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A New CNC System for Free-form Body Machining with a Cylindrical Tool

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0. Synopses

Free-form surface machining is usually performed with an NC milling machine and a ball end milling cutter. Since this conventional method is basically sculpting on a plane, it is not suitable for three dimensional body machining. This article will introduce a new machining method for three dimensional body with free-form surface and newly developed machine tool suitable for such machining.

1. Introduction/Historical Background

This article introduces a recently developed new free-form surface machining system. It is a combined application of computer technology and control engineering.

As the origin of machine tool we could refer an ancient potter's wheel. Modern machine tools with mechanical power are invented during the era of Industrial Revolution, e.g., the boring lathe by J. Wilkinson, 1774: the screw cutting lathe by H. Maudslay. In these machine tools the position of cutting tools are controlled manually. The shape of workpiece is therefore restricted to some combination of plane, cylinder, cone and spiral. To produce workpiece of arbitrary shape or body with free-form surface, copying machines are introduced into the machine tools in 1930s. A prototype or a model with handwork is necessary in the copying machines. Various types of automatic lathes were developed in 20th century. Every motion of such a lathe had to be sequentially predetermined with a series of cams and gearing. The NC machines that can fabricate a workpiece of arbitrary shape defined by coded numerical data appeared after development of the modern electronic computer.

In the numerical control of machine tool, relative position of the workpiece and the tool under operation is preliminary coded as a sequence of numerical data, and the position of the tool is controlled by a computer that delivers the numerical data to a servosystem(1),(2). Soon after the development of the first electronic computer (ENIAC, 1946), computers were applied to control milling machines (e.g. Servomechanism Lab. MIT, USA, 1950) and free-form surface machining was applied to produce parts of airplanes. After this time the numerical control of machine tool grew to a common technology and widely applied to all types of machine tools, such as lathes, milling and boring machines. The machining center was developed as the machine tool especially suitable to computer control. A machining center involves automatic tool changer, and can perform various kind of machining on one bed. CNC(computerized numerical control) machine tools which include a computer as an integral part succeeded early punched tape type NC machine tools. Today NC is almost synonymous with CNC. The fundamental function of these NC and CNC machine tools is to control tool position corresponding to the direction given by the program in the computer. Special program languages for the control of the NC machines were developed and the utility of NC machines was improved with evolution of software.

On the other hand design technologies have also highly developed with introduction of the computer in these years. Complicated but optimal shapes come out as computation result. Common use of the computer graphics allows us to design and designate with ease free-form surfaces on a computer. Machining of a free-form surface on machine tools, even with the sophisticated recent CNC machine tools, remains as a difficult task. A cause of the difficulty lies in the physical fact that the surface forming is restricted geometrically and dynamically with the shape and size of the tool. In drilling for example, position and the depth is controlled through instruction on actuator, but the diameter cannot be changed without changing the drill itself. Only a certain cylindrical surface is formed with a drill. It is not possible to make a designed non-circular hole with a drill. In turning operation a point tool tip draws a circle on the workpiece in normal operation. Tool tip motion synchronized with spindle rotation will result non-circular cross section. Turning of non-circular cross section on a lathe was practiced already as a copying lathe (3): various means for non-circular turning were exploited also for NC lathes. The restrictions based on tool shape and cutting condition remain however, and allow to turn only limited cross sectional shape. Figure 1 illustrates the tool interference in turning of a non-circular cross section. Larger rate of change of radius in the cross section requires larger relief and rake angles, thus no substantial angle for the single point tool can remain, therefore the turning becomes impossible. The requirement of free-form body machining is becoming stronger in recent years, since the costumers are requiring not only high function but also beautiful shape for industrial products. Still now there are only limited forming methods for such free-form surfaces. We have only a profile

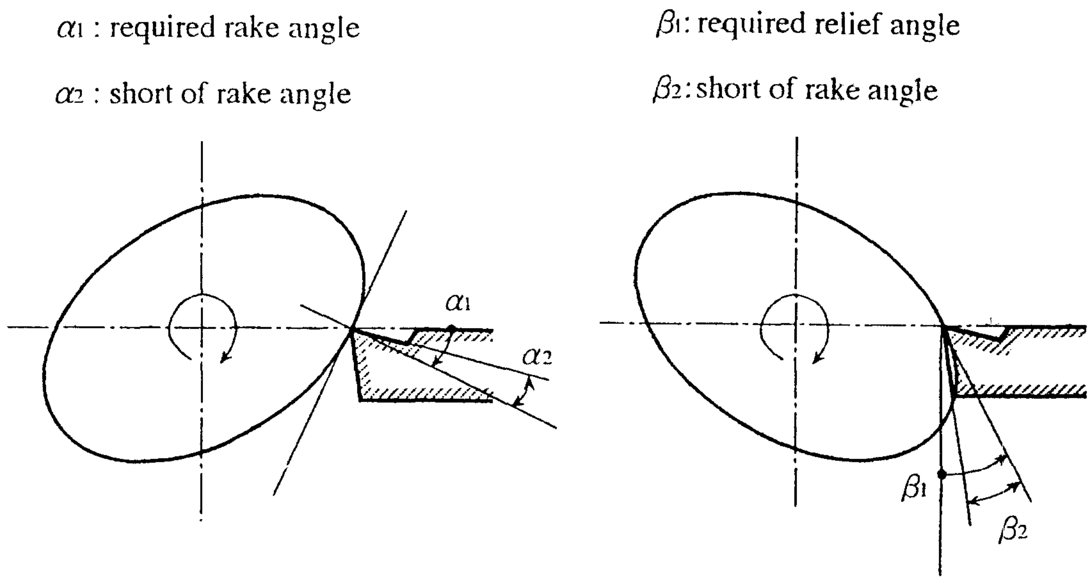


Fig.1 Tool shape problem in noncircular turning

milling machine and a die milling machine with a ball end milling cutter for this purpose. These machines sculpt concave and convex on a plate, therefore they are not suitable to form three dimensional bodies. This is the background of our motive to create free-form body machining system.

In the followings we will explain a newly developed free-form machining system in which a cylindrical tool similar with an end milling cutter or a cylindrical grinder is used. Tool and control method require a suitable type machine tool in general. A new type machine tool is designed for this machining method. In the developed system the shape that should be created is stored as an array data in a memory device of a computer. The other data array for tool positioning is calculated from the shape data array. Although this machining system is also not free from the restriction induced from the tool shape, it has some advantages to machine a class of three dimensional bodies.

2. Principle of free-form body machining with a cylindrical tool

Consider a three dimensional body supported with an axis, say C-axis, and rotated around the axis. A cylinder comes in contact with the body on its side surface as shown in Figure 2. Figure 3 shows a projection of contour of the body and the cylinder on the z-x plane. In Figure 3 we can observe the relation between the axis of the cylinder and the contact point P. We assume that the x-coordinate of the contact point is uniquely determined as a function of z-coordinate of the cylinder when the angle of rotation around the C-axis and the cylinder diameter are given. Under this

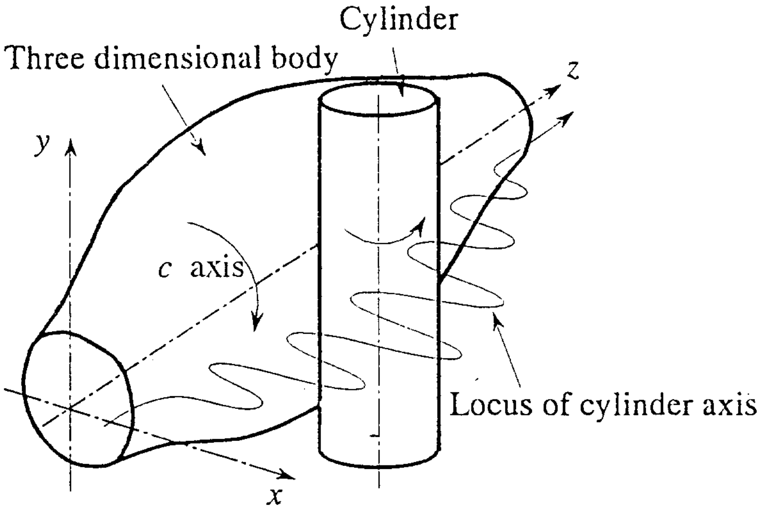
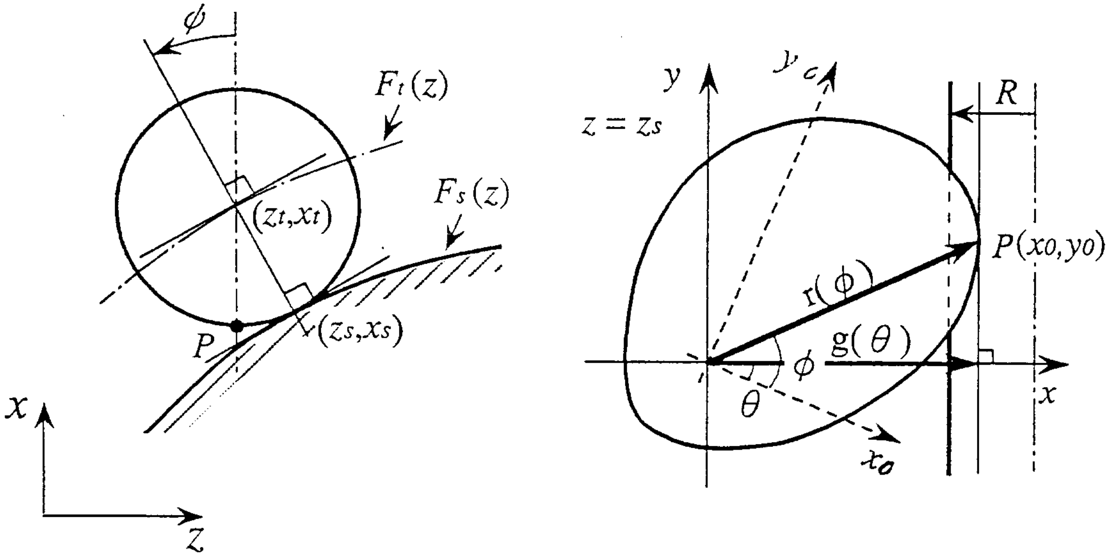


Fig.2 Contact of three dimensional body and cylinder



(a) z -x plane projection

(b) cross section at $z = z_s$

Fig.3 Projection to z -x plane and cross section at $z = z_s$

assumption the surface of the body is determined by the set of the contact points. If the contact point is not uniquely determined, then the cylinder diameter may be too large or the shape of the body may not be suitable for this machining method.

Above principle can be applied to produce three dimensional bodies. It can be applied also to measurement of figure of three dimensional bodies (4). We will explain here mainly the application in machining (5): for measurement we will refer briefly later.

If the cylinder previously assigned is a cylindrical tool similar to an end milling cutter and the body is a workpiece, we can create various three dimensional bodies with free-form surface (6). An example feature of a machine tool to realize the above contact principle is illustrated in Figure 4. A cylindrical tool is mounted on a cross slide that slides on a carriage. Following the usual coordinate system of an NC turning center z-axis is taken in the feed direction of the carriage: x-axis is taken in the direction of the cross slide motion: y-coordinate is taken in the direction of the cylindrical tool. These three axes construct a Cartesian coordinate system. The workpiece is clamped with a chuck on the main spindle: the rotation angle of the main spindle is C-axis.

The contact point of the tool and the workpiece is the point on the free-form surface to be manufactured. If carriage displacement z and rotation angle of C-axis(θ) is given, a corresponding displacement of the cylindrical tool, namely x-coordinate of the tool is uniquely determined. Let us determine an algorithm to find out the x-coordinate of the axis of the cylindrical tool from the coordinates of points on the workpiece surface.

In Figure 3(a) $F_s(z)$ is a projection of outline of the imaged body and $F_t(z)$ is a projection of the envelope of the center of the cylindrical tool. We have the following relations for coordinate of contact point (z_s, x_s) and the coordinate of the tool center (z_t, x_t) ;

$$z_s=z_t+R\sin(\psi) \quad ....(1)$$

$$x_s=x_t-R\cos(\psi) ....(2)$$

$$\tan(\psi)=F_s'(z_s) ....(3)$$

where $F_s'(z)=dF_s/dz$.

These two curves F_s and F_t are determined if a rotation angle of the body is given. For the three dimensional body we shall find relation between contour of cross sections and the projected outline $F_s(z)$. Let us take the polar coordinate for expression of the surface of the body

$$r=r(z,\ \phi). \qquad ....(4)$$

The cross section of the body at $z=z_s$ is shown in Figure 3(b). The projection x_s on z-x plane of the contact point P at the rotation angle (θ) is given by

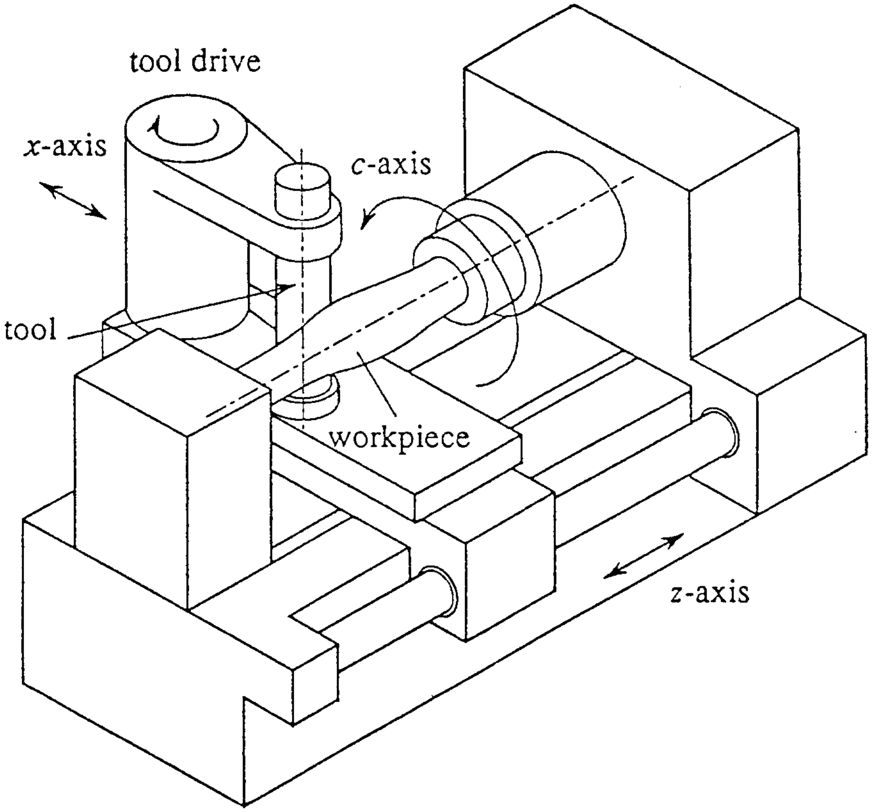


Fig.4 Configuration of new machine tool

$$x_s = \max\{r(z_s, \phi)\cos(\phi - \theta)\}, \quad \text{where } 0 < \phi < 2\pi$$
$$= x_s(z_s). \qquad \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Equation (4) gives functional relation between xs and zs, namely $F_s(z)$. Thus if the surface of the body is defined by a numerical data set or by appropriate equations, then we can find (z_t, x_t) using relations (1)-(3) and (5). The surface expressed by Equation (4) will be generated when the cylindrical tool is displaced along the surface (z_t, x_t).

An actual tool path to machine the intended three dimensional body shall be stored in a computer and transmitted to suitable servo actuators. On the application of above principle we must determine a computation procedure to give the tool path. Following is a sample procedure.

(A) A discrete data set of $r(z_i, \phi)$ for nodes $(\phi_0, \phi_1, \cdots, \phi_{n-1}, \phi_n)$ and $(z_0 = 0, z_1, \cdots, z_m = L)$ shall be calculated and stored as the first two dimensional array in a computer memory. This is a simple process if the surface is given in form of a single equation. If the surface is given only with a numerical data set, it will require some computation effort, such as interpolation including selection of suitable formulae. If physical model is given, an appropriate measuring system to obtain the numerical data set is also required.

(B) Define z_s, and calculate $x_s(\theta_i, z_j)$ with the aid of Equation (5), corresponding to discrete angles $\theta=0, \theta_1, \ldots, 2\pi$. The result shall be stored as the second two dimensional array (z_{sj}, x_{si}).

(C) Pick up a partial array from the second two dimensional array for a fixed value of θ, then calculate interpolation function $F_s(z_j)$ from which we can calculate $F_s'(z_j)$. These values are stored in the third two dimensional array.

(D) Get $z_j=z_s$, $x_s(\theta_i, z_j)=x_s$ and $F_s'(z_j)$ from the data arrays and substitute them into Equations (1) - (3). Then we have $z_t(i, j)$ and $x_t(i, j)$. Store these values in the 4th and 5th two dimensional array.

(E) Since $x_t(i, j)$ are not equally spaced value, we have to select a suitable interpolation function to give relation between z_t and x_t for an arbitrary value of z_t, and obtain data of x_t for equally spaced value of z_t.

(G) Now we can define the 6th data array for $x_t(*(i), z_t(j))$, in which $\theta(i)$ and $z_t(j)$ are equally spaced;

$$\theta(i)=i\Delta\theta, \quad \Delta\theta=2\pi/N, \quad (i=1,2,\ldots,N)$$

$$z_t(j)=j\Delta z, \quad \Delta z=\text{const.}, \ (j=1,2,\ldots,M).$$

This gives x-coordinate of the center of the cylindrical tool to create the objected three dimensional body.

(H) By operation of the machine tool, rotary angle ** and feed of the carriage *z are given in single time step, and a data in the 6th array, $x_t(\theta(i), z_t(j))$, is read out.

We use only the 6th data array for the machining, although several arrays appeared in the calculation. Figure 5 illustrates a flow chart for the data processing.

The shape measurement of this kind of body is possible if this machining principle is inversely traced. In measurement we use a cylinder as a probe and get a set of data $\{z_t(\theta), x_t(\theta)\}$ when the probe comes contact with the object body. Since

$$F_s'(z_s)=F_t'(z_t), \quad \ldots\ldots\ldots..(6)$$

value of * is determined by Equation (3). Therefore we can determine points $\{z_s(\theta), x_s(\theta)\}$ on projection of the surface of the body. Since we have already found the relation $x_s=g(\theta)$, we can calculate the contour of the cross section of the body $r=r(\phi)$ by the following relations:

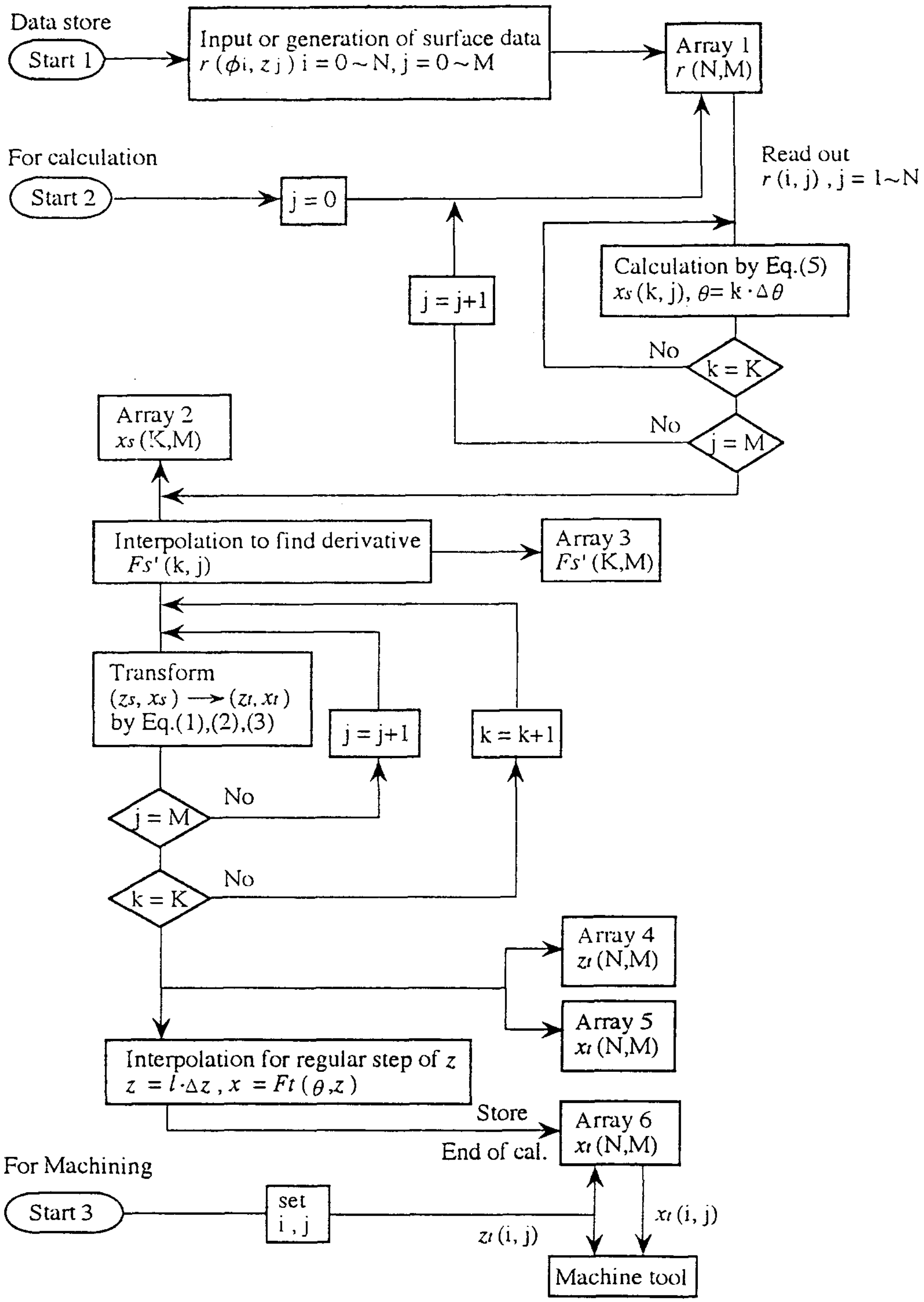


Fig.5 Flow Chart for calculation procedure

$r=[g^2+(g')^2]^{1/2}$ ....(7),

$\phi = \theta + \mathrm{Arctan}(g'/g)$ ....(8),

where $g'=dg/d\theta$.

3. Construction and control of the machine tool

The machining process, that includes from data generation to machine tool operation described above, is only feasible with existence of computer.

The cylindrical tool is similar to an end milling cutter in shape but different in function and dimension. Its function is similar to plane milling cutter. So we must design and produce a new tool. Although a CNC turning center or a cam shaft grinding machine may be modified to perform the required operation, a new design of machine tool suitable for the machining principle is desirable. Therefore the author designed and constructed new machine tool on which the machining principle will be verified and various control algorithms can be performed (7),(8). Figure 5 depicts basic structure of the designed machine tool. Coordinate and axis of the machine follow a CNC turning center. The workpiece is held with a chuck mounted on a headstock of which rotation angle is controlled as the C-axis. The cylindrical tool is driven by a drive motor. The tool and the motor are mounted on a cross slide of which motion is controlled by x-axis. The cross slide is mounted on a carriage that is controlled with z-axis. Important dimensions of the constructed machine tool are as follows:

swing on the bed; 440 mm, swing on the cross slide; 108 mm, maximum distance between centers; 625 mm.

A plain milling cutter with long flute length (diameter; 30mm, length of flute;150mm, number of flutes; 4) is designed and used as the cylindrical tool. The tool is supported at both ends to reduce deflection induced by cutting load. The tool is driven with a velocity suitable for the material of the workpiece. Arrangement of machine axis and controller are shown diagrammatically in Figure 6.

Electric servosystems with AC servomotors control z-axis and the C-axis: an electrohydraulic servosystem controls the x-axis. The electrohydraulic servosystem of the x-axis can respond for fast response that is required in the non-circular turning. An electric servosystem may be substituted for x-axis control if the machine would be used only for the free-form body machining in this paper. Each servosystem has own independent feedback loop. The control loops constructed as depicted in Figure 7. A 5 kW AC servomotor with rated speed 2000 RPM drives C-axis. A 1.5 kW AC servomotor with rated speed 2000 RPM drives z-axis. The rotation of the z-axis motor is translated to linear motion through a ball screw with 6mm lead. A cylinder of 100 mm stroke with 8.8 cm^2 effective area drives x-axis. Servovalve with rated pressure 140bar with nominal no-load flow rate 20 l/min controls the displacement of the cylinder.

The total system is administrated with a personal computer. The output from the computer is transmitted to each axis through each respective 16 bit D/A converter with 10 ms time step. Flow of signals between the computer and control axes is shown in Figure 6. Rotation angle of each servomotor is detected by respective rotary encoder that puts 3000 pulses in one revolution. Therefore the resolutions are 0.12 degree for C-axis and 2 μm for z-axis. Each detected angle is fed back to the controller involved and transmitted to the computer. Displacement of the hydraulic cylinder, i.e., displacement along x-axis is detected by an LVDT and fed back to the servo amplifier and the computer. The gain constant of the servo-amplifier is made adjustable to study response,

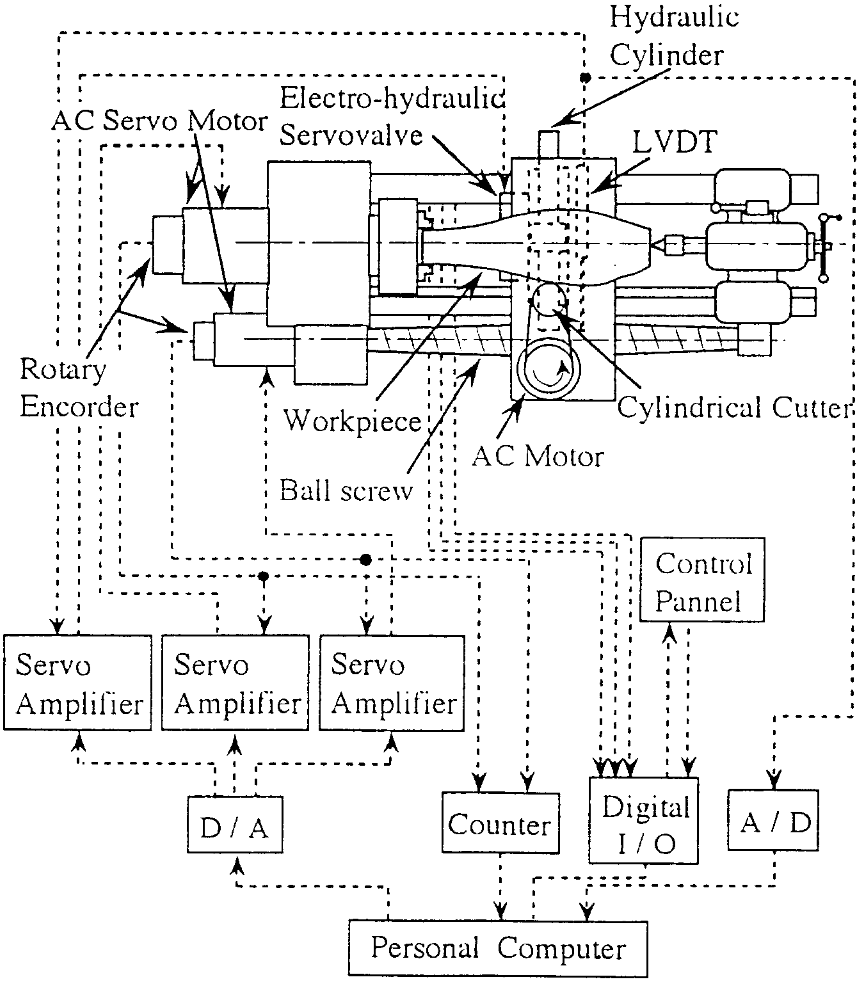


Fig.6 Schematic of machine tool and control device

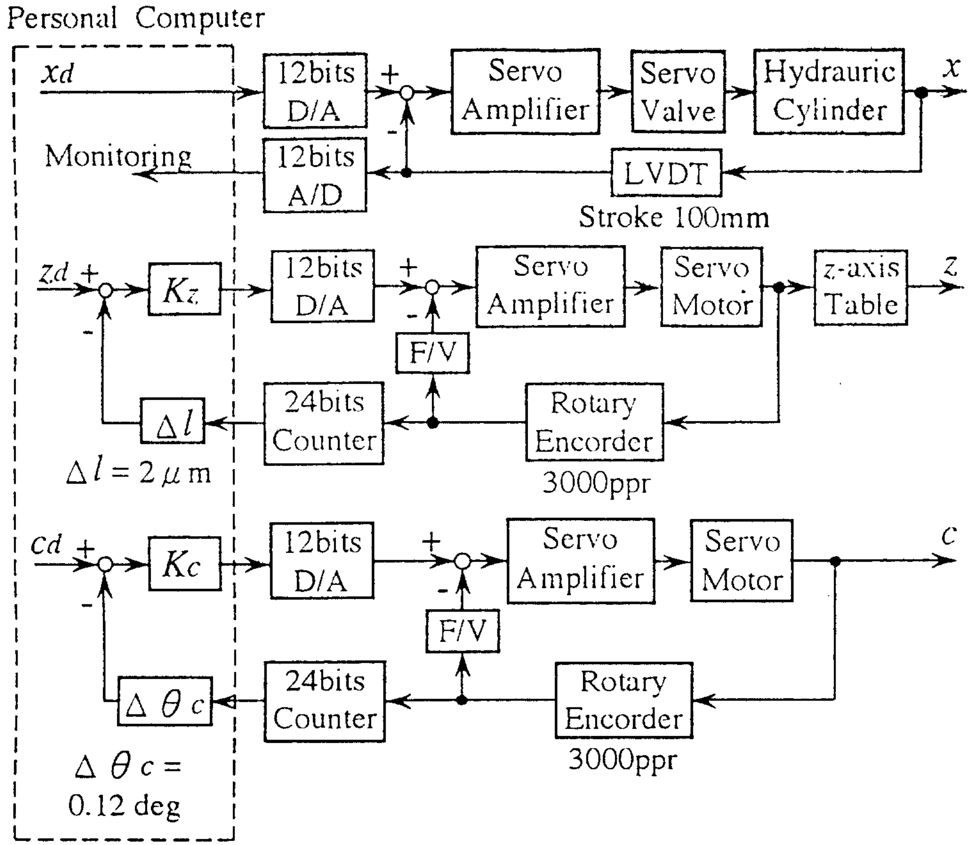


Fig.7 Control system

resolution and static precision of the x-axis control. The program to operate the system was written in C-language.

The function implanted in the personal computer is as follows:

(a) To receive geometry of a three dimensional body in data of r (z, θ) and to store it in a storage device.

(b) To examine whether the geometry of the body satisfies the condition of machining feasibility; to select or confine a suitable tool radius.

(c) To receive a calculation program to perform the data processing described in the preceding chapter, calculate the tool position data array x_t ($\theta(i)$, $z_t(j)$) and store it in a storage device.

(d) To perform necessary preparation for NC control, such as origin definition and initialization for the machine tool axes.

(e) To receive control algorithm for each axis and perform it through a suitable data manipulation.

(f) To give motion instructions to each control axis.

(g) To monitor operation of the machine tool, state of control system and workpiece under machining.

The constructed machine tool involves standard safety device. Although the safety device is also connected with the computer and the control axes, explanation for it is not given here, since it is well known technology in machine tool builders.

4. Implantation of Control algorithm

Putting a computer at the center of control, we can give various compensation on reference signals. It means that the position data read out from the memory is processed to get better machining accuracy.

Some control algorithms are implanted in recent CNC machine tools. Error compensation algorithms are treated in non-circular turning. We explain here the application of compensation for our machine tool.

Let pulse transfer function of a servosystem is $G(z^{-1})$ and the z -transform of reference signal is $R(z^{-1})$, then the output becomes $R(z^{-1})G(z^{-1})$ if no disturbance is added. Therefore input sequence with known future values, such as the input for machine tools, may be modified to $R(z^{-1})=C(z^{-1})/G(z^{-1})$ for object value $C(z^{-1})$. This inverse transfer function method had been applied in the past with usual transfer function of the Laplace transform. In application of the same principle to a digital control system we must pay attention to the fact that $1/G(z^{-1})$ could have unstable poles. The ZPTEC by Tomizuka (1990) is a technique to get rid of unstable poles.

Since the sequence of the tool path coordinate is known before operation of machine tool in our machining system, input modification of every kind can be done in computer easily. Figure 8 depicts the modification applied to the x-axis control. Let us approximate the servosystem with a first order system for simplicity.

$$G(z^{-1})=b_0 z^{-1}/\{1+a_1 z^{-1}\} \quad ....(6)$$

No unstable pole exists in this approximation. The parameters appeared in this expression have identified using the least squares method for the actual servosystem.

Using Equation (6) we have the following modified input signal

$$u(k)=\{x_t(k+1)+a_1 x_t(k)\}/b_0, \quad ....(7)$$

where $x_t(k)$ and $u(k)$ are object value and control input at time $t=k\Delta t$ (Δt is sampling interval) respectively. This simple modification of reference signal gives good compensation effect on the machining accuracy. Figure 8 shows an example of the compensation. Similar implantation of control algorithm is possible for other control axes.

The parameters to express system dynamics may vary with loads and other operating conditions. The control system can include an adaptive system to estimate the parameters of the physical system and use them to adjust the parameters in Equation (6). Figure 9 shows the adaptive control system that includes a parameter adjustment loop. The system is considered a self tuning regulator (STR) with feed forward loop. With this system, parameter estimate based on the first order approximation will give always good compensation comparable with higher order model when the sampling interval is sufficiently short. This prediction is based upon the fact that continuous change of a physical phenomenon can be described with a linear relation of infinitesimal change of the describing variable of the phenomenon and corresponding infinitesimal time change. Figure 10 illustrates effects of these compensations.

5. Conclusion

The machining method using side surface of a cylinder described in this article will open a new scheme on the free surface machining technology. It supplies an effective machining of three dimensional bodies, especially of axial shapes, that is difficult to form with conventional free surface machining such as ball milling cutters on CNC milling machine. Like other machining, this method also cannot be free from the restriction brought out from tool shape. The first restriction is that all cross sections of the body perpendicular at least one axis must be an ovaloid. In other words a half line from an arbitrary point in a cross section intersects only once with the contour of the

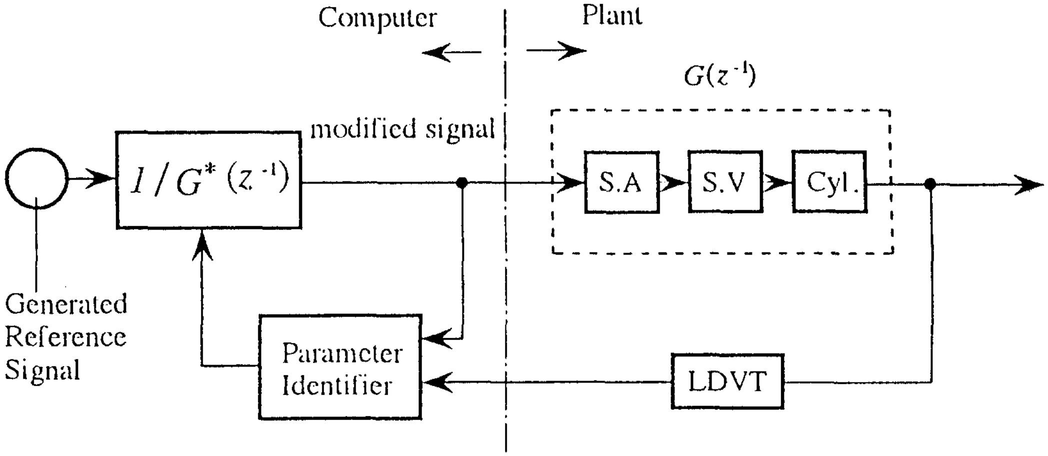
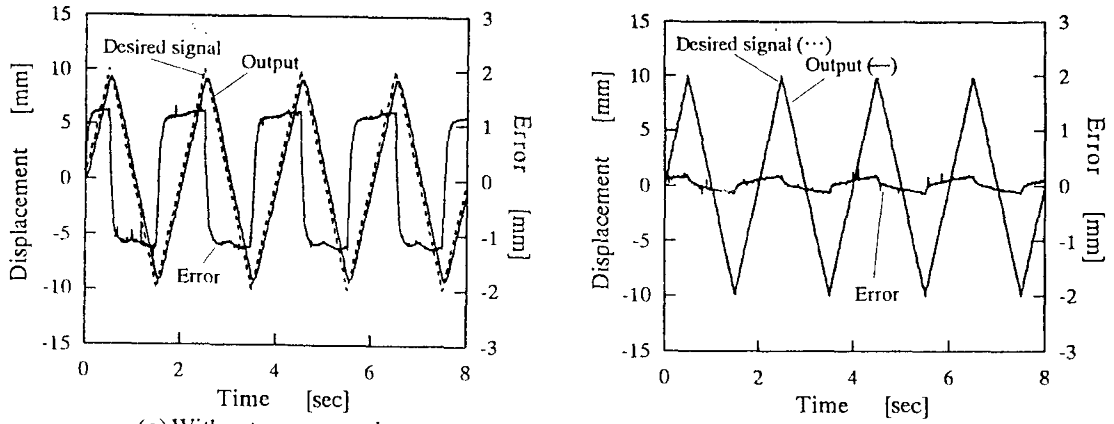
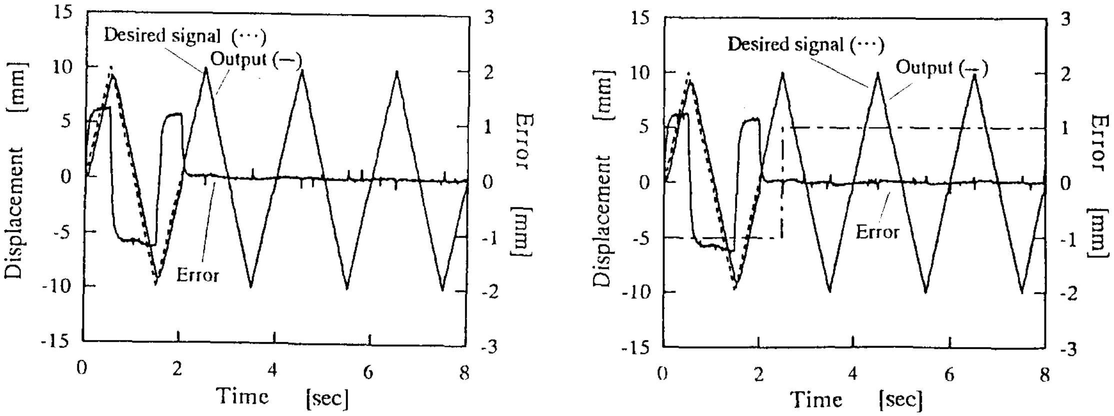


Fig.9 Compensation with adaptive system



(a) Without compensation

(b) Feedforward with fixed parameter



(c) Adaptive control with 1st order model

(d) Adaptive control with 2nd order model

Fig.10 Effect of compensations

cross section. The second restriction is that the minimum radius of curvature of projection of the body must be larger than the tool cylinder radius. The machining system has many advantages. The first is that the cutting velocity can be selected free from the other operating conditions. Chips are short and similar to those with the milling machine: hence rejection of chips is easy. The cutting points on the tool distribute on flutes, therefore tool change interval to respond tool wear becomes longer. Various compensation techniques based on the control theory can be implanted without difficulty.

This machining principle assumes large ability of data processing and simultaneous numerical control of the multiple control axes. The machining system becomes feasible only through effective use of modern computer technology.

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