DYNAMIC MODELING AND CONTROL OF THE MILLING PROCESS

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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., fees and speeds) is left to the experience and judgement of the part programmer, who tends to select conservative values. Unfortunately, this results in a reduction of the production rate. Adaptive control (AC) systems are aimed at providing an additional level of control to automatically adjust the operating parameters on-line, so as to maximizd the metal removal rate (MRR). AC systems, however, are not widely used in practice due to the following factors:

1. A lack of detailed understanding of the machining process.

2. Reliability problems with sensors and other hardware associated with AC systems.

3. Machining time may comprise as little as 5% of the total production time, thus, increases in MRR may not have a significant impact on production rates without significant improvement in tool changing, parts handling, etc.

4. 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:

1. 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.

2. To develop a laboratory system to evaluate the variable-gain AC controller through machining tests.

PROGRAM ACHIEVEMENTS 9/81 TO 9/82: This section presents a brief description of the work done in the first year [1-2]. During this period work began in both the theoretical and the experimental studies.

The theoretical investigation began by reviewing the literature pertinent to AC systems, and through a digital simulation study of a candidate adaptive control system. The primary results of this work included, the clear statement of the problem, the documentaiton of past attempts at solving the problem, and the foundation work on developing and applying variable gain AC controllers to manufacturing systems.

The experimental studies began by assembling the experimental equipment necessary to complete our second goal. A PDP-11/23 laboratory computer system was installed. We also began building the required machine tool interfaces.

PROGRAM ACHIEVEMENTS 9/82 TO 9/83: During the second year our efforts have concentrated primarily on finishing the development and testing of the experimental system. Some additional work has also been done on the theoretical studies, specifically, the continuation of candidate controller evaluation via numerical simulations [3-4].

The theoretical work involved design and simulation studies of a fixed-gain controller and a model reference adaptive controller (MRAC) for the milling process based on a simple first-order difference equation model for milling.

The experimental work consisted of the completion of the laboratory system, including the computer interface to the milling machine, the force measurement system, and the feedrate override system.

PROGRAM ACHIEVEMENTS 9/83 TO 9/84: During the past year we have completed development and testing of the laboratory process control system for milling. We have used the laboratory system for conducting both open-loop and closed-loop cutting tests. We have used the test results to develop a process model for milling, as well as for the design of variable-gain adaptive process controllers for milling. These studies we discussed in detail below. We have also developed simulation and control software as described in [5-6], and studied reduced sensitivity controller designs as an alternative to adaptive process control [7].

INTRODUCTION

In the machining of metals automated machines take the form of Numerically Controlled (NC) or Computer Numerically Controlled (CNC) machine tools. These machines are capable of operating with greatly reduced operator input, and have resulted in significant improvements in productivity in medium to large batch production. IN NC and CNC machines the part program specifies the feeds and speeds to be used throughout the operation, and these are selected based on the most severe conditions expected. This means that at all other times during the cut the metal removal rate (MRR), hence the productivity, could be increased by manipulating the feeds and speeds. This observation has precipitated the application of process control to manipulate the feedrates in an attempt to optimize the metal removal rate. Some measure of the process, cuch as cutting force, is used to adjust the feed to maintain a constant, optimum, force level. The literature has reported improvements in the MRR from 20% to 80% when using these process controllers.[1] These process controllers are often, inaccurately, referred to as adaptive control systems.

These cutting process controllers have introduced some new problems. They may not perform as designed and may even become unstable or cause tool breakage [2]. This is believed to be the result of the large variations in the static and dynamic behavior of the cutting process. To address this problem it has been proposed that controllers which adapt to these variations in process characteristics be applied to cutting processes such as turning and milling [1,2]. To apply any type of process controller, a model of the process dynamics is required. The modeling and experimental work reported here provides insight into the difficulties that occur with fixed gain feedback controllers when the process parameters vary, as well as the foundation necessary for the effective application of an adaptive controller. The first section discusses the experimental and simulation facilities used in this research. The section on milling models discusses the data collection procedure, the results and a second order model of the process and how this model changes when the cutting conditions change. This model is quite useful in the explanation of the performance problems associated with fixed gain controllers. The final section summarizes the work reported and proposes further research.

EXPERIMENTAL AND SIMULATION FACILITIES

This section describes the experimental system used in our research. Included is a discussion of some of the considerations in selecting manipulated and measured quantities and the required hardware. Also included is a brief discussion of the software used to generate the simulation results shown in later sections.

Digital simulations have been used extensively in this research. These simulations allow us to quickly evaluate controller performance under a wide variety of operation conditions. These simulations are particularly valuable in evaluating the effects of changes in plant parameters on controller performance. It is difficult to use conventional design techniques on complicated transfer functions that have variable coefficients. In addition, adaptive controllers are nonlinear and simulations are frequently the only reasonable method for evaluating their performance.

All simulations in this paper were done on a laboratory minicomputer using the SIMULA digital simulation package developed for this project [5]. The program allows the user to input any set of plant and controller equations. The simulation is then performed by solving the plant equations using a short time step, a fourth order Runge Kutta algorithm and real arithmetic. The controller equations are solved in discrete time using integer arithmetic with a fixed word size. The program also simulates the behavior of the Analog-to-digital converters and the digital-to-analog converters (DAC's) taking into account discretization errors and saturation. Thus, the practical aspects of digital controller design are included, except that the simulations do not run in real time, or include measurement noise.

A diagram of the experimental system is shown in figure 1. The CNC milling machine is equipped with a two horsepower spindle drive and a stepping motor driven table. This mill is a standard commercial unit modified so that the programmed feedrate can be adjusted using a voltage from the (DAC). This allows the computer to adjust the feedrate from 0 to 125% of the programmed feedrate value.

A three component dynamometer is used to measure the cutting forces. This dynamometer mounts on the mill table and uses semiconductor strain gauges to generate signals proportional to the cutting force components. This system is rugged and relatively simple. The main problem with this type of dynamometer is that it adds some flexibility to the system. Since the dynamometer possesses flexibility and mass it acts as a low pass filter, and if not correctly designed, this filtering may occur at a low enough frequency that important information is removed from the from the force signal. The dynamometer used in this study was built in house and has low pass break frequencies of 300 Hz or higher in each direction. Commercial units should be available with higher break frequencies. The 300 Hz unit worked well in our studies since the important frequencies in our experiments were all below 50 Hz. The actual frequencies of interest are determined by the spindle speed and the number of teeth on the cutter.

There are several other approaches reported in the literature for monitoring the cutting process. A common approach is to measure torque rather than forces. There are various methods of measuring torque such as magnetic induction [9], deflections [10], and strain gauges. The torque measurements provide somewhat less information about the process. There is information about the forces but none about the direction of the force. As far as the controllers discussed in this paper are concerned we are only interested in the magnitude of the force so torque measurements could also be used. Another possible measurement of the process is the spindle power. The primary advantages of power measurements is that they are relatively easy to ake and the instrumentation has no significant effect on the signal being measured. There are, however, some difficulties associated with power measurements. These arise from the fact that the power signal contains information about both the process, and how much power is being used to "cut air" (usually referred to as tare power). It is frequently difficult so separate the tare power characteristics from those of the process [11].

The signal from the dynamometer is amplified then passed through a low pass filter. The filter is necessary to prevent aliasing problems due to sampling as well as to eliminate noise resulting from the spindle motor and the stepping motor drives. The filtered signal is read using the ADC. Both the ADC and DAC are commercially available 12 bit converters.

MILLING MODELS: FORCES & DYNAMICS

Before we can do a good job of controlling the milling process we need to understand some things about the dynamics of milling. Specifically, we need to know how the cutting mechanics affect the signals and inputs used for controlling the process. We also need a transfer function that describes the dynamics of the process. It is also interesting to know if the process parameters change with the cutting conditions. These issues are addressed in this section.

Much of the work in tool wear and cutting mechanics is applied to the turning process where the cut is continuous and the depth of cut does not vary as a result of the mechanics of the process. In milling the situation is more complicated. Figure 2 shows the top view of a slot milling operation. The circle in the center of the block is the cutter which would be moving in the direction of the top of the page. For the sake of this discussion assume the cutter has a single tooth.

The first difference between milling and turning is that the cut is an interrupted cut, each tooth of the cutter is cutting for at most a little more than half a revolution. In figure 2 the tool is cutting only from point A to point C. When the tooth is cutting air, from C back around to A, there is no force generated. This interrupted cut produces a series of periodic pulses. The dashed circle in the figure is the path of the tool on the next revolution. Here it is clear that the depth of cut varies throughout the cut. The depth increases from zero at point A to its maximum at B then decreases again to zero from B to C. It can also be seen that the orientation of the cutting forces changes continuously as the cutter rotates.

We have been discussing the forces due to a single tooth. Most milling cutters have two or more teeth. The total force is the vectorial sum of the forces due to each tooth.

The issue is further complicated by the fact that force dynamometers resolve the forces into x, y, z components. The x and y components lie in the plane of the table while z is the thrust direction. The forces shown in this paper are all resultant forces defined as follows,

$$F_R = (F_x^2 + F_y^2) \qquad (1)$$

where F_x and F_y are the x and y force components respectively. The z component is omitted to reduce the computation time because it is small compared to the other two. It is also possible to use only one of the components, but this becomes complicated if the feed is not along the x or y direction. Figure 3 shows the x and y force components as well as the resultant force for a two tooth cutter.

The basic mechanics of milling are covered in a paper by Tlusty and MacNeil [12]. This analysis assumes that the cutter is perfectly mounted and that there is no cutter runout. Based on the analysis in [12] figure 4 shows simulated resultant forces, and actual machining forces, using a 4 tooth cutter. This figure clearly shows some of the complications resulting from runout. This runout may be caused by variations in tooth height or more commonly by tool mounting errors. A more detailed analysis is presented in reference [13] where the effects of runout are accounted for.

In the force feedback controller as well as the adaptive controllers the objective is to adjust the feedrate to maintain a constant force. It is not important to control these periodic fluctuations due to the cutting mechanics or runout. We are interested in controlling the changes that occur because of the variations in the process. The problem is, how to determine if the force level has changed. Some researchers have used peak forces [14]. Dornfeld and Tomizuka [15] used a scheme that integrates the forces over one revolution. We feel that the force signal to be used is determined by the application. If the primary constraint on the force is due to tool breakage peak force is probably the most important. If the primary concern is tool deflection the average force is probably the most useful. A common restriction in optimization studies is the tool wear rate, although it is not clear how the choice of force signature relates to the wear. The controller results presented later in this paper all use a 4 tooth cutter which produces a realitively smooth resultant force. A low pass filter is used to average out the runout effects.

Now that we have a basic understanding of the mechanics of milling we can proceed to the development and evaluation of a dynamic model. It should be noted at the outset that we are not concerned with finding an exact, highly detailed model, but we need to determine the structure of the process model. We are also interested in determining if the parameters in the model vary significantly with cutting conditions. This will determine if adaptive control is necessary. To do this we conducted a series of experiments on the milling of 1020 CR steel. The cutting tool was a 12.7 mm diameter high speed steel (HSS) cutter with four teeth. The process was given a step input voltage to the feedrate override circuit and the forces were sampled. The step took the feed from 25.4 mm/min to 50.8 mm/min. This experiment was repeated at three different depths and at two different spindle speeds. Figures 5 to 8 show the resultant forces.

Several interesting general observations can be made from this data. First, the milling process is usually modeled as being first order. However, the process appears to have the characteristics of a second order system. This is evident primarily at low depths of cut.

To further examine these results the second order transfer function,

$$\frac{F_R(s)}{V(s)} \qquad \frac{KW_n^2}{s^2 + 2\xi W_n s + W_n^2} \qquad (2)$$

has been fit to the data. Table 1 shows the resulting values of the gain, K, the damping ξ and the natural frequency W_n. These values were found by evaluating K from the steady state values. Then, ξ was estimated from the shape of the response and W_n was calculated by fitting the transfer function to the data using the previously obtained values of K and ξ.

The second general observation is that the process dynamics change significantly with the cutting conditions. Fig. 9 to 11 show how K and ξ vary with depth. In this modeling we have assumed W_n remains constant at 3 rad/sec. Fig. 11 shows that the damping increases fairly linearly with depth and decreases slightly with spindle speed. The variation in K is somewhat more complicated. K varies nonlinearly with depth and decreases slightly with cutting speed.

To further examine this a more detailed look at the system is required. The above model represents the dynamic behavior of the entire system including the mill table, feedrate override circuits, the dynamics of the cutting process as well as those of the measurement system. This is the model necessary for controller design, but it is valuable to look at the dynamics of the cutting process independent of the mill and measurement dynamics. Fig. 12 shows a block diagram of the entire controlled system. Here G_{OR} is the tranfer function for the feedrate override circuit.

$$G_{OR} = f_p/3.92 \text{ volts} \qquad (3)$$

where f_p is the programmed feedrate. The next two blocks containing the terms $1/N$ and $1/N_T$ convert the table feed to the feed per tooth, f. N is the spindle speed and N_T is the number of teeth. The dynamics of the dynamometer and amplifier are lumped together in G_D, which over the frequency range of interest can be treated as a simple gain. Normally, the sampled output of the amplifier is convereted back to force units, i.e. the gains of the dynamometer, amplifier and the analog to digital converter are removed. This means that we can treat the system as if the resultant force could be sampled directly. Combining the first three blocks in Fig. 12 and removing the measurement dynamics results in the block diagram of Fig. 13. Since the first block contains only a gain the dynamics must be solely due to the cutting process. Furthermore, since the gain decreases with feed and increases nonlinearly with depth the following model has been fit to the data,

$$\frac{F_R(s)}{f(s)} = \frac{K_s a^{\alpha} f^{\beta} W_n^{2}}{s^2 + 2\xi W_n s + W_n^{2}} \qquad (4)$$

From Fig. 11, the variation in ξ can be modeled,

$$\xi = 0.4 * a - .65 \qquad (5)$$

where a is the depth of cut in mm. K_s is the specific cutting force and includes the effects of tool, and workpiece material, tool sharpness and cutting speed, etc. In this case K_s was found to be 2500 N/mm/tooth. The constant β was found to be 1.4 and α was 0.27.

The model given in equation (4) is somewhat different than those usually used for milling. First, it is a second order model. The process has generally been treated as a first order system [15]. Second, a model frequently used in turning [16] is given by;

$$F_R = Cah^{n} \qquad (6)$$

where C is a constant, h is the average chip thickness and n is a constant, usually less than one. This relationship is similar to that of equation (4). The gain of equation (6) is proportional to the axial depth of cut while our experimental results indicate that the gain is proportional to the depth raised to some exponent. It is also interesting to note that research in turning shows the value of α to be 0.3 [16]. We found a value of 0.27 for α from our experiments.

FIXED GAIN CONTROLLER PERFORMANCE

Now that a suitable model has been developed, candidate controller designs can be evaluated. Two controllers are considered in this section. Both proportional plus integral (PI) and linear model reference controllers (LMRC) have been evaluated using simulations and the PI controller has been implemented on the actual system.

Both controllers were designed for a depth of cut of 2.5mm. When a suitable design was completed the controller performance was simulated with the depth of cut varying from 2mm to 4mm in 1mm steps as shown in Fig. 14.

In the case of the LMRC the reference model was selected as,

$$\frac{Y^*(z)}{R(z)} = \frac{2.075z + 1.944}{z^2 - 1.767z + .787} \qquad (51)$$

where Y^* is the output of the reference model and $r(k)$ is the reference input. This model has the same structure as the actual plant but has an overall gain of 200 and a damping ratio of 0.8. The control law is given by

$$u(k) = -1.767y^*(k) + 0.787y^*(k-1) + 2.075r(k) + 1.944r(k-1) \qquad (8)$$

This produces the performance of Fig. 15 for the design conditions. This performance is acceptable. There is only a small overshoot and the system response has been improved. However, Fig. 16 shows the resultant force when the depth is allowed to vary, and it is clear that the controller is quite sensitive to parameter variation. This performance is unacceptable due to the steady state tracking errors.

Figure 17 shows the simulation results for a PI controller under the same variation in depth of cut. Here the performance is somewhat better. The controller is doing a good job of maintaining the reference force but, there are rather large overshoots at the step changes. If the force constraint is based on tool breakage these overshoots would probably break the tool. In the machining test, shown in figure 18, the overshot is not quite as bad as predicted by these simulations. This is because in the simulations the changes in bepth occur instantaneously across the entire tool. In the actual cut the tool gradually advances into the new depth. This allows the controller to reduce the feedrate before the new depth affects the entire tool. At higher feedrates, however, we expect this effect to be small, and behavior more like that in Fig. 17.

The machining test shown in figure 18 were conducted on 1020 CR steel. The spindle speed was 575 rpm, with a programmed feedrate of 50.8mm/min. The tool was a HSS cutter with four teech as used in the modeling experiment. In the first section of the cut, at the 2 mm. depth, the controller saturates before the reference value is reached. Figure 19 shows the feedrate versus time. In the 3mm. depth the feedrate is reduced then further reduced in the 4 mm depth. Finally the feedrate is increased to the maximum value as the tool exits the cut.

Figure 20 shows the resultant force in machining Aluminum. Here the depth of cut is constant at 4 mm and the spindle speed has been increased to 1200 rpm. In this case the performance is much worse than that for steel. When the tool begins to enter the work there is a 50% overshoot which takes approximately 20 seconds to decay.

SUMMARY & CONCLUSIONS

The purpose of the work presented in this paper was to develop a model for the milling process that could be used for controller design and to examine the effects of changes in the process on the parameters of the model. We were also interested in how these changes affect the performance of fixed gain controllers. The main results can be summarized as follows:

1) The milling process mechanics produce a periodic flucuation in forces. This is due to the interrupted cut, and the varying radial depth of cut. The choice of signal processing to be applied is dependent on the nature of the force constraint.

2) The data presented in this paper indicates that the milling process posseses dynamics of higher order than the first order model frequently used. We have chosen a second order transfer function of model the cutting process dynamics.

3) The parameters of this second order model vary significantly with cutting conditions. The gain of the system increases exponentially with the axial depth of cut. The damping of the system also increases linearly with depth. Both vary with material properties.

The primary conclusion to be drawn from this work is that the variations in the process can cause degradation in the performance of fixed gain controllers. Furhtermore, these problems may occur in a very unpredictable manner. Because the changes in damping and gain have opposite effects on the stability of the system, there may be regions where the performance is acceptable, others where the controller is unstable or where the performance is sluggish but stable. These performance problems clearly indicate the need for an adaptive process controller.

This work has also pointed out three areas where work is needed:
(i) Further research in tool wear is need so that its role in process control can be established; (ii) Further work is required to accurately characterise and explain the dynamics of the milling process; (iii) Further research is indicated in applying adaptive control to the milling process. We will be pursuing this third area of research during the final six months of the project.

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PROGRAM OBJECTIVES FOR 9/84 TO 2/85: During the final six months of the project we will finish our proposed work by conducting cutting tests using an MRAC based process control system for milling. These tests will produce results for direct comparison with the test results presented in this report. We will analyze and interpret the results of these tests and prepare a final report summarizing our observations and recommendations.

DOCUMENTATION: References [1-7] from the above list are available upon request.

COLLABORATORS: During the course of the study we have had assistance in the form of tool and workpiece material donations from General Electric's Carbolloy Division, Kennametal Inc., and TRW Inc. Dr. William Powers from the Ford Scientific Research Laboratory has been participating as a member of the doctoral thesis committee for L.K. Lauderbaugh. Also, presentation of

this work to members of the UM Consortium of Diagnostic Sensing and Control for Metal Cutting has provided useful feedback. These members include Caterpillar, Deere and Company, Eaton, Ex-Cell-O, General Electric, Giddings and Lewis, and Lodge and Shipley. Professor Yoram Koren of the Technion-Israel Institute of Technology has continued his participation in the project even though he is no longer at the University of Michigan. He came to the UM during August 1984 and consulted with us on the project.