Variable Gain Adaptive Control System for Turning

Oren Masory, Texas A&M University, College Station, Texas
Yoram Koren, Technion, Israel Institute of Technology, Haifa, Israel

Abstract

Adaptive control as applied to machine tool systems refers to control of the operating parameters based on measurement of the process characteristics. Even the simplest adaptive control system with feedrate control based on cutting force measurements, is quite complex. The adaptive control loop is of a sampled-data nature with a nonlinear variable gain which depends on the operating parameters themselves. Experiments have shown that an operating computer numerical control/adaptive control system can become unstable due to changes in depth-of-cut or spindle speed.

The purpose of the present paper is to demonstrate a new design method for machine tool adaptive control systems. The proposed method is based on simultaneous estimation of process parameters and control of the cutting process. The parameter estimation is based on available measurements of the cutting force. The estimator is used to modify the adaptive control controller gain in real-time in order to achieve an effective and stable system.

Keywords: Adaptive Control, Variable Gain Controllers, Numerical Control, Machine Tools, Computerized Systems.

In the past decade the number of computerized numerical control (CNC) systems has grown tremendously in almost every field of manufacturing. A common drawback of most of these systems is that their operating parameters such as speeds or feedrates are prescribed either by a part programmer and consequently depends on his experience and knowledge[1] or by a relatively static database. In order to preserve the tool even under the most adverse conditions (which in reality will seldom occur), the part programmer prefers to select conservative values for the operating parameters which consequently slow down the system's production.

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 that are based on automatic control of the operating parameters, using measurements of the machining process characteristics. Adaptive control systems for machine tools can be classified into two categories: (1) adaptive control optimization (ACO), and (2) adaptive control constraints (ACC). Adaptive control optimization refers to systems in which a given index of performance (usually an economic function) is extremized subject to constraints. With adaptive control constraints, the machining parameters are maximized such that the system always operates on a specified constraint. The constraint will normally arise because of the physics of the process, the performance of the machine tool, the control system, etc.

Although there has been considerable research on the development of ACO systems[2-6] hardly any of these systems are used in practice. The major problems with such systems have been difficulties in defining realistic indexes of performance and the lack of suitable sensors which can reliably measure the necessary parameters on-line in a production environment.

Practically all the AC systems which are used in production today[7-12] are of the ACC type and seldom involve the control of more than one operating parameter.[13] Similarly, the main objective of the ACC system in the present paper is to increase the productivity of a machine tool in rough cutting by applying the highest feedrates compatible with a maximum allowable cutting force. What is novel in the present force-constrained AC system is the use of bilevel adaptive control, whereby the gain of the control loop, as well as the feed, is also adapted to the cutting process. It is demonstrated that this approach provides more stable operation, especially when wide variations in the machining parameters are encountered.

Adaptive Control Loop

The AC system shown in *Figure 1* is basically a force feedback loop where the feed, f, adapts itself to the actual cutting force F, and varies according to changes in work conditions as cutting proceeds. The AC loop functions in a sampled-data mode. The actual cutting force component is sampled every T seconds (typically $T = 0.1$ seconds) and converted to a digital signal F_c which is immediately compared in the computer with a predetermined allowable reference force F_r. The difference between the F_r and F_c is the force error:

$$E(i) = F_r(i) - F_c(i)$$

where:

the index (i) indicates the i^{th} sampling.

The error E is used as the input to the AC controller which sends a correction signal to the feedrate routine contained in the CNC control program. A positive difference increases the programmed feedrate and consequently increases the actual force, thereby decreasing the error E, and vice versa.

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

$$W(i) = W(i\text{-}1) + TE(i) \qquad (1)$$

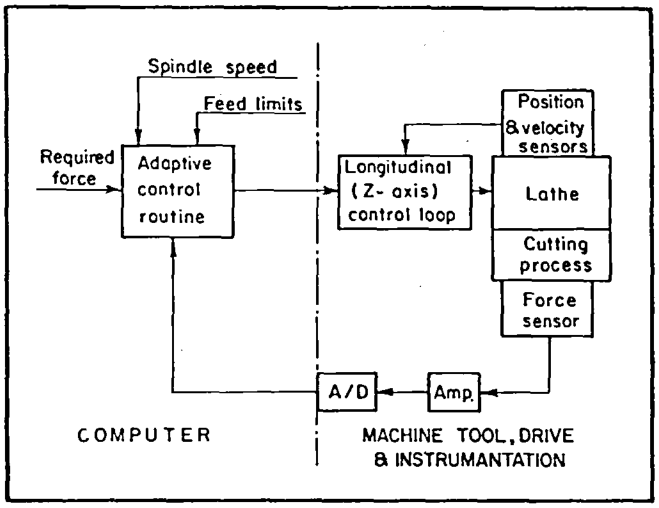

Figure 1
Adaptive Control System for a Lathe

and then:

$$U(i) = K_c' W(i) \qquad (2)$$

Eqs. (1) and (2) can be combined into a more efficient form for programming:

$$U(i) = U(i\text{-}1) + K_c E(i) \qquad (3)$$

where:

K_c is a constant ($K_c = TK_c'$ denoted as the controller gain.

As long as there is an error, the command U varies the machine feedrate so as to correct this error. At the steady state, however, the error in the force is zero, causing the condition $U(i) = U(i\text{-}1)$, which means that the feedrate command is constant, maintaining the actual force equal to the reference one.

The selection of the gain K_c is critical to the operation of the AC system. For type 0 and type 1 systems, 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 with a mechanically stable system always becomes zero.

The Stability Problem

The main research efforts in ACC systems have been devoted to the problem of eliminating chatter[14,15] and to the determination of the programmed constraints, such as cutting power,[16] or force.[17,18] Experimental work has demonstrated that a proper selection of the controller gain K_c is very critical if wide variations in depth-of-cut, feed, and spindle speed are permitted in the system.[19,20] The reason is that in the AC system, as is shown in *Figure 1*, the cutting process itself is part of the control loop. Therefore, variations in the process directly affect the control parameters of the loop, and consequently the AC system might become unstable.

Experimental results demonstrating this stability problem are shown in *Figures 2* and *3*. For these experiments, the controller gain was $K_c = 0.5$ and the sampling period $T = 0.1$ second. As seen in *Figure 2*, the feed before engagement was selected at 0.5 mm/rev. At the start of cutting, the feed is immediately reduced to approximately 0.4 mm/rev. The depth-of-cut is increased by increments of 2 mm, and the system is stable as long as the depth-of-cut does not exceed 4 mm.

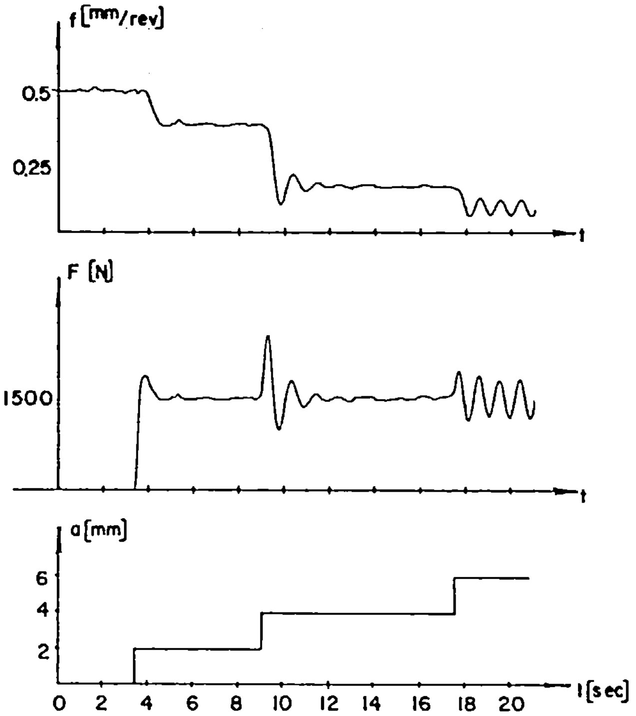

Figure 2
Response to Changes in Depth-of-Cut in a Conventional Adaptive Control System

However, at 6 mm, the system becomes unstable with oscillations of approximately 2 Hz. This is the natural frequency of the servo loop and is not caused by chatter. Furthermore, when running the system with different spindle speeds and constant depth-of-cut, the same phenomenon occurred. With a slower spindle speed, the system became unstable as shown in *Figure 3*.

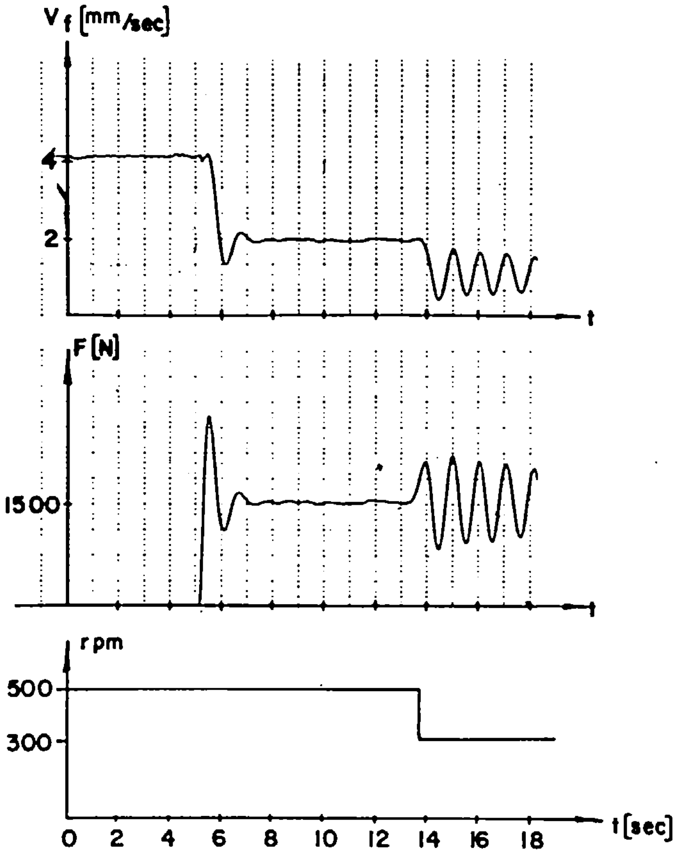

Figure 3
Response to Changes in Spindle Speed in a Conventional Adaptive Control System

Instability in the AC systems is not a familiar phenomenon to people on the shop floor, since most of them do not use AC systems in production. Users of AC production systems encounter this unstable condition rather infrequently in practice, since their part programmers are experienced enough to avoid large changes in depth-of-cut and/or spindle speed. This, however, means that the productivity rate is decreased and the objective of the AC system is not fully achieved. The experimental evidence presented here shows that this type of instability does occur, which prompted a more detailed study of the AC loop.

It is known from control theory that the open-loop gain is the dominant parameter which determined system stability.

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

$$V_f = K_n U \tag{4}$$

where:

K_n is the gain of the CNC servo system.

The machining feed, f, is given by:

$$f = (60/n)\ V_f \tag{5}$$

where:

n is the spindle speed in rpm.

The cutting force F is a function of the feed and the depth-of-cut (a) and can be approximated by:

$$F = K_s\ a f^p = (K_s a f^{p-1}) f \tag{6}$$

where:

K_s is the specific cutting force and p is a constant ($p<1$), both depending on the workpiece and tool materials.

The average value of p in our experiments was 0.7 (workpiece material: 1045 steel, and a carbide tool).

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

$$F_c = K_e F \tag{7}$$

Combining Eqs. (2) and (4) thru (6) yields:

$$F_c = KW$$

where:

K, the open-loop gain, is defined by:

$$K = 60 K_c' K_n K_e K_s\ (a/n) f^{p-1} \tag{8}$$

It is known from control theory that most systems have an upper allowable limit to their open-loop gain. This limit is prescribed by the dynamics of the system and the sampling period T, and if exceeded, the system becomes unstable.[21] An acceptable gain is usually regarded as about one-half of this value. If K is much smaller, the transient response is very slow.

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 unstable conditions as seen in *Figures 2* and *3*. One might think that a possible solution would be to select a very small K_c to decrease the open-loop gain below its stability limit even at the largest allowable depth-of-cut and a minimum permissible spindle speed.

The result of this approach is demonstrated in *Figure 4* for $K_c = 0.0625$. At a depth-of-cut of 2 mm, the transient behavior is very slow and the steady state force reaches the preselected reference value of F_r = 1500 N only after a relatively long time. However, if the chip load is too big (a = 4 mm), the recovery time from the initial impact is too long and the tool insert breaks.

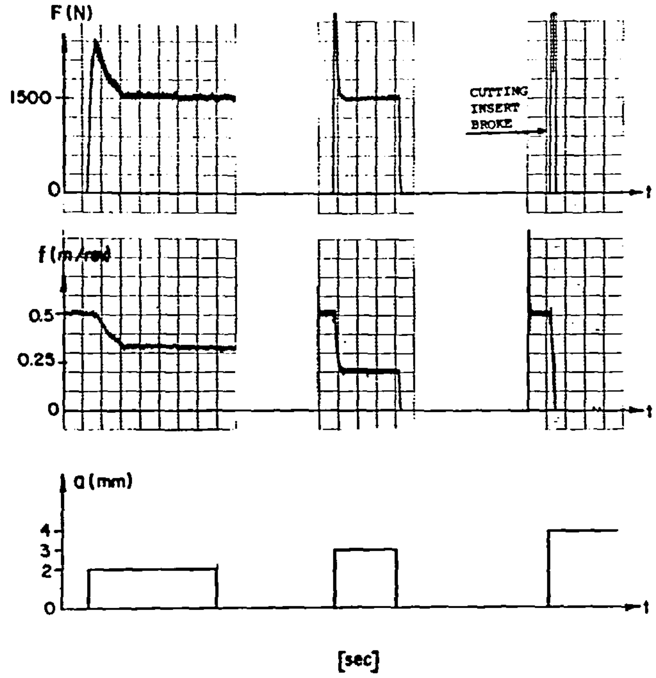

Figure 4
Tool Breakage Due to Controller Low Gain

It can be seen 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 can 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 the AC system design. The system should operate with a variable gain K_c which adapts itself to the cutting parameters.

The necessity for this type of approach has been mentioned in another work[20] and has been explicitly stated by Stute[22] in the report of the American Machine Tool Task Force. Also, Mathias[12] states that Macotech Corporation's commercial MACXX-C system has a simple variable control gain algorithm which "decreases the control loop gain at the onset of any feedrate oscillation" to avoid AC control loop instability, but he does not propose a systematic method to adjust the gain.

The remainder of this paper describes a structured approach to the solution of this problem, which involves an estimation in real-time of the "gain" of the cutting process, and a subsequent adaptation of the AC controller gain (K_c) to the changing conditions of the cutting process.

The Estimator Algorithm

The cutting process estimator should measure the quantity $K_s\ (a/n)f^{p-1}$ which affects the open-loop gain in Eq. (8). 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:

$$K_p = 60K_nK_eK_s(a/n)f^{p-1} \tag{9}$$

At steady state, K_p is given by:

$$K_p = F_c/U \tag{10}$$

Since the values of both F_c and U are available within the computer, K_p be readily calculated. Subsequently, the controller gain K_c can be adjusted in real-time according to the equation:

$$K_c = K/K_p \tag{11}$$

in order to maintain the desired open-loop gain K.

The subroutines which perform the process estimation and the controller gain adjustment should function in real-time and be programmed on the CNC computer, which is typically a simple microcomputer. Therefore, it is recommended that these subroutines be written in assembly language using only basic instructions such as "add", "subtract", "compare", etc. Unfortunately, implementation of the algorithm based upon Eqs. (10) and (11) requires a direct division, which has two drawbacks: (1) a division is a slow operation in assembly language if hardware mathematics is not available, and (2) since the measurement F_c contains noise, the estimated gain K_p will follow the noise level, and consequently the controller gain K_c will also adapt itself to the noise variations.

A block diagram of an alternative approach which avoids direct division is shown in *Figure 5*. 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, $K_m \neq K_p$, so an error E_m is generated:

$$E_m = F_c - F_e = F_c - UK_m \tag{12}$$

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

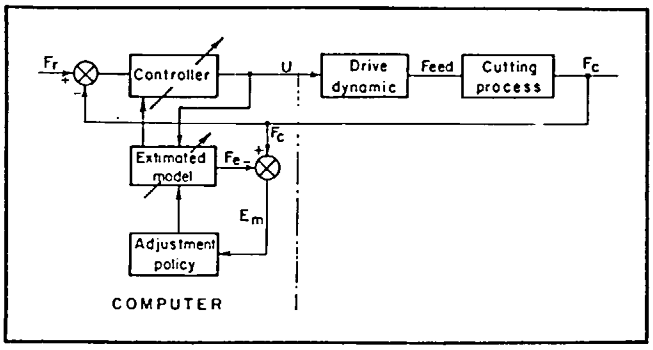

Figure 5
Process Estimation Scheme of the Adaptive Control System

$$E_m = U(K_p - K_m) \tag{13}$$

The estimated model 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:

$$K_m = C_1 \int E_m dt \tag{14}$$

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

$$E_m(i+1) = F_c(i) - U(i)\ K_m(i) \tag{15}$$

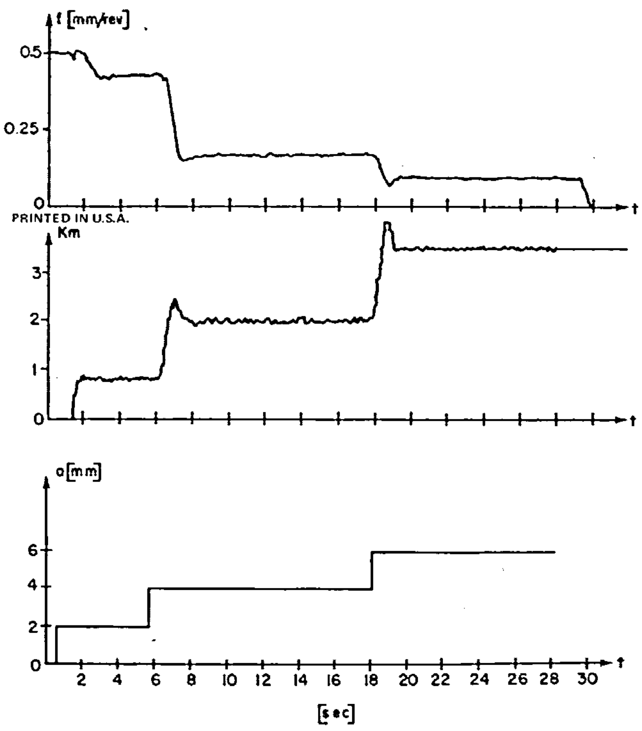

Figure 6
Estimator Response for Step Changes in Depth-of-Cut (n = 500 rpm)

$$K_m(i+1) = K_m(i) + C_1E_m(i+1) \qquad (16)$$

These equations can be readily implemented in assembly language. The constant C_1 has been selected to be 1/4, which simplifies the multiplication in Eq. (16) to two "shift" operations. Another advantage of this algorithm is the smoothing effect achieved by the integration in Eq. (16).

A typical experimental output of the estimator is shown in *Figure 6*. In this experiment, the depth-of-cut was increased step wise from 2 to 4 mm, and then to 6 mm. The AC loop automatically reduces the machining feed to maintain a constant required force.

The estimated model gain, K_m, reaches a steady state value after a short transient period. Note that the value of K_m does not increase proportionally with the depth-of-cut but also depends on the value of the feed f, as can be seen from Eq. (9). Similar

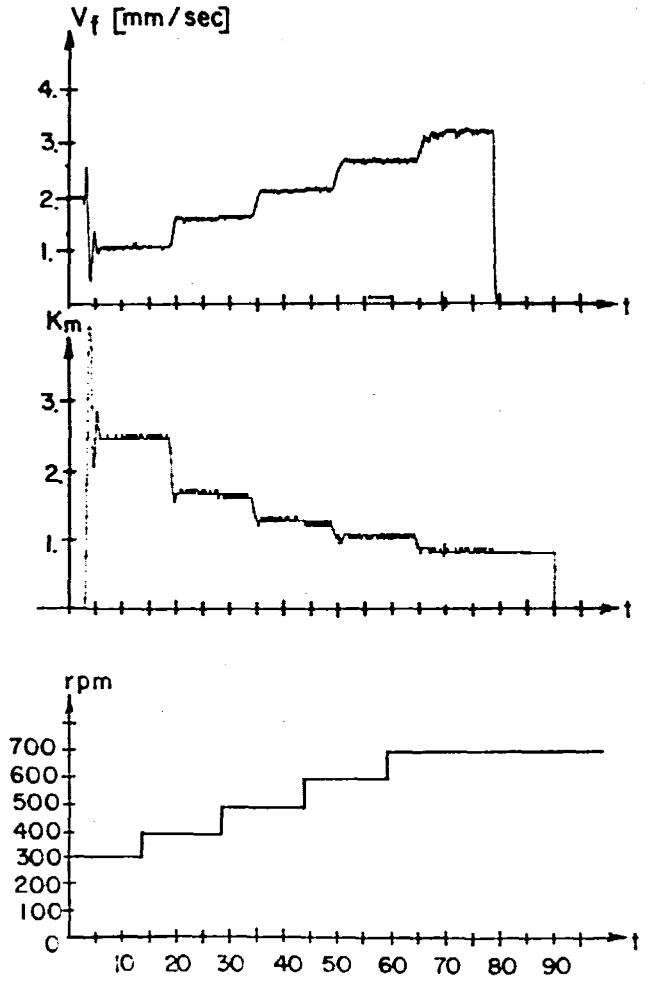

Figure 7
Estimator Response for Step Changes in Spindle Speed

tests have been performed for changes in spindle speed and a typical result with $a = 3$ mm is shown in *Figure 7*.

The speed was increased in 100 rpm steps and the feedrate V_f was subsequently increased by the system in order to maintain a constant cutting force. The estimated gain K_m, which is approximated by Eq. (9), follows the changes in the rpm. The experiments verify that the expected value of the cutting process gain can always be obtained.

Variable Gain Algorithm

The objective of the proposed adaptive control loop is to maintain a constant open-loop gain despite variations in the cutting parameters. By combining Eqs. (8) and (9) the open-loop gain is defined by:

$$K = K_cK_p \qquad (17)$$

and substitution of the estimated value K_m for K_p yields:

$$K = K_cK_m \qquad (18)$$

The constant open-loop gain can be obtained by adjusting the controller gain K_c according to variations of K_m. As in the case of the estimation algorithm, direct division is avoided by using the following integration policy:

$$E_c(i+1) = K - K_c(i)K_m(i) \qquad (19)$$

$$K_c(i+1) = K_c(i) + C_2E_c(i+1) \qquad (20)$$

Again, the integration algorithm in Eq. (20) guarantees that $E_c = 0$ at the steady state, which means that the desired gain can be achieved.

A set of experiments were performed to compare the conventional AC with the proposed variable gain AC system. The experimental system consisted of a 70 hp lathe controlled by an 8-bit microcomputer. In these experiments, the controller gain in the conventional AC was $K_c = 0.5$, the sampling period $T = 0.1$ seconds, and the integration constants in the proposed system were set to $C_1 = C_2 = 1/4$.

The AC open-loop gain has an upper limit obtained from stability considerations, which in our experimental system was $K = 1.33$ sec.$^{-1}$. An "optimal" K should be about one-half of this limiting value. However, in order to demonstrate the performance of the proposed system, an open-loop gain of 1.25 sec.$^{-1}$, which is very close to the stability limit, was selected.

The objective of the first two experiments which are shown in *Figures 8* and *9*, was to remedy the unstable conditions obtained in *Figures 2* and *3* for the conventional AC system. In *Figure 2*, it can be seen that the conventional AC system became unstable for a depth-of-cut of 6 mm. By contrast, it can be seen in *Figure 8*, that the proposed system was always stable. The value of K_c was automatically reduced from 1.5 to 0.52 and then to 0.33 with the progressive increase in the depth-of-cut from 2 to 4 mm, and then to 6 mm.

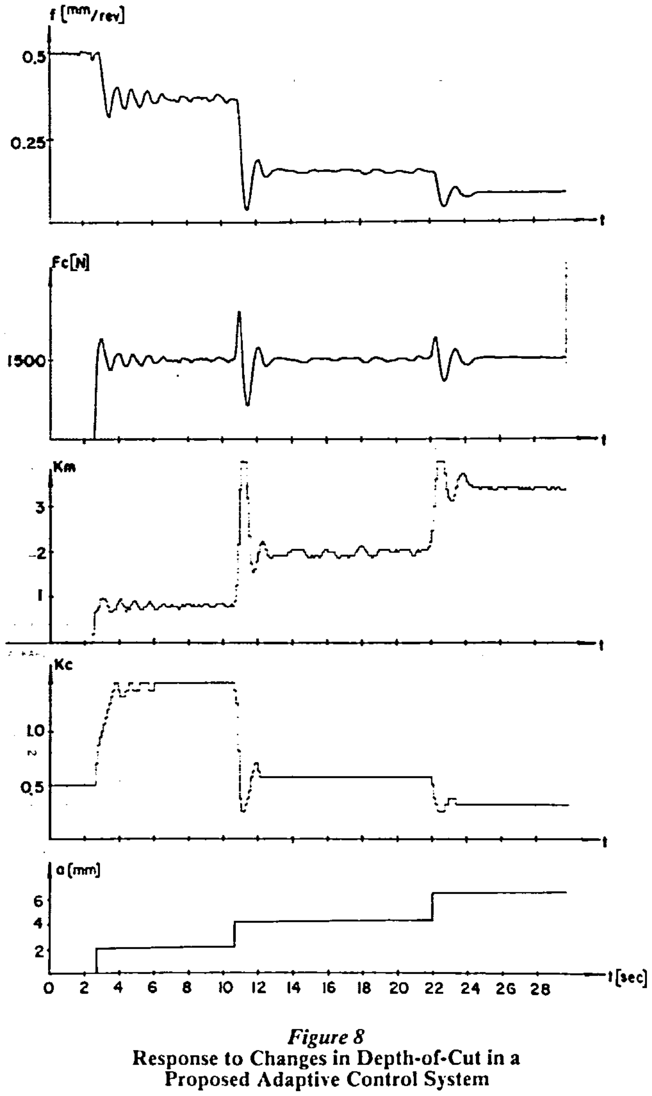

Figure 8
Response to Changes in Depth-of-Cut in a Proposed Adaptive Control System

Likewise, in *Figure 3* the conventional AC became unstable with the decrease of spindle speed from 500 to 300 rpm. By contrast, the proposed system (*Figure 9*) adapted itself automatically to the speed change and the system remained stable, by an automatic reduction in the gain K_c. The oscillations at the transient periods can be eliminated by reducing

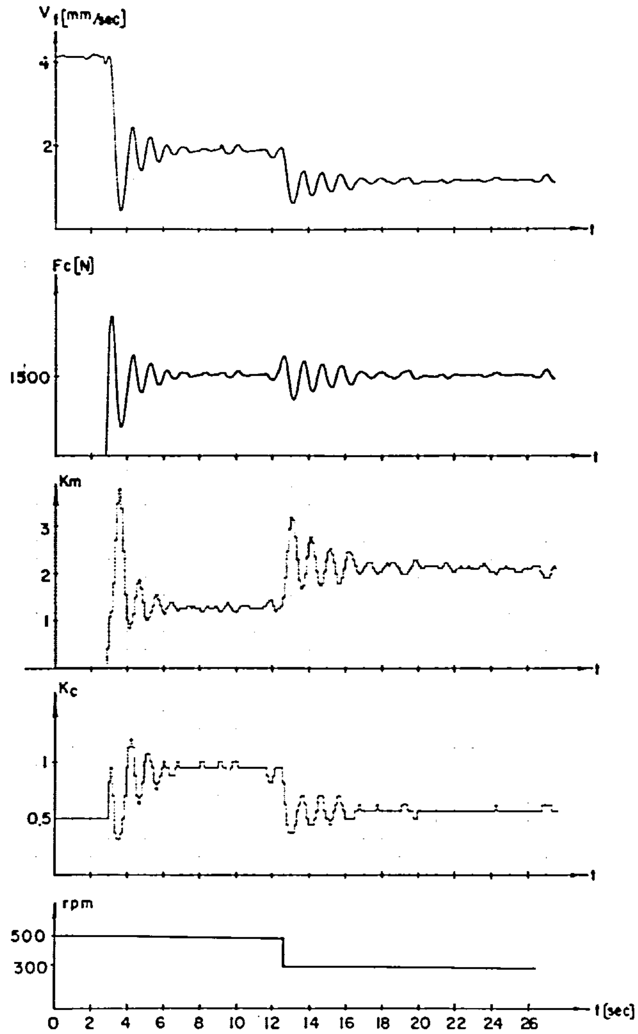

Figure 9
Response to Changes in Spindle Speed in a Proposed Adaptive Control System

the open-loop gain to a lower value, e.g., $K = 0.65$.

Another set of experiments to compare the two systems was performed with constant cutting parameters which cause unstable initial conditions. *Figure 10* shows unstable conditions obtained with a conventional AC at 500 rpm and a controller gain set to $K_c = 1.25$.

By contrast, the proposed variable gain AC system (*Figure 11*) automatically reduced the gain to $K_c = 0.78$ in order to meet the stability require-

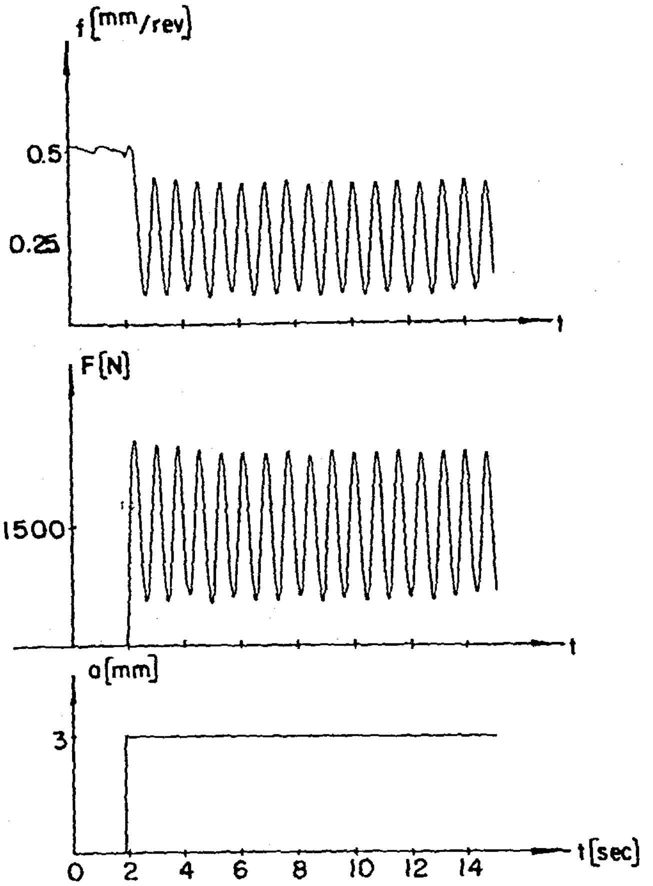

Figure 10
System Response to Unstable Initial Cutting Conditions Conventional Adaptive Control

ment, while the systems maintained the required force value by varying the machining feed.

Concluding Remarks

In adaptive control constraints systems for machining, the cutting process itself is contained in the adaptive control loop. Therefore, drastic variations in the process parameters affect the AC loop gain and can cause instability of the control system.

A method is proposed for modifying the controller gain according to the process variations in order to maintain stability of the entire system. The system actually contains two adaptive control loops: (1) the conventional loop which adapts the machining feed, and (2) the model-reference loop which adapts the controller gain to obtain the open-loop gain reference value. The proposed solution does not require any additional hardware and only modifications to the AC controller software are needed.

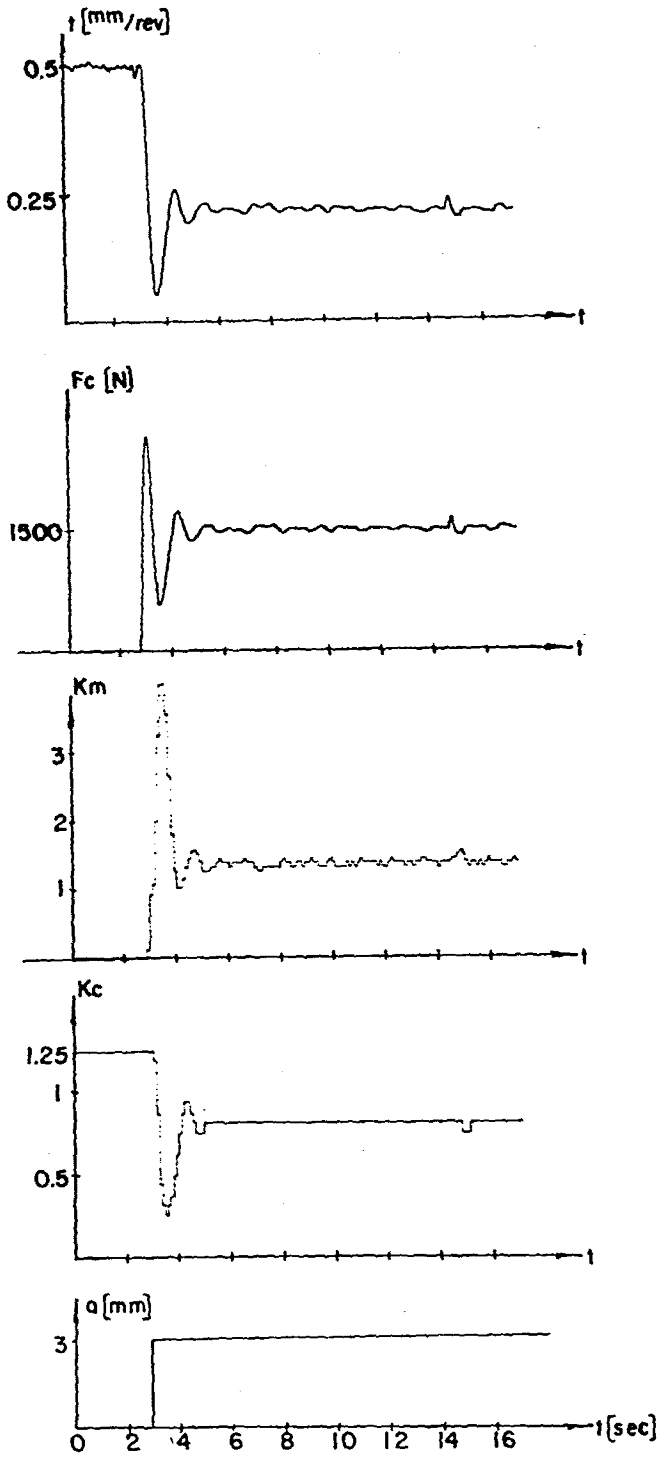

Figure 11
System Response to Unstable Initial Cutting Conditions Proposed System

Acknowledgement

The authors would like to thank the Gutwirth Research Foundation at the Technion, Israel Institute of Technology for a grant received to accomplish this research.

References

1. Y. Koren, *Computer Control of Manufacturing Systems*, McGraw-Hill Book Co., New York, 1983.
2. R. Centner, "Final Report on Development of Active Control Technique for Numerically Controlled Milling Machine", Technical Documentary Report ML-TDR-64-279, U.S. Air Force Base, Wright-Patterson Air Force Base, August 1964.
3. A. Mathias, "An Effective System for Adaptive Control of the Milling Process", SME Paper MS68-202, Society of Manufacturing Engineers, Dearborn, Michigan, 1968.
4. L. W. Colwell, J. R. Frederic, and L. J. Quachenbush, "Research in Support of Numerical and Adaptive Control in Manufacturing", The University of Michigan, Ann Arbor, Michigan, 1969.
5. B. R. Beadle and J. G. Bollinger, "Computer Adaptive Control of Machine Tools", *Annals of the CIRP*, 1970.
6. R. Bedini, G. G. Lisini, and P. C. Pinotti, "Experiments on Adaptive Control of a Milling Machine", ASME Tranactions, *Journal of Engineering for Industry*, February 1976.
7. A. Mathias, "Adaptive Controlled Profile Milling", SME Technical Paper MS70-563, Society of Manufacturing Engineers, Dearborn, Michigan, 1970.
8. M. P. Groover, "A Definition and Survey of Adaptive Control Machining", SME Technical Paper MS70-561, Society of Manufacturing Engineers, Dearborn, Michigan, 1970.
9. T. R. Frecka, "Torque Controlled Drilling", *IEEE-IAS Machine Tools Industry Conference Proceedings*, Milwaukee, Wisconsin, October 1975.
10. A. Mathias, "New Developments in Adaptive Control of Milling Machines", *IEEE-IAS Machine Tools Industry Conference Proceedings*, Milwaukee, Wisconsin, October 1975.
11. A. Mathias, "An Adaptive Controlled Milling Machine", SME Technical Paper MS76-260, Society of Manufacturing Engineers, Dearborn, Michigan, 1976.
12. A. Mathias, "Software Adaptive Control-Optimum Productivity for CAM", SME Technical Paper MS77-252, Society of Manufacturing Engineers, Dearborn, Michigan, 1977.
13. B. R. Beadle and J. G. Bollinger, "A Constrained Search Adaptive Controller for Metal Cutting", *Proceedings of the 2nd NAMRC Conference*, University of Wisconsin-Madison, Madison, Wisconsin, May 1974, pp. 273-280.
14. M. Weck, E. Verhaag, and M. Gather, "Adaptive Control for Face-Milling Operations with Strategies for Avoiding Chatter-Vibrations and for Automatic Cut Distribution", *Annals of the CIRP*, Volume 24, 1975, pp. 405-409.
15. T. Inamura, T. Senda, and T. Sata, "Computer Control of Chattering in Turning Operation", *Annals of the CIRP*, Volume 26, 1977, pp. 181-186.
16. A. DeFilippi and R. Ippolito, "The Influence of Constraints on Cutting Condition Optimization", *Annals of the CIRP*, Volume 24, 1975, pp. 417-421.
17. J. Tlusty and M. Elbestawi, "Constraints in Adaptive Control with Flexible End Mills", *Annals of the CIRP*, Volume 28, 1979, pp. 253-255.
18. J. Tlusty and M. Elbestawi, "Analysis of Transient in an Adaptive Control Servomechanism for Milling with Constant Force", *ASME Journal of Engineering for Industry*, Volume 99, No. 3, August 1977.
19. O. Masory and Y. Koren, "Adaptive Control System for Turning", *Annals of the CIRP*, Volume 29, No. 1, 1980, pp. 281-284.
20. Y. Koren and O. Masory, "Adaptive Control with Process Estimation", *Annals of the CIRP*, Volume 30, No. 1, 1981, pp. 373-376.
21. Y. Koren and J. G. Bollinger, "Design Parameters for Sampled-Data Drives for CNC Machine Tools", *IEEE Transaction on Industry Applications*, Volume 1A-14, No. 3, May/June 1978.
22. G. Stute, "Adaptive Control", *Proceedings of the Machine Tool Task Force Conference*, Volume 4, Chapter 7.14, October 1980.

Author(s) Biography

Oren Masory is an Assistant Professor of Mechanical Engineering at Texas A&M University in College Station, Texas. He earned his B.S.M.E., M.S.M.E. and Ph.D. in 1974, 1977, and 1980 respectively, from the Technion, Israel Institute of Technology, Haifa, Israel. His current research and teaching activities are in the areas of computer control of manufacturing systems and robotics. Dr. Masory's professional affiliations include RI/SME and ASME.

Yoram Koren is Head of the Robotics Laboratory in the Faculty of Mechanical Engineering at the Technion, Israel Institute of Technology, Haifa, Israel. From 1980 to 1982, Dr. Koren served as the Goebel Professor of the College of Engineering, and as Director of the Integrated Design and Manufacturing Division at the University of Michigan, Ann Arbor, Michigan. His research interests are in the areas of robotics, adaptive control, and computerized manufacturing. Dr. Koren has written more than 50 papers in these areas, as well as having authored a textbook entitled *Computer Control of Manufacturing Systems*. He is a member of NAMRI/SME, RI/SME, ASME, and CIRP.