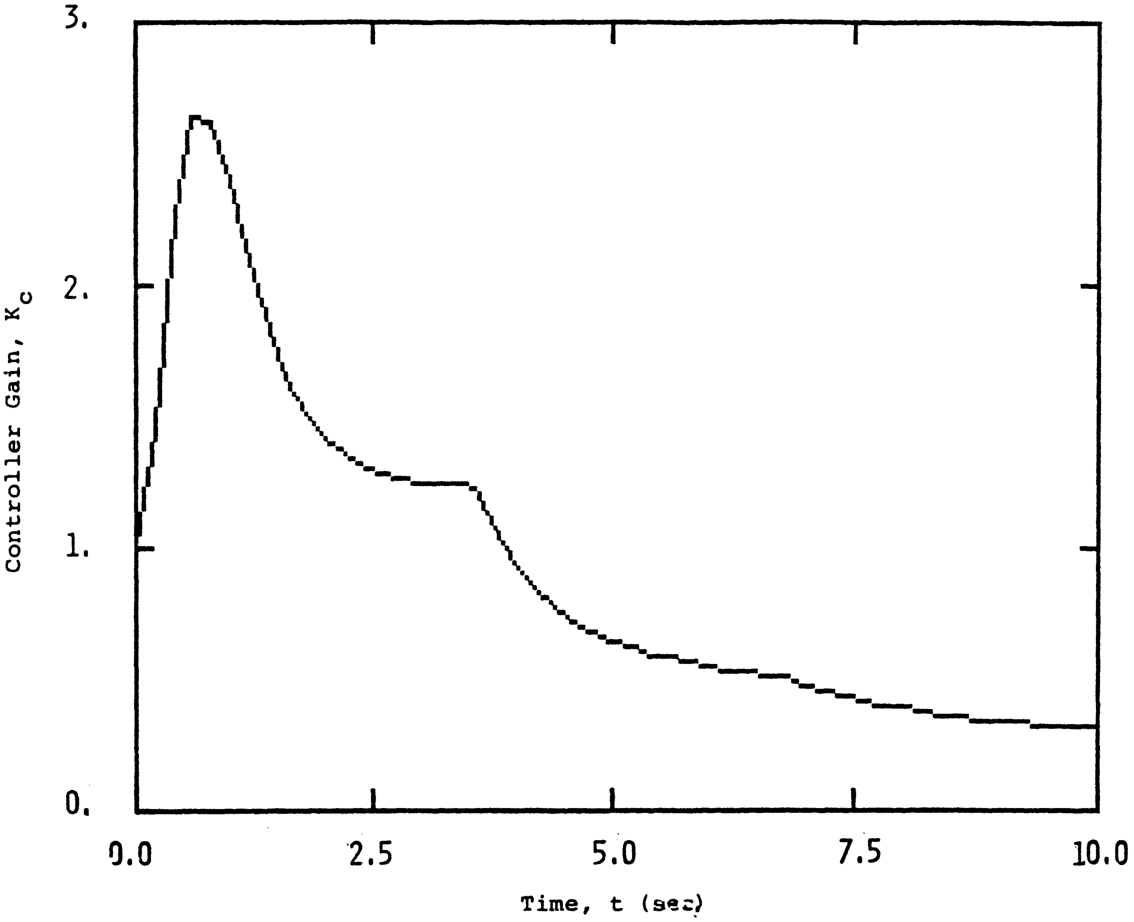


Figure 8 Simulated Model Gain versus Time for a Variable-Gain AC System with $c_1 = 0.001$ and $c_2 = 0.5$

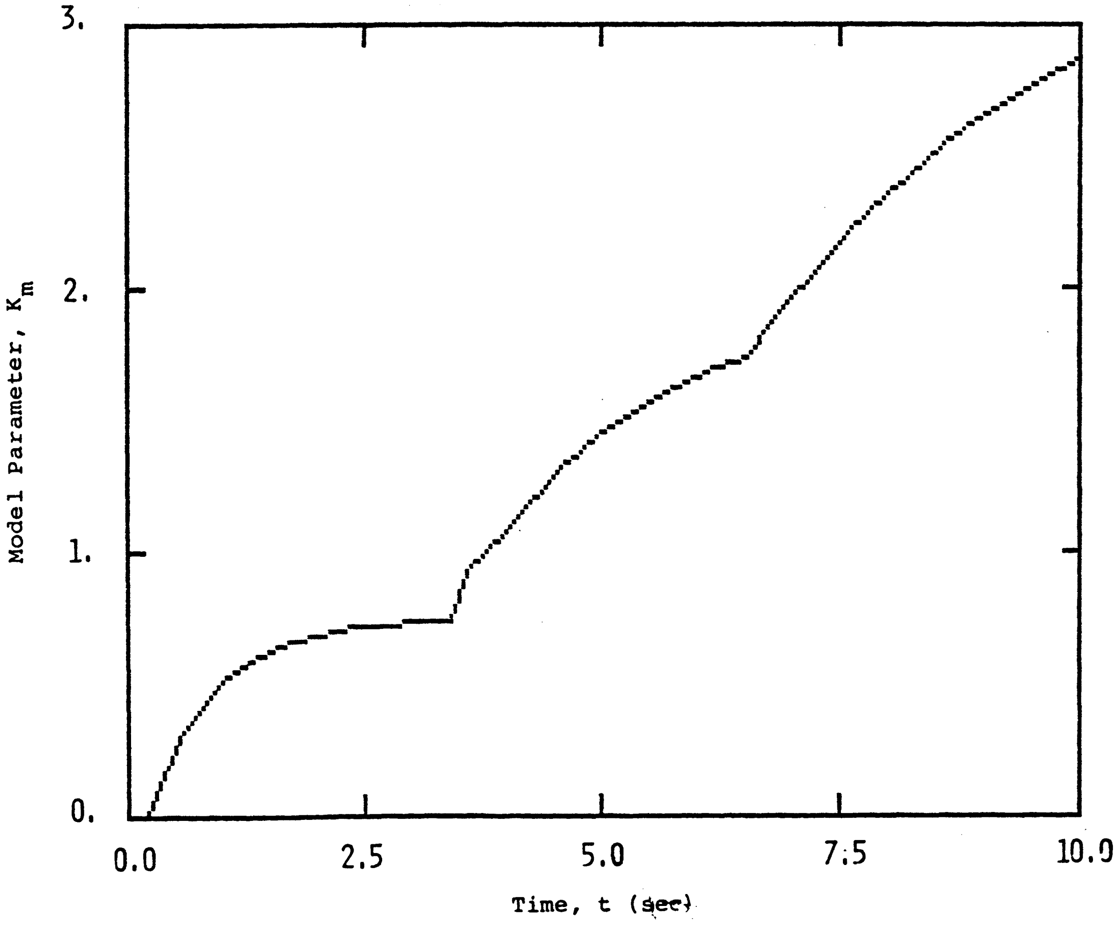


Figure 8 Simulated Model Gain versus Time for a Variable-Gain AC System with $c_1 = 0.001$ and $c_2 = 0.5$

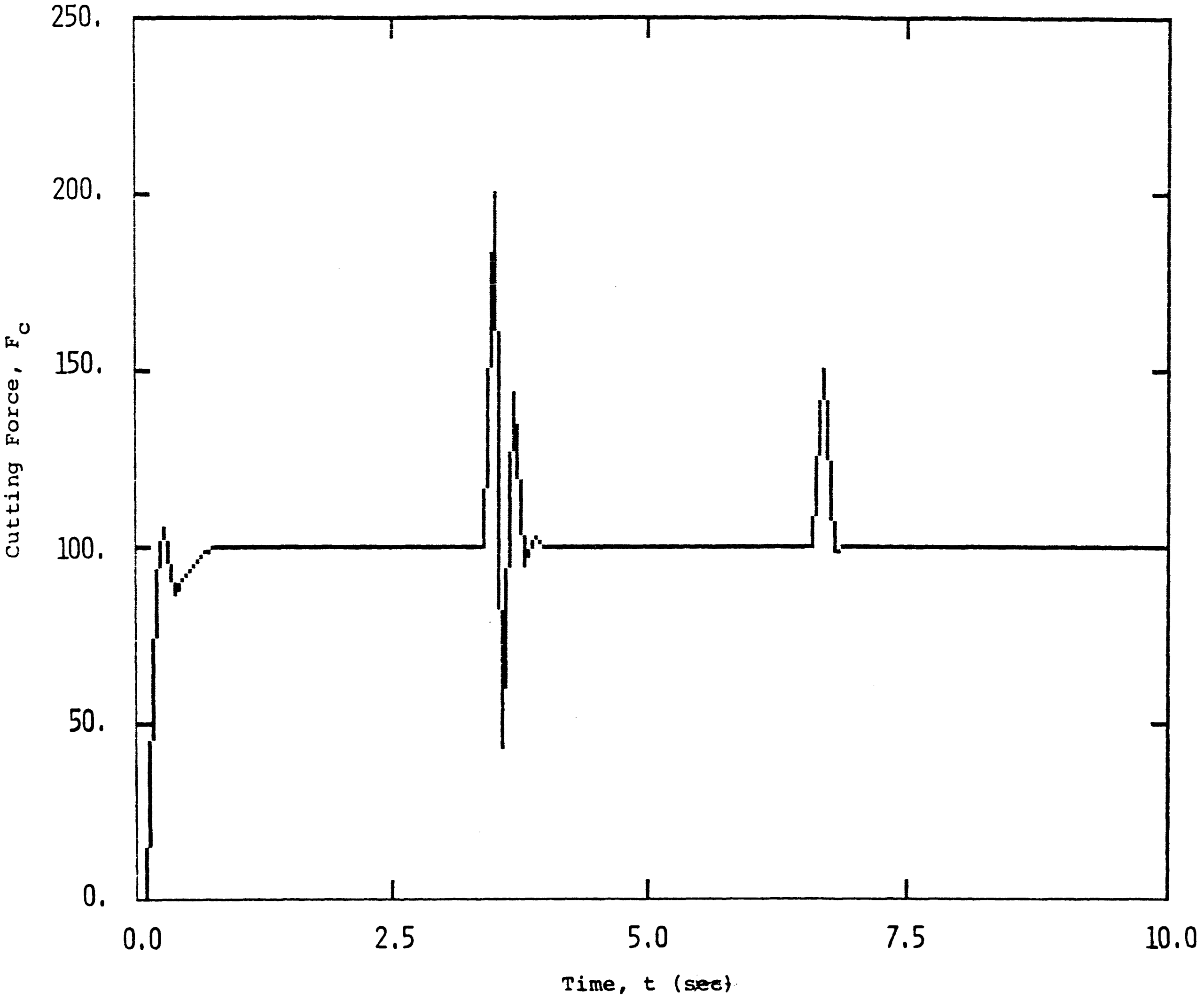


Figure 9 Simulated Force versus Time for a Variable-Gain AC System With c_1 = .015 and c_2 = 0.1

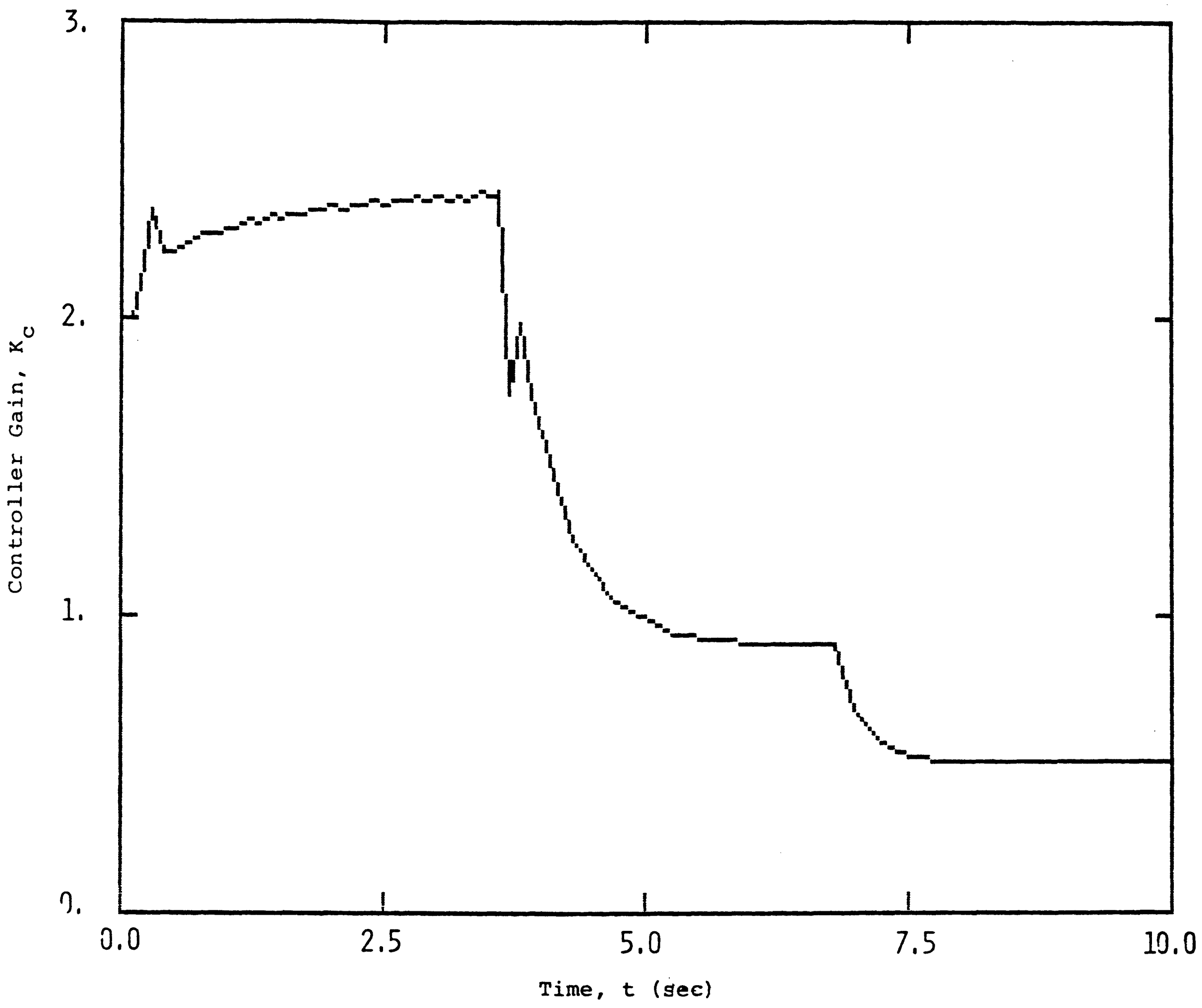


Figure 10 Simulated Controller Gain versus Time for a Variable-Gain AC System with c_1 = .015 and c_2 = 0.1

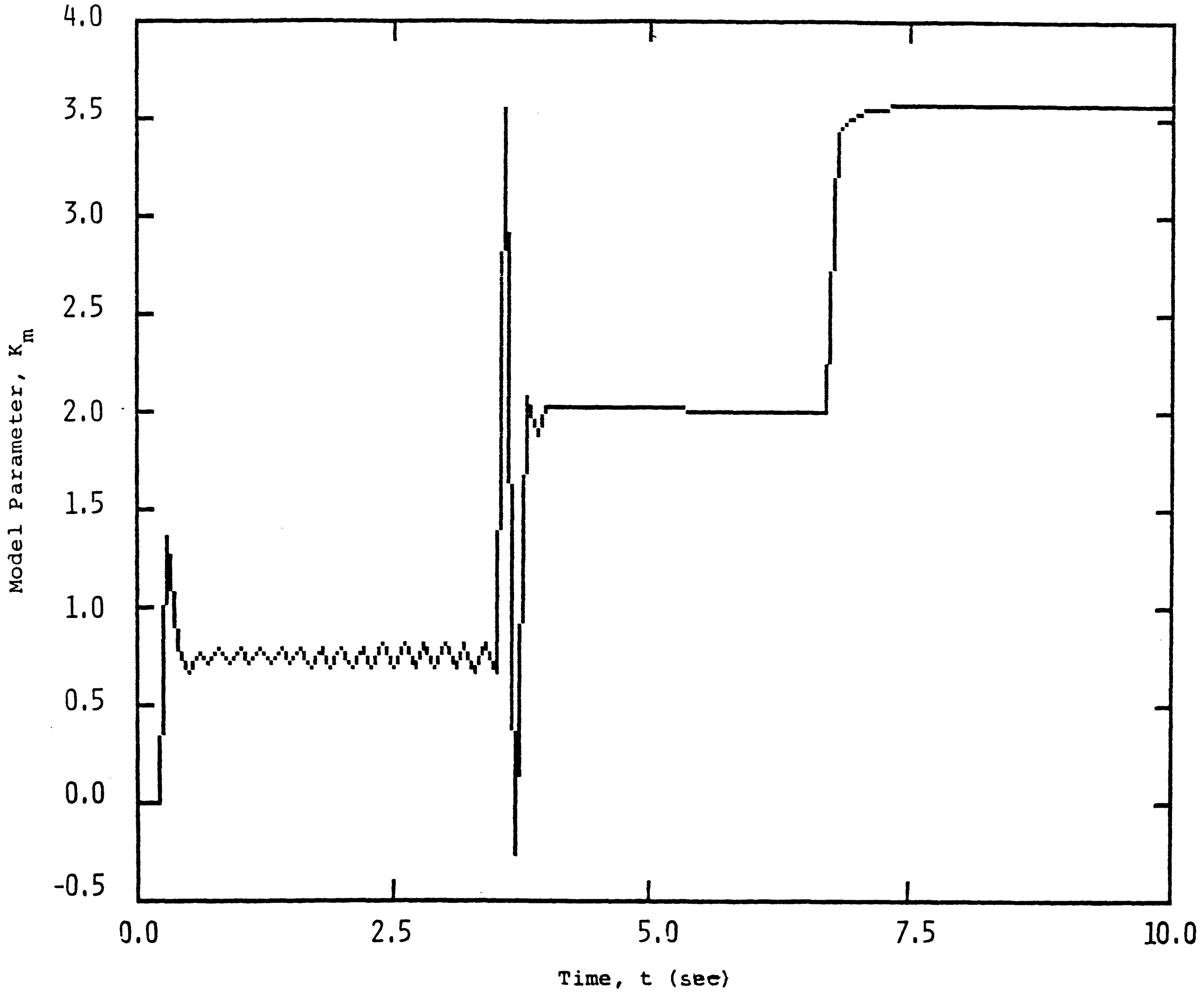


Figure 11 Simulated Model Gain versus Time for a Variable-Gain AC System with $c_1 = .015$ and $c_2 = 0.1$

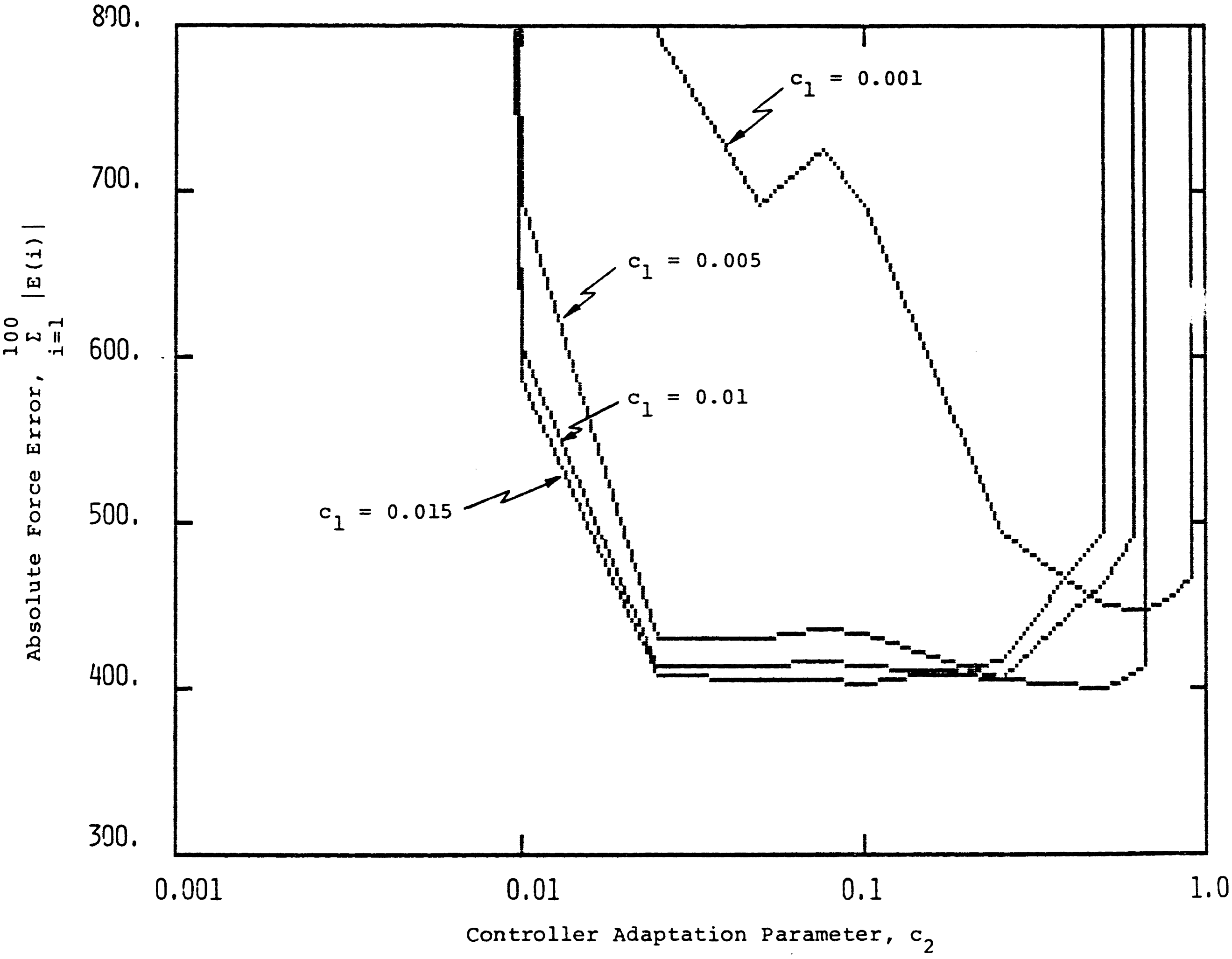


Figure 12 Absolute Error versus Controller Gain Adaptation Parameter c_2 for Several Values of the Parameter Estimation Parameter c_1

period used was $\Delta t = 0.1$ second in all cases. Fig. 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. Fig. 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. Fig. 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. Fig. 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.

Experimental Studies: During the past year, we have assembled the equipment necessary to undertake the proposed experimental studies. A PDP-11/23 laboratory computer system, complete with analog-to-digital converters, digital-to-analog converters, programmable clock, and digital (parallel) input-output ports, has been purchased. The computer system is equipped with the usual peripherals (CRT, disk drives, and printer), and has the following software systems available: (i) RT-11 operating system with MACRO assembler and FORTRAN, and (ii) UCSD P-system operating system with UCSD Pascal and FORTRAN '77. This computer system will be used to implement the variable-gain AC controller on both a LeBlond NC Lathe and a Bridgeport CNC milling machine, which are available in our departmental laboratories.

The interfacing of the computer system to the machine tools requires cutting force and/or power sensors which provide the feedback to the computer from the cutting process. The

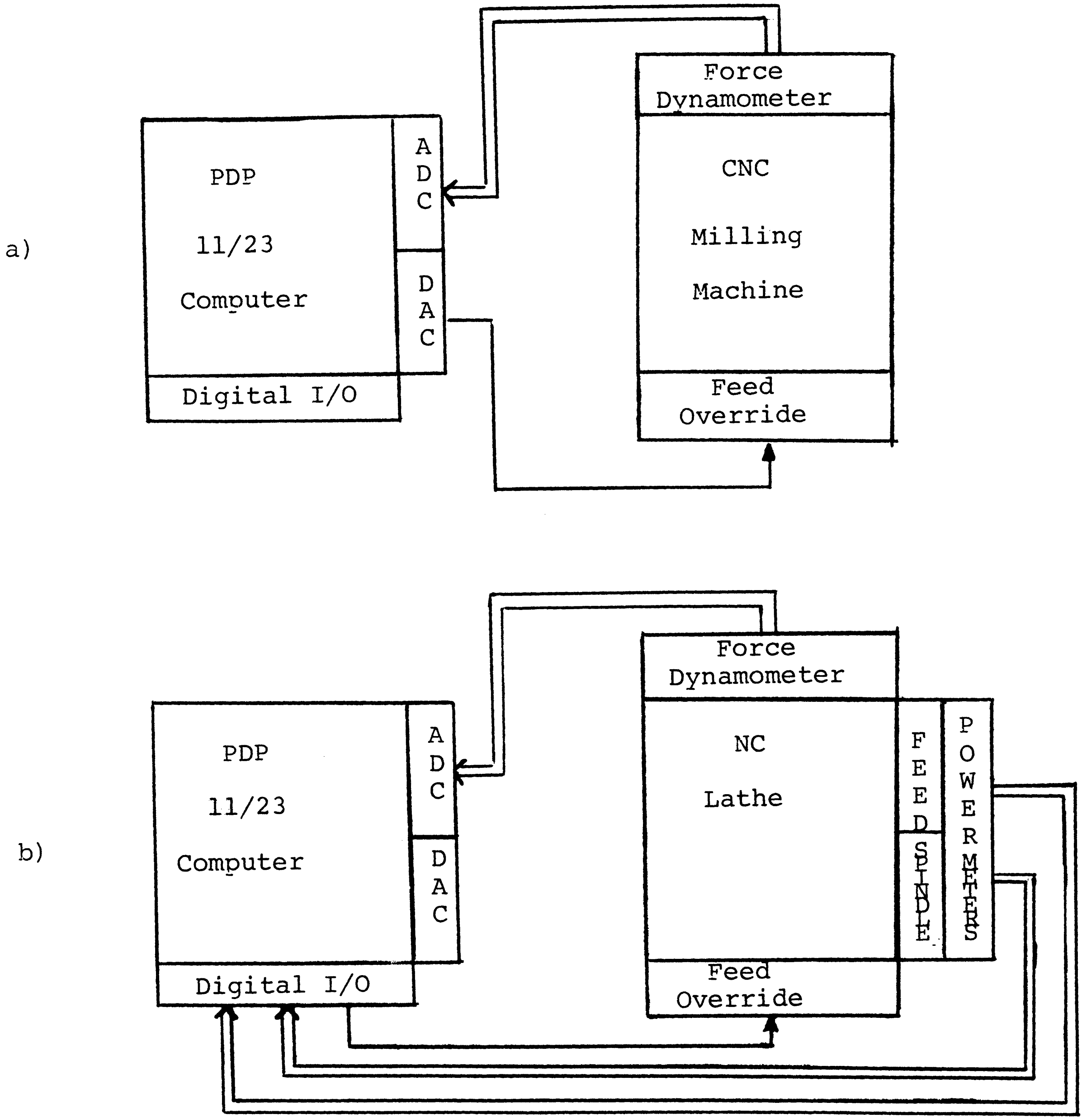


Figure 13 Schematic of Laboratory System for
a) CNC Milling Machine, and
b) NC Lathe

computer manipulates the feedrate on the machine tools through the feedrate override circuits. The experimental systems are illustrated schematically in Fig. 13. Note that both cutting force and power signals are available as feedback signals on the NC Lathe system, and their relative usefulness for AC will also be investigated. Due to the feedrate override electronics on the NC lathe, the feedrate cannot be continously adjusted. It can be adjusted in discrete steps of 15% of the full programmed feedrate from 0% to 150%. Also note that a power monitor is not used on the CNC mill, since the mill feed drives are stepping motors. The feedrate on the CNC mill can be continously adjusted in the range 0% to 150% of the full programmed feedrate.

While the required computer-machine tool interfaces, as described above, are essentially complete, they have not been tested. In the coming months we will be testing the system, developing the required software modules, and designing the required machining tests. The machining tests will be designed to evaluate,

(i) The comparative performance of conventional versus variable-gain AC systems.
(ii) The performance of variable-gain AC systems for widely varying tool-workpiece properties.
(iii) The relative advantages of cutting force sensors versus power monitors as the feedback element in a variable-gain AC system for turning.

We expect to begin our machining tests on the CNC mill during the summer of 1983, and to conduct machining tests on the NC lathe during the Fall of 1983.

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OBJECTIVES FOR THE NEXT YEAR (9/82 to 8/83)

The program objectives for the next year are:

1) To continue analytical and simulation studies of candidate controller designs. Specifically we will investigate an Adaptive Model Following Controller (AMFC) design, stability requirements, methods for selecting adaptation parameters, and methods for selecting the sampling frequency.
2) To develop the required software on the PDP-11/23 system. Specifically we will develop programs to test the interfaces that have been completed, to implement the AC on the milling machine, and to compare different AC strategies. Required modifications to implement the AC on the lathe will be started in August 1983.
3) To conduct a series of machining tests on the CNC milling machine. These tests will involve conventional AC controllers as well as candidate parameter adaptive AC controllers. Several different tool and material combinations will be tested. These tests will provide the results required for comparison between conventional and parameter adaptive AC strategies.

DOCUMENTATION

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