Adaptive Control with Process Estimation

Y. Koren and O. Masory, Technion-Israel Institute of Technology — Submitted by S. Malkin (1)

Summary: A frequent problem encountered during machining with Adaptive Control Constraint (ACC) systems is deterioration of system stability, which is caused by changes in the process parameters such as depth-of-cut or spindle speed. In order to solve the stability problem, the process parameters have to be estimated on-line and immediately used by the ACC control program. In the present paper, a simple computer algorithm is presented for on-line estimation of the process parameters in turning. By applying the proposed method, variations in the process are compensated by subsequent changes in the AC loop gain in order to maintain the stability of the whole system. The method has been demonstrated on a high-power CNC lathe using a small microcomputer as the AC controller in which both the ACC program and the software estimator were stored.

Introduction

Adaptive Control Constraint (ACC) systems for milling and turning are today beyond the R & D stage. The main idea in these systems is to increase the productivity of a machine tool system by applying the highest feedrates that are compatable with a maximum allowable cutting force or spindle torque. Since the ACC system uses the CNC computer [1], the investment in hardware is minimal; only a sensor and its associated analog-to-digital converter (ADC) are required.

The main research efforts in ACC systems have been devoted to the problem of chatter elimination [2,3] and to the determination of the programmed constraints, such as cutting power [4] or force [5]. The present paper is concerned with a different aspect of ACC, namely, the stability of the control system. The ACC system, as is shown in Fig. 1 for turning, is basically a feedback loop where the feed f adapts itself to the actual cutting force F. However, it should be noted that in this system, the cutting process itself is part of the control loop. Therefore, variations in the process directly affect the parameters of the control loop and can cause the ACC system to become unstable.

It has been theoretically and experimentally demonstrated that either an increase in the depth-of-cut, a, or a decrease in the spindle speed, n, in turning can cause instability of the entire CNC-ACC system [6]. These two parameters are both contained in the open-loop gain of the ACC. Increasing this gain beyond a certain limit causes oscillations at low frequency (~2 Hz). This gain K can be expressed by the equation:

$$K = K_c K_h K_s a/n \qquad (1)$$

where K_c is the controller gain which can be modified in the computer;
K_h is the gain of the CNC hardware system, which is fixed by the CNC manufacturer and the force sensory system;
K_s is the specific cutting force which depends on the workpiece and tool material as well as on the feed itself, and is defined by the ratio F/(fa).

It has also been shown [6] that selecting a very small K_c in Eq. [1] in order to decrease the loop gain and thus avoid oscillations at large depths-of-cut leads to other problems. When K_c is too small, the transient behavior is very sluggish, yielding long recovery times from initial impacts at medium depths-of-cut, and as a result, the tool insert may break. This brought us to the conclusion that an ACC system which allows wide variations in the depth-of-cut and spindle speed should operate with a constant open-loop gain K. This can be accomplished by adding a software "process estimator" to approximate the quantity (K_s a/n) in real-time. If the value of (K_sa/n) is increased, the controller gain K_c is decreased, and vice-versa, in order to maintain a constant open-loop gain.

The Estimator Algorithm

A simplified block diagram respesentation of the CNC/ACC system is shown in Fig. 2. The transfer-function $G_1(s)$ represents the hardware servo loop of the CNC which provides an axial feedrate given here in mm/sec. The computer output U is proportional to the required feedrate. The gain H represents the force sensor electronics and the ADC gain, and consequently its output F, is proportional to the actual force F_c. Since a direct estimation of the quantity (K_sa/n) requires additional sensors and input channels to the computer, it is worthwhile to estimate the value of ($K_h K_s$a/n). At steady-state the latter is given by

$$K_h K_s a/n = F_c/U = K_p \qquad (2)$$

Since both F_c and U are available within the computer, the process gain K_p can be readily derived. Subsequently, the controller gain K_c could be adjusted according to the equation:

$$K_c = K/K_p \qquad (3)$$

where K is a given constant equal to the desired open-loop gain.

The process estimator 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", "compage", etc. Unfortunately, implementation of the algorithm based upon eqs. (2) and (3) requires a direct division, which is a very complicated and slow operation in assembly lanauage.

A block diagram of an alternative approach which avoids direct division is shown in Fig. 3. The "estimated model" block contains an estimated gain K_m which is multiplied by the input U. Since in general $K_m \neq K_p$, an error E_m is generated

$$E_m = F_c - F_e = F_c - UK_m$$

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

$$E_m = U(K_p - K_m) \qquad (5)$$

The estimated model K_m should be automatically adjusted to reduce this error. The simplest adjustment policy is to apply a proportional algorithm

$$K_m = CE_m \qquad (6)$$

where C is a small constant. However, this approach cannot be implemented here since it assumes that an estimation error always exists. If the difference between the values of K_m and K_p becomes small, the product CE_m vanishes and K_m cannot be adjusted to obtain the desired condition $K_m = K_p$. On the other hand, if C is selected too big, K_m does not converge. To remedy this problem, an integration algorithm is proposed:

$$K_m = C\int E_m dt \qquad (7)$$

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

$$E_m(i+1) = F_c(i) - U(i)\, K_m(i) \qquad (8)$$

$$K_m(i+1) = K_m(i) + C_1\, E_m(i+1) \qquad (9)$$

which can be readily implemented in assembly language

The constant C_1 has been selected to be 1/4, which simplifies the multiplication in Eq. (9) to two "shift" operations. Another advantage of this algorithm is the smoothing effect achieved by the integration in Eq. (9).

A typical experimental output of the estimator is shown in Fig. 4. In this experiment, the depth-of-cut was increased step-wise from 2 to 4 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 the following equation:

$$K_m \simeq K_p = \frac{K_h K_s a}{n} = \frac{K_h F}{nf} = \frac{K_h K_s' af^{0.7}}{n f} = \frac{ka}{f^{0.3}} \qquad (10)$$

where k is a constant for a certain spindle speed.

Similar tests have been performed for changes in spindle speed. The expected value of the gain of the cutting process has always been obtained.

Variable Gain Algorithm

The adaptive control loop should maintain a constant open-loop gain K, given by

$$K = K_c K_m \qquad (11)$$

where the estimated gain K_m has been substituted for K_p in Eq. (3). The constant 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:

$$E_c(i + 1) = K - K_c(i)K_m(i) \qquad (12)$$

$$K_c(i + 1) = K_c(i) + C_2 E_c(i + 1) \qquad (13)$$

Again, the integration algorithm in Eq. (13) 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 ACC system with the proposed variable-gain ACC 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 ACC was $K_c = 0.5$ and the sampling period T = 0.1 sec. The integration constants in the proposed system are set to $C_1 = C_2 = 1/4$. The ACC open-loop gain has an upper limit obtained from stability considerations which, in our expermental 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. Some results obtained are presented in Figs. 5-7. In Fig. 5a, it can be seen that the conventional ACC system became unstable for a depth-of-cut of 6 mm. By contrast, the proposed system was always stable. As is seen in Fig. 5b, 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 and then to 6 mm.

In Fig. 6, the depth-of-cut was increased linearly and the conventional system (Fig. 6a) became unstable at a certain depth-of-cut. With the proposed system, however, the controller gain was varied according to the model estimated value of K_m. System stability was maintained throughout the entire machining range up to 8 mm depth-of-cut.

In the final experiment, the spindle speed was changed from 500 rpm to 300 rpm, as seen in Fig. 7. Again the conventional ACC (Fig. 7a) became unstable, while the proposed system (Fig. 7b) adapted itself automatically to the speed change and the system remained stable.

Conclusions

In ACC 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 a constant open-loop gain to maintain stability. The system actually contains two adaptive control loops: the conventional loop which adapts the machining feed, and an additional one which adapts the controller gain. The need for this type of structure for ACC systems has also been recommended by the American Machine Tool Task Force [7]. The commercial adaptive control system MACXX-C of Macotech Corporation also contains an automatic gain control system [8]. However, the operation of this system is not based on any sophisticated algorithm, but simply "decreases the control loop gain at the onset of any feedrate oscillation" [8].

The proposed algorithms for process estimation and automatic gain variation contain two constants C_1 and C_2. Improper choice of these constants can lead to instability of the whole system. The next logical step should be to find a method for optimal selection of C_1 and C_2 as well as the selection of the sampling period T.

References

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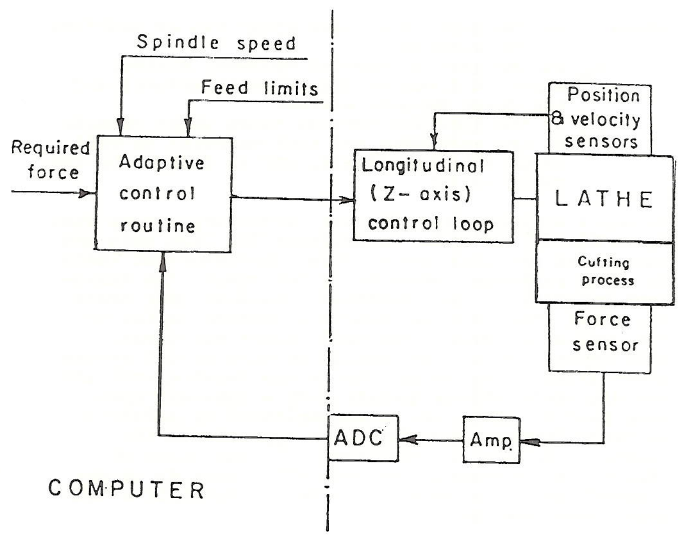

Fig. 1 Adaptive control system for a lathe

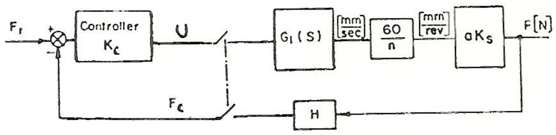

Fig. 2 Block diagram of AC system

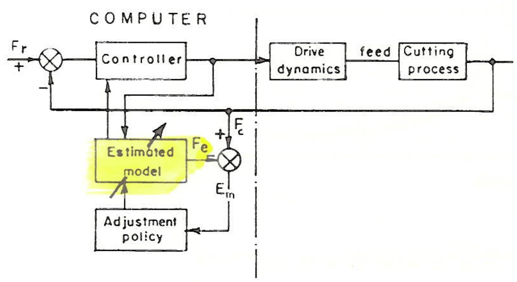

Fig. 3 Process estimation scheme of the AC system

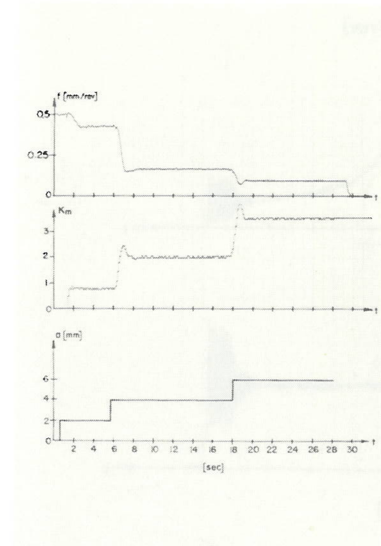

Fig. 4 Estimator response for step changes in depth-of-cut (n = 500 rpm)

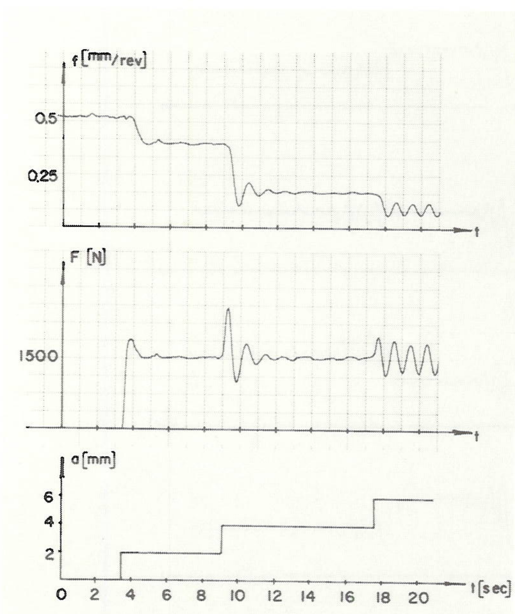

Fig. 5 a. Conventional AC system response to changes in depth-of-cut (n = 500 rpm)

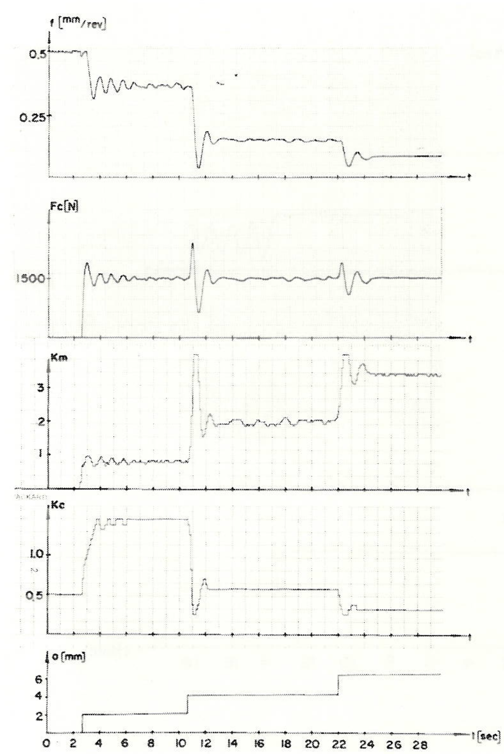

Fig. 5 b. Proposed AC system response to changes in depth-of-cut (n = 500 rpm)

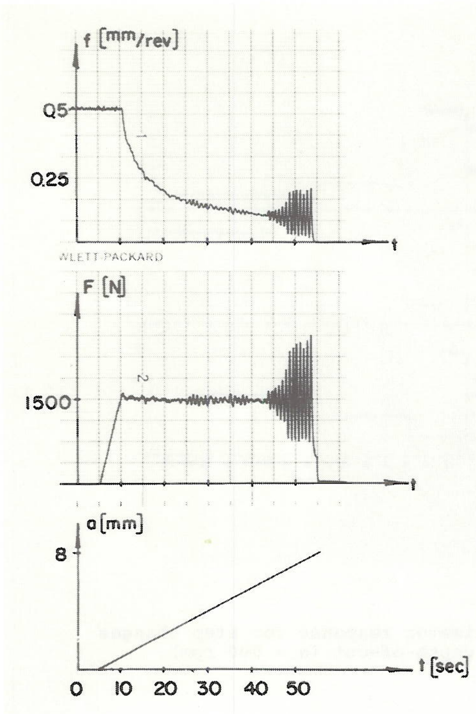

Fig. 6 a. Conventional AC system response to linear change in depth-of-cut (n = 500 rpm)

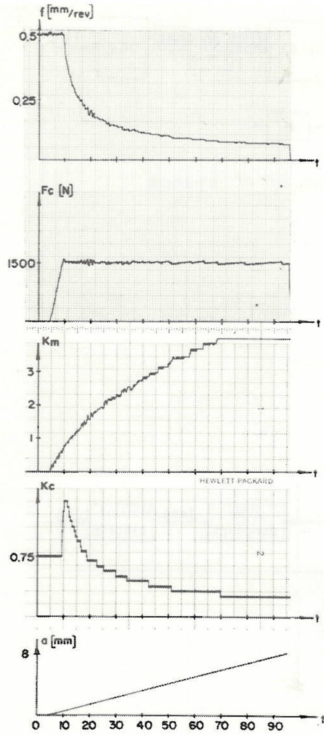

Fig. 6 b. Proposed system response to linear change in depth-of-cut (n = 500 rpm)

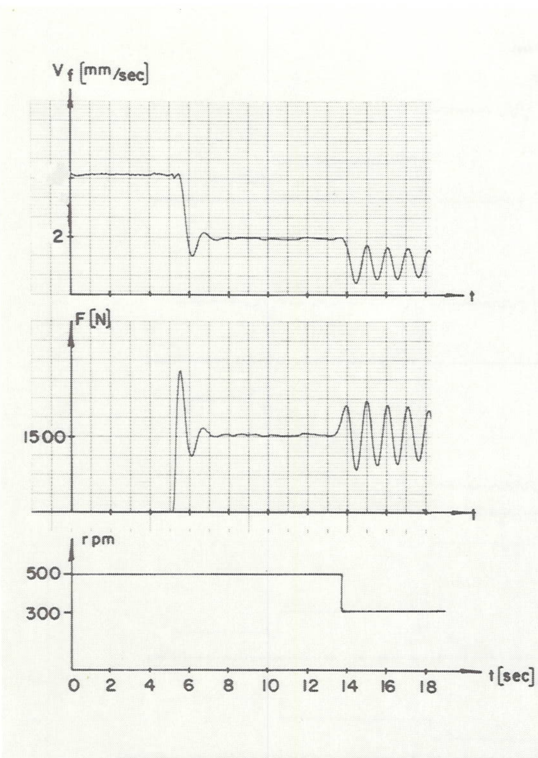

Fig. 7 a. Conventional AC system response to change in spindle speed

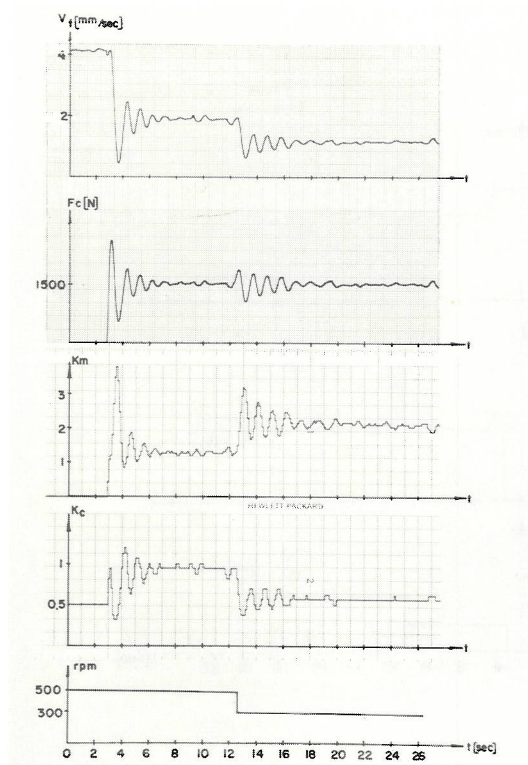

Fig. 7 b. Proposed system response to change in spindle speed.