Module 5

CNC Machines

Lesson
24
CNC Machines: Interpolation, Control and Drive

Instructional Objectives

After learning the lesson students should be able to

A. Define the major subsystems for motion control

B. Describe the major features of an interpolator for a contouring CNC system

C. Distinguish and compare open loop control and closed loop CNC

D. Name desirable features of feed and spindle drives of CNC machines

Introduction

The most critical and specialised activity in a CNC is axis management, which involves interpolation, servo control and drive of the motion axes. Axis management tasks can be processed by one or more dedicated CPUs. Often, the interpolation and the servo control tasks for the several motion axes can be split between the various CPUs. Both point-to-point (PTP) interpolators and contouring interpolators are available on a machine. As we shall see below, interpolation for PTP axes is extremely simple, and involves only providing the final position coordinates to the control system. For contouring systems, however, the interpolator must cyclically compute motion set points. We describe the process of contour generation by interpolation first. Once the set points are generated, these are provided to the servo control loops that compute the control inputs, based on the set points and the motion feedbacks (for closed loop systems) and provide such control inputs to the motor drive system. Basic approaches for control are described next to the interpolation. Finally, the drive system is to receive these inputs, in analog or digital form and would compute quantities such as voltage and current references and apply to the motor. Such details of CNC drive systems are also presented

Contour Generation by Interpolation

In contouring systems the machining path is usually constructed from a combination of linear and circular segments. It is only necessary to specify the coordinates of the initial and final points of each segment, and the feed rate. The operation of producing the required shape based on this information is termed interpolation and the corresponding unit is the “interpolator”. The interpolator coordinates the motion along the machine axes, which are separately driven, by providing reference positions instant by instant for the position-and velocity-control loops, to generate the required machining path. Typical interpolators are capable of generating linear and circular paths.

Basically there are two types of CNCs, the reference-pulse and the reference words systems. These two CNC types require distinct interpolation routines in the control program to generate their corresponding reference signals (pulses or binary words). In the reference-pulse system, the computer produces a sequence of reference pulses for each axis of motion, each pulse generating a motion of one BLU. The accumulated number of pulses represents position, and the pulse frequency is proportional to the axis velocity. These pulses can either actuate a stepping motor in an open loop system, or be fed as a reference to a closed-loop system. With the sampled-data technique the control loop of each axis is closed through the computer itself, which generates reference binary words.

Reference-pulse interpolators are simpler to program, but there is a restriction on the maximum axis velocity imposed by the interpolation execution time. Reference-pulse interpolators execute cyclically with a clock. The maximum axis velocity is proportional to the maximum attainable clock frequency, which, in turn, depends on the execution time of the interpolator algorithm. Consequently, reference-pulse interpolators are often written in assembly language to improve the computing speed so as to attain higher maximum attainable axis velocity.

Point to Ponder: 1

A. *Is it possible to have a reference pulse interpolator for a CNC machine with dc drive*?

B. *What limits the speed of operation in reference word interpolator based systems*?

Below we present a linear reference pulse interpolation technique. At the heart of the interpolator is a Digital Differential Analyser (DDA) algorithm.

DDA Algorithm

DDA is essentially an algorithm for digital integration and generates a pulse train varying in frequency. Digital integration is performed by successive additions using an Euler approximation method shown in Fig. 24.1.

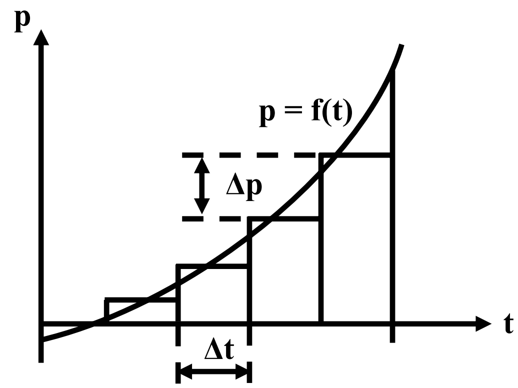


Fig. 24.1 Backward Euler Integration

From the above, let,

$$z(t) = \int_0^t p\, dt$$

The value of z at $t = k\Delta t$ is denoted by z_k, which may be written as:

$$z_k = z_{k-1} + \Delta z_k$$

where

$$\Delta z_k = p_k\ \Delta t$$

The value of p_k can in turn be modified by incrementing or decrementing it by Δp, which is either 1 or 0. The DDA integrator operates cyclically at a frequency f provided by an external clock. At each iteration the variable p is added to the register q so that,

$$q_k = q_{k-1} + p_k$$

At intervals this addition would generate an overflow bit, which is fed as the output reference pulse. Obviously, the higher the value of p the higher would be the frequency of generation of an overflow and a reference pulse. Thus the rate of generartion of the reference pulse would be proportional to the value of *p*.

A schematic diagram of a DDA integrator is shown in Fig. 24.2. It consists of two n-bit registers, *p* and *q*, and one adder.

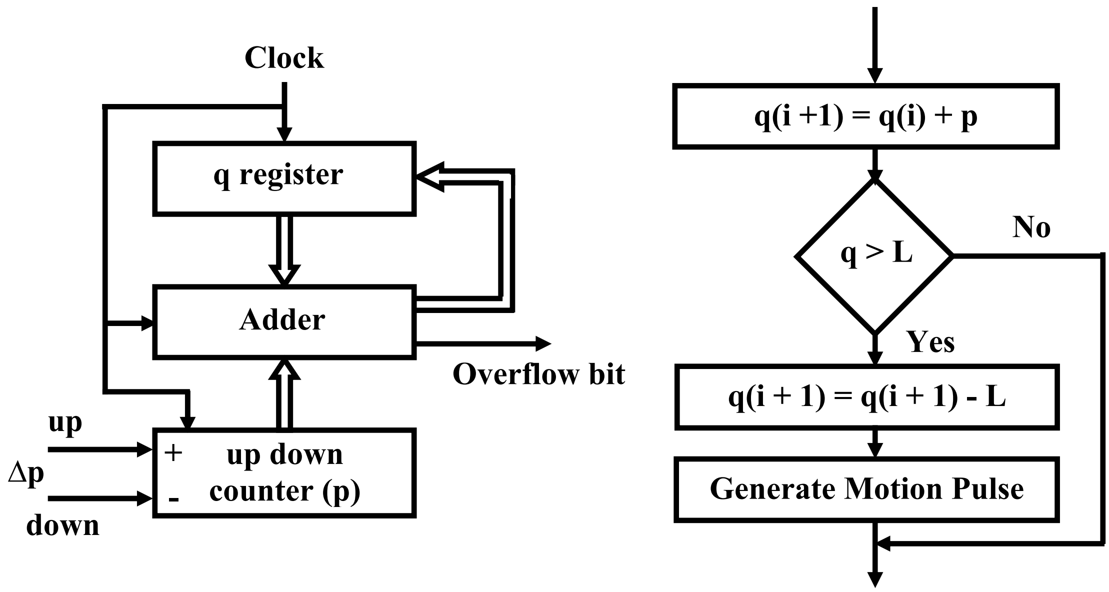


Fig. 24.2 DDA Integrator Schematics and Flowchart

A symbolic representation of a DDA integrator is showing in Fig. 24.3.

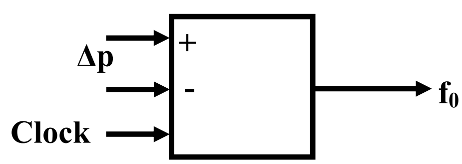


Fig. 24.3 A symbolic representation of a DDA integrator

With the advent of fast microprocessors, the need for hardwired DDA's have reduced. Instead, the DDA algorithm is implemented using the registers of the microprocessor, in software.

Linear Reference Pulse Interpolation

The ability to control the movement along a straight line between given initial and final coordinates is termed linear interpolation. In this lesson only 2-D linear interpolators are discussed. A 2-D linear interpolator supplies velocity commands, in pulses per second, simultaneously to two machine axes, and adjusts the ratio between the pulse frequencies depending on the slope of the trajectory. For example, consider the case in Fig. 24.4, where a straight path has to be cut between points A and B. Note that movement along each axis takes place by 1 BLU for every reference pulse along the axis. The interpolator therefore has to provide pulses to each axis at definite rates (say, from Figure 24.4, a and b pulses per second, along X and y axes respectively) with respect to time.

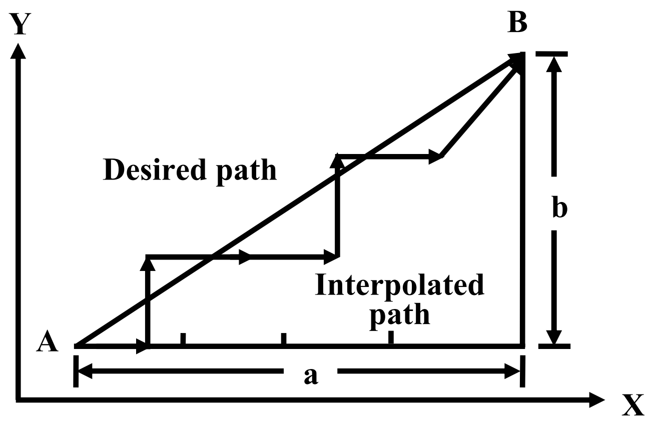


Fig. 24.4 2D linear interpolation

A 2-D linear interpolator based on DDA integration is shown in Fig. 24.5.

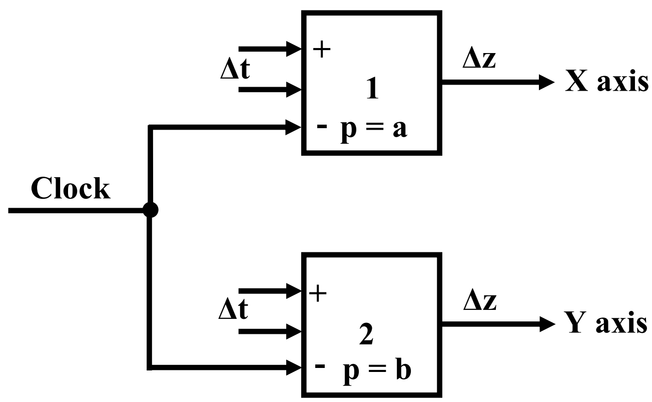


Fig. 24.5 DDA-based Linear Reference Pulse Interpolator.

A common clock controls both the integrators. The output pulses actuate stepping motors in open-loop systems, where each pulse causes a single step motion, or can be fed as reference to closed-loop systems. In addition to maintaining the proper velocity ratio between the two axes, a desired velocity along the path need also be maintained. This is achieved by controlling the clock frequency of the first two DDAs.

Reference-word Circular Interpolators

In reference pulse systems a pulse train of varying frequency is output to the servo control module. The servo system for an axis causes an incremental displacement along the axis, for each pulse. As mentioned before, this can cause a speed limitation for the CNC, depending on the execution speed of the interpolation loop. In contrast, in reference word interpolation systems the maximum velocity is not limited by the execution speed of the processor. . The interpolation subroutines continuously provide velocity set points to the servo system, which realizes it through the drive. In this lesson we discuss a circular interpolation using the reference word method. This require the use of a “controlled speed drive” rather then a “position servo”.
In circular interpolation, at a constant tangential velocity, *V* and radius *R*, the axial velocities satisfy the following equations:

$$V_x(t) = V \sin\ \theta(t)$$
$$V_y(t) = V \cos\ \theta(t)$$

The velocity components V_x and V_y are computed by the circular interpolator and are supplied as reference inputs to the computer closed loops. Actually what is generated is a polygon inscribed on a circle. At the beginning of each side the interpolator provides new velocity references to the axes. The more the number of sides of the polygon, the better is the accuracy of the generated circle. The optimal number of sides is the smallest one for which the path error is within one BLU.

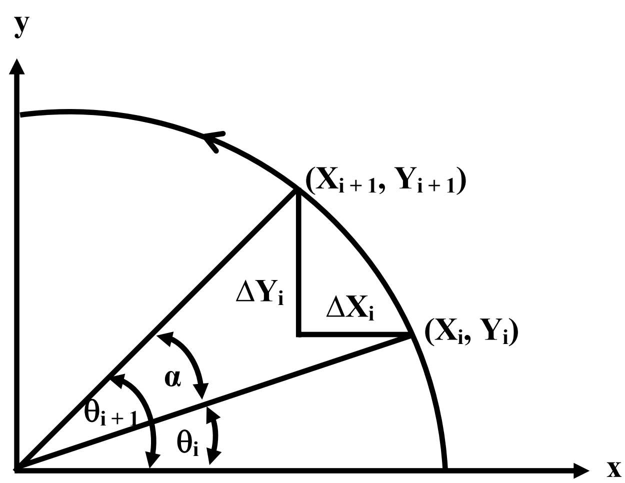


Fig. 24.6 Position and velocities at two successive points on a circle

From Fig. 24.6 one can derive the following recursive update eqns. for the two coordinate axes.

$$X(i+1) = AX(i) - BY(i)$$
$$Y(i+1) = AY(i) + BX(i)$$

where, $A = \cos\ \alpha$ and $B = \sin\ \alpha$. The velocity set points for the axis drives are computed as follows.

$$\Delta X(i) = X(i+1) - X(i) = (A-1)X(i) - BY(i)$$
$$\Delta Y(i) = Y(i+1) - Y(i) = (A-1)Y(i) + BX(i)$$
$$V_x(i) = K\ \Delta X(i)$$
$$V_y(i) = K\ \Delta Y(i)$$

where $K = V/R\alpha$. These velocity set points are provided to the servo control systems which are described below.

Point to Ponder: 2

A. *Devise a scheme for changing the feedrate in an interpolator.*

B. *How does one choose the value of α for circular reference word interpolation?*

Servo Control

Servo control consists of all the activities, which allow several axes to effectively maintain the trajectory calculated by the interpolator. In CNC systems the position and velocity of the machine tool axes must be controlled closely and in a coordinated manner. Each axis is separately driven and follows the command signal produced by the interpolator. The control system can be either open-loop (as in PTP systems) or closed-loop (as in contouring systems).

Control of PTP Systems

In PTP systems only the final position of the table is controlled and the trajectory of motion in between the final and initial points are of no concern, since the tool is not cutting metal during motion. Open-loop controls using stepping motors as the drive devices of the machine table can be utilized in on small-sized point-to-point systems in which the load torque is small and constant. To save machine time, the table travels at high velocities. However, in open loop control there is no feedback of the actual position of the table. Therefore, the velocity must be gradually reduced towards the end, to avoid overshooting the final position, due to the limited braking torque compared to the momentum of the drive system and the table at high speed.

As already explained in Lesson 23, PTP systems can use incremental or absolute programming. In incremental point-to-point systems a counter is loaded with the incremental coordinate of the destination by the interpolator. In closed loop systems it is decremented by pulses from the encoder, which indicate actual axis motion. In open loop control it is decremented at a suitable rate, by a pulse generator, as the step motor has turns by one step angle for each pulse. The motor is decelerated based on the content of the counter, which represents the distance to the destination point. A block diagram of an open-loop point-to-point control system for incremental programming for a single axis is shown in Fig. 24.7. When the motor axis reaches the destination point, counter content is zero.

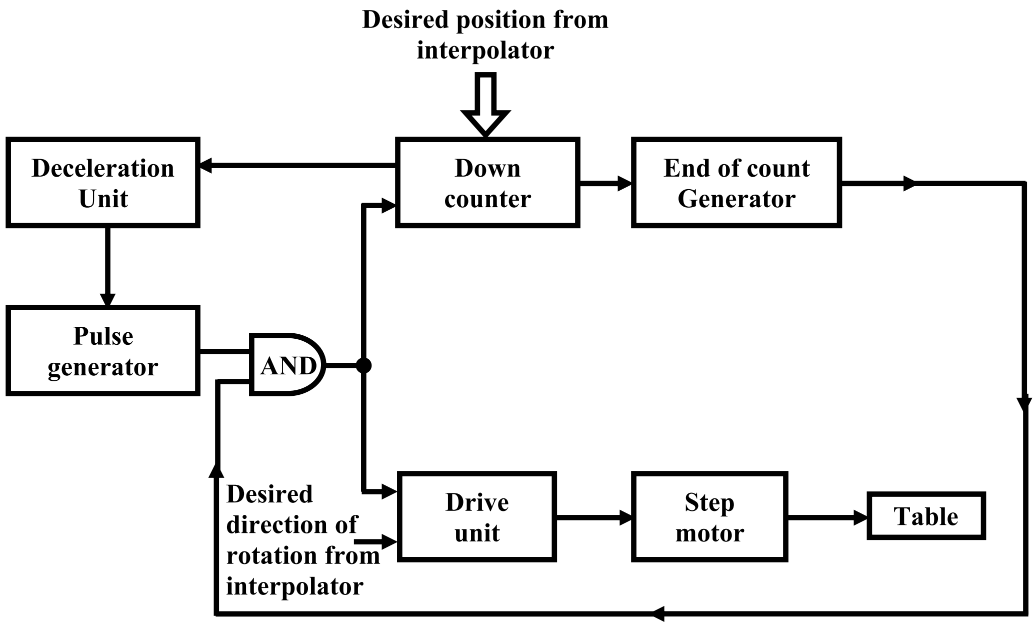


Fig. 24.7 Incremental open-loop control for PTP systems

In open loop control, it is implicitly assumed that the shaft rotates by 1 BLU for every command pulse applied to the drive. Thus the pulse generator frequency cannot be increased beyond a certain level, which depends on the load, since then the stepper motor would not be able to turn under the load with each pulse. To obviate this difficulty, feedback is used. The incremental change in the shaft position is taken from an incremental position sensor, such as an encoder, on the leadscrew, as shown in Fig. 24.8. The encoder

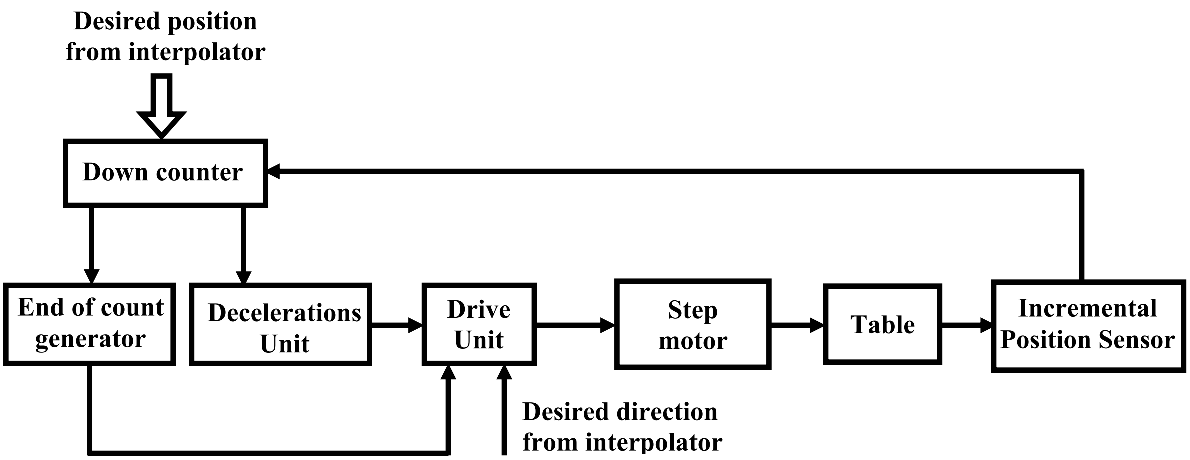


Fig. 24.8 Block diagram of closed-loop incremental PTP system

pulses, which represent the actual motion, feed the down counter rather than the command pulses produced by the pulse generator in the open-loop control.

The decelerator circuit slows down the motor before the target point in order to avoid overshoot. Note that, even in a closed loop system, to avoid errors due to backlash in gears, an overshoot is to be avoided. When the table is at a close distance of the target point, the table "creeps" toward the final point at very low velocity, before it stops.

In absolute positioning systems utilizing an incremental feedback device, two alternative sequences of pulses from the incremental encoder, one for each direction of motion, feed the up and down inputs of a *position counter*. Thus, its contents are incremented for a rightward movement of the corresponding axis and are decremented for a leftward motion. The position counter value, therefore, indicate the actual absolute position of the axis. A *command register* is loaded with the required absolute destination position of the axis, by the interpolator. The *subtractor unit* indicates the instantaneous actual difference between the required and actual position, which is the distance to the target point. The subtractor output is the position error of the loop. Till the subtractor output is zero, pulses are fed through a deceleration circuit to the motor.

Control of Contouring Systems

In contouring systems the tool is cutting while the machine axes are moving. The contour of the part is determined by the ratio between the velocities, along the two axes. The control in contouring systems operates in closed loop. Therefore, a contouring system uses a cascade control structure involving an inner velocity loop and an outer position loop for each feed axis improved dynamic response. In such systems the interpolator generate reference signals (in form of a sequence pulses or position words) for each axis of motion, in a coordinated manner so that a desired contour is generated.

Typical cascade control structure of contouring systems is shown in Fig. 24.9. It uses an inner velocity feedback loops incorporating a tachometer usually mounted directly on the motor shaft and an outer position feedback loop which is capable of measuring incremental (such as from an incremental encoder) or absolute angular position of the leadscrew shaft (such as a resolver or inductosyn).

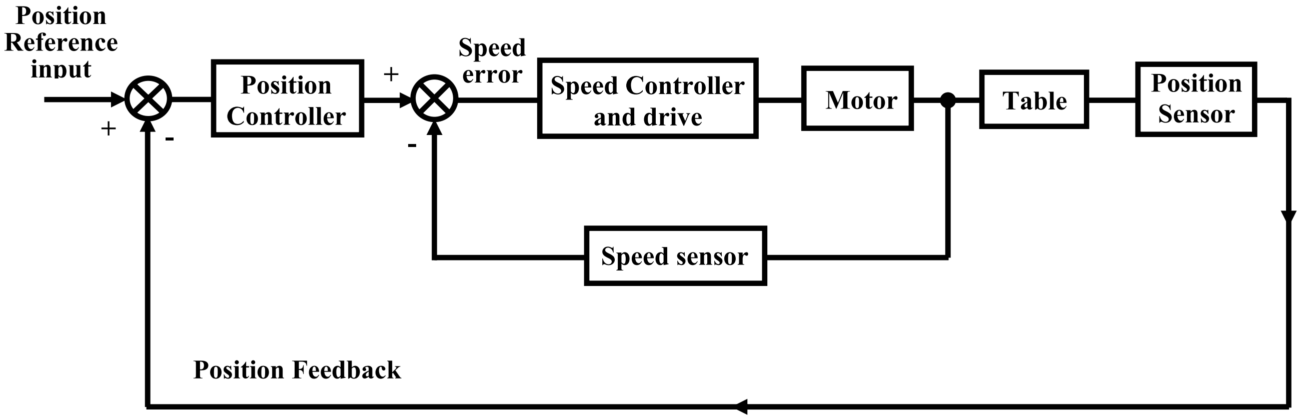


Fig. 24.9 Control loop of a contouring system

In encoder-based systems each pulse indicates a motion of 1 BLU of axis travel. Therefore, the number of pulses over a period represents incremental change in position over the period and the encoder pulse frequency is proportional to the axis velocity. In such a system, fed from a reference pulse interpolator the comparison is done by an up-down counter which is fed by two sequences of pulses: reference pulses from the interpolator and feedback pulses generated by the encoder. The counter produces a number representing the instantaneous *position error* in pulse units. This number can be converted by the DAC and fed to an analog position control system. A typical electronic PLC function module board for CNC drives is described below.

Point to Ponder: 3

A. *Do you think the closed loop PTP system control loop would work for arbitry axis velocities? Justify your answer.*

B. *What type controllers would you prefer for a cascade position controller for a contouring system?*

A Typical PLC-based Motion Control Board for CNC Drive

A PLC may be enhanced by a motion control or a position control module to control a CNC machine. A position control module is suited to the positioning operation requiring a high degree of accuracy with fast closed-loop position control of two axes. The module measures and processed the digital impulses of the position measuring system (actual values) and provides the drives with their respective rotational speed set point values for position to be reached. The functional parameters of the position control module can be set and stored in the on-board memory. The central controller provides the set point values, parameters and control commands and reads the actual values.

Position Control Module

- Shaft encoder input
- Onboard dedicated high speed CPU
- Motor drive set point output
- Digital IO
- Programmer port
- Set point from data bus

Fig. 24.10 A typical PLC Function module for Axis Control in a CNC

The module contains an on-board micro-processor which controls the measuring and processing of the actual values and emits, according to the design function, two rotational speed set point values. On the module there are plug-in connectors for position encoders. Either an incremental or absolute coded position encoder can be connected. Provision may also exist to accommodate plug-in connections for the analog speed set point values, the digital inputs and outputs (possibly for limit switches), as well as programmer interfaces. The functions of the position control module are controlled through the microprocessor software on the board EPROM. The data for the individual operating mode (machine date, operation data, process data) are provided via the programmer interface and are store on the on-board RAM.

If incremental encoders are used for the measuring of actual values, their pulses are counted up or down by a 16-bit counter, depending on direction of rotation of the motor and can be doubled or quadrupled. When an absolute position encoder is connected, a GRAY-code with a maximum of 20 bit is processed by the operation mode.

The set point output can take place via analog voltage outputs with a typical resolution of ± 11 bit. To improve the resolution in the lower speed range, a reference voltage for the DAC, individually switched for each section, with output voltage ranges between 0 and ± 1.25 V, ± 10V etc., may be provided by the operating mode.

Digital inputs (end limit switches, reference point, external stop) and digital outputs (loop controller release) are generally available for each axis.

The instantaneous position of the two axes is determined from pulse generated by the position encoders. A position controller (P controller) calculates the current rotational speed set point from the difference between the actual position and its set point. This is output as an analog signal (+ 10 V) and is available for the speed controller of the static converter of the particular axis.

Operator input is possible either from the programmable controller or from programmer via two interfaces. Position set points are calculated from user commands and the interpretation of traversing programs. Incremental position encoders can be connected to the module.

Both axes can be controlled from a programmer unit. Set points, actual values of process parameters such as speed or position, error and other information is displayed on the screen. Appropriate communication software is required for using the programmer unit (and for programming) and downloading the program onto the on-board memory. The positioning module can then be operated and tested independently of the programmable controller.

Before the positioning module and the processor module of a PLC system are able to communicate, the appropriate standard function blocks and the standard function blocks for communications processors must be loaded into the processor.

Axis and Spindle Drives

The primary function of the drive is to cause motion of the controlled machine tool member (spindle, slide, etc.) to conform as closely as possible to the motion commands issued by the CNC system. In order to maintain a constant material removal rate, the spindle and the tool movements have to be coordinated such that the spindle has a constant power and the slide has a constant torque over varying speed. In order to ensure a high degree of consistency in production, variable speed drives are necessary. With the developments in power electronics and microprocessor systems, variable drive systems have been developed. These are smaller in size, very efficient, highly reliable and meet all the stringent demands of the modern automatic machine tools. A discussion of variable speed drives for AC and DC motors can be found in Lessons 33-35. For CNC, typically AC/DC Servo and Stepper motor drives are used. For spindle drive adjustable speed DC or Induction motor drives are used.

Spindle Drives

The requirements of a spindle drive are mainly to control the set speed accurately within a wide constant power band, in the face of torque disturbances occurring with variations in material hardness. Large speed ranges up to 10-20,000 rpm and 1:1000 rangeability is often needed. The dc spindle drives are commonly used in machine tools. However, with the advent of microprocessor-based ac frequency inverter, of late, the ac drives are being preferred to dc drives as they offer many advantages. One of the main advantages with the microprocessor-based frequency inverter is the possibility of using the spindle motor for C-axis applications for speed control in the range of 1:10,00,000 with positioning. High overload capacity is also needed for unintended overloads on the spindle, say, due to an inappropriate feed.

Feed Drives

A feed drive consists of a feed servomotor and an electronic controller. Unlike a spindle motor, the feed motor needs to operate with constant torque characteristics. The drive speed should be extremely variable with a speed range of at least 1: 20,000, which means that both at a maximum speed, say of 2-3000 rpm, and at a minimum speed of 0.1 rpm, the feed motor must run smoothly. Positioning resolution corresponding to angular rotations of angular minutes is needed with quick response four-quadrant operation that needs a high torque-inertia ratio. Also, in contouring operations, where a prescribed path has to be followed continuously, several feed drives have to work simultaneously. This requires a fast response and matched dynamic characteristics high bandwidth for different axes.

Variable speed dc feed drives are very common in machine tools because of their simple control techniques. However, with the advent of the latest power electronic devices and control techniques ac feed drives are becoming popular due to certain advantages.

Point to Ponder: 4

A. *For the motion control board:*
    a. *Where is the interpolator situated?*
    b. *Where are the position and velocity loops situated?*

B. *Why should a feed drive operate in constant torque mode, while the spindle drive should operate in a constant power mode?*

Lesson Summary

In this lesson, the following topics related to CNC machines have been discussed.

A. Reference pulse and reference word interpolators

B. Linear and Circular Interpolation

C. Digital Integration with a DDA

D. Open loop and closed loop control

E. Control of PTP and Contouring Systems

F. Characteristics of Feed and Spindle Drives

Answers, Remarks and Hints to Points to Ponder

Point to Ponder: 1

A. *Is it possible to have a reference pulse interpolator for a CNC machine with dc drive?*

Ans: Yes, it is. Consider a closed loop system with an incremental encoder feedback. Implement an up-down counter with the pulse train from reference pulse interpolator driving the count-up input and the pulse train from the encoder driving the count-down input. The counter value indicates the instantaneous position error which can be used to drive say an analog controller through a DAC.

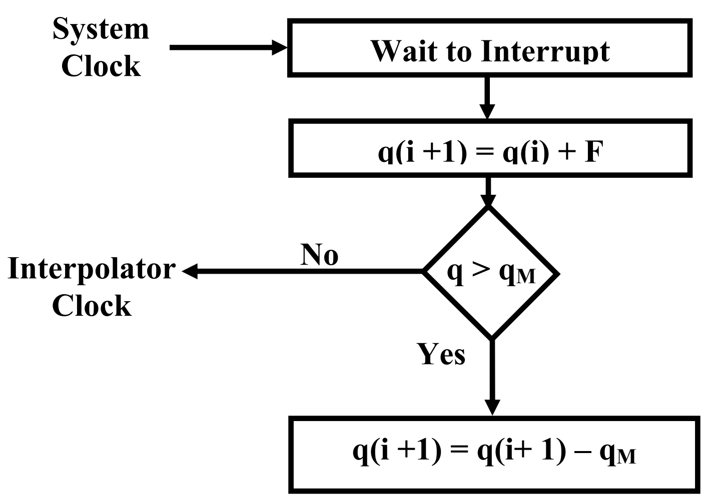
B. *What limits the speed of operation in reference word interpolator based systems?*

Ans: The servo system dynamics limit it, rather than the interpolator loop execution time. This is especially true when one is cutting angles and corners.

Point to Ponder: 2

A. *Devise a scheme for changing the feedrate in an interpolator.*

Ans: This can be done by generating the interpolator clock input using an DDA integrator as shown below. Note that by changing the constant F, the interpolator clock frequency can be changed.



B. *How does one choose the value of α for circular reference word interpolation?*

Ans: The upper bound is decided by the maximum allowable deviation from a perfect circle. The lower bound is decided by loop execution speed of the interpolator.

Point to Ponder: 3

A. *Do you think the closed loop PTP system control loop would work for arbitrary axis velocities? Justify your answer.*

Ans: May not be. One of the reasons being that with high axial velocities there would be position overshoots. However, unless the counter can represent negative position errors correctly correct positions would not be reached.

B. *What type controllers would you prefer for a cascade position controller for a contouring system?*

Ans: Typically P or PD controllers are used in the position loop, since there is already one speed to position integration built into the open loop dynamics. Inner velocity loop controllers are generally proportional (usually a servo amplifier).

Point to Ponder: 4

C. *For the motion control board:*

  a. *Where is the interpolator situated?*

  Ans: The interpolator must be situated external to the board, such as, in a PLC processor module.

  b. *Where are the position and velocity loops situated?*

  Ans: The position loop is implemented in the on-board software. Since the board provides velocity set points, it is assumed that the speed loop exists within the drive system.

D. *Why should a feed drive operate in constant torque mode, while the spindle drive should operate in a constant power mode?*

Ans: Because both torque on the feed drive motor and the power of the spindle motor can be shown to be roughly proportional to the material removal rate in machining. For a required degree of finish, a certain maximum material removal rate is possible. This is set through speed, feed and depth of cut settings. For all possible settings, to be able to obtain the best possible material removal rates, the feed and spindle motors should operate in their constant torque and constant power regions, respectively.

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