A New Method for Tool-Path Generation and Adaptive Interpolation of A Three-Axis CNC Milling Machine

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Abstract- *In this paper we present a new method for tool-path generation and adaptive interpolation for a three-axis CNC milling machine. This method satisfied the force and / or the error conditions by using a variable-direction variable-feedrate strategy based on Maximum Feedrate Map. The proposed adaptive interpolator modifies the cutting path and the moving direction according to the actual instantaneous position error in real time. It also adaptively slows down the speed of the cutting tool if the position error exceeds a permissible threshold so as to decrease the error. As the cutting points on the spline at each cycle are not calculated beforehand, memory requirement for the interpolator drastically reduces. The significance of the proposed method on the reduction of the cutting error in the presence of disturbance is demonstrated via computer simulations.*

Keywords: *Maximum Feedrate Map - Path Planning - Adaptive Interpolation.*

1- Introduction

In order to increase the efficiency of CNC machines and to prevent undesirable events such as the increase of the cutting error and excessive deflection or breakage of the cutting tool during the machining process, there have been proposed several methods for optimal generation of cutting tool-path and feedrate profile [1, 2, 3, 4].

However, in the traditional methods, tool-paths remain fixed and feedrate value is chosen constant along each path. This requires the part programmer to choose the feedrate value of the entire path based on the *worst-case strategy*. With such a method, the point on the path that has the largest axial and radial depth of cut and/or the biggest amount of curvature would be used to compute the feedrate value such that the cutting force and/or position error does not exceed the permissible thresholds for that point.

The worst-case strategy obviously results in slow machining process and low productivity of the CNC machines. Using the new techniques, the feedrate value at each point of the cutting tool-path is computed according to the maximum permissible values of the cutting force and the machining error. This would decrease the feedrate value in the critical areas of the cutting path that have larger curvature or larger depth of cut. By such methods, not only the machining period reduces, but also the conditions of maximum permissible force and error are satisfied during the machining.

One of the best techniques for off-line optimization of the cutting tool-paths and feedrate profiles is that of the *Maximum Feedrate Map,* which was proposed in 1997 for the first time [1]. The method given in [1] is for ball-end milling in a three-axis CNC machine. However, the method may well be used for rough machining, semi-finishing and finishing levels. Moreover, by considering both force and error models, force and error conditions will be simultaneously satisfied during the machining period. The strategy for the generation of the cutting tool-paths and feedrate profiles by using the maximum feedrate map can be classified in three different modules, which are summarized below [1]:

1- Control point selection module: In this module, first, the *control surface,* which is the final desired surface to be produce, is projected on the *X-Y* plane. Then, several *control points* are selected on the projected surface. For simplicity, the control points are usually equally spaced along *X* and *Y* axes and the density of the points in the entire projected surface is chosen constant.

2- Maximum feedrate map module: In this module, *maximum feedrate boundaries* are generated for each control point of the surface. The distance between a control point and any point on its maximum feedrate boundaries is proportional to the maximum allowable feedrate value of the cutting tool when moving along that direction, and the points inside the maximum feedrate boundary show the allowable feedrate values for different directions.

   The maximum feedrate map may be generated using force and/or error models. If both force and error models are used, two different maximum feedrate boundaries are generated for each control point. The points that lie within both boundaries determine the allowable feedrate values that satisfy both conditions.

3- Cutting path and feedrate selection module: In this module, optimal cutting tool-paths and feedrate profiles are determined using the following rule: *On each of the control points, the optimal direction of movement of the cutting tool is the one that is relative to the maximum feedrate value. The feedrate value corresponding to the optimal direction is the optimal feedrate value.*

In most CAD/CAM systems, the data that specify the cutting tool-paths and the machining parameters are stored in a DXF file format. The cutting paths are usually divided into several simple segments such as straight lines or circle arcs. In some CAD/CAM systems, these pieces of information are converted to G-code commands, which can be executed by the CNC machine, while in others these simple paths are defined by Spline functions.

In each machine cycle, the interpolator calculates the next position of the cutting tool using the current tool position and the shape of the path. At the beginning of the next machine cycle, the new desired position is fed to the position control loops of different axes as the reference input, and the tool moves towards this position during that machine cycle.

The methods that have been previously proposed for automatic computation of the feedrate mostly make use of the error analysis. These methods may be used for on-line or off-line computation of the feedrate. For example, in [1,2,5], off-line computation of feedrate has been discussed. In case of on-line feedrate computation, the interpolator and/or the controller may be adaptive. In [6], feedrate values are computed on-line so that some limitations such as maximum error, maximum acceleration, the required speed of the servo system, and the continuity of differential paths are satisfied. In [7], a cross-coupled controller for feedrate is proposed that is based on the interaction of the errors of different axes. Adaptive controllers may also be used for the purpose of restricting error [8], preventing chatter [9, 10], and compensating the errors caused by thermal effects [11, 12, 13].

One of the major problems in adaptive interpolators is position error due to the existence of unavoidable transients. The ongoing change of the target position with various target feedrates results in ongoing transient. Since the actual position of the cutting tool at the end of the machine cycle is not necessarily the same as the reference position due to the controller time constant, there will remain some amount of position error. Generally, the cutting tool moves close the cutting path instead of moving exactly on it. As the controller alone cannot totally remove this error, the need for modifying set point position by the interpolator becomes obvious.

In this paper, we will design an adaptive interpolator for a more accurate tool-path generation and compensation of the position error in a three-axis CNC milling machine. As usual, the optimal feedrate values and the cutting directions on each of the control points will be hypothetically derived from the maximum feedrate map. For each cutting path, these values will be fed into the memory of the on-line interpolator to generate cutting points in real time. As the cutting points on the spline curve for each cycle are not calculated beforehand, the memory needed for the interpolator will be minimized. The interpolator modifies the next position value that was generated by spline function so as to diminish the predicted transient error due to the controller. The interpolator will also modify the target position and the feedrate based on the actual current position error. Thus, machining will be accomplished using the optimal cutting paths and feedrate profiles, and in each machine cycle the interpolator compensates the deviation of the cutting tool from the desired path. In the next sections, we will discuss our method in detail, and we will compare the proposed method with the traditional ones by means of computer simulations.

2- Design of the Interpolator

In this paper, a novel adaptive interpolator has been proposed for a three-axis CNC machine. Since our design is based on the maximum feedrate map, adaptive interpolation is merely undertaken along X and Y axes while the position of the tool along Z axis is obtained by directly interpolating the data in the CAD model based on the target position given by adaptive interpolator in X-Y plane.

Figure 1 shows the general diagram of the system consisting of the path planner, adaptive interpolator, controllers, drivers, and motors of a three axis CNC system.

The discrete data that define the desired paths and the feedrate values on the paths are produced in the path planner based on the Maximum Feedrate Map and the data of the current path are temporarily stored in the memory of the interpolator. These data consist of the cutting tool positions along X, Y, and Z axes and the corresponding feedrate values only for the control points on the current path. The cutting data corresponding to the points between these control points are computed on-line by means of Spline functions. When the movement of the cutting tool on the current path is completed, the control points in the memory of the interpolator are replaced with the new points corresponding to the new path. The online computation of the tool position and feedrate drastically reduces the volume of the cutting data. Besides, since the cutting paths are not approximated by several differential paths, the accuracy of the tool-path generation is increased.

After the interpolator computes the current reference positions for all axes at the beginning of the machine cycle, it feeds them to the three position loops of the machine. As can be seen in Figure 1, the actual positions of the cutting tool are also fed to the on-line interpolator and the next reference positions are modified by means of these values.

As we mentioned, due to the controller time constant, the cutting tool usually follows the desired cutting path with some ongoing transient errors. To investigate a remedy for this problem, let us assume curve C in Figure 2 is the desired path that the cutting tool should traverse in X-Y plane along Y^{+} direction. Further, assume that point A is the actual position of the cutting tool at the beginning of one of the machining cycles, and A_1 is the point on curve C that has the same ordinate as point A along Y direction. Similar to the calculation of desired positions, the desired feedrate values are calculated by Spline functions using discrete values of feedrate at control points on curve C. Let $f_x(y_1)$ denote the desired feedrate value along X axis at point A_1, where y_1 is the ordinate of point A_1. Therefore, $T{\cdot}f_x(y_1)$ is the desired distance that the cutting tool should move during the machine cycle T. If we draw a hypothetical circle centered at point A with a radius equal to $T{\cdot}f_x(y_1)$, it will generally intersect path C at two different points R and S. Since we suppose the cutting tool moves along the Y^{+}

direction, point R, which has greater Y coordinate relative to S, is considered as the next reference point and its coordinates are fed to the X and Y position control loops.

If the machine cycle is large enough relative to the time constant of the position loop, then after time T, the cutting tool will be exactly on the path. Although this would make the machining error zero at the beginning of each machining cycle, it is not practical as it causes the cutting tool to come to rest at the end of each machine cycle. In other word, in this case, the tool stays on each of the reference positions. This can be harmful to the mechanical parts of the machine and prevents continuous contouring. Practically, the machine cycle length is such that before the cutting tool reaches the current reference position, the next reference position is defined for the tool. This causes some predictable position inaccuracy in tool-path generation as the cutting error remains in each cycle. In Figure 2, point B is the point that the cutting tool actually reaches in the next step, and thus, the distance between point B and the desired curve is the introduced error.

3- Improved Method for On-Line Path Generation

The above-mentioned inaccuracy can be reduced by the improved method that we propose here. In Figure 5, a typical step response of the position loop along X axis is shown. In this figure, $T{\cdot}f_x(y_1)$ indicates the desired tool displacement along X axis during one machine cycle. If the current position of the cutting tool is zero, then after time T the tool displacement along X axis is equal to d_1, which could be simply estimated using the step response of the position loop and the value of T.

Now, let us consider the movement of the cutting tool along both X and Y axes. Due to small movements in each machine cycle, the tool moves from the current point to the next reference point on a straight line. Since after time T the cutting tool essentially reaches to point B, we can write the following identity:

$$AB/_{AR} = d_1/_{T \cdot f_x(y_1)} \qquad (1)$$

Let us define scaling factor s as:

$$s = \frac{T \cdot f_x(y_1)}{d_1} \qquad (2)$$

where factor s is greater than unity. Since point B in Figure 2 is not located on the circle, the actual feedrate is smaller than the desired feedrate by the above factor. Besides, the position error is not fully compensated in each machine cycle.

The first problem can be easily solved by increasing the feedrate value according to the following equation:

$$\hat{f}_x(y_1) = s \cdot f_x(y_1) \qquad (3)$$

where $\hat{f}_x(y_1)$ is the modified feedrate at point A. Although, this achieves the desired feedrate, an important part of the position error still remains since the desired length of traverse is not properly modified. To solve this problem, it is reasonable to choose another reference point that is farther from R relative to the current point A and on the direction of AR. This point is shown in Figure 3 as point D whose distance from A is calculated from the following equation:

$$AD/_{AR} = AR/_{AB} \qquad (4)$$

Using definition given in (2), we have:

$$AD = s \cdot AR \qquad (5)$$

Practically, because of the kinetic inertia of the system this ratio should be chosen a little smaller. The improved method can be compared with the method in which the feedrate is scaled but the desired length of traverse is not modified. As shown in Figure 3, in the improved method, the cutting tool moves along an almost straight path towards point D. At time T, the cutting tool will be almost at point R, which is on the desired path C. Therefore the position error is vanished theoretically at the end of each machine cycle. However, if we had modified the feedrate value without modifying the desired length of traverse, then the next point would have theoretically been point F, which is the intersection of the desired path C and a circle with radius equal to $s{\cdot}T{\cdot}f_x(y_1)$. In this case, after time T the cutting tool would have been practically on point E. Although in this case the cutting tool would have moved with the desired speed, there would have remained some position error whose amount is equal to the distance between point E and curve C.

4- Adaptive Interpolation for Error Reduction

The proposed interpolator has also ability to adaptively reduce the feedrate when the position error exceeds a permissible threshold due to disturbances. This causes error to be always restricted below a threshold defined by the user. As was shown in the block diagram of Figure 1, the actual position of the cutting tool is fed back to the interpolator. This feedback information is used to eliminate error due to unavoidable transient when the machine works in normal condition. We can also use this information to reduce error due to disturbances. The disturbance could be as a result of changes in the hardness the part material from that of the information used to produce the Maximum Feedrate Map, changes in the sharpness of the cutting tool, and changes in friction due to variations in the quantity and quality of lubrication, etc.

To incorporate this capability, we have defined a feedrate reduction curve, which is the value of a feedrate reduction factor as a function of position error. If the position error exceeds a threshold, the feedrate value is immediately multiplied by the feedrate reduction factor that is smaller than unity. The more the position error exceeds the threshold, the more the feedrate value is decreased. The feedrate value remains as computed originally when the position error is lower than the threshold. This function can be defined as:

$$k_f = \begin{cases} 1 & \text{if} \quad er \le er_{th} \\ \exp\left[-\dfrac{er - er_{th}}{\sigma} \right] & \text{if} \quad er > er_{th} \end{cases} \qquad (6)$$

where k_f is the feedrate reduction factor, er is the distance between the desired position and the actual position, er_{th} is the threshold error, and σ is a time constant to be chosen such that the interpolator yields satisfactory performance. In our simulations er_{th} and σ were chosen 1×10^{-4} mm and 3.33×10^{-4} respectively. Figure 4 shows the curve of the feedrate reduction factor as a function of position error. This curve should be tuned carefully to have a proper error reduction. If the feedrate values are originally determined by means of the maximum feedrate map using both force and error analysis, then the error reduction will be done more accurately relative to the case that the maximum feedrate map is generated only using the cutting force analysis alone.

5- Design of the PID controller

A PID controller was designed for each axis of the CNC machine. The PID controllers diminish the steady state error of the position loops and provide desirable step response. Several methods may be used for the computation of the PID gains. The method that we used is that of the CHR. A 15dB gain margin and 65.75 degree Phase margin was achieved for the closed loop system, which are quite satisfactory.

The set point for the PID controller is calculated by the on-line interpolator. The error signal, which is the difference between this value and the actual position of the cutting tool, is fed to the PID controller, which, in turn, provides velocity set point for the driver of the corresponding axis. The torque generated by the motor overcomes the cutting torque disturbances, and the current position of the tool for each machine axis is measured through its encoder.

6- Simulation Results

In Figure 6 the block diagram of the overall simulated system including the interpolator, the controller, and the process is displayed. The diagram has been defined in the Simulink toolbox of MATLAB. The Drive and process blocks include the velocity loops of the X and Y axes and motor dynamics. In the interpolator block, the reference inputs for the position loops are computed on-line.

In all simulations, the sampling period is chosen three milliseconds while the time needed to get a steady state response of the position loop is approximately 15 milliseconds. In Figure 7, the desired cutting tool-path in the X-Y plane as well as individual axes versus time are displayed. In the simulations, we have imposed a step-shaped Torque disturbance to the process to investigate the ability of the system to reject it.

A hypothetical feedrate profile is also chosen for the path and is shown in Figure 8. As stated before, this curve can be produced by interpolating the control points in the maximum feedrate map.

Simulation #1:

In the first simulation, we used the original method of interpolation, not the improved one. We have also deactivated the adaptive interpolation mechanism. The results are displayed in figures 9 and 10.

It is seen from the figures that the desired feedrate profile has been achieved. The error curve has two significant local maxima, which occurs at t=0.17 sec and t=0.6 sec. The first maximum which is approximately 3×10^{-4} mm, is due to the tool-path generation and this type of error is reduced in the next simulations by the improved and adaptive methods. The second local maximum of the curve is due to the disturbance imposed on the system and the generated error is vanished by the PID controller immediately. The control signal and the motor voltage curves are displayed in Figure 10.

Simulation #2:

In this simulation by using the improved method, the machining error due to the tool-path generation has been decreased to 2.2×10^{-4} mm that is approximately 27% lower than what we achieved from the previous simulation. The results of this simulation are shown in figures 11 and 12.

Simulation #3:

In this simulation using the proposed methods of adaptive interpolation and the improved method, the error of the tool-path generation has been restricted in the $[0 \;\; 1.6\times10^{-4}]$ mm interval. Simulation results are displayed in Figures 13 and 14.

In this simulation, the interpolated feedrate profile is lower than the original curve in some time intervals and this is the reason why the machining error has been decreased. The feedrate is also decreased when the disturbance has been imposed but the fast restriction of this type of error is mainly due to the action of the PID controller and not the interpolator. It should also be noted that the restriction of the tool-path generation error (i.e. the first local maximum) is completely done by means of the interpolator and the PID controller does not observe this type of error at all.

7- Conclusion

In this paper, we proposed a new method for on-line interpolation and reduction of the position error in a three-axis CNC milling machine. The adaptive interpolator modifies the cutting path and the moving direction according to the instantaneous position error at each cycle. It also slows down the cutting tool speed if the position error exceeds a permissible threshold based on a feedrate reduction curve. Since the proposed method uses a variable feedrate strategy, force and error conditions can be optimally satisfied, and the efficiency of the machine increases considerably. We also showed by simulations that our method has considerable effect on the reduction of the cutting error.

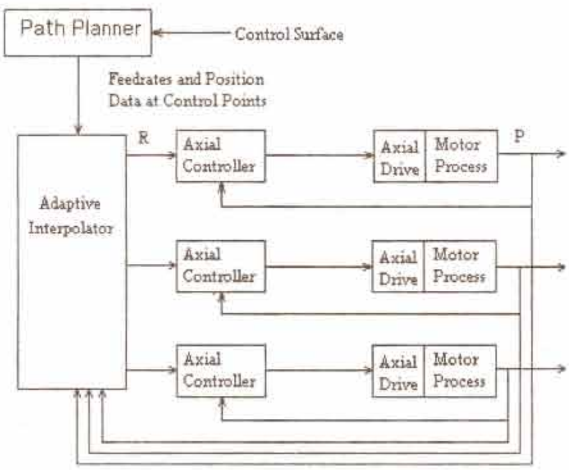

Figure 1 The general diagram of the system.

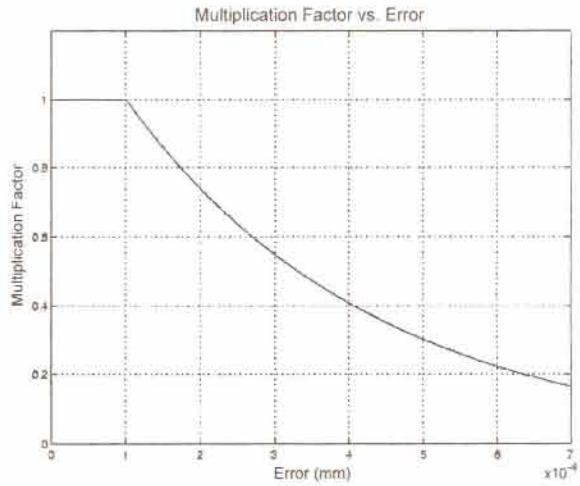

Figure 4 Feedrate reduction curve.

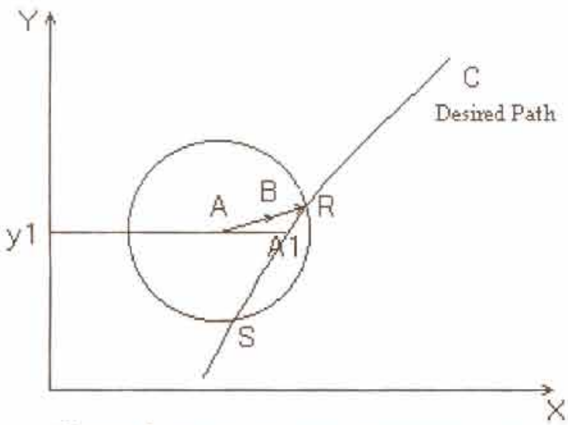

Figure 2 Finding the next desired position.

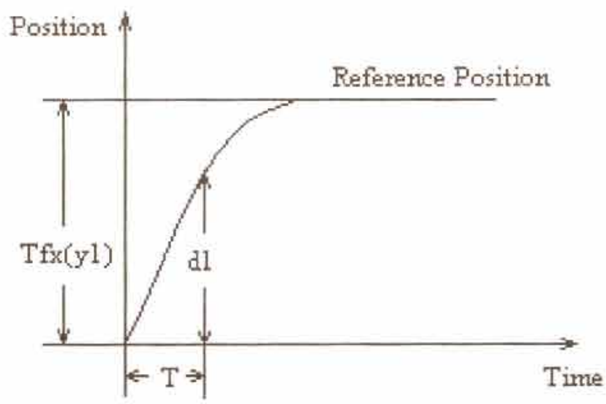

Figure 5 Typical step response of the position loop.

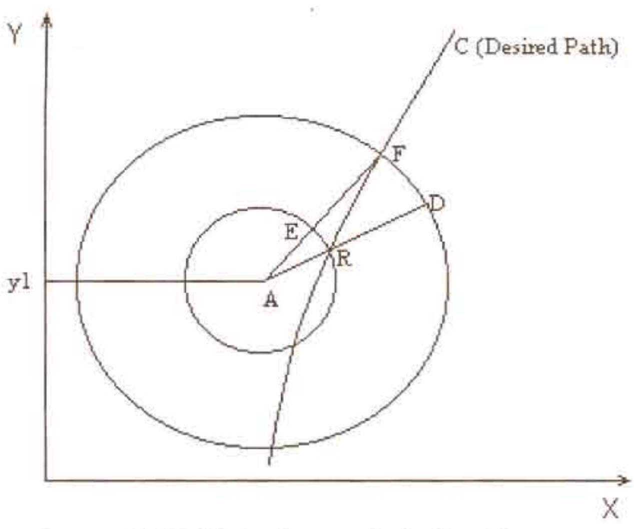

Figure 3 Modifying the next desired position.

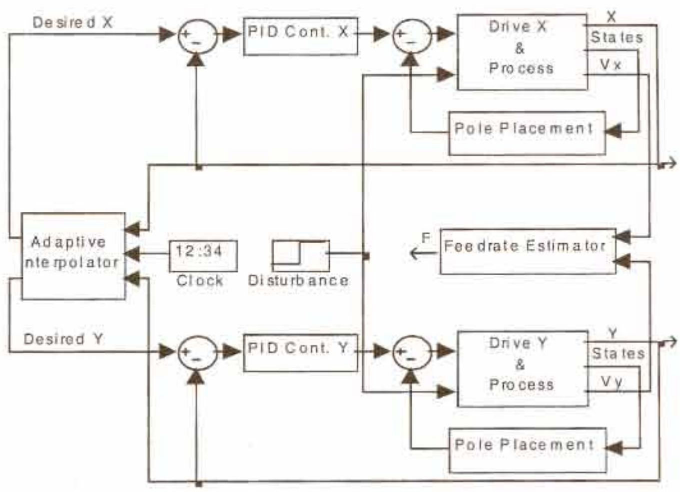

Figure 6 Block diagram of the overall system.

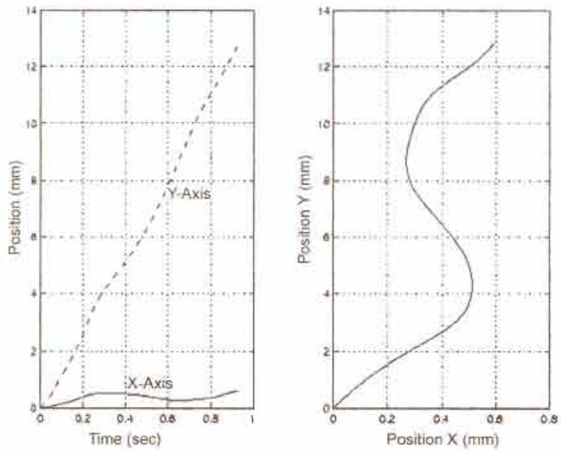

Figure 7 Cutting tool-path in the *X-Y* plane and for individual axes.

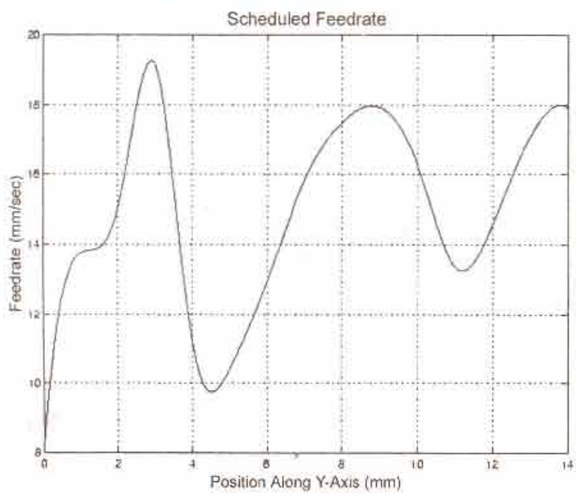

Figure 8 The feedrate profile.

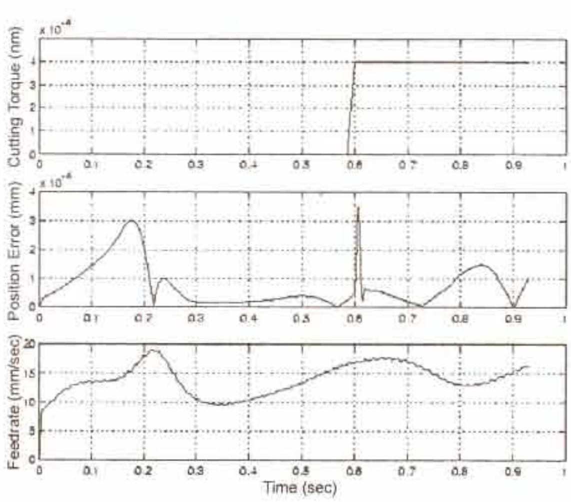

Figure 9 Cutting Torque, position error, and actual feedrate for Simulation #1.

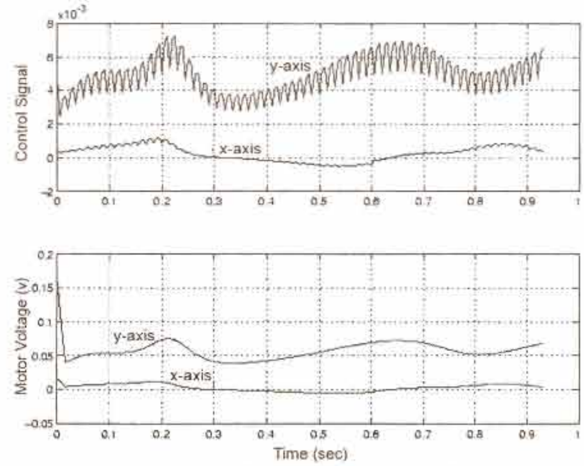

Figure 10 Motor voltage and control signal for Simulation #1

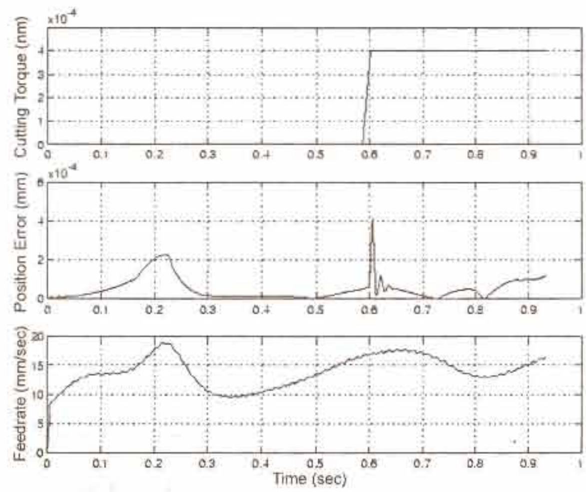

Figure 11 Cutting Torque, position error, and actual feedrate for Simulation #2

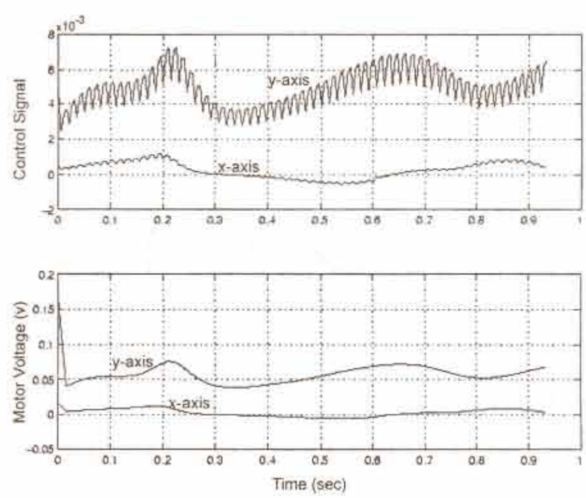

Figure 12 Motor voltage and control signal for Simulation #2

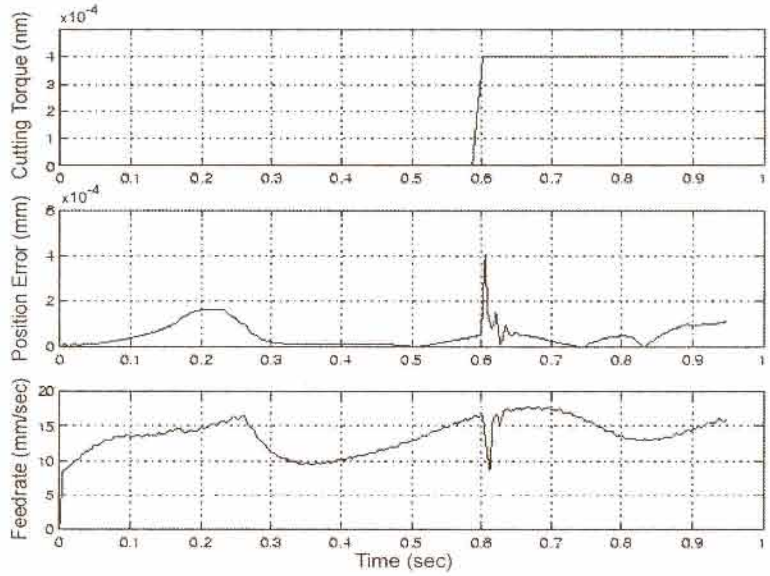

Figure 13 Cutting Torque, position error, and actual feedrate for Simulation #3

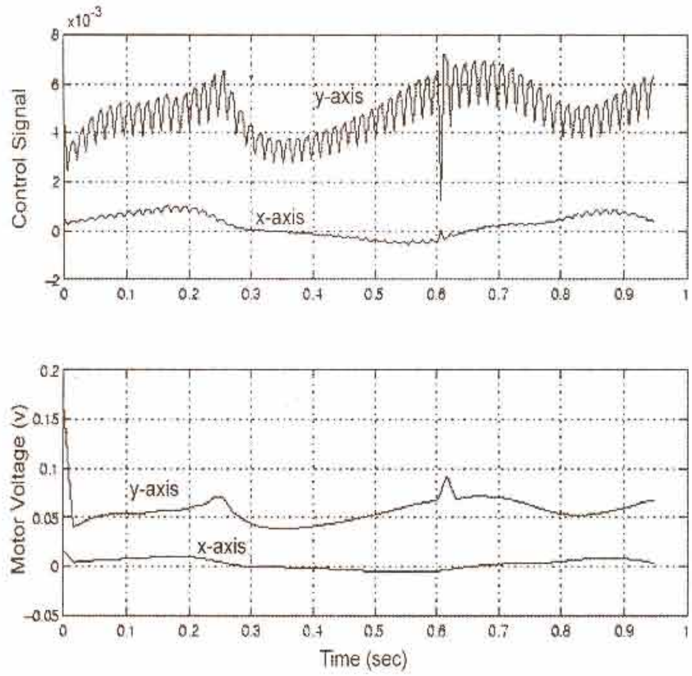

Figure 14 Motor voltage and control signal for Simulation #3

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