TECHNICAL UNIVERSITY OF LIBEREC

Faculty of Mechanical Engineering

Department of Manufacturing System

Design of the Servodrives for the table of CNC boring center

Návrh servopohonů pro stůl CNC vyvrtávačky

DIPLOMA PROJECT

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TECHNICAL UNIVERSITY OF LIBEREC

Faculty of Mechanical Engineering Department of Manufacturing System

Study discipline: **2301 T – Manufacturing System**

Design of the Servodrives for the table of CNC boring center

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Extent of the Diploma project :

Number of pages:	47
Number of appendix:	2
Number of figures:	18
Number of tables:	2
Number of graphs:	1

In Liberce 25.05.2004

THEME: Design of the Servodrives for the table of CNC boring center

ANNOTATION:

The diploma work deals with design of servodrive of CNC machine tool axis. Theoretical part includes introduction and characteristics of servodrives and CNC systems.
Main part defines kinematics and dynamics of given axis with respect to boring and milling technology.
Design of the servodrive for the CNC axis and check calculation regarding achievement of maximum velocity and acceleration.
Take into account less usual solution (two leading screws gantry type, rotating nut and linear drive).

TÉMA: Návrh servopohonů pro stůl CNC vyvrtávačky

ANOTACE:

Diplomová práce se zabývá návrhem servopohonu pro souřadnici CNC obráběcího stroje. Teoretická část zahrnuje úvod a charakteristiky servopohonů a CNC řídících systémů. Hlavní část definuje statické, kinematické a dynamické vlastnosti zadaní osy se zřetelem k technologii vyvrtávání a frézování.
Dále je proveden návrh CNC osy pro zadanou rychlost a zrychlení. Jsou uvažována méně obvyklá řešení (dva šrouby gantry, rotující matice a lineární pohon).

Declaration

I declare that I developed my diploma project independently with aid of referred literature under the control of supervisor and consultant.

In LIBEREC 25.05.2004 …………………………..

Amir Reza Amiri

Acknowledgement:

I would like to say, from all the people that have helped me through out my studies. My greatest gratitude goes to my parents for their patience and constant support during all stages of my life, without which I would have never made it so far.

I would like to take this opportunity to express my sincere thanks to my lecturer namely Prof. Jan Skalla, Csc. and my dear friend Dr. Mohsen Gharazi and also thanks a lot to the Mechanical Department for their instruction and advises during my course and project work, also my thanks and gratefulness to the teaching staff and administration especially the Mechanical Department for all of the assistance and support which they have given during my course of study.

List of some abbreviation

m_x	[kg]	mass of the table
v_{max}		max speed
n_{max}	[rpm]	max revolution per min.
A		speed reduction mechanism none- direct
u		guide way
F_T	[N]	resistance of the guide
Fa	[N]	friction
t_1	[s]	acceleration time
N_1	[rpm]	Critical speed
N_2	[rpm]	speed according DN factor
N_{max}	[rpm]	allowable rotational speed considerations
l_a and l_b	[mm]	mounting distance
E	[Nmm^{-2}]	Young modulus
I	[mm^4]	min geometrical of inertia
λ		Coefficient for condition support
γ	[kg/mm^3]	density
C_a	[kN]	parameters of ball screw selected
F_{omax}	[kN]	Allowable axial load considerations
d	[mm]	diameter
D	[mm]	Ball screw diameter
f_s		safety factor
f_w		load factor
L	[rpm]	life calculation

1 Introduction

The servo control is the closed loop control of position velocity and current. Word ”servo” is derived from the same root as “servant”. Servo loops follow commands as well as possible. The output of a servo loop is a torque (or, equivalently, current) command, which is delivered to the motor control algorithms and circuits. The servo loop takes a position and/or velocity command and calculates the torque needed to satisfy that command. The motor controller produces torque in response to the servo loop output. AC and DC servo drives are widely used in motion control applications such as machine tools, packaging, printing, robots, textiles, and food processing. The motion control algorithms are based on the mechatronics assumption of nearly ideal electromagnetic torque control. This assumes ideal field orientation and current regulators of bandwidths desired. Feedback devices, chiefly encoders and resolves, are employed in these systems to sense motor position and to calculate the sample average motor velocity, albeit with significant average velocity resolution limitations. The majority Of motion control algorithms employed in industrial applications are of two forms: 1)an average velocity loop is cascaded with a position loop ,or 2): state variable loops(proportional-integral-differential, PID position loops) are closed in parallel.

Servo drives provide three primary functions:

1. servo control
2. Motor control
3. power conversion

1.1 Servo control

Servo control is defined as regulation of velocity and position of a motor based on a feedback signal. The most basic servo loop is the velocity loop. The velocity loop produces a torque command in order to minimize the error between velocity command and velocity feedback. Most servo systems require position control in addition to velocity control. The most common way to provide position control is to add a position loop in “cascade” or series with a velocity loop. Sometimes (very rarely) a single PID Position loop is used to provide position and velocity control with out an explicit velocity loop. Servo loops have to be “tuned” for each application. Tuning is the process of Setting servo gains and other parameters. Higher servo gains provide higher level of performance, but they also move the system closer to instability. Low-pass filter are commonly used in series with the velocity loop to reduce high frequency stability problems. Filters must be tuned at the same time the servo loops are tuned. Some drive manufacturers to deal with demanding applications provide advanced control algorithms. The algorithms may be necessary because the mechanics of the system do not allow the use of standard servo loops, or because the requirements of the application may not be satisfied with standard servo control loops.

1.2 Motor control

Motor control describes the process of producing actual torque in response to the torque command from the servo control loops. For brush motors motor control is simply the control of current in motor winding because the torque produced by the motor is approximately proportional to the current in the winding. Most industrial servo controllers rely on current loops. Current loops are similar in structure to velocity loops, but they operate at much higher frequencies. A current loop takes a current command (usually just the output of the velocity loop) and compares it to a current feedback signal and generates an output, which is essentially a voltage command. If the system needs more torque, the current loop responds by increasing the voltage applied to the motor until the right amount of current is produced. Tuning current loops is complicated. Manufactures usually tune current loops for a motor.

1.3 Power conversion

Servo drives provide power to the motor. Control algorithms rely on the ability of the power stage to produce the current that will make the torque that will satisfy the speed and position loops. Power transistors provide current to the motor windings through a process called modulation. The amount of power that can be delivered to the motor is a function of the voltage applied and the current rating of the drive.

1.4 Boring center machines

A machining centre tailored to **mect** the users precise, individual, specification. A system of solutions rather than a machine design. Users can build their own custom configurations from the range of standard solutions, tried and tested in the field and guaranteeing top reliability .The machining centre can be equipped with the multi function worktable or the mobile holt-down accessory bars to provide ideal working conditions. It could be felted with the endwise multi-function work table which enables the machining of all component types and a variety of materials inducting solid wood, muff, chipboard, alleys and plastics. This solution is ideal for nesting jobs, cutting shapes from panels, which repairer high vacuum capacity. There is some CNC boring and routing centers with alternated work process. Like Tech 80 that supplementary stop to increase working area in x direction to 3230mm and it has pneumatic panel loading assistance device to allow the correct positioning of large and heavy panels avoiding friction on the working tables .There is another classic model of CNC machine that has a fined column, a live spindle and Column, a live spindle and crosswise adjust table rotary table it is the smallest CNC machine manufactured by TOS Varnsdorf. For example another type of boring machine are : floor type horizontal boring mill, this machine provides high cutting performance within the entire operating area and high comfort of user functions. The combination of the progressive and traditional features of its construction and cutting edge technology provides the user with excellent conditions for the efficient machining of large size and heavy weight work pieces while using the most demanding technological processes model WRD 150 (Q) machine is progressive floor type machine with a ram and live work spindle. It is continually controlled in four axis.(X,Y,Z,W)The main drive as other drives for the machine axis are digital AC type siemens.

Model	Rapid traverse X,Y	Rapid traverse	Man working speed	Man work piece mass

		Z,W		
WR 150	16000 mm/min	12000mm/min	128000 mm/min	25000kg
WR 130	16000 mm/min	12000 mm/min		
WH(Q) 150 CNC	10000mm/min	8000 mm/min		

2 Electric drives

Drive systems are important components of every NC machine. The characteristics of the drives exert a powerful influence on the quality of the work pieces and the speed of the machine. For this reason, spindle drives and servo drives are subject to relatively stringent requirements.

2.1 Overview

Standard equipment for modern machine tools includes electric drives for feed motions and for the main spindle. The standard setup also provides means for controlling the rotational speeds of these drives. Drives of this type generally comprise the following components (Figure 2.1):

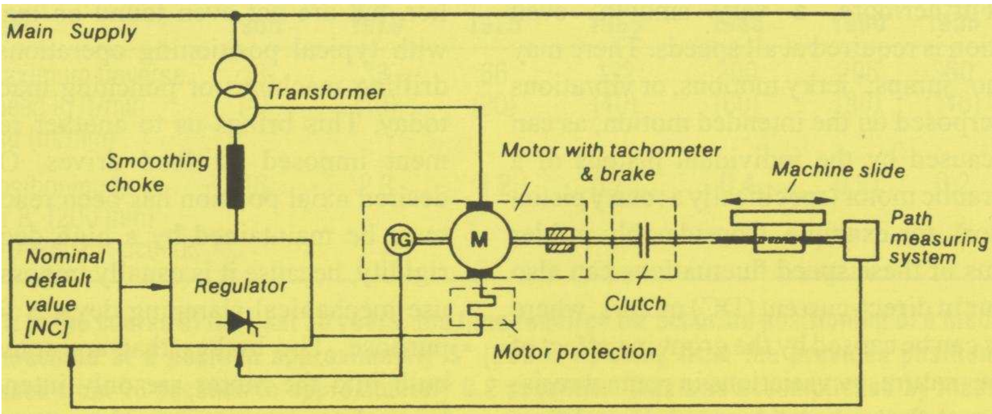


Figure 2.1 Schematic diagram of feed drive

- a motor with a tachometer (in old drives)and, in some cases, a holding brake

- a controller with a power amplifier, for spindle drives with field power amplifier
- in some cases, a power transformer and smoothing chokes
- a mechanical clutch, sometimes provided with overload protection
- a motor protection device to guard against over current or excess temperature
- in some cases, an encoder flange mounted to the free end of the shaft, serving as a path measuring system for a feed drive or as an angle encoder for a spindle drive
- for some spindle drives, a change speed transmission with a fixed or variable gear ratio, for the purpose of making the rated motor speed conform more closely to the required speed or torque conditions.

Furthermore, both feed drives and main drives must satisfy the demands for minimal maintenance requirements, wear, noise, vibration, heating, space requirements, and price. Figure 2.1 shows schematics for a feed drive and a main spindle drive.

2.2 Feed drives

Because of the required degree of accuracy, the axial motions of NC machines must conform to the target values specified by the numeric control. This must be accomplished very precisely, with a high degree of repeatability, and without delay (if possible). It must also be independent of counteracting forces such as cutting force, friction, or moment of inertia. The traverse speed must be as high as possible, thus minimizing the time required for exact positioning. In recent years it has become possible to satisfy the demands placed on these drives to an almost inconceivable extent.

Furthermore, a very smooth, even motion is required at all speeds. There may be no "jumps," jerky motions, or vibrations superposed on the intended motion, as can be caused by the individual pistons of a hydraulic motor (specifically a rotary piston motor), for example. Considerably milder forms of these speed fluctuations can also occur in direct-current (DC) motors, where they can be caused by the grooving effect of the armature, by variations in contact resistance at the commutator, or by amplifiers using silicon-controlled rectifiers (SCRs).

Even a slight humming or resonance ; the motor will impair the surface of the machined work piece to such an extent that the user of the machine may later reject it. Motors with finely balanced armatures are even used in some grinding machines for this reason.

In continuous path control operations, a separate drive is required for each NC axis, so that any desired contour can be produced in any plane or spatial form. Central drives (single-motor drives) with clutches and a brake for each axis were used earlier, but are not even found on machines with typical positioning operations (e.g.-drilling machines or punching machines) today. This brings us to another requirement imposed on feed drives. Once a desired axial position has been reached, it must be maintained by a high degree of rigidity, because it is usually impossible to use mechanical clamping devices for this purpose. The brakes that are sometime built into the motor are only intended to bring the motor to a complete stop within an acceptable length of time, or to prevent the NC axis from drifting out of position when a power failure or an emergency stop occurs.

High-quality feed drives are also expected to exhibit a fast dynamic response. This means that the drive must execute speed changes as quickly as possible, without "overshoot."

These characteristics can also be collectively described as reaction speed. The following motors are used for feed drives.

1. **Direct-current (DC) motors.** Most of these motors are excited by permanent magnets; only a few are separately excited. Shunt-wound motors (in which the field winding is also supplied by the armature voltage) are never used for this purpose.
2. **Three-phase motors.** Most of these are synchronous motors, but there has been a recent increase in the use of asynchronous motors, which may boast speeds up to 6,000 rpm and high starting torque (a.k.a. "locked rotor torque").

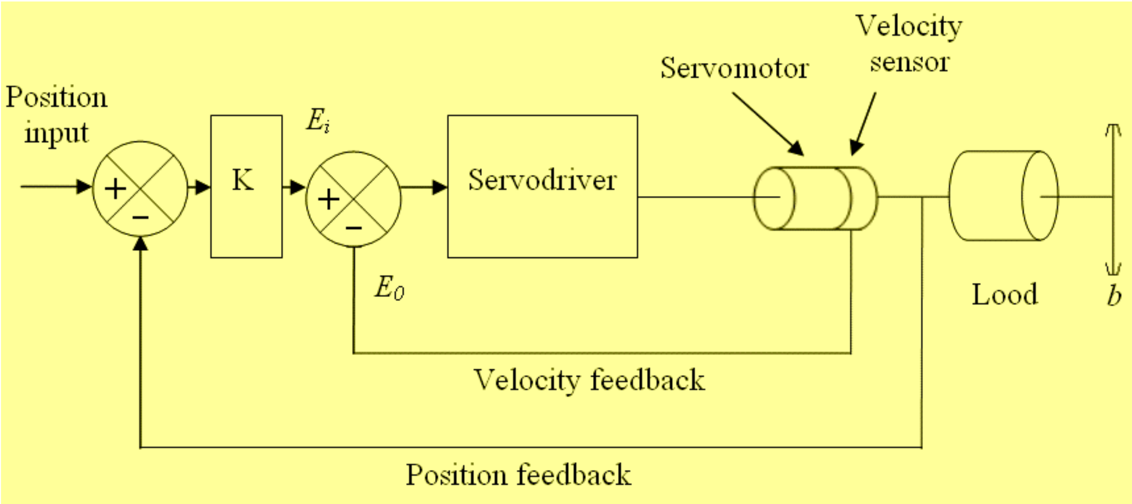
Both of these motor types are supplied from the main power line via special devices known as power converters. In order to achieve the required dynamic characteristics and rigidity, these motors are ordinarily operated in a closed speed control loop with a precision tachometer, which is used to measure the actual speed.

3. **Stepping motors.** These motors can be operated either by purely electrical methods or with hydraulic torque amplifiers. They require neither a tachometer nor path measuring systems to provide feedback

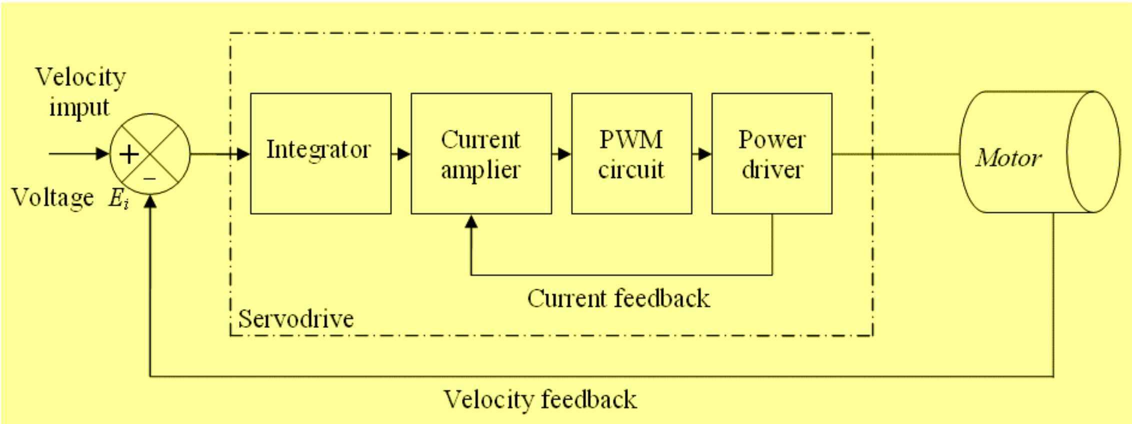
2.3 Electronic motion control of DC servomotors

There are many different types of electronic motion controllers or servo drivers for servomotors. Most servo drivers are designed for speed control of dc servomotors.

They improve the efficiency of operating servomotors. Figure 2.2 shows a block diagram of a high-speed, high-precision positional servo with speed control using a servo driver and servomotor combination. This servo driver is designed to obtain motor speed proportional to the voltage E_i. Figure 2.2l(b) shows a functional block diagram for the servo driver.



(a)



(b)

Figure 2.2 (a) High speed, high precision positional servo system with speed control using a servo driver, servomotor combination. (b) functional diagram of servo driver

2.4 DC Feed Drives

This type of drive has been available for years in tested and proven designs. Because of progress in the field of magnetic materials, motors excited by permanent magnets with 4, 6, or 8 magnetic poles are used exclusively today (Figure 2.3).

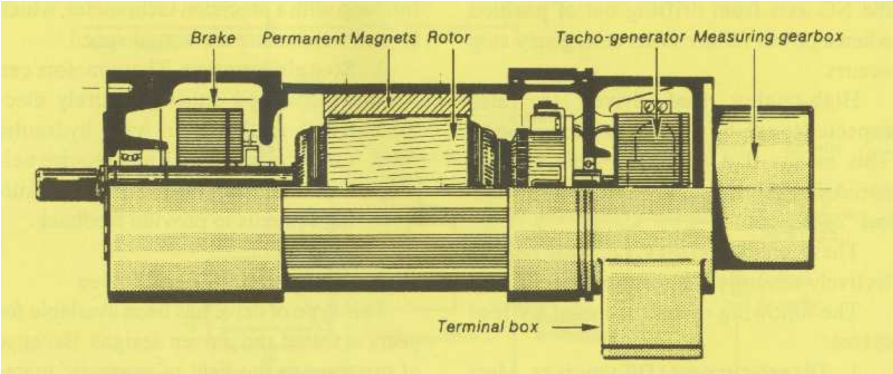


Figure 2.3 Direct current feed motor with built in brake and tachometer

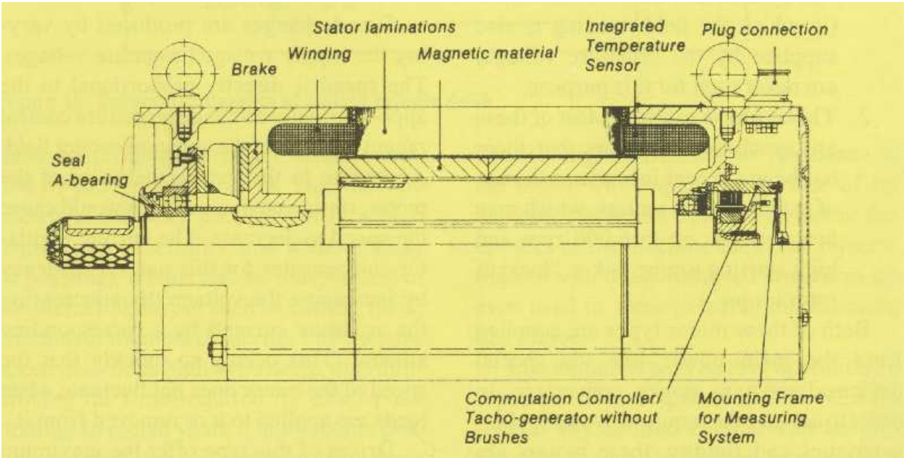


Figure 2.4 Brushless servomotor developed from the three phase synchronous motor, with built in commutation sensor.

Speed changes are produced by varying the supply voltage (armature voltage).The speed is directly proportional to the applied armature voltage (armature control range) because of the constant exciter field. According to the natural behavior of the motor, static or dynamic loads would cause the speed to decrease. The velocity regulator compensates for this natural tendency by increasing its output (thus increasing the armature current) by a corresponding amount. This occurs so quickly that the speed of the motor does fluctuate when loads are applied to it or removed from it. Drives of this type offer the maximum torque down to zero speed. However, the effective peak torque decreases as the speed increases, because of the commutation limit. The current regulator must limit the current as a function of speed, so that the commutation limit can not be exceeded. Without this safeguard, severe sparking on the carbon brushes will destroy the commutator.

Under these circumstances, DC feed motors of increasing size and torque can only be used at reduced speeds. In order to minimize this effect, DC feed motors are equipped with greater commutator diameters and greater numbers of commutator segments than ordinary DC motors (Figure 2.5).

Another type of construction that is frequently used is the "pancake motor," nicknamed for its disk-shaped rotor. In this type of motor, the conductors are attached to a disk made of an insulating material. This disk rotates between the exciter magnets (Figure 2.5). Because the armature contains no iron and the mass moment of inertia is low, this motor can achieve very low time constants, i.e., high acceleration values.

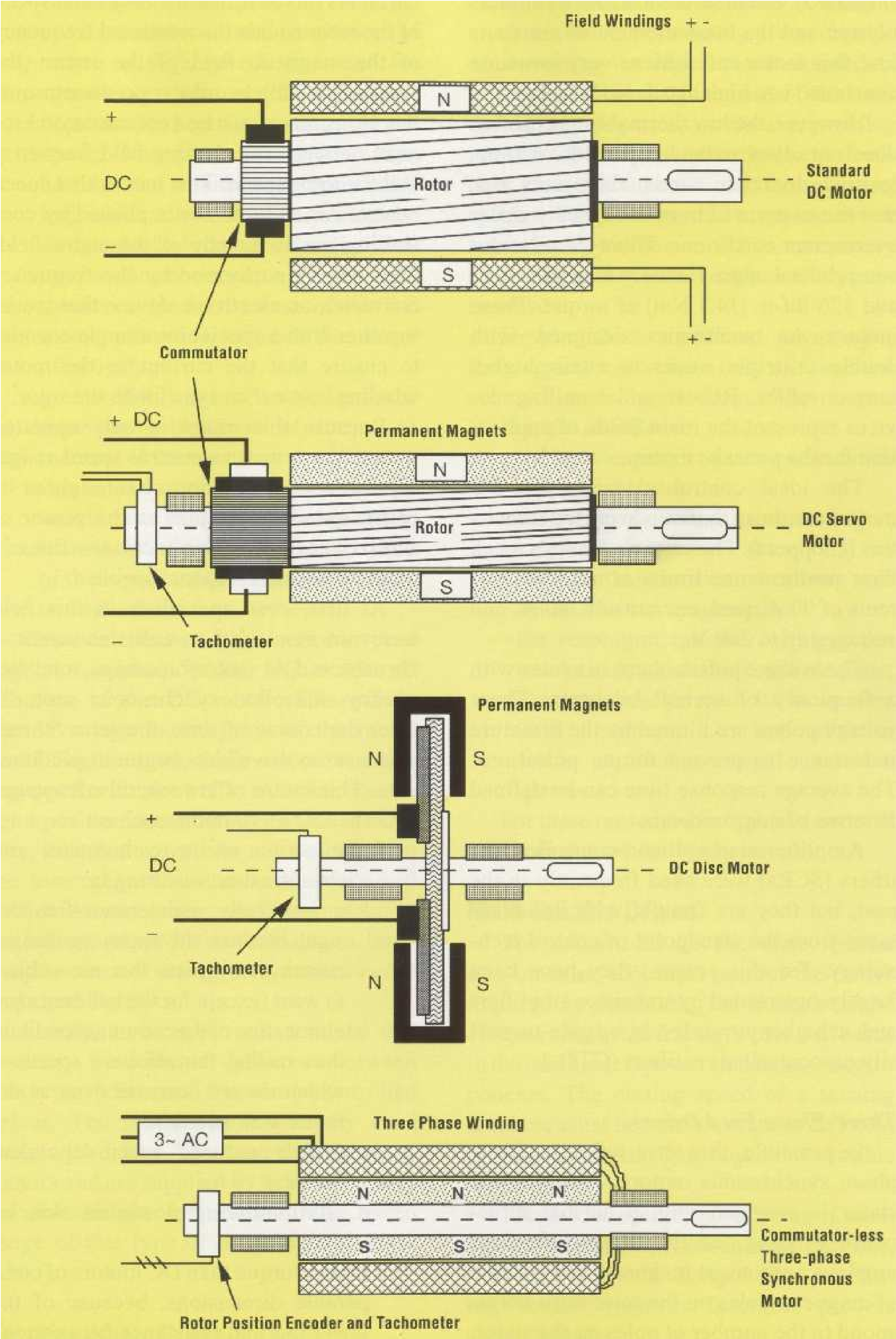


Figure 2.5 Types of motor construction

However, the low thermal time constant does not allow extended periods of overloading. In other words, there is a risk that the motor will burn out quickly under over current conditions. This type of motor can produce approximately 6 hp (4.5 kW) and 126 lbf in (14.3 Nm) of torque. These motors are sometimes designed with double or triple rotors to attain higher torque values. Robots and handling devices represent the main fields of application for the pancake motor.

The ideal control elements for DC motors are those that utilize switched transistors (choppers). The control elements reach their performance limits at nominal currents of 90 A, peak currents of 180 A, and voltages up to 200 V.

The voltage pulses occur in cycles with a frequency of several kilohertz. These voltage pulses are filtered by the armature inductance to prevent torque pulsations. The average response time can be defined in terms of microseconds.

Amplifiers using silicon-controlled rectifiers (SCRs) were used frequently in the past, but they are fraught with disadvantages from the standpoint of control technology. For this reason, they have been largely superseded by transistor amplifiers and, at higher power levels, by gate-turnoff silicon-controlled rectifiers (GTOs).

2.5 Three-Phase Feed Drives

In principle, this term refers to three phase synchronous motors, in which the stator is provided with a normal three phase winding and the salient-pole rotor employs permanent magnets. The number of magnetic poles on the rotor must correspond to the number of poles on the stator.

The essential characteristic of the synchronous motor is that the rotational speed of the rotor equals the rotational frequency of the magnetic field of the stator (the "rotating field"). In order to produce torque, therefore, there must be a constant synchronism between the rotating field frequency and the rotor speed. This means that speed control can only be accomplished by controlling the frequency of the stator field. This task is performed by the frequency converter, an electronic device that works together with a special rotor angle encoder to ensure that the current in the motor winding rotates "in sync" with the rotor.

Because this motor is only operated within the armature control speed range, it produces constant torque throughout its entire speed range, just as the power of a direct current motor increases linearly with increasing rotational speed.

At first, even specialists in this field were not sure what to call this motor "brushless DC motor," perhaps, or "frequency-controlled synchronous motor?" Over the course of time, the term "three phase servo drive" has begun to predominate. This motor offers several advantages over the DC servomotor, such as:

- elimination of the commutator and carbon brushes, resulting in:

  a) a practically maintenance-free design, because the motor no longer contains any parts that are subject to wear (except for the ball bearings)

  b) elimination of the commutation limit, thus raising the effective speeds which do not decrease even as the motor size increases

  c) greatly reduced speed-dependent losses

  d) elimination of contamination by carbon dust
- higher torque than DC motors of comparable dimensions, because of the lower thermal resistance between the winding and the environment
- full torque at zero speed
- no commutator related limitation of torque at high speeds (no need for speed-dependent current limiting)
- because the heat loss occurs in the stator, three-phase servomotors can be subjected to intense external cooling, which allows them to always be designed with full protection; the cooling air does not need to pass through the inside (as in the case of the DC motor) in order to cool the motor effectively
- greater ability to accelerate, due to the more favorable ratio of torque to moment of inertia
- significantly more favorable power-to- weight ratio (by a factor as high as 5) than in DC feed motors, as a result of the higher torque values and effective speeds.

However, the cost of the electronic speed regulator is considerably higher than in the case of the DC motor. This offsets the advantage in the price of the motor itself. Furthermore, these motors must be equipped with electronic encoders for the rotor position, as well as extra fans. Therefore, cost estimates can not be based on the assumption that standard motors will suffice. An increasing number of machines are being equipped with these drives, however, because of their greatly superior control characteristics.

Finally, it is important to note that there is a fundamental difference between this type of drive and frequency-controlled drives. The latter are occasionally used as spindle drives. They use asynchronous motors and are supplied by generators with variable output frequencies. The speed range of this type of drive is only about 1:10.

2.6 Stepping Motor Drives

Stepping motors would seem to be especially well suited to numerically controlled machine tools, because they are capable of converting the digital dimensional data into mechanical displacement of the axes by "direct" means, i.e., without any analog intermediate stage, and without any feedback from a tachometer or path measuring system. Furthermore, the stepping motor is practically maintenance free, completely enclosed (in most cases), and relatively economical.

Despite these significant advantages, the stepping motor finds only minimal use on machine tools nowadays. The reasons for this are as follows:

- the low stepping frequencies, i.e., inadequate feed rates
- the relatively low maximum torque, i.e., low acceleration values
- the risk that transient overloads will cause a loss of synchronism
- the resolution (number of steps per revolution), which is often inadequate; even at a resolution of 0.004 in./step (0.01 mm/step), it is impossible to attain sufficient rapid traverse speeds.

For these reasons, this type of drive will not be discussed further here.

2.7 Safety Devices

The servo drives and spindle drives of NC machines are typically pushed to the very limits of their performance capabilities. For this reason, a reliable monitoring method must be used to absolutely ensure that the limit values are not exceeded, so that damage is prevented.

These operating limits of the motor are determined by:

- the generation of heat in the winding (and in the magnets and bearings, if applicable)
- the commutation limit (brush sparking) in DC motors
- the demagnetization limit in motors excited by permanent magnets
- the pull-out torque in asynchronous and synchronous motors
- the centrifugal forces at over speeds (i.e., above the rated speed).

In the absence of effective protection against overloads, the motor can become unusable after only a short period of operation.

The generation of heat in the motor is monitored by built-in thermal switches and additional bimetallic relays in the armature circuit. The motor's design must provide for mounting it in a manner which is conducive to air circulation, so that the energy lost as heat is dissipated effectively.

Effective current limiting is necessary for the prevention of brush sparking and dangerous over currents. This current limiting protection must also restrict the short-circuit current that occurs when a motor "locks up" and provide for rapid shutoff. Over speeds can be prevented by mean, of over speed governors or, in the simplest case, by monitoring the tachometer voltage.

3 NC machine tool drive control

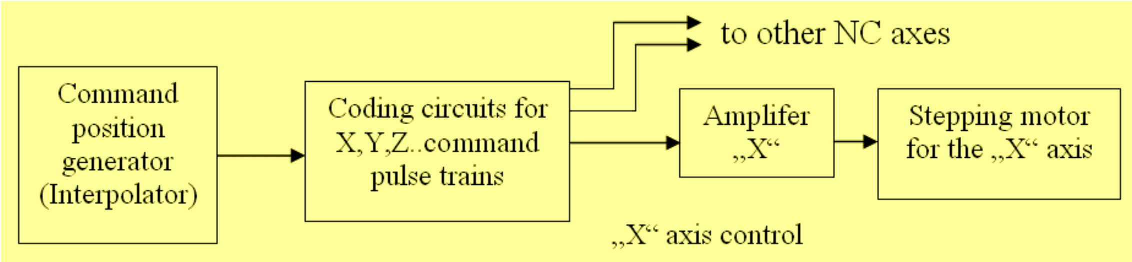
Companies in the NC machine tool sector are under constant pressure to increase both the productivity and machining quality of their machines. In addition to reduced costs in the production process, new machine concepts are required which allow flexible and cost-effective handling and inter handing functions.

Increasing both the machining speed and machining quality puts high demands on the dynamic and thermal behavior of the feed systems of modern machines. This trend is supported by considerable progress in the development of control systems and dynamic drive motors. In contrast, the mechanical components in the drive are often the weakest link when seeking improvements in dynamic behavior. The classical NC axis with a locating/non-locating bearing arrangement is currently limited to a speed range of 30 to 60 m/min and acceleration up to 10 m/s^2.

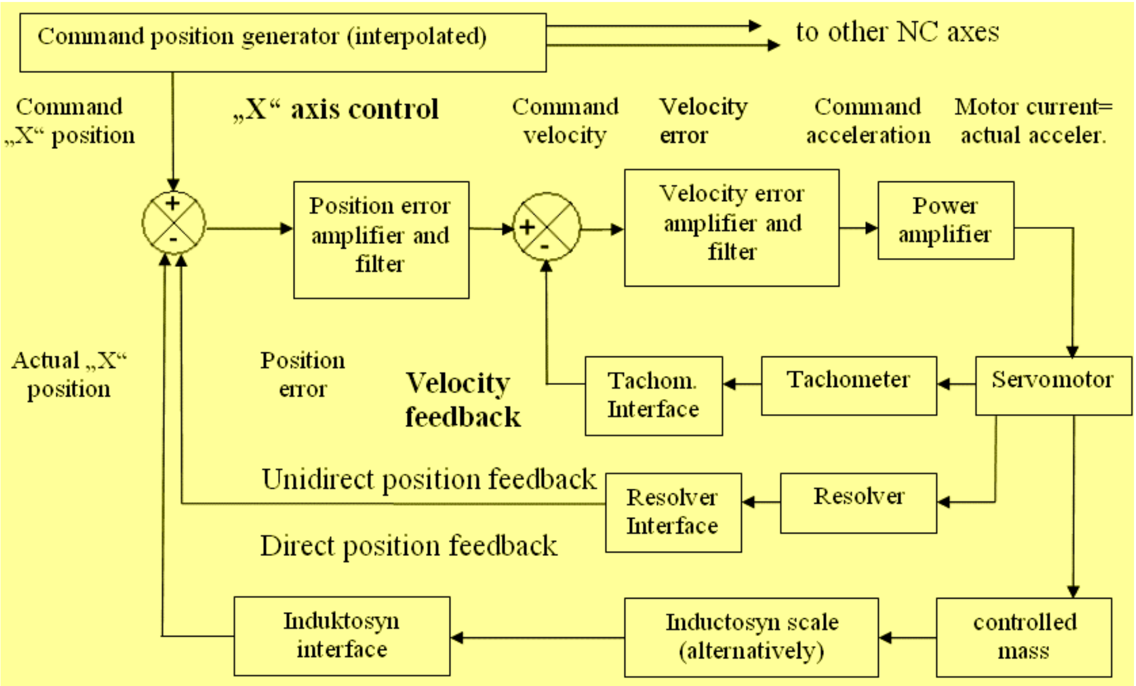
One possibility for overcoming these technical limitations is the linear drive, whose particular features offer a clear increase in dynamic characteristics. This system converts electrical energy directly into motion without the use of mechanical elements. Test drives of this type have achieved acceleration values of 10 to 12 times acceleration due to gravity and speeds up to 100 m/min.

In contrast to these general benefits, however, drives of this type have lower dynamic rigidity than electromechanical feed systems, greater influence of the thermal flux to the machine structure, significant sensitivity to load parameter fluctuations and, in particular, significantly higher system costs; the linear drive cannot be seen as the ideal solution for all applications. It is therefore considered mainly for light machining applications. It is not feasible for the manufacture of large, heavy components requiring high machining forces.

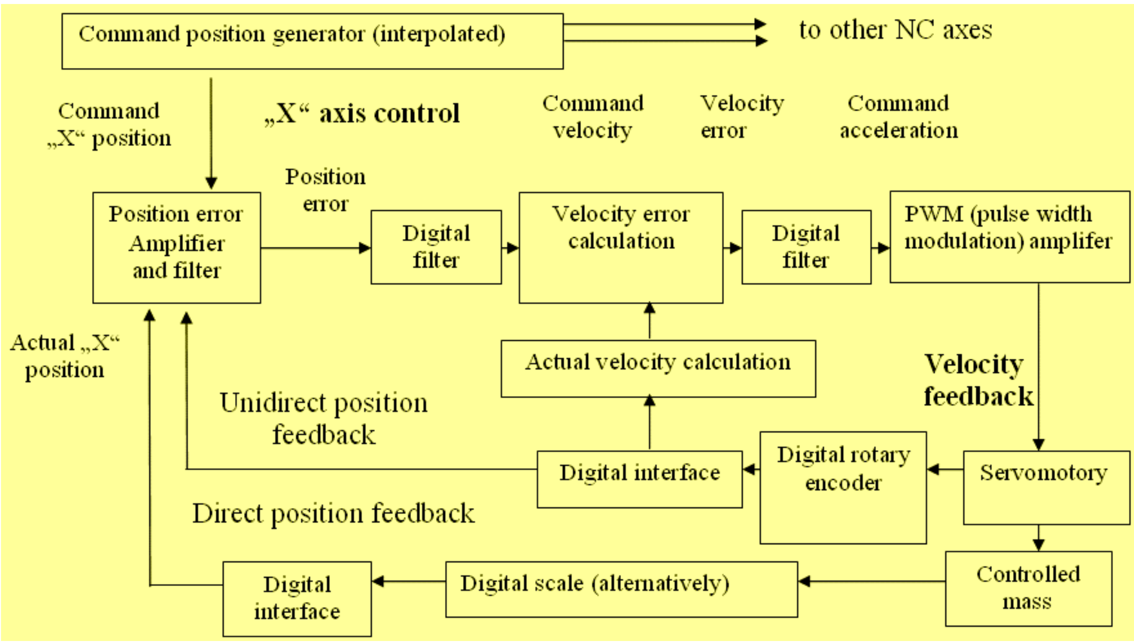
Interpolation process generates only command position data, which are then used as control information for CNC drive systems. Figure 3.1 depicts three basic types of drives for NC axes, these being the open loop drive with stepping motors, analog closed loop drive with DC servomotors and digital closed loop drive with DC servomotors. Many other versions have appeared in practice, mostly as combination of shown principles.



(a) An open loop drive system with stepping motors



(b) A close loop analog drive system with DC servomotors



(c) A close loop digital drive system with DC servomotors

Figure 3.1 Three common types of NC machine drives

The open loop drive system with stepping motors acts upon the control commands of the CNC system without applying any position feedback loop. Without the position feedback information, there is no way for the control system to know actual position of the NC axes during the system operation. Open loop systems are very sensitive to the load resistance and can be used only for lighter and slower machines.

With the closed loop drive system, position and velocity feedback loops are used to monitor continually the actual position and velocity and correct any discrepancy between desired and actual system performance. In latest NC drives, additional internal loops like acceleration and motor current feedback loops may be used to reach highest quality of motion control (not shown in the picture). Feedback loops can be either analog or digital. Analog drives measure the actual position and velocity in voltage levels. Resolvers are typically used for measuring of position, while tachometers for measuring of velocity, but many analog drives are using incremental or absolute digital measuring of position as well.

Digital drives do not evaluate the position or velocity errors in a form of analog voltage. Errors are calculated like difference between two digital values representing the command and actual positions or velocities. Analog tachogenerator are now replaced by digital calculation of actual velocity from the actual position data. Control current of servomotors is gained by contactless power switching based on the **PWM – Pluse Width Modulation principle.**

3.1 Control Loops

3.1.1 Concept of closed loop control

Most of closed loops control systems share four basic elements: a control law (Regulator), a power converter, a plant (such as a motor), and a feedback device. Most closed loops have three key signals: a command that directs the loop to move a response, and a disturbance, which hampers that control. These features are common in loops used to control motion, pressure, voltage, current, temperature, and flow.

What does a control law do?

A control law (Regulator) minimizes error. Control laws (Regulator), such a proportional-integral (PI) algorithms, are high gain functions. They amplify errors as much as possible so that even small errors will generate a command to the power converter. A typical control law in a servo system is a PI velocity controller.

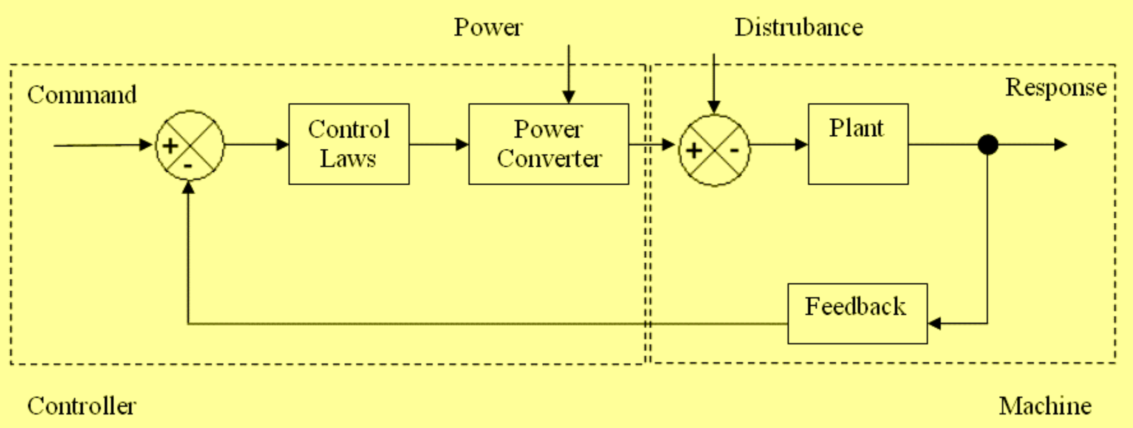


Figure 3.2

What is PI control?

PI control uses two gains, one directly on the error and the other on the integral of the error, to reduce the error magnitude. The proportional gain responds to high-frequency errors. The integral gain responds to low-frequency errors, accumulating error over time so that even small errors will eventually cause the drive to produce a lot of torque. With an integral gain, a loop will eventually respond with full power to cancel even small DC errors.

What does the power Converter do?

The power converter produces power that moves the plant. If the system is working well, the power from the power converter will cause the plant move in such a way that the feedback will move very close to the command. Without a power converter, a control system cannot move the plant to follow the command. For a servo system, the power converter is the current loop and the power transistors

3.2 Investigation of accuracy problems

High frequency perturbations

High-frequency perturbations are problems of accuracy where the motor moves about rapidly. These problems are usually accompanied by audible noise. The perturbations are usually random and the motor shaft may feel grainy or it may jitter. The negative impact may be objective, such as a poor finish on a machined surface. On the other hand, the concerns may be subjective, such as where the engineer is concerned that the perturbations may reflect poorly on the overall value of the machine.

Low frequency vibrations

Low-frequency vibrations are repeatable oscillations with a frequency proportional to the motor speed. They often cause a pronounced hum, especially as the motor turns faster. This may cause "waves" to form on the finish of a machined surface or they may cause uneven coating on a web-handling machine.

Zero-speed position error

Zero-speed position error is where the motor will not move to the correct position. Here, the concern is that the motor comes to rest. For problems of excessive activity when the motor should come to rest, see "High-frequency perturbations" above. Also, the concern here is independent of load. For problems where a load disturbs the position, see "Poor static stiffness" and "Poor dynamic stiffness," below.

Excessive following error

Excessive following error indicates that the motor does not follow the command well at speed, especially at high speed.

Poor static stiffness

Poor static stiffness is where the motor will not hold position in the face of low-frequency disturbances, such as gravity or friction. Poor dynamical Poor dynamic stiffness is where the motor will not hold position in the face of high-frequency disturbances, such as on a machine tool, the disturbances created when individual cutter blades contact a work piece.

Limit cycles

Limit cycles are the low-frequency (typically < 1 Hz), low amplitude (typically < 0.1 mm) oscillations seen on machine tools and other precision equipment.

4 CNC – Computer Numerical Control

Within only a few years, numerical controls have become smaller, faster, more powerful and user friendly. Many functions and tasks have also been added, making it possible to attain a higher degree of automation. CNC systems are intended to greatly increase the productivity of the machines they control and the people who use them.

4.1 Definition

The term "CNC" (computer numerical control) denotes a numerical control that contains one or more microprocessors to execute the control functions. Visible features of a CNC system include the display monitor and keyboard (Figure 4.1).

Figure 4.1 TNC 426 continuous path control for milling machines and machining centers with up to five digitally controlled NC axes and one spindle. These controls are especially characterized by their user interfaces, which are specifically oriented toward use "on the shop floor." (Heidenhain)

The operating system of the control, also known as CNC software, encompasses all required functions, such as interpolation, position feedback control, speed control, screen displays, editing, data storage, and data processing. The CNC system also requires a machine/control interface program, which is created by the machine manufacturer and integrated into the

Programmable Logic Controller (PLC). This program contains all machine-related logical associations and interlocks for special sequences of functions (e.g., changing tools and work pieces, limiting axial motion).

Because all modern CNC systems are constructed according to this basic principle, and contain at least one microprocessor, the terms NC and CNC can be considered synonymous.

4.2 Basic NC functions

The classic task of numerical control has been the precise control of relative motion between the tool and work piece on a machine tool, but new tasks and functions are constantly being added (Figure 4.2).

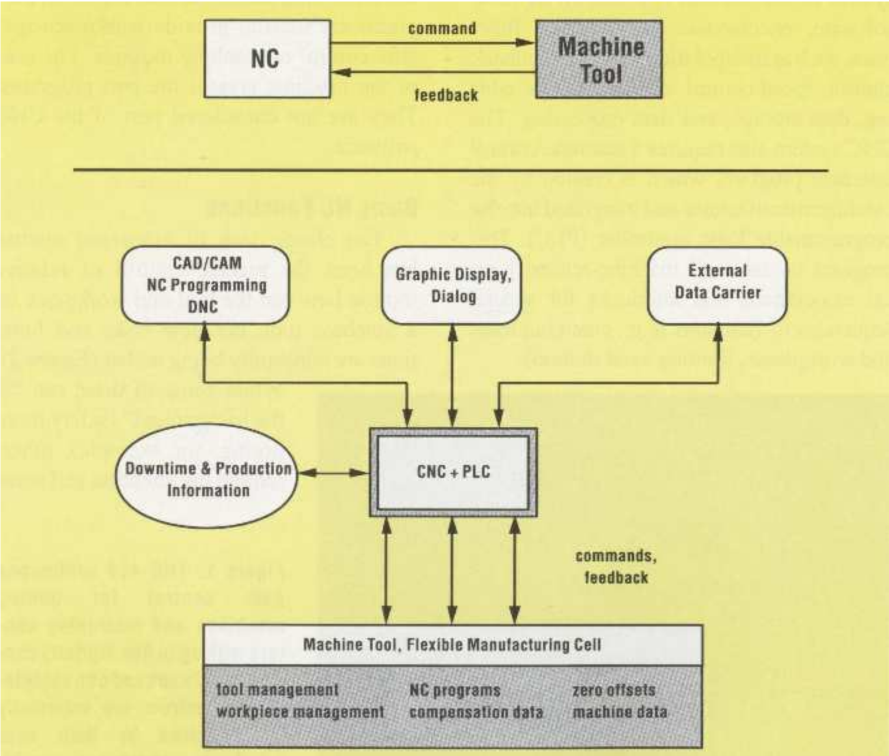


Figure 4.2 Performance comparison between NC and CNC. CNC systems feature a considerably larger range of functions, which can be customized and expanded.

Some elements of a basic modern CNC setup include:

- a large color graphics monitor (Figure 4.1) for displays, programming, simulations, operations, and diagnostic functions
- an interactive approach to guiding and instructing the user in at least two selectable languages (for immigrant workers or foreign service staff).
- program memory of 500 kb or more for various programs, compensation values, tool data, offset tables, and cycles
- a bus-coupled or integrated PLC with a high processing speed to control the on/off commands
- software limit switches as a replacement for mechanical limit switches and the wiring required by them

- manufacturing data collection and an automatic logbook for the documentation of operating errors, problem reports, function sequences, warnings, and interventions.

There are also new functions that are intended to make the machine more accurate, reliable, and user-friendly. Examples of these include:

- temperature error compensation for machine inaccuracies related to temperature
- random tool access, allowing tools to be found and changed more quickly
- monitoring of tool breakage and tool life for automatic operation
- automatic input of tool data into the area of storage reserved for compensation values
- simultaneous control of synchronous principal axes and asynchronous auxiliary axes without waiting times
- input of machine parameter values via keyboard instead of tedious adjustments at start-up.

Many other new functions are constantly being added.

In an automated manufacturing process, numerical controls assume many additional functions and tasks. These functions are taken for granted today, but their true significance is often overlooked and underestimated.

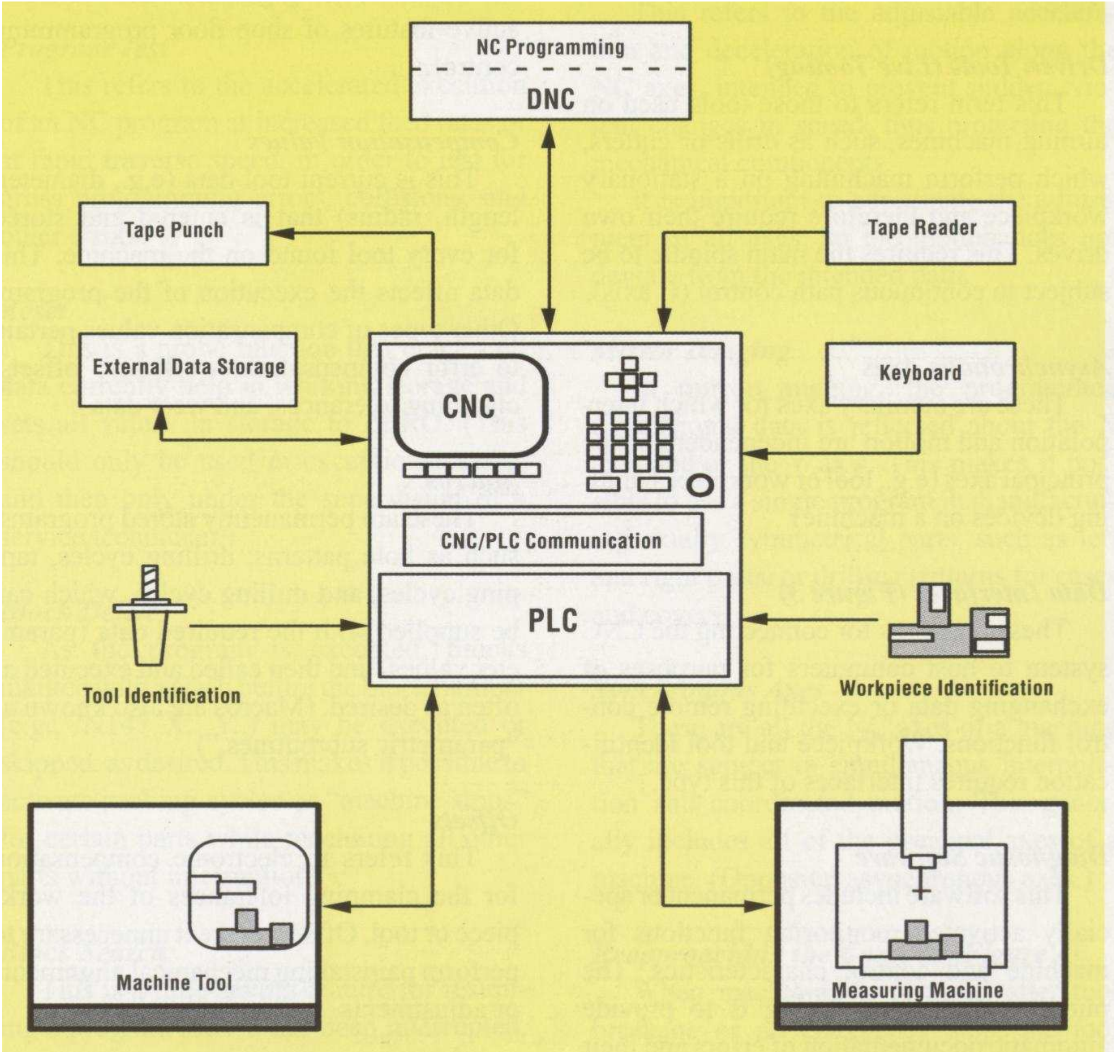


Figure 4.3 Powerful CNC/PLC systems feature multiple data interfaces for transmitting data that are relevant manufacturing.

4.3 Special CNC functions

As a rule, the manufacturer determines the capabilities and expandability of the CNC system during design and development. However, new CNC designs go beyond these limitations by providing an open software interface to the CNC system software, thus allowing the machine manufacturer and user to integrate their own special functions and know-how at a later time.

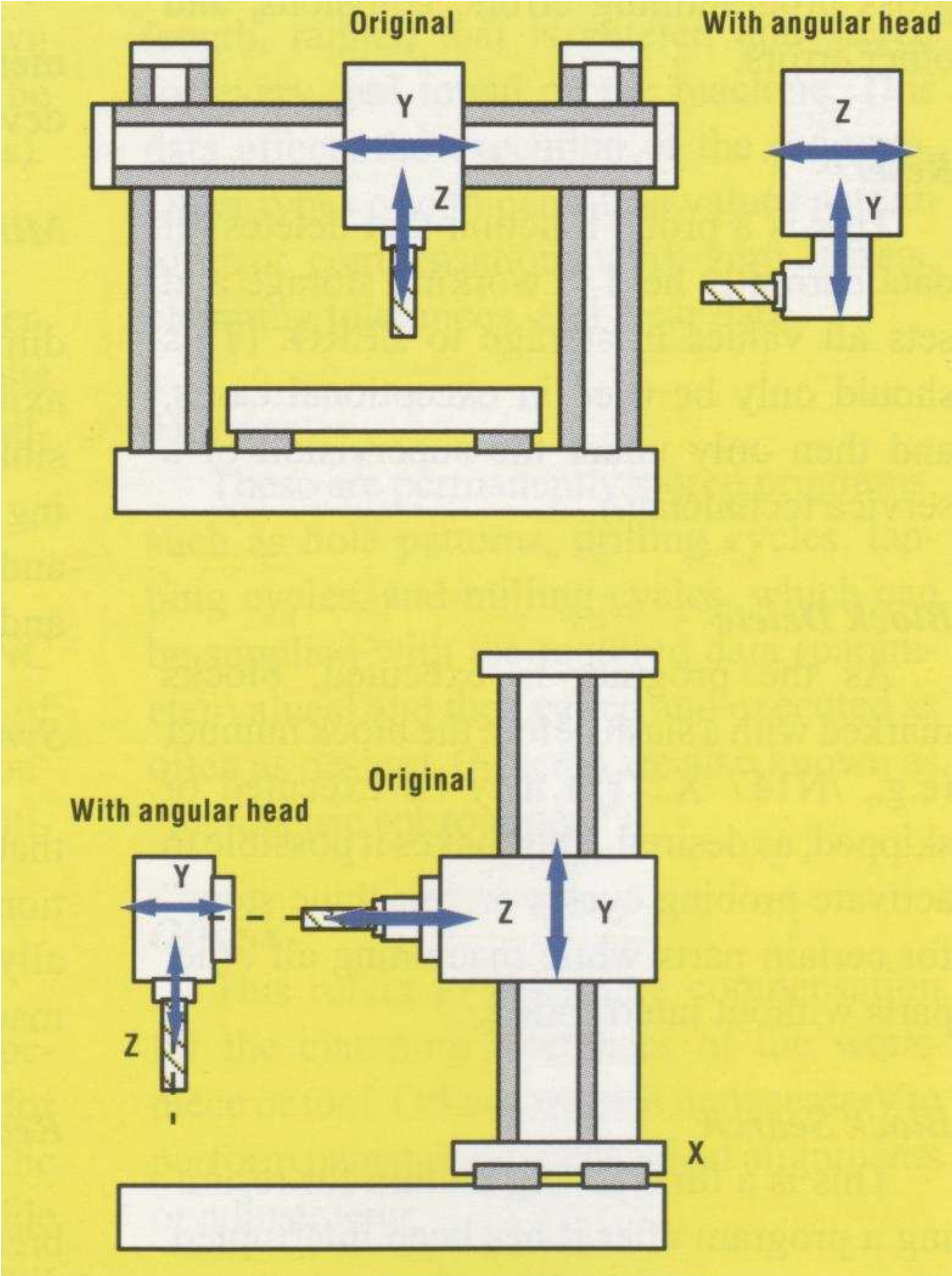


Figure 4.4 Axis exchange. An attached angle head makes it possible to exchange the Y and Z axes and thus use NC programs that were written for a vertical Z axis.

To this end, the CNC provides special programming software that can be used to integrate special solutions of this type. This even provides access to the graphical features of the control, so that user help systems, menus, and dynamic simulations can be represented graphically. This also makes it quite simple to adapt a machine tool CNC system for use in controlling a pallet transport system. This affords the machine manufacturer the opportunity to test its new developments at an early stage in the process, without having to inform the CNC manufacturer.

4.4 The future of CNC

The processing speed of microprocessors has increased considerably in recent years. This increased processing speed, combined with fast dynamic RAM components, has produced standard PCs of tremendous computing power. Processor boards have also become economical as a result of the enormous quantities in which they are mass-produced.

As a result, CNC manufacturers will increasingly turn away from expensive custom hardware development and make much greater use of standard processor boards. The use of multiple microprocessors within a single CNC system is especially likely to become obsolete, thus eliminating the problems associated with this approach. The computing power that is available today is even sufficient for multiaxial machines and complex control tasks. The advantages of this strategy are clear.

- Standard components save money and time.
- Technology is constantly maintained at the most advanced level.
- There is a reduced burden on internal bus connections in the CNC system.
- Block cycle times and sampling rates become shorter than 1 ms.
- The international availability of replacement parts is ensured.
- Many existing software packages can be used.
- Interfaces to all types of peripheral devices are readily available.
- User interfaces based on Windows operating systems are widely recognized and accepted.

Even a single microprocessor has enough computing power to control CNC and PLC functions. This also offers several advantages, such as:

- reduced programming expense for special applications
- minimization of time spent on user training
- real-time process control capabilities
- ability to control complex tool changing and work piece-changing functions.

The third type of technological improvement to be mentioned here is "integrated drive management," which has had a critical influence on the speed of CNC machines.

Integrated drive management increases the reaction speed of the drives and allows the gain factors and amplification factors of the control loops to reach levels that are unattainable with conventional separate CNC and drive systems using cascaded current and speed regulators.

This integration produces the following improvements:

- faster exchange of data between CNC system and drives
- considerable shortening of reaction times as a result of direct control of the control elements themselves
- very high amplification values in the control loops, which minimize lag errors and thus defects in shape
- extremely high dynamic path accuracy
- acceptable ratio of external inertia to internal inertia of the drive
- comprehensive diagnostics, supported by graphics.

CNC manufacturers who do not follow this trend will remain stuck in overpriced custom development, and will constantly lag behind the current state of the technology.

4.5 Summary

CNC systems are special, powerful electronic controls with integrated process computer functions. They have made it possible to satisfy almost all user demands for functionality, reliability, accuracy, speed, and safety with respect to both the machine and the control. Within the span of a few years, simple machines capable of understanding only numbers have developed into data-processing manufacturing systems that can be adjusted to the desired degree of automation. The "open CNC system" is intended to provide the user with even greater capabilities at an acceptable price. On this point, however, it is also important to warn that users are increasingly searching for a universal standard control.

The tendency toward greater machine level intelligence was first made possible by CNC technology, and it will continue to increase. The power of future CNC generations will be comparable to personal computers or even greater, especially with respect to data input, data management, and data storage. Constant improvements in electronic components will also continue to make CNC systems faster in their processing, more flexible in their adaptation, and more universal in their application. This will require the machine manufacturer to develop its own software add-ons, however. Manufacturers of CNC systems will have to ensure that their developments remain affordable.

Another area of responsibility that entails constantly changing requirements is connection of CNC systems to data networks for purposes of transferring the following types of data:

NC programs; drawings in the form of CAD data blocks; test plans; quality assurance data; collected and analyzed manufacturing data; data related to service maintenance; and diagnosis provided by teleservice or on the internet; etc.

In the broadest sense, any type of information that exists in databases and may not be useful for production planning, the production process itself, or production refinement can be received and used by the CNC system via a network connection. In the very near future, it will be possible to download new function modules or updates directly from such networks and install them in the CNC system (just as PC software updates are downloaded from the internet today). Because commercially available PC boards and operating systems are increasingly being used as the core of CNC systems, it is not difficult for PC-literate personnel to carry out the necessary procedures. This also forms the basis for an increase in the "life expectancy" of newer generations of CNC technology. The first CNC brands to fulfill these requirements are already on the market.

5 Design of the servo drives for the NC axis

For designing the servo drive for the table of CNC boring centre it must be consider the calculations of:

1. Screw
2. Bearing
3. Drive

5.1 Calculation of the screw :

Firstly it should be started with calculation of the screw :

Condition for selection:

Mass of the table (x) when m_x : 15000[kg]

Mass of the work piece: 12000[kg]

Stroke length (screw length) : 3000[mm]

Max speed v_{max} : 40[m/min] (transverse velocity)

Max acceleration /deceleration: 4[m/s^2]

Max revolution per min (for pitch 32[m/rev]) n_{max} : 1280[rpm]

Back lash approximately: zero (pre loaded joints)

Speed reduction mechanism none–direct coupling) A : 1

Guide way: rolling u : 0,003 (under no load)

Resistance of the guide way F_T = 800[N]

Items selected

screw diameter : 80[mm] screw THK BNF 8020A-5

pitch h_s : 32[mm/rev]

nut (preloaded type)

Friction $Fa_1 = F_T = 800[N]$

v_{max} = 40[m/min]

$$v_{max} = 40[m/\min] = \frac{40}{60} = 0{,}67[m/s]$$

Acceleration time $t_1 = \frac{v_{max}}{a}$

$$t = \frac{v_{max}}{a} = \frac{0,67}{4} \sim 0,16[s]$$

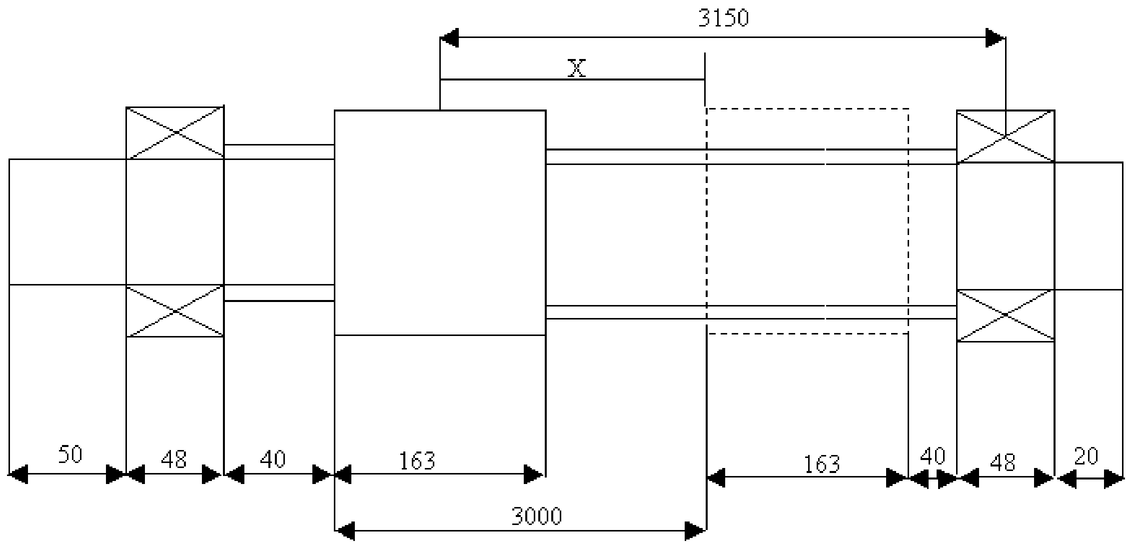


Figure 5.1

acceleration + friction force:

$$Fa_2 = a \cdot m_x + Fa_1 = 4 \cdot (15000 + 12000) + 800 = 108\,800[N]$$

$$Fa_3 = a \cdot m_x + Fa_2 = 4 \cdot (15000 + 12000) - 800 = 107200[N]$$

$$Fa_{max} = Fa_2 = 108800[N]$$

max total force (Fa_2 + cutting force(10000))

$$Fa_4 = Fa_2 + 10000$$

$$Fa_4 = 118800[N]$$

x axis stroke = 3[m] = 3000[mm]

Nut length = 163[mm]

Bearing set length = 48[mm]

Stroke reserve = 40[mm]

Mounting distance la = 3145.5 =3150[mm]

Allowable Buckling load:

$$P_1 = 0{,}5 \cdot n \cdot \pi^2 \cdot E \cdot \frac{I}{(l_a)^2}$$

$$P_1 = 0{,}5 \cdot 4 \cdot (3{,}14)^2 \cdot (2{,}06 \cdot 10^5) \cdot \frac{(2009600)}{(3251)^2} \approx 834000[N]$$

$$Fa_4 = 118800[N] << \frac{P_1}{2}$$

Allowable tensile and compressive load:

$$P_2 = \delta \cdot \frac{\pi}{4} \cdot d_1^2$$

$$P_2 = 147 \cdot \frac{3{,}14}{4} \cdot (80)^2 = \underline{738528}[N]$$

$$Fa_4 = 118800[N] << \frac{P_2}{2} \qquad (369264)$$

Allowable tensile and compressive load are much greater than max total force.

Allowable rotational speed considerations:

$$N_{max} = \frac{V_{max}}{h}$$

$$N_{max} = \frac{0{,}67[m/s]}{0{,}032[mm/rev]} \cdot 60\left[\frac{s}{min}\right] = 1256{,}25 \text{ rpm}$$

Critical speed of screw shaft:

Critical speed N_1

$$N_1 = \frac{60 \cdot \lambda^2}{2\pi \cdot l_b^2} \cdot \sqrt{\frac{E \cdot 10^3 \cdot I}{\gamma \cdot A}} \cdot 0{,}8x$$

For ϕ80 is not available rotating nut sys,

$N_1 \approx \underline{1200}[rpm]$ so,its necessary to dec max speed from 40m/min

cross section $A = \frac{\pi}{4} \cdot d_1^2 = \underline{5024}\ [mm^2]$ to 30m/min.

young modus E = 2,06 · 10^5 MPA

min geometrical of inertia $I = \frac{\pi}{64} \cdot d_1^4 = \underline{2009600}\ mm^4$

γ = density : 7,85 · 10^{-6}[kg/mm^3]

diameter of screw shaft d_1 = 80[mm]

l_b = 3150[mm]

coefficient for supporting condition λ = 4,73 (from catalog THK)

N_2: speed according DN factor (15000[mm·rev/min])

$$N_1 = \frac{150000}{D} = \frac{150000}{82{,}7} = \underline{1814}\,\text{rpm}$$ D=ball screw diameter

parameters of ball screw selected: (from catalouge THK)

(for ø 80) C_a= 163,7[kN]

C_{0a} = 589[kN]

Allowable axial loaded considerations:

$$F_{0\max} = \frac{c_{0a}}{f_s}$$ f_s - (safety factor)

$$F_{0\max} = \frac{589}{2} \Rightarrow \underline{294{,}5}[\text{kN}]$$

6 Calculation of Rigidity:

Rigidity of the total system is equal to the some of the all inverses of the rigidity of the components (screw shaft, nut as mounted on the shaft, supporting bearings, supporting housing, etc).

Nut Rigidity:

: When preload is applied to a nut firstly, the elastic deformation is increases as the preload, as applied so that rigidity is increases when the theoretical deformation is not taken into to account, actual shearing of the load betaken different contact surfaces. The elasticity of the nut and screw shaft the practices values given in catalogue are lower than theoretical values for this reason.
The rigidity values are taken from THL catalogue.

. **Elastic deformation of screw shaft :**

Preload is proportional to it's length and inversely proportional to the square or root diameter. According to the relative importance of the screw deformation (from rigidity of the total system), too large and increase in the preload of the nut and supporting bearings yields a limited increase of rigidity and notably increases the preload torque and therefore the running temperature, the preload stated in catalogue for each dimension is optimum and shouldn't be increased.
Rigidity is given by K_w =3430 N/μm, when K is from the table page 261 (THK) rigidity between screw and nut

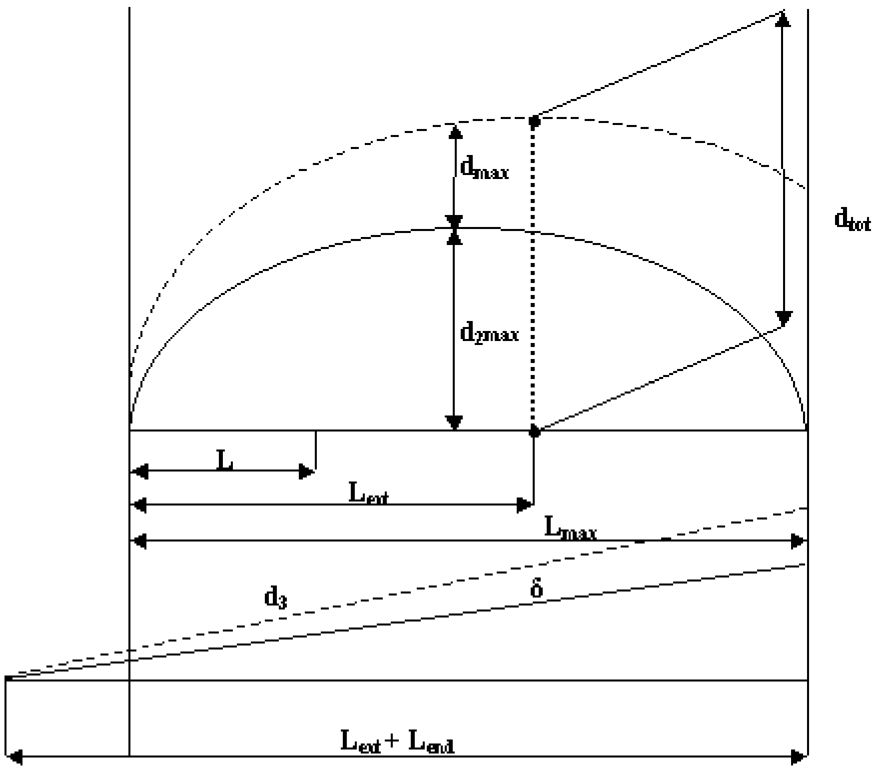
Rigidity of screw shaft:

.

Length of the nut=163 [mm] from THK catalog

$$L_{max} = stroke + 2reserve + bearing$$

$$L_{max} = 3000 + (2.40) + 70 = 3150mm$$



Graph 6.1

Modulus for twist deformation

$G = 9.10^{10}\ N/m^2$

$E = 2,05.10^{11}$

Inertia of the plane

$J_A = \pi D^4 / 32$

$J_A = \pi(0,070)^4 / 32 = 2,35.10^{-6}\ m^4$

$\delta = L_{max} / GJ_A$

$\delta = 3150. / (9.10^{10}).(2,35.10^{-6}) = 1,5.10^{-5}$ rad/Nm

natural freq. Of support on screw compliance.

For finding natural frequency

$$f_{\circ} = \frac{1}{2\pi}.\frac{1}{\sqrt{m.d_{tot}}}$$

d_{tot} is $d_1 + d_2\max + d_{3\max}$

m=total mass

$d_1 = d_{nut} + d_{bear.}$

$d_1 \approx 6{,}3.10^{-10}$ from catalogue THK

$0.5\,L_{max} = 1575\text{ mm}$ torsional compliance at $L_{max}/2$

$$0.5\,\delta max = \frac{L_{max/2} + L}{GJ} = \frac{1{,}575 + 0{,}05}{9.10^{10}.2{,}35.10^{-6}} = 7{,}7.10^{-6}\left[\frac{rad}{Nm}\right]$$

torsional compliance at $L_{max}/2$ after conversion on linear movement

$$d_3\max = \delta_{\frac{Lmax}{2}}.\left(\frac{h}{2\pi}\right)^2 = 7{,}7.10^{-6}.2{,}6.10^{-5} = 20.10^{-11} = 2.10^{-10}\left[\frac{m}{N}\right]$$

We are searching for max of compliance d_2+d_3 .the torsional compliance converted on Linear movement d_2 is five times smaller than tensional compliance d_3 (see next fomulas) . in this case is possible to take the max in distance $L_{max}/2$.

$d_3 = 2.10^{-10}\left[\frac{m}{N}\right]$, $d_{2max} = L_{max}/4EA = 10.10^{-10}$

$d_{2\,max} + d_{3max} = 2.10^{-10} + 10.10^{-10} = 12.10^{-10}$

so $d_1 + d_{2max} + d_{3\,max} = 6{,}3.10^{-10} + 2.10^{-10} + 10.10^{-10} = 18{,}3.10^{-10}$ [m/N]

natural frequency

$$f_{\circ} = \frac{1}{2\pi}.\frac{1}{\sqrt{27000.18{,}3.10^{-10}}} \approx 22\,[Hz]$$ max. work piece.

$$f_{\circ} = \frac{1}{2\pi}.\frac{1}{\sqrt{15000.18{,}3.10^{-10}}} \approx 29\,[Hz]$$ without work piece.

6 Selecting of the Bearing

Bearing is a mechanical device that can transmit tongue and or rotary motion from one shaft to another at fined or varying angles of intersection of the shafts axis. There is some companies (General bearing) that can produce a variety of universal joint (u joint) bearing cups and bearing assemblies . Loading, size, environment and seating requirements are taken into account in the design of every u –joint bearing and the design varies according to the specific requirements of the customer .There is several bearings: ball bearing –tapered roller bearing spherical roller bearings and cylindrical roller bearings. It has been used here angular ball bearing type zkln 70(inner) from the Ina catalogue. It has been this type in instance of (needle axial bearing) because of friction moment .

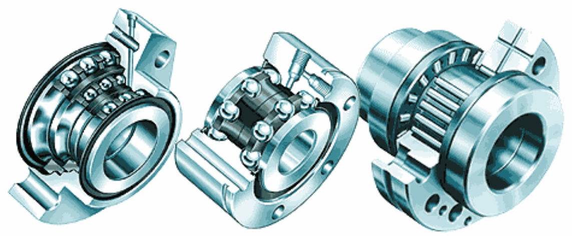


Figure 7.1 3 kind of bearing DKLFA, ZKLF and ZARF

7 Selection of the drives

Conditions of choosing type of motor:

Kinematics view:

Screw speed < maximum speed [rpm]

Static's view

Total torque of load < maximum motor torque [Nm]

When the total torque of load depend on friction, cutting, ACC/dec.

Servo design:

1. Back lash +Lost motion < 0.01 mm

   When the lost motion is given by (2*friction force)/rigidity

2. Natural frequency $f_O = \frac{1}{2}\pi\sqrt{k/m} = \frac{\frac{1}{2}\pi\sqrt{x}}{J} \geq 30\ \text{Hz, or } 20\ \text{Hz}$
3. Friction (including screw friction torque).
4. Total load inertia (total + screw)

Motor torque:

$F_F = 800$ Friction force

$M_{SF} = 85\ \text{Nm}$ Friction torque of screw

$$M_{tot\ F} = M_{SF} + F_F + \frac{h}{2\pi} = 85 + 800.\frac{0{,}032}{6{,}28} = 89{,}07 \approx 90\ [\text{Nm}]$$

Inertia of motor:

Screw inertia

$J_s = 0{,}316\ \text{kgcm}^2/\text{mm} = 0{,}316.10^{-4}\ \text{kgm}^2/\text{mm}$ (from catalogue)

$J_s = 0{,}316.10^{-5}.3409 = 1077210^{-5} = 0{,}108\text{kgm}^2$

$$J_{red} = m.\left(\frac{h}{2\pi}\right)^2$$

$$J_{red_{min}} = 15000.\left(\frac{0,032}{2\pi}\right)^2 = 0,38\ {kg}/{m^2}$$

$$J_{red_{max}} = 27000.\left(\frac{h}{2\pi}\right)^2 = 0,38.\frac{27}{15} = 0,68\ {kg}/{m^2}$$

$J_m = 0,071$ form catalog

$J_{sm} = J_s + J_{red} = 0,49 \div 0,79 kgm^3$

a=4 m/s^2 , and F_{acc}=2700.4=108000 N

$F_{tot}= F_{acc}+ F_{cut}$

F_{tot}= 108000+10000=118000N

$$M_{tot} = \frac{h}{2\pi} F_{tot} = \frac{0,032}{2\pi}.118000 = 601 Nm \text{ (the torque)}$$

1FT6134 ----> M_{max}=280Nm

$$M_{tot} \approx 0,9.M_{max} = 0,9.280 = 252 Nm$$

$$J_{tot} = J_m + J_s + J_{Lred} = 0,055 + 0,108 + 0,68 = 0,743\ kgm^2$$

$$\varepsilon_{maxm} = \frac{M_{tot}}{J_{tot}} = \frac{252}{0,743} = 339\ \frac{rad}{s^2} \quad \text{max. acc. on motor}$$

$$a_{max} = \varepsilon_{max}\frac{h_s}{2\pi} = 399\frac{0,032}{2\pi} = 1,72\frac{m}{s^2} \approx 1,7\frac{m}{s^2}$$

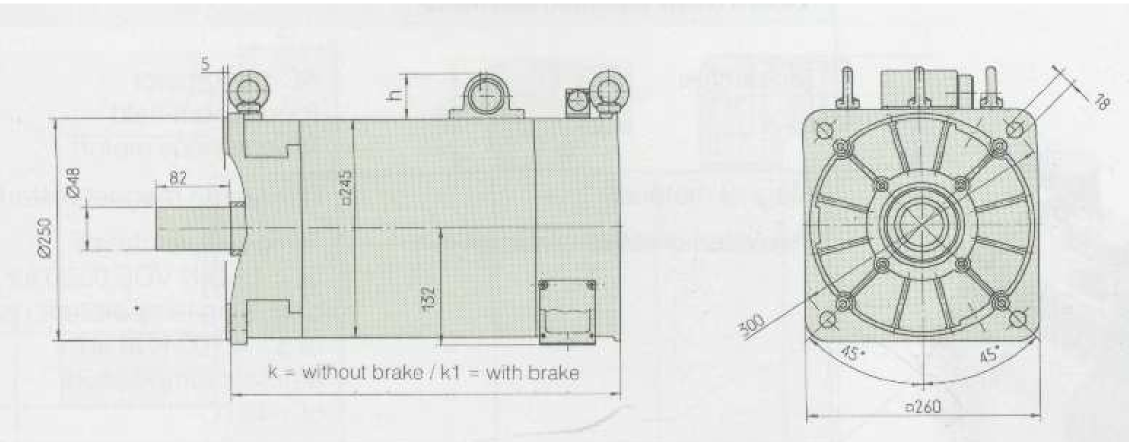


Figure 8.1 Motor

8 Calculation for fatigue life

		q	F_i [kN]	h_i [rpm]
1	acc./dec. (for a=1,7 m/s^2)	5%	37	310
2	rough milling	27%	10,8 (11)	470
3	drilling	20%	6,8 (7)	0
4	rapid traverse (v=const.) (30m/min)	10%	0,8 (1)	940
5	finishing (milling)	20%	3,8(4)	600
6	Machining at v=0	20%	5,8 (6)	0

Table 8.1 Table of working cycle (according to TOS Varnsdorf)

Mean rotational speed:

$$h_{ekv} = \frac{q_1 h_1 + q_2 h_2 + ...}{100}$$

$$h_{ekv} = \frac{5.(310) + 25.(470) + 20.(0) + 10.(940) + 20.(600) + 20.(0)}{100} = 356$$

$$F_{ekv} = \sqrt[3]{\frac{F_1^3 q_1 h_1 + F_2^3 q_2 h_2 + ...}{h_{ekv}.100}}$$

$$F_{ekv} = \sqrt[3]{\frac{(37)^3.310.5 + (11)^3.470.25 + (1)^3.940.70 + 4.800.20 + 0}{347.100}} = 13,95 \approx 14\,KN$$

fatigue life in rpm:

$$L = \left(\frac{C_a}{F_{ekv}}\right)^3.10^6 = \left(\frac{589000}{14000}\right)^3.10^6 = 7,4.10^{10}\,[rpm]$$

fatigue life in hours:

$$L_h = \frac{L}{h_{ekv}.60} = \frac{7,4.10^{10}}{347.60} = 3,4.10^6\,h$$

9 Conclusion

Calculation of the screw shows,that given Parameters (40m/min and 4m/s^2) Are Not reachable for machine of this size. Problem of velocity is in screw Critical speed which limits its velocity to 1256 [rpm]. With maximum Possible lead 32mm/rev the max velocity is around 30m/min(screw at app 940rpm). Of course it is possible to use screw with greater dia (100 mm) which raises the critical speed. But in all other parameters the srew 80mm is so oversized ,that we decided to limit max velocity to 30m/min . acceleration lies in the drive moving mass (table +screw+motor)is so high that greatest motor from siemens catalogue develops only 1,7 m/s^2(Notice : acceleration with 100mm screw will be even smaller). The parameters of fatique life is greatly oversized (3.10^6 hrs).

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