Adaptive Control System for Turning

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Summary: An adaptive control (AC) system is described for turning on a lathe. In this system, a programmed cutting force is compared with the actual cutting force; the difference provides correction to the feed. It is demonstrated that the effective AC loop gain depends on both depth-of-cut and spindle speed and thereby influence system stability. A method to maintain a constant system gain is proposed.

Introduction

The adaptive control (AC) of machining processes is a logical extension of the computerized numerical control (CNC) systems. In CNC systems, the cutting speed and feed are prescribed by the part programmer and consequently depend on his experience and knowledge. By contrast, the main idea in adaptive control is the control of the cutting process by on-line calculation and setting of the optimal operating parameters [1] subject to machining constraints. Such adaptive control systems have been previously developed for milling with constrained normal force [2] or cutter deflection [3]. In the present paper, an adaptive control system is described for turning on a lathe with a constant cutting force constraint.

AC Control System

The AC system shown in Fig. 1 is basically a feedback loop where the feed f adapts itself to the actual cutting force F_c, and varies accordingly to changes in work conditions as cutting proceeds. The AC loop functions in a sampled-data mode. The actual power force F_c is sampled every T seconds (typically T = 0.1 sec.) and is immediately compared in the computer with predetermined allowable reference force F_r. The difference between the 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 which sends a correction signal to the feed-rate routine contained in the CNC control program. A positive difference increases the programmed feed-rate and consequently increases the actual force, thereby decreasing the error E, and vice-versa.

Controller Policy

The simplest policy for an AC controller is to provide feed-rate corrections proportional to the force error E. The basic software structure for such a controller is as follows:

The force error is

$$E(i) = F_r(i) - F_c(i) \tag{1}$$

where the index (i) indicates the i-th sampling. The command signal U from the controller is

$$U(i) = U_o + K_c\, E(i) \tag{2}$$

where K_c is the controller gain and U_o is a reference value. The resulting computer feed-rate command V_f to the servo loops at the i-th sampling (or to the interpolator in a multi-axial mode) is given by:

$$V_f(i) = K_f U(i) \tag{3}$$

Where K_f is a constant associated with the feed-rate routine. The feed-rate value $K_f U_o$ may be preselected so as to avoid tool breakage when the tool initially impacts the workpiece at the start of the cutting.

Both K_c and K_f are integral parts of the overall open loop gain K. Due to stability considerations, K should be kept very small (e.g., we have found for T = 0.1s that K>3 causes instability). However, since the steady-state force error E is inversely proportional to K, it is clear that this error becomes very large for small K's, so that the desired force cannot be achieved. Therefore, the policy given by Eq. (2) is not suitable for AC systems for machine tools.

In order to completely eliminate the force error, the controller command U should be proportional to the time integral of the force error. As long as there is an error, there will always be feed-rate variations in a direction to correct this error. At the steady-state, however, the error in the force is zero.

The simplest structure for such an integral policy can be written:

$$U(i) = U(i-1) + K_c E(i) \tag{4}$$

In this case the controller gain K_c is proportional to the sampling period T. The feed-rate command V_f due to the controller command U is given by Eq. (3). 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.

Experimental Results

This integral policy has been implemented on a high power CNC lathe. A typical result for $K_c = 0.5$ is shown in Fig. 2. The feed before engagement was selected as 0.5 mm/rev. At the start of cutting, the feed is immediately reduced to approximately 0.25 mm/rev. 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 $F_r = 1500N$. The corresponding feed is decreased.

When increasing the controller gain to $K_c = 0.625$, an unexpected instability phenomenon was encountered. As seen in Fig. 3, the system is stable as long as the depth-of-cut does not exceed 4 mm. But 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 more unstable, as shown in Fig. 4. The big influence of the spindle speed and depth-of-cut on the system stability prompted a more detailed study of the AC loop.

Model of the CNC/AC System

The CNC system of the lathe is based on the reference pulse method [4], whereby the reference signals from the computer are transmitted as a sequence of pulses for each axis-of-motion, each pulse generating a motion of one basic length-unit (BLU). The accumulated number of pulses represent position, and the pulse frequency is proportional to the axis velocity. In the present system, 1 BLU = 0.01 mm. By assuming that the servo loops can be modelled as a second order system, the transfer function can be written:

$$G_1(s) = \frac{(BLU)\,\omega_n^2}{s^2 + 2\zeta\,\omega_n s + \omega_n^2} \quad \left[\frac{mm}{pulse}\right] \tag{5}$$

The relationship between machining feed f and the axis velocity V_f is given by:

$$\frac{f}{V_f} = \frac{60}{n} \quad \left[\frac{sec}{rev}\right] \tag{6}$$

where n is the spindle speed in rpm. The force F_c can be assumed to be proportional to the feed and depth-of-cut, a:

$$\frac{F_c}{f} = K_s\, a \quad \left[\frac{Newton}{mm/rev}\right] \tag{7}$$

where K_s is the specific force coefficient which depends on the workpiece and tool material.

A block diagram representation of the CNC/AC system is shown in Fig. 5. The feedback gain H in Fig. 5 represents the force sensor electronics and ADC gains. The overall open-loop gain K is obtained from Eqs. (3) to (7) as:

$$K = K_c \, K_f \, H \, (BLU) \, 60 \, K_s \, a/n \tag{8}$$

or more simply

$$K = K_c \, K_f \, K_p \tag{9}$$

where

$$K_p = 60 \, H(BLU) \, K_s \, a/n \tag{10}$$

From Eq. (8) it is apparent that the depth-of-cut and the spindle speed are part of the loop gain. Increasing the depth-of-cut increases the actual loop gain, thereby causing the oscillations as seen in Fig. 3. Likewise, reducing the spindle speed also increases the gain, again leading to the instability seen in Fig. 4.

Selecting a very small K_c in Eq.(4) to decrease the loop gain and thus avoid oscillations at large depths-of-cut will cause other problems. When K_c is very small, the transient behavior is very slow and the steady-state error reaches its zero value only after a relatively long time. This is illustrated in the first two drawings of Fig. 6 corresponding to K= 0.0625. If the chip-load is too big and K_c is too small, the recovery time from the initial impact takes too long, and the tool insert might break. This is exactly what happened in our test.

Discussion and Conclusions

A major problem in the design of an AC loop for machine tools is the selection of the integral controller gain K_c. If K_c is small, the tool might break. If K_c is big, the loop gain becomes bigger with increased depth-of-cut or reduced spindle speed and the AC loop can become unstable. As a consequence, only one conclusion can be drawn: the open loop gain of the AC system, K, should be maintained constant during the cutting process.

In order to maintain constant gain, it is necessary to add an additional routine to the AC system for on-line estimation of the magnitude of aK_s/n. One possible estimating scheme is shown in Fig. 7. The error E between the actual force and the estimated force F_e is used to correct the estimated gain K_e given by:

$$K_e = \frac{F_e}{V_f} \tag{11}$$

An important feature of this scheme is it avoids direct division which takes too much time for on-line programming. Furthermore, the uncertainty in off-line specification of the specific force coefficient K_s does not enter into the AC loop as it is calculated on-line. To maintain a constant open loop gain K given by Eq. (9), the controller gain K_c should be adjusted on-line according to the equation:

$$K_c = \frac{K}{K_f \, K_e} \tag{12}$$

In this way the dynamic behavior of the system remains unchanged and AC loop instabilities are avoided.

Acknowledgement

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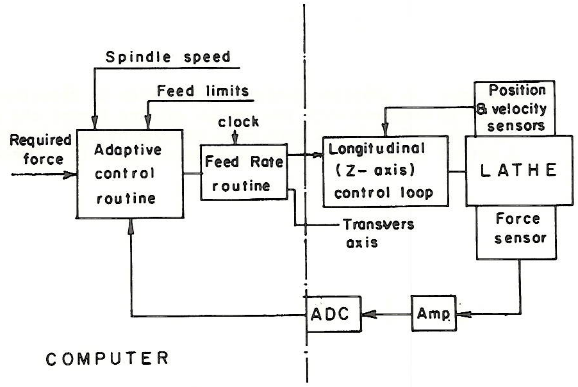

Fig. 1. Adaptive control system for a lathe

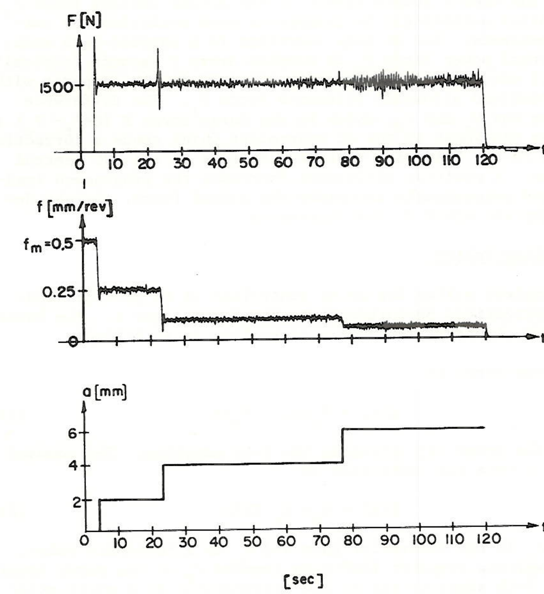

Fig. 2. System response with K_c= 0.5 and variable depth-of-cut (All experiments performed with P-25 coated carbide inserts and SAE 1045, steel 190 Brinell).

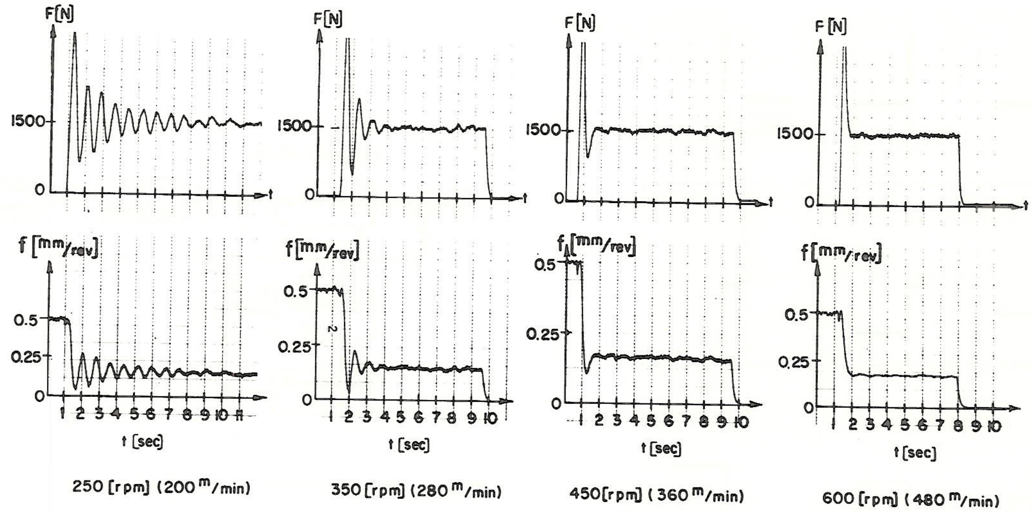

Fig. 4. Influence of spindle speed on stability (α = 2.5 mm; T = 0.1s; K_c = 0.5)

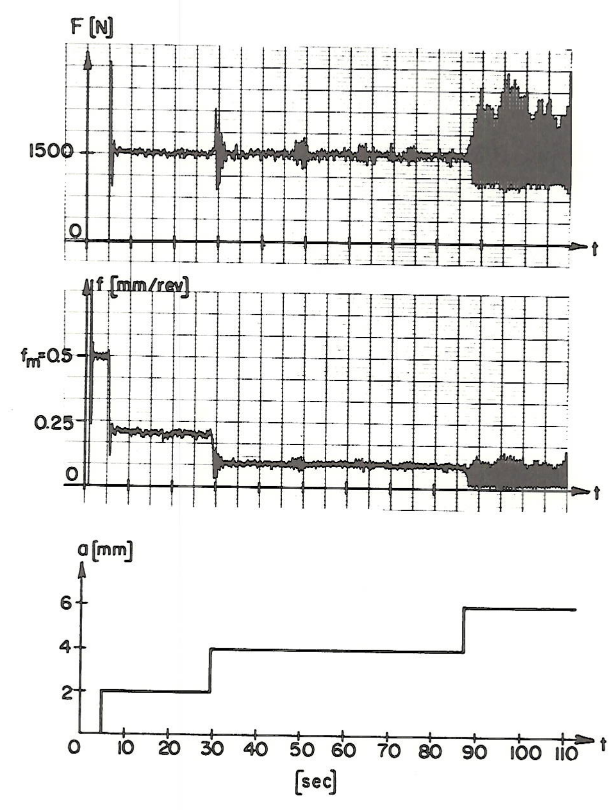

Fig. 3. System response with K_c = 0.625 and variable depth-of cut.

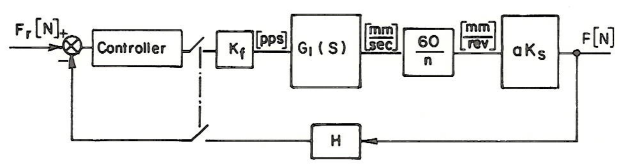

Fig. 5. Block diagram of AC system

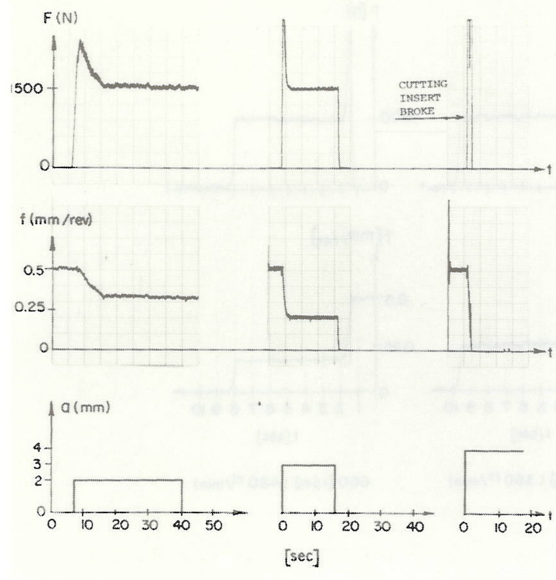

Fig. 6. System response with $K_c = 0.0625$

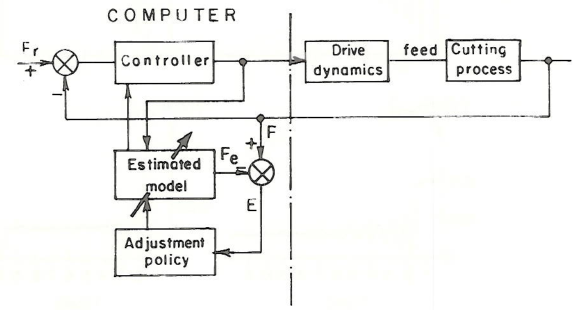

Fig. 7. Identification scheme of AC system