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Y-2186

A MACHINE-TOOL CONTROL SYSTEM FOR TURNING NONAXISYMMETRIC SURFACES

S. S. Douglass
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A MACHINE-TOOL CONTROL SYSTEM FOR TURNING NONAXISYMMETRIC SURFACES

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ABSTRACT

A development program has been initiated to allow on-axis turning of nonaxisymmetric surfaces. A short-travel high-speed slide is mounted on a precision, numerically controlled, two-axis turning machine. The motion of the auxiliary slide is synchronized with the spindle and the two remaining slides. This report defines the workpiece geometry and requirements, calculations for the slide motion, techniques for real-time command generation, and planned equipment set.

CONTENTS

SUMMARY

An attempt to broaden the capability of an existing, numerically controlled turning machine to include the generation of nonaxisymmetric surfaces has been initiated. An auxiliary slide, synchronized with the spindle and the two remaining slides, provides the short, high-speed motion required by the workpiece nonaxisymmetry.

Although the results of this effort to determine the feasibility of generating nonaxisymmetric contours by turning will be compared with the specified performance goals, primary interest lies in extending the state of the art. Thus, the program can be viewed as successful even if the somewhat stringent performance goals are not fully satisfied.

INTRODUCTION

Turning constitutes one of the most-important and frequently employed manufacturing operations. Besides generating surfaces of revolution, turning provides an excellent combination of close-tolerance shaping and high material-removal rate. Consequently, extensive development effort has been invested at the Oak Ridge Y-12 Plant[a] to improve turning machines, tools, sensors, and other system components.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the Department of Energy.

NONAXISYMMETRIC SURFACE TURNING SYSTEM

NEED FOR A HIGH-SPEED SLIDE CAPABILITY

Currently, turning operations continue to be confined basically to the generation of axisymmetric contours; ie, all cross sections perpendicular to the axis of symmetry are circular. To produce noncircular cross sections, one slide must be driven synchronously with spindle rotation. However, spindles are often operated at speeds greater than 100 rpm for two reasons: (1) the cutting action, and, consequently, the surface finish, tends to deteriorate when the surface speed is below a material-dependent minimum; (2) economic considerations demand the highest possible material-removal rate. Therefore, because of a relatively high spindle-speed requirement, synchronization of slide motion with spindle speed is extremely difficult. Although the desired motion may be described mathematically with only two linear axes, physical realization of the required response is impossible because of the slide masses. The only known industrial turning machines operated in this manner are the "bottle" lathes, whose spindle speeds are usually below 100 rpm and whose accuracy is relatively coarse.

Several applications exist where high-speed slides, such as those just described, would be particularly valuable. These applications can generally be categorized as having either nonaxisymmetric contours or special features (either elevations or depressions) on otherwise axisymmetric contours.

Examples of the first category are the parabolic reflector surfaces, required in the optics industry, wherein high accuracy is demanded in both shape and surface finish. A parabolic surface can certainly be produced by rotation about its axis of symmetry. Consider, however, the off-axis parabolic sector illustrated by the shaded area in Figure 1.

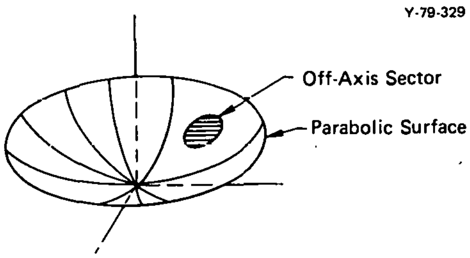

Figure 1. OFF-AXIS SECTOR OF A PARABOLIC SURFACE (Concave Upward)

This particular sector is not a figure of revolution about any intersecting axis and, hence, cannot be turned directly. Generation of off-axis sectors by conventional means requires either that the entire parabolic surface be turned to obtain only the isolated sector or that a very expensive manual operation be applied to the selected portion. If the distance from the off-axis sector to the axis of symmetry is sufficiently large, the first alternative may be impossible because of insufficient machine capacity. A synchronized high speed could, therefore, provide a strong economic improvement in the manufacturing of these surfaces.

An example of the second category is a groove or depression that is necessary for assembly with a mating part. Close-tolerance machining of the feature is required for reasons of strength or weight distribution. If this feature can be generated simultaneously with the surrounding surface, the cost of production should be reduced significantly.

DESCRIPTION OF THE PROPOSED SYSTEM

The configuration of a typical, high-precision, numerically controlled turning machine is illustrated in Figure 2. The workpiece is mounted on the face of the spindle which is fixed on the Y slide. The cutting tool is attached to the end of the boring bar mounted on the X slide.

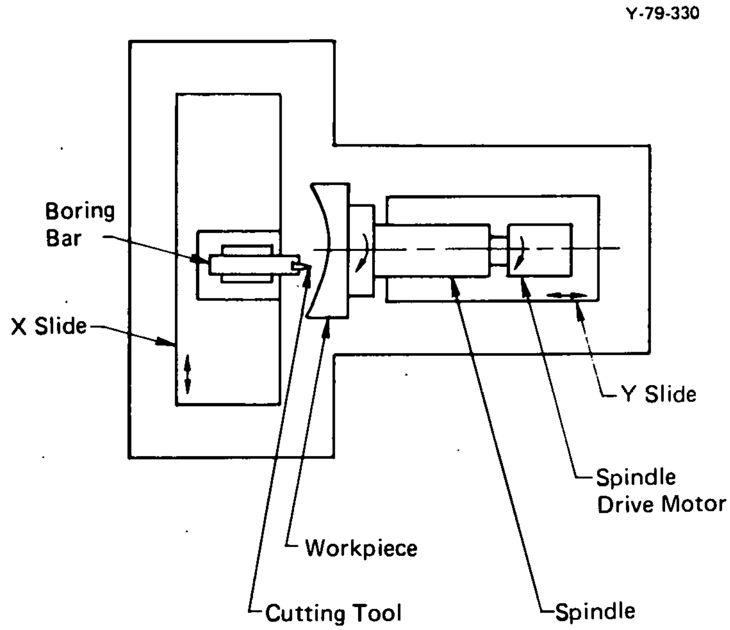

Figure 2. TYPICAL NUMERICALLY CONTROLLED TURNING MACHINE.

Slide motions are provided by rotation of a precision lead screw within a nut fixed to the slide. The lead screw is driven by a motor (either electric or hydraulic) controlled by the machine control unit. To follow a prescribed path, position and velocity information for each slide is read from a punched tape into the machine control unit (MCU). Feedback of the same quantities from slide sensors to the MCU closes the system loops. Since the slide motions are coupled only by command inputs, the accuracy of the generated surface depends on the ability of the MCU to match the two motions in time. Generally, this requirement can be met since the slide response is usually much faster than the rate at which new commands are issued. The motions, therefore, are essentially steady state.

For the most part, MCU control of the spindle is limited to speed control through tachometer feedback. Except for machines which possess a threading capability, no effort is generally made to account for the spindle rotational position.

An indication of the success of the present control systems in performing their function is reflected by the quality of the generated surfaces. In a solid, easily machined metal part, a spherical surface can be produced to tolerances of less than 10 μm (400 μin). By incorporating improvements such as air bearings, diamond tools, and laser interferometers, the accuracy can be improved further by more than an order of magnitude.

The capability to generate nonaxisymmetric surfaces with existing turning machines requires a number of additions and modifications. Figure 3 illustrates the machining system planned for this project. The existing X and Y slides will generate the primary linear motions, while a third slide (denoted Z) will be mounted on the X slide. With the cutting tool now fixed on the Z slide, nonaxisymmetric contours can be produced.

The development activities associated with the project can be separated into three basic areas.

1. Provide a slide and control system with sufficient stiffness and speed to permit the accuracy goals detailed. This is basically a closed-loop control problem.

2. Synchronize the motion of the Z slide with that of the two remaining slides and the spindle. Since no account is presently made of the spindle rotational position, some means must be provided for referencing the Z-slide motion to the spindle.

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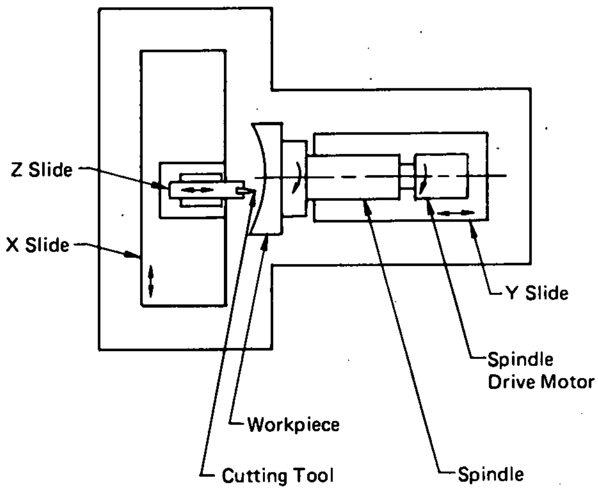

Figure 3. TURNING MACHINE WITH SLIDE ADDED.

3. Generate commands to the Z-slide control system. Conventional reading of punched or magnetic tape is unlikely because of the rate and number of commands. Hence, the commands will probably have to be generated in real time.

After the objectives of the project are defined, a mathematical development is shown which prescribes the motion requirements of the Z slide. This development is followed by the explanation of the technique planned for generating the Z-slide commands as synchronized with spindle rotation. Finally, a description of some of the planned equipment is included.

DEFINITION OF OBJECTIVES

For the purpose of this investigation, the following statement is used to establish the performance goals:

It is desired to produce, by diamond turning, an off-axis parabolic sector defined by (1) a focal length of 2.01 m (79.15 in); (2) a perpendicular distance from the sector center to the axis of the parabola of 0.7112 m (28 in); and (3) a sector diameter of approximately 0.406 m (16 in).

The major thrust of the proposed effort lies in the development of the fast-responding slide and in the synchronization of this slide with other machine motions. It is not intended that the Z-slide control be required to compensate for errors inherent in the basic machine.

DEFINITION OF Z-AXIS MOTION

A paraboloid of revolution about the Z_1 axis with its vertex at the origin is defined by

$$Z_1 = \frac{X_1^2 + Y_1^2}{4p} = \frac{X_1^2 + Y_1^2}{c} \tag{1}$$

where (0, 0, p) are the coordinates of the focus and $Z_1 = -p$ defines the plane of the directrix. Figure 4 illustrates a cross section of this surface.

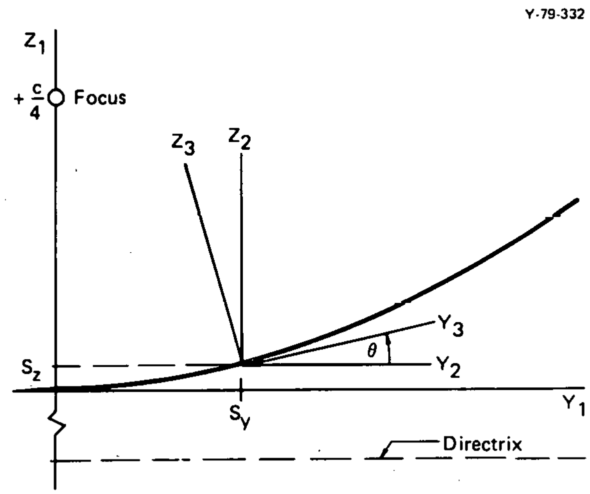

Figure 4. DEFINITION OF COORDINATE SYSTEMS.

A new coordinate system is desired to describe (in a particular fashion) a relatively small, off-axis sector of the parabolic surface. Let the sector of interest be centered at (O, Sy, Sz). The desired coordinate system has its origin at this point, and the transformed Z_1 axis is normal to the surface of the paraboloid at the new origin. Two coordinate transformations—the first pure translation and the second pure rotation through an angle θ—produces the equation of the paraboloid in the new coordinate system.

Translation:

$$\begin{aligned} X_1 &= X_2 \\ Y_1 &= Y_2 + S_y \\ Z_1 &= Z_2 + S_z \end{aligned} \tag{2}$$

where

$$S_z = Z_1 \Big|_{\substack{X_1 = 0 \\ Y_1 = S_y}} = \frac{S_y^2}{c} .$$

Rotation:

$$\begin{aligned} X_2 &= X_3 \\ Y_2 &= Y_3 \cos\theta - Z_3 \sin\theta \\ Z_2 &= Y_3 \sin\theta + Z_3 \cos\theta \end{aligned} \tag{3}$$

where

$$\tan\theta = \left.\frac{\partial Z_2}{\partial Y_2}\right|_{\substack{X_2=0\\ Y_2=0}} = \frac{2S_y}{c}\ .$$

Application of these transforming relations to Equation 1 yields

$$Z_3 = a_1 + (\cot\theta)Y_3 - a_1\sqrt{1 + a_2Y_3 - a_3X_3^2} \qquad (4)$$

where

$$a_1 = \frac{S_y}{\sin^3\theta}$$

$$a_2 = \frac{2\sin^2\theta\,\cos\theta}{S_y} \qquad (5)$$

$$a_3 = \frac{\sin^4\theta}{S_y^2}\ .$$

If these rectangular coordinates are, in turn, transformed into cylindrical coordinates by

$$X_3 = \bar{R}\cos\phi$$

$$Y_3 = \bar{R}\sin\phi \qquad (6)$$

$$Z_3 = Z_3\ .$$

Equation 4 takes the form

$$Z_3 = a_1 + (\cot\theta)\bar{R}\sin\phi - a_1\sqrt{1 + a_2\bar{R}\sin\phi - a_3\bar{R}^2\cos^2\phi}\ . \qquad (7)$$

Figure 5 illustrates an off-axis paraboloidal surface in the $\bar{R}\phi Z_3$ coordinate system. As defined in Equation 6, the origin of ϕ is along the X_3 axis.

Figure 5 also illustrates the edge of a cutting tool of radius, r_t, whose center is located R_{tc} from the spindle axis. The line from the tool center to the point of tangency of tool and paraboloid forms the angle α with Z_3 axis. This angle is defined by

$$\alpha = \tan^{-1}\left(\frac{Z_3}{\bar{R}}\right) \tag{8}$$

or

$$\tan\alpha = (\cot\theta)\bar{R}\sin\phi - \frac{(\cot\theta)\sin\phi - \frac{\sin\theta}{S_Y}\bar{R}\cos^2\phi}{\sqrt{1 + a_2\bar{R}\sin\phi - a_3\bar{R}^2\cos^2\phi}} \,. \tag{9}$$

Since the machine commands are intended to control the path of the center of the tool, Relation 9 is used in the final coordinate transformation.

$$R_{tc} = \bar{R} - r_t \sin\alpha$$
$$Z_4 = Z_3 + r_t \cos\alpha \,. \tag{10}$$

It is seen in Equations 7 and 10 that if R_{tc} (or $\bar{R}$) is fixed, Z_4 is not constant but rather a function of ϕ and, hence, indicates the nonaxisymmetry of the surface.

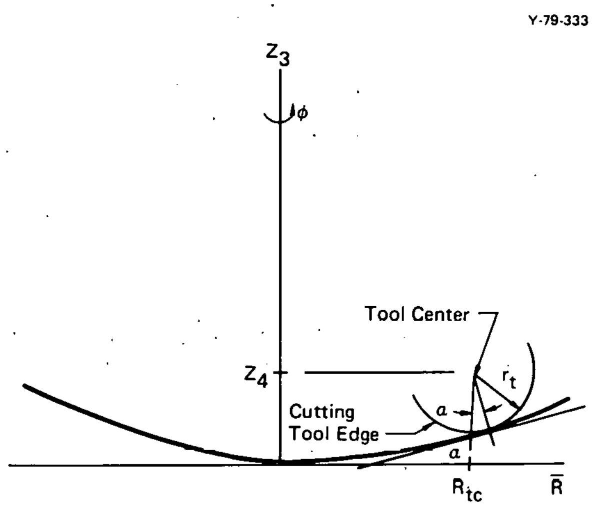

Figure 5. CROSS SECTION OF PARABOLOID IN $\bar{R}Z_3$ PLANE.

The machining system under study replaces the Z_4 (R_{tc},ϕ) motion with two parallel motions

$$Z_4(X,\phi) = Y(X) \pm Z(X,\phi) \tag{11}$$

where $X = R_{tc}$ to conform to commonly accepted numerical control nonmenclature and where the sign in the defining relation will be determined presently. The new machining system, therefore, utilizes the existing axial slide Y to provide the gross portion of Z_4 while a third slide—the Z slide—provides only the ϕ-dependent motion required by the nonaxisymmetry. The Z slide is mounted on the X slide and carries the tool in short motions parallel to the Y slide.

If the Z slide is to provide only the within-rotation variations of the surface in the Y direction, a determination must be made of the surface extrema at an arbitrary, but fixed, value of X.

The condition $\frac{\partial Z_3}{\partial \phi} = 0$ is applied.

$$\frac{\partial Z_3}{\partial \phi} = (\cot\theta)\bar{R}\cos\phi \left(1 - \frac{1 + \frac{\sin^2\theta}{S_y \cos\theta}\bar{R}\sin\phi}{\sqrt{1 + a_2\bar{R}\sin\phi - a_3\bar{R}^2\cos^2\phi}} \right). \tag{12}$$

Two unequal minima are found at $\phi = \pm\frac{\pi}{2}$. The absolute minimum occurs at $\phi = +\frac{\pi}{2}$ and yields

$$Z_{3,min}(\bar{R}) = a_1 \left(1 - \sqrt{1 + a_2\bar{R}} \right). \tag{13}$$

Two equal maxima are found at

$$\phi = \sin^{-1}\left[-\left(\frac{S_y \cos\theta}{\bar{R}\sin^2\theta} \right) \left(1 - \sqrt{1 - \frac{\bar{R}}{S_y}^2 \sin^2\theta} \right) \right] \tag{14}$$

and are given by

$$Z_{3,max}(\bar{R}) = \left(\frac{S_y}{\sin\theta} \right) \left(1 - \sqrt{1 - \frac{\bar{R}}{S_y}^2 \sin^2\theta} \right). \tag{15}$$

For simplicity in computation of the Z-slide commands, the gross axial slide motion Y(X) will be defined as

$$Y(X) = Z_{3,max}(X) \tag{16}$$

and Equation 11 then becomes

$$Z(X,\phi) = Z_4(X,\phi) - Y(X)$$

or

$$Z_4(X,\phi) = a_1 \left\{ 1 - \left[1 + a_2(X + r_t \sin\alpha)\sin\phi - a_3(X + r_t\sin\alpha)^2\cos^2\phi \right]^{1/2} \right\} + (\cot\theta)(X + r_t\sin\alpha)\sin\phi - Y(X) \tag{17}$$

where

$$Y(X) = \left(\frac{S_y}{\sin\theta} \right) \left(1 - \sqrt{1 + \frac{X + r_t \sin\alpha}{S_y}^2 \sin^2\theta} \right) \tag{18}$$

and α is defined as a function of $\bar{R}$ evaluated at the ϕ given by Equation 14.

Figure 6 illustrates the dependence of Z on ϕ at various values of X. The plots clearly indicate two dissimilar cycles of Z in every spindle rotation. Furthermore, the maximum motion of the Z slide is seen to be slightly less than 0.2 mm (0.008 in). For purposes of worst-case estimates only, the motion can be assumed sinusoidal with half amplitude of 0.1 mm and frequency (twice the maximum spindle speed) of 10 Hz. Accordingly, the maximum velocity and acceleration can be estimated as 6.35 mm/sec (0.25 in/sec) and 0.401 m/sec^2 (15.79 in/sec^2) respectively. These values will be used wherever such estimates are needed.

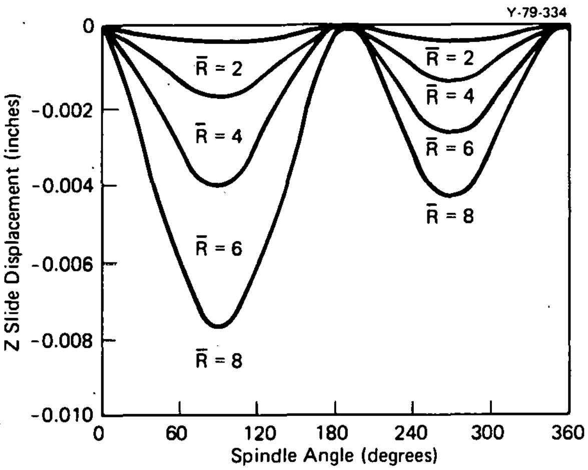

Figure 6. VARIATION OF Z SLIDE WITH SPINDLE ROTATION.

The most convenient and available slide-position sensor possessing the range, accuracy, and speed capabilities for the project is a noncontact capacitance gage. Because this gage is calibrated in English rather than metric units, the remainder of this report will utilize English units in its numerical descriptions.

GENERATION OF COMMANDS TO THE Z-SLIDE CONTROLLER

Before determining a method for supplying commands to the Z slide, it must be recalled that the control of the X and Y slides is furnished by an existing machine control unit. Therefore, it is desired that any additional controls have minimum impact on present equipment; ie, if desired, the present base machine can be returned to its original condition.

Obviously, the simplest means of supplying information to the Z slide would be provided via punched tape through an added channel in an existing machine control unit. When the rate of command inputs to the Z slide is considered, however, it is equally obvious that this alternative is not possible because of both the relatively slow speed of the tape reader and the amount of information that would have to be stored on tape. This pair of conditions virtually dictate that the Z-slide commands be generated in real time rather than precomputed off line and stored.

A second approach for generating the Z-slide commands might be the use of a microcomputer or minicomputer to calculate the commands in real time. This technique also fails, however, because of the computation speed required. For example, the worst-case Z-slide velocity was estimated earlier to be approximately 0.25 in/sec. If the computer could calculate the Z-position commands (given by Equation 17) in so short a time as 100 microseconds, the slide would move in 25-microinch steps in this region. This condition would render the surface finish unacceptable and the contour accuracy marginal at best.

Examination of Figure 6 suggests that the Z motion might be approximated in simpler form by the product of two components, one of which varies rapidly in time and the other slowly. The fast component would probably be ϕ-dependent while the slower component would be some function of Z. Such an expression could have the form

$$Z(X,\phi) = Z_4(X,\phi) - Y(X). \tag{19}$$

Several brief attempts were made to derive a simple approximation of this form. Finally, Equation 17 was expanded in a Fourier series,

$$Z(X,\phi) = C_0(X) + \sum_i \left[C_i(X)\cos(i\phi) + S_i\sin(i\phi)\right], \tag{20}$$

at X = 8 inches, the largest expected value of X. The purpose of this exercise was to determine the number of significant terms at the probable worst case (largest Z motion). The coefficients resulting from this expansion, with i-19, are listed in Table 1. Because the position resolution for the system had been tentatively desired near the one-microinch level, it was anticipated that truncation of the series might be exercised at coefficient values below 10^{-7} inches. The coefficient values listed in Table 1 show that the series intrinsically offered truncation at approximately this level; and, hence, the choice of significant terms was simplified.

The same expansion was performed at several other values of X over the range $0 < X < 8$ with similar results. In each case, the terms of greatest significance corresponded to those in Table 1. Therefore, it was decided to attempt to approximate Equation 17 with the series

Table 1

COEFFICIENTS OF FOURIER EXPANSION OF Z(X,ϕ) AT X = 8 IN

i	C_i	S_i
0	−3.129212 E-3	
1	−8.706122 E-10	−1.659055 E-3
2	3.009743 E-3	1.498976 E-9
3	1.636414 E-9	−1.283845 E-5
4	−5.471358 E-8	−2.409634 E-10
5	−1.803095 E-10	−9.868042 E-10
6	7.522339 E-10	−3.314755 E-10
7	−8.699309 E-10	4.801228 E-10
8	−1.186554 E-9	2.628988 E-10
9	6.358859 E-10	−6.323951 E-10
10	−1.153152 E-9	−1.005770 E-9
11	−1.263566 E-9	−1.317052 E-10
12	−1.030912 E-9	−4.570582 E-10
13	−1.370105 E-9	−6.901405 E-10
14	−7.910119 E-10	−7.132519 E-10
15	3.072071 E-10	−9.102900 E-10
16	1.231549 E-9	−8.889092 E-10
17	1.266274 E-9	−6.782497 E-10
18	2.283308 E-10	5.107422 E-10
19	−6.987747 E-10	−6.062522 E-10

$$Z(X,\phi) = C_0(X) + S_1(X)\sin(\phi) + C_2(X)\cos(2\phi) + S_3(X)\sin(3\phi)\,. \tag{21}$$

Without attempting to detail the hardware components involved in implementing Equation 21, the following general requirements are seen: (1) represent to the Z-slide command generator the spindle angle ϕ and X-slide position; (2) form the appropriate trigonometric function of spindle angle; (3) generate the X-dependent coefficients; and (4) form the indicated products and summations.

All of the hardware components are constrained to combine in an essentially continuous fashion; ie, steps of no greater than approximately one microinch.

Considerations of hardware implementation led to the conclusion that perhaps the series approximation Equation 21 might best be represented by a sum of terms in power of sin ϕ. Thus, by employing trigonometric identities for cos(2ϕ) and sin(3ϕ), the following series was formed:

$$Z(X,\phi) = C_{00}(X) + C_{01}(X)\sin(\phi) + C_{02}(X)\sin^2(\phi) + C_{03}(X)\sin^3(\phi) \qquad (22)$$

where

$$\begin{aligned} C_{00}(X) &= C_0(X) + C_2(X) \\ C_{01}(X) &= S_1(X) + 3S_3(X) \\ C_{02}(X) &= -2C_2(X) \\ C_{03}(X) &= -4S_3(X)\,. \end{aligned} \qquad (23)$$

In comparison to the hardware components previously required, Equation 22 requires (1) generating the sine of the spindle angle, ie, sin(ϕ); (2) forming powers, products, and summations; and (3) generating the X-dependent coefficient values.

It will be seen that the essentially continuous constraint on the Z-slide command signal can be satisfied quite easily with the hardware necessary to implement Equation 20.

It was then decided that the most general-purpose solution might be provided by (1) determining the minimum X spacing of coefficient data; (2) generating these data at the preselected intervals on a large, off-line digital computer; (3) storing the coefficients in Erasable and Electrically Reprogrammable Read Only Memory (EPROM); and (4) using a microcomputer to receive X slide position data and to output the appropriate coefficient data through digital to analog converters (DACs).

Because the accuracy of the interpolated coefficients varies with the spacing between interpolation end points, it was necessary to determine the X grid spacing which restrained the stored data to a reasonable size while satisfying accuracy requirements. End-point spacing of 0.25 inch in X were found to be insufficiently accurate; however, 0.1 inch increments proved satisfactory.

The command signal representing Equation 17 is, therefore, approximated by the series, shown in Equation 22, where the coefficient values are generated via interpolation between values generated by the Fourier expansion. The accuracy of the mathematical scheme was tested in a Fortran simulation with values selected as typical and worst case. The deviation from theoretical $Z(X,\phi)$ is, at most, about 0.1 microinch at the interpolation end points, while the maximum error occurs about midway between the interpolation end points and varies up to slightly less than one-half microinch.

Information flow for generation of Z-slide commands is illustrated in general terms in Figure 7. Note that X position and spindle angle information are required inputs to the calculations.

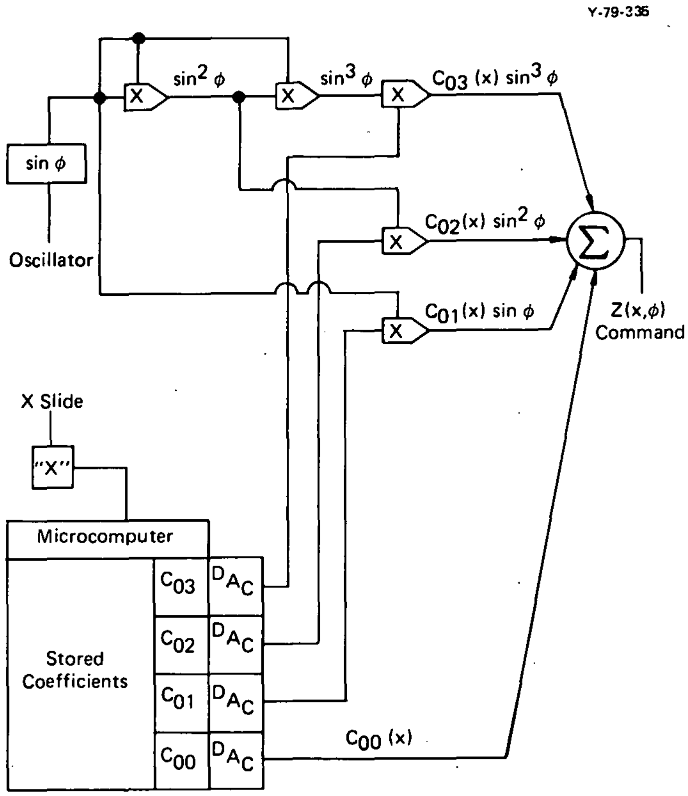

Figure 7. SCHEMATIC OF Z-SLIDE COMMAND GENERATOR.

DESCRIPTION OF EQUIPMENT

Figure 8 illustrates the prototype Z slide. The motion is supported on a pressurized air film to eliminate the stick-slip nonlinearity of Coulomb friction. The slide has about two inches of travel, but this is reduced by the range of the position sensor (a capacitance gage) to approximately 20 mils. This range limitation poses no difficulty for the problem under study (less than 8 mils total motion required), but it could prove troublesome for a more rapidly changing surface. The slide itself is a hollow square aluminum bar whose weight is under six pounds. It is directly coupled to the coil of a linear motor, also shown in Figure 8. The total driven weight of the slide, tool holder, and motor coil is about six and one-half pounds. The slide control system will be an analog, closed-position loop, Type 1 system, probably requiring rate feedback in a minor loop for dynamic damping. The expected difficulties in slide control stem from the combination of bandwidth, gain and sensitivity to noise. If the system bandwidth is to exceed the input signal frequency by an order of magnitude, bandwidth of 100 Hz is indicated. Simultaneously, the gain must be sufficiently high to keep the dynamic error below 10 microinches. Meanwhile, the system must be relatively insensitive to the combination of electrical noise and vibration produced by the cutting tool mounted directly on the slide.

Command inputs to the slide control system will be represented by the signal resulting from the command generator schematically depicted in Figure 7. It is seen in this figure that an analog signal proportional to sin ϕ is a required input. Several means of providing this function were considered. Finally, it was decided to build a low frequency (under 10 Hz)

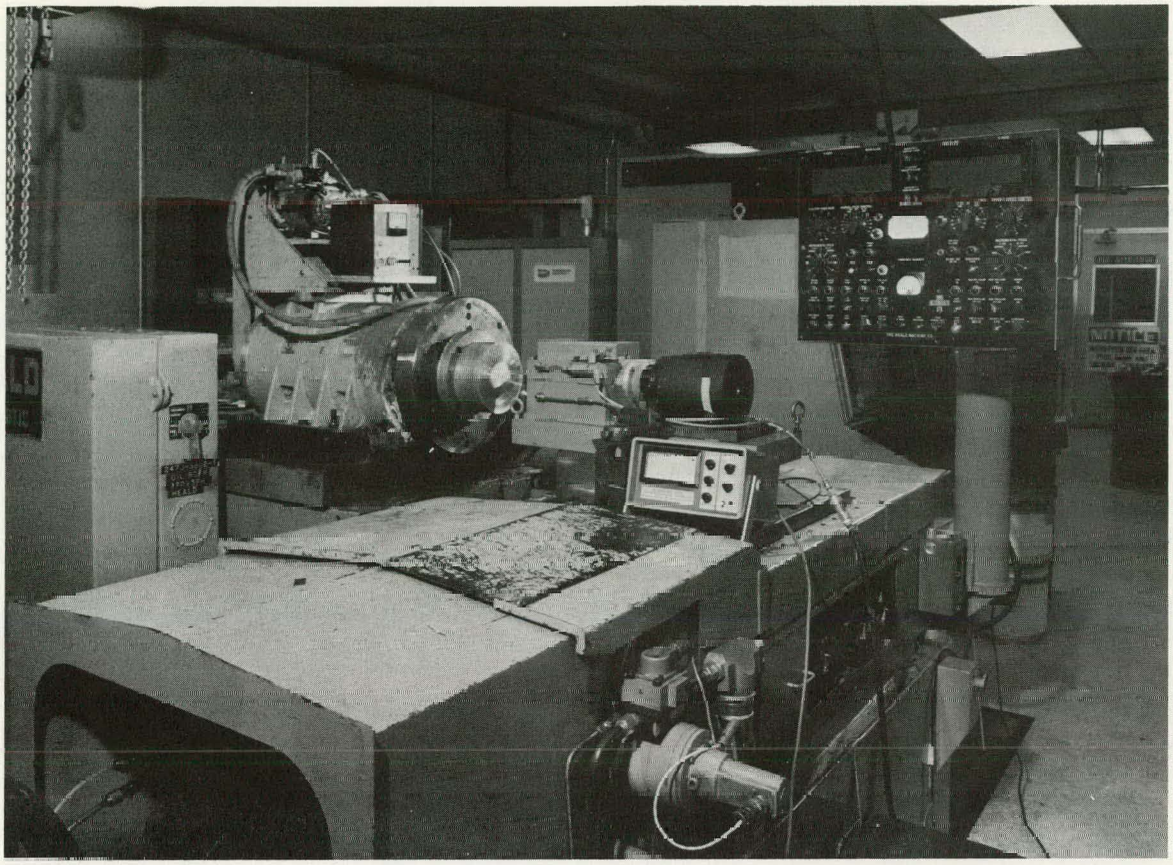

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Figure 8. PROTOTYPE Z-SLIDE MOUNTED AS PROPOSED.

voltage-controlled oscillator as shown in Figure 9. A tachometer attached to the spindle produces a voltage proportional to the rotational speed for input to the oscillator. To reduce sumulative error, the integrators are reset to initial conditions at each spindle rotation by a pulse from a photodiode sensing a mark on the spindle periphery.

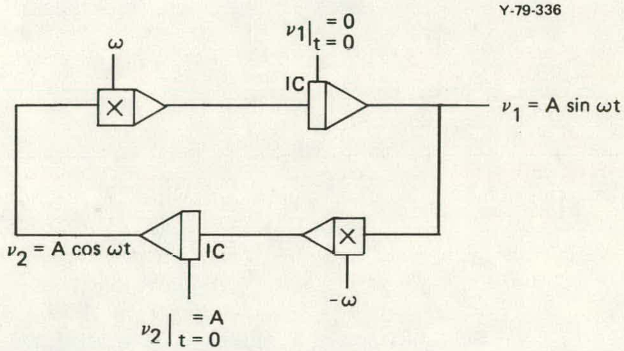

Figure 9. SCHEMATIC DIAGRAM OF LOW FREQUENCY VOLTAGE CONTROLLED OSCILLATOR.

Both X and Y-slide positions will be measured by laser interferometers. The X-slide position will be transmitted to the microcomputer. At preselected X positions, new coefficient data will flow from the microcomputer through the digital to analog converters. Each analog coefficient signal will then be multipled by the appropriate power of sin ϕ and the products will be summed to yield the command input to the slide.

In addition to the auxiliary equipment and considerations required by the capability for nonaxisymmetric turning, a considerable effort is being expended on the machine upon which the Z slide is mounted. This machine is being equipped with air-bearing slideways, laser interferometric slide position and velocity sensors, new drive motors, vibration isolators, and numerical control. Concurrently, this work is being conducted with the development of the Z slide. Present plans call for the base machine to be completed in March 1979. After mounting the Z slide on the machine and testing the system, machining tests should be conducted in June 1979 or thereabout.

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