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Understanding Features and Requirements of Power Drives for Performance Improvement of the CNC Machines

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Abstract—*A Computerised Numerical Control (CNC) machine tool is basically similar to a conventional machine tool. The functional capabilities of CNC machine tools in terms of machining are also not much different from those of conventional ones. The major difference is in the way in which the machine functions and slide/tool movements are executed and controlled. In order to provide automatic and precise motion control to the CNC machine's elements such as work table, tool spindle, tool changer, etc., the CNC machines are provided with a Power Drive System or simply Drive Mechanism which is simply a motor coupled with some mechanism to achieve the controlled and desired motion. The primary movement is supplied by the motor referred to as Power Drive or simply Drive and the associated mechanism converts this primary motion of the drive into the desired and precise movement of the CNC elements. The power drives used on CNC machines may be Electrical Drives, Hydraulic Drives, or Pneumatic Drives. Generally, a CNC machine is provided with a combination of these drives depending on the merits and demerits associated with a drive for the specific and intended use. The CNC machines are provided with three major Drive mechanisms viz. Spindle Drive Mechanism, Feed Drive Mechanism and Automatic Tool Changer (ATC). As the dynamic characteristics of the power drives and drive mechanisms exert considerable influence on the accuracy, machining precision and the overall performance and capability of the CNC machine, their study and critical analysis is warranted.*

Keywords: *Numerical Control; Computerized Numerical Control; NC; CNC; CNC machines; Performance of CNC machines; Electrical Drives; Power Drives; Motors; Selection of Motors*

1. INTRODUCTION

Computerised Numerical Control (CNC) machines are those machines which are controlled by numbers while making use of computers for processing the information fed to these machines. The numbers used for controlling these machines are actually alpha-numerals and are popularly known as Codes of CNC Machines e.g. G Codes, M Codes, etc. These codes are arranged in a logical sequence depending on the type and sequence of operations to be performed on a job. This logical sequence of CNC codes is simply known as Part Program. These part programs are fed to the Controller which is the brain of the CNC machine, for processing and execution of these instructions and referred to as CNC Programming. Thus, CNC Machines have the ability to process data specifying features and dimensions of the finished part and convert them to command signals which are used to drive the actuators (motors) to produce the finished part [1,2,3,4,5].

In order to provide automatic and precise motion control to the CNC machine's elements such as work table, tool spindle, tool changer, etc., the CNC machines are provided with a Drive System or Drive Mechanism which is simply a motor coupled with some mechanism to achieve the controlled and desired motion. The primary movement is supplied by the motor referred to as Power Drive or simply Drive and the associated mechanism converts this primary motion of the drive into the desired and precise movement of the CNC elements. The drives used on CNC machines may be Electrical, Hydraulic or Pneumatic Drives. Generally, a CNC machine is provided with a combination of these drives depending on the merits and demerits associated with a drive for the specific and intended use. The CNC machines are provided with three major Drive mechanisms which form the subject of critical analysis and evaluation of this study. The first drive mechanism is referred to as Spindle Drive Mechanism which is used to provide the power to main spindle for cutting action; the second is referred to as Feed Drive Mechanism which is used to provide controlled and accurate movement of the various axis; and the third referred to as Automatic Tool Changer (ATC) is used for the positioning of the cutting tool holders or magazine at a particular location for the purpose of loading or dumping of the cutting tools. As the dynamic characteristics of the power drives and drive mechanisms exert considerable influence on the accuracy, machining precision and the overall performance and capability of the CNC machine, their study and critical analysis is warranted [6.7].

Electric drives in the CNC machines are the main control elements for generating mechanical movement. Hence, it is important to handle efficient conditions when CNC micro machines are in the machining processes and this condition is linked with the electric machine; the machining precision in electric drives depend on the position controller that has to minimize the position error generated when load torque disturbances or parametric changes appear. The sources of the general machining errors include table positioning, cutting parameters, thermal response characteristics, machine geometric defect, vibration and wear of the cutting tools [8,9]. In recent decades, numerous research efforts to develop machine tools with positioning performances at the nanometre level or better have been undertaken. Achieving such performance creates challenges for the metrology systems (sensors systems), with semiconductor patterning and inspection machines setting these high demands. Most breakthroughs have been achieved by separating metrology from the moving elements [10,11].

The dynamic behaviour of the drive system itself is of course non-linear, owing predominantly to the effect of the backlash (reversing errors) and coulomb friction which cannot be entirely eliminated. The stiffness in different parts of the drive system also affects the dynamic behaviour of the control loops while accounting for some of the discrepancies between the actual tolerances of the finished product and the desired dimensions. There is a need to introduce new algorithms to compute realistic time-optimal feed rates for Cartesian CNC machines with axis drive motors subject to both current and voltage limits [7,12,13].

2. POWER DRIVES

The drives or actuators or motors used to power the various elements of CNC machines are Electrical, Hydraulic and Pneumatic drives [6]. However, any CNC machine could make use of any one or combination of these three types of drives depending upon the suitability and appropriateness of that type of drive for the intended purpose. Moreover, the selection of a particular type of drive may get altered with the change in operating range and requirement of some special characteristics of a CNC machine.

Electrical drives are those which drive their power from electricity, Hydraulic drives are those which have hydraulic oil as the medium of power and Pneumatic drives makes use of air pressure. Each of these drives is associated with certain merits and demerits which forms their selection criteria for use in CNC machines. Electrical drives which shall be dealt exclusively in the later sections due to their major advantage that they are relatively small in size, easy to control, and offer no major disadvantage especially when employed for spindle and axes movements in a CNC machine.

Hydraulic drives have high power to size ratio which makes it suitable for heavy duty assignments on CNC machines like automatic chucking of jobs. It is specially employed when there is a need of much pressure in low volumetric area. It also provides smooth motion along with a great degree of accuracy. The major setback associated with hydraulic drives is the regular maintenance for plugging leakage of oil used as working medium, fire hazards because of the fuel oil used as working medium, and requires treatment for protection against corrosion caused by the hydraulic oil in the hydraulic system of the CNC machine. CNC machine is such type of machine where several jobs are executed in compact area and in less time. In such scenario, hydraulic systems play a big role to execute several functions. Hydraulic Pressure in CNC machine is developed by hydraulic power pack which is a combination of several hydraulic components. Hydraulic circuit is a close circuit. A hydraulic pump is incorporated to raise the pressure up to desired system pressure and that system pressure is distributed to various work places through solenoid valves and regulated through hydraulic pressure regulators.

In contrast to Hydraulic drives, the Pneumatic drives does not pose any fire hazard or any major corrosion problem and their operation are cheaper as the working medium is air which is freely available. However, these pneumatic drives produces less power, their positioning control is weak and creates a lot of noise. Important components of a pneumatic system are: (a) Air filters which are used to filter out the contaminants from the air (b) Compressor which is used to generate Compressed air (c) Air cooler is used to reduce the temperature of the compressed air (d) Dryer is used to separate the moisture in the air (e) Control Valves are used to regulate, control and monitor the flow direction, pressure etc. of the compressed air (f) Air Actuator comprising of air cylinders and motors to obtain the required movements of mechanical elements of pneumatic system (g) Electric Motor as a prime mover of compressor to convert electrical energy into mechanical energy (h) Receiver tank to store the compressed air from the compressor.

Either of the Pneumatic or Hydraulic Systems is mainly employed on the CNC machines for one or more of the following functions: Tool clamp / de-clamp operation; Work pallet clamp / de-clamp operation; and Rotational axis clamp / de-clamp operation. Although, electrical drives are mainly used in CNC machines for rotational operation, but for some cases where positional feed-back and breaking is not so necessary, hydraulically / pneumatically operated motor is used for rotation. Such as turret rotation for automatic tool changing in turning center where a hydraulically / pneumatically operated motor is usually incorporated with geneva wheel and gear train.

3. POWER REQUIREMENTS OF CNC MACHINE DRIVES

Out of the three major drive mechanisms [6] viz. Spindle Drive Mechanism, Feed Drive Mechanism and Automatic Tool Changer (ATC) provided on the CNC machines, the spindle drive mechanism and feed drive mechanism is employed with an electrical drive or motor. It is the ATC which employs Hydraulic / Pneumatic systems with or without an electrical drive exclusively for the positioning of tool / turret / tool magazine. Thus, electrical drives have a special place in the drive mechanisms of a CNC machine. In CNC machines, usually AC, DC, servo and stepper electrical drives are used.

The two major drive mechanisms used in CNC machines employing electrical drive are of two categories viz. Spindle drive mechanism to provide the main spindle power for cutting action; and Feed drive mechanism to drive the axis of CNC machines. This categorization of drive mechanisms used on CNC machines employing electrical drives is based on the varying requirements of the spindle drive mechanism and feed drive mechanism and shall be helpful in a better selection and probable improvement of the electrical drive employed to these mechanisms for its intended use.

3.1. Features and Power Requirement of the Spindle Drive Mechanism

The primary purpose of the spindle drive is to provide and maintain a constant angular velocity to the work-piece or cutting tool mounted on it. It becomes more important when there is a variation in the hardness in the material of the work-piece as the variation in the angular velocity will adversely affect the surface finish of the work-piece to be machined. It is also required of the electrical drive (motor) for spindle drive to bear high overloads due to either varying material hardness of the work-piece being machined or excess feed provided by the machinist or both. The electrical drive should be such that it could provide a high step-less or continuous range of speeds varying from 10 to 20,000 rpm. This capability of the electrical drive is required to machine a wide range of materials and to obtain a desired surface finish for the job to be machined. It is also expected of the electrical drive for spindle drive to be a compact one and operates smoothly. Moreover, in some cases, the spindle motor can be made to accurately position by means of feedback to the controller of CNC machine for functions such as orientation for tool changing, and in machining situations that require coordinated and synchronized movement of tool and work-piece. For these requirements on the spindle drive of the CNC machine tools mostly employ DC spindle drives. But as of late, the AC drives are preferred to DC drives due to the advent of microprocessor-based AC frequency inverter [6].

3.2. Features and Power Requirement of the Feed Drive Mechanism

The main purpose of the feed drive mechanism is to provide the accurate and precise movements to the slide or table of a CNC machine in order to effect the movement of work-piece or tool in different directions and orientations to achieve the desired machining of the work-piece. Movement of the slide or work-table in each direction which are called the axis of the CNC machine is controlled by a specific electrical drive for that direction or axis. However, in order to achieve a movement of the work-piece or tool in an orientation other than the major directions or axis of the CNC machine, a controlled and coordinated movement is made by the different electrical drives of the various axis of the CNC machine to achieve the desired orientation of the work-piece or table. Moreover, there are certain machining situations that require controlled, coordinated and synchronized movements of the work-piece as well as tool. This situation requires that all the electrical drives of the various axes of the CNC machines as well as of the tool make controlled, coordinated and synchronized movements to achieve the desired orientation of the tool and work-piece and hence desired machining of the work-piece. But, this feature is not available on every CNC machine and requires a compatible controller along with appropriate electrical drives and other hardware/software requirements.

Owing to the unique features of the feed drive mechanism, the electrical drives to power them needs to possess certain characteristics. In order to overcome the friction as well as working forces, these motors are required to provide constant torque to the feed drive mechanism. The rotor inertia of these motors should be low to enable quick braking and start-up required for different movements of these feed drives mechanisms. The real challenge for these motors is during contouring operations where several feed drives and the associated mechanisms have to make accurate, controlled and synchronized movements and thus are required to possess many characteristics like extremely small positioning resolution, low rotor inertia, quick response, and a step-less speed range from 0.1 rpm to 20,000 rpm. Moreover, these motors should be smooth in functioning and compact in design in order to conveniently deliver high torque to weight ratio. For these requirements of feed drive motors, variable speed DC drives or motors have been used, but now-a days AC drives or motors are more popular [6].

4. AN OVERVIEW OF ELECTRICAL DRIVES

In CNC machines, Electric drives or Electric motors are widely used for position and speed control of tool as well as various axes of CNC machines. This control is exerted through the Power Drive Systems comprising of electric motor coupled with an associated mechanism to effect the movements of the motor to the tool / work-table. The motors can be classified into two groups namely DC motors and AC motors.

4.1. DC Motors

A DC motor is a device that converts direct current (electrical energy) into rotation of an element (mechanical energy). These motors can further be classified into brushed DC motor and brushless DC motors. The various advantages and disadvantages [6] associated with these brushed as well as brushless DC motors are as follows:

The brushed DC motors are simple in their design and also cost effective. Moreover, the speed of a brushed DC motor could be easily controlled at high speeds. However, a brushed DC motor requires high maintenance specially their brushes gets wear fast. But, a brushed DC motor is difficult to reliably control at low speeds.

The brushless DC motors are more efficient and precise due to computer control mechanism; absence of brushes eliminates the problem of wear and sparking of brushes; creates less noise; easy to cool due to positioning of electromagnets at the stator; motor can operate at speeds above 10,000 rpm under loaded and unloaded conditions; and responsiveness and quick acceleration due to low rotor inertia. But, the brushless DC motors are complex due to the presence of additional system wiring to power the electronic commutation circuitry and requirement of computer controller. Thus, also possess higher initial cost.

4.2. AC Motors

AC motor is a device that converts alternating current (electrical energy) into rotation of an element (mechanical energy). The main limitation of AC motors over DC motors is that speed is more difficult to control in AC motors. To overcome this limitation, AC motors are equipped with variable frequency drives but the improved speed control comes together with a reduced power quality.

AC motors can be classified into synchronous motors and asynchronous or induction motors. A synchronous motor is an AC motor which runs at constant speed fixed by frequency of the system. It requires direct current (DC) for excitation and has low starting torque, and hence is suited for applications that start with a low load. If a synchronous motor loses lock with the line frequency it will stall. It cannot start by itself, hence has to be started by an auxiliary motor. Asynchronous motors also known as Induction motors are quite commonly used in industrial automation. Induction motors can be classified [6] into two types: (1) Single-phase induction motor: It has one stator winding and a squirrel cage rotor. It operates with a single-phase power supply and requires an auxiliary means to start the motor. (2) Three-phase induction motor: The rotating magnetic field is produced by the balanced three-phase power supply. These motors can have squirrel cage or wound rotors and are self-starting.

A comparison of merits and demerits [14] associated with synchronous and asynchronous (induction) motors is as follows: (a) Synchronous motor runs at a constant speed at a given frequency irrespective of the load. But, the speed of an asynchronous (induction) motor reduces with the increase in the load (b) Synchronous motor can be operated at a wide range of power factors, both lagging and leading, whereas asynchronous motor always runs with a lagging power factor (p.f.) which can be very low at diminishing loads (c) Synchronous motor is not self-starting and requires an external DC excitation, where as an asynchronous motor can be self-started (d) Synchronous motor's torque does not get affected by the changes applied in the voltage as much as an asynchronous motor's gets affected (e) Synchronous motors are usually expensive and complicated when compared to the asynchronous motors which are less expensive and user friendly (f) Synchronous motors are efficient and good for low-speed drives (below 300 rpm) because their power factor can always be adjusted to 1.0. On the other hand, asynchronous motors are excellent for speeds above 600 rpm (g) Unlike asynchronous motors, synchronous motors can be run at ultra-low speeds by using high power electronic converters which generate very low frequencies.

5. ELECTRICAL DRIVES OF CNC MACHINES

Due to special requirements on the electrical drives (motors) for the drive systems of CNC machines to have a precise control on their angular position, velocity and acceleration, two classes of motors are employed viz. stepper motors and servo-motors.

5.1. Stepper Motors

Stepper motor is a specially designed brushless DC motor that can be driven by giving excitation pulses to the phase windings. They are driven by a stepping sequence which is generated by a controller. AC driven stepper motors are also available which basically convert AC to DC and gets higher voltage for better torque characteristics on a wide range of speeds. Stepper motor may also be categorized as a class of brushless AC synchronous electric motor that converts digital pulses into mechanical shaft rotation [6,15].

A stepper motor is different from an ordinary DC motor in many ways like a stepper motor has permanent magnets on the inside and rotate (making up the rotor), while the coils are on the outside and stay static (making up the stator). The other difference between an ordinary DC motor and a stepper motor is in the design of the stator and the rotor. Instead of one large magnet on the outside (the stator) and one large coil rotating inside it (the rotor), a stepper motor has an inner magnet effectively divided up into many separate sections, which look like teeth on a gear wheel. The outer coils have corresponding teeth that provide magnetic impulses, attracting, repelling, and making the teeth of the inner wheel rotate by small steps. Another difference is that a stepper motor can stay still, in a certain position, once it's rotated through a particular angle which is particularly required in a robotic arm or an axis / work table of a CNC machine, which might have to rotate/move a certain amount and then remain in precisely that spot. This feature is sometimes called holding torque which simply means a stepping motor's ability to stay still.

Every revolution of the stepper motor is divided into a discrete number of steps, in many cases 200 steps, and the motor must sent a separate pulse for each step. The stepper motor can only take one step at a time and each step is of the same size. Since each pulse causes the motor to rotate a precise angle, typically 1.8°, the motor's position can be controlled without any feedback mechanism. As the digital pulses increase in frequency, the step movement changes into continuous rotation, with the speed of rotation directly proportional to the frequency of the pulses. The various types of stepper motors are: Variable Reluctance Stepper Motor; Permanent Magnet Stepper Motor; and Hybrid Stepper Motor [6].

The various advantages and disadvantages associated with the stepper motors [16] are as follows: safe, durable and inexpensive; needs no feedback mechanism due to their high repeatability; possess plug and play feature; available in standard sizes and performance levels; safe to mechanical overload and suitable for a wide range of frictional and inertial loads; ability to drive many loads without gear mechanism due to their excellent low speed torque. On the other hand, stepper motors produces low output power for a comparable size and weight; less efficient as stepper motors continue to consume substantial power irrespective of load; micro-stepping feature is required to run the motor smoothly and avoid resonance; no information on missed steps; creates noise and heat at high speed and load conditions; produces less torque at high speeds; slow acceleration on high loads due to low torque to inertia ratio.

5.2. Servo Motors

Servomotors are not a specific class of motor although the term servomotor is often used to refer to a motor suitable for use in closed-loop control systems that require feedback mechanisms. Servomotors may be AC/DC/Brushless DC motors being controlled using servo-mechanism. The servo-system is shown in the following Figure 1:

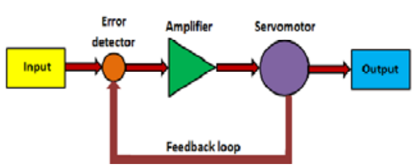

Figure 1: Servo system block diagram [6]

Servo motor is negative feed-back controlled (closed loop) having position and velocity sensors. The servo mechanism makes use of a suitable feed back device which could either be an encoder or a resolver. Thus, servo motors are also called Control Motors. Its speed is reduced with an increase in torque by gear mechanism.

A DC servo motor is actually an assembly of four separate components, namely: DC motor, gear assembly, position-sensing and a control circuit. DC operated servomotors usually respond to error signal abruptly and accelerate the load quickly. In AC servo motors, the magnetic force is generated by a permanent magnet and current which further produce the torque. It has no brushes so there is little noise/vibration.

Servo motors provide high intermittent torque; high torque to inertia ratio required for quick acceleration; feed back and control mechanism for both position and velocity; smooth and quiet in operation; wide speed range; available in wide range of size and power. However, the wide range of servo motors' configurations available creates confusion in the selection of an appropriate servo motor. Servo motors are costlier than stepper motors and do require setting of associated feed back and control mechanism [6].

6. DISCUSSION

The selection of power drives or motors could be bewildering especially for applications like drive mechanisms of a CNC machine which are required for very high accurate and precise movements. The selection of these motors depends on the features and requirements of these drive systems and the characteristics offered by these motors. However, in some situations, the characteristics of these motors could be improved using suitable control circuits. Moreover, suitable control circuits shall also be available, in case these motors are operated out of range either accidentally or otherwise. The drive mechanisms of CNC machines make use of either Stepper Motors for open loop control and Servo Motors for closed loop control.

In the very general sense, the servo motor provides precise positioning control by use of a feedback element, for example encoder or resolver, the spindle motor is velocity controlled. They both can consist of various technologies, i.e. DC brushed, AC Sinusoidal (synchronous) and Brushless DC, the spindle motor can also be a common AC induction motor type. In some cases the spindle motor can be made to accurately position by means of feedback to the controller for functions such as orientation for tool changing and can even be done with induction motor technology, usually 3 phase type. In the case of the servo motor, proportional-integral-derivative (PID) feedback loop allows interpolated moves between axes. However, the stepper motors are mainly used on small CNC machines operating without a feed-back mechanism. This research puts a complete detail and understanding of various power drives used for CNC machines and invokes for further research into Stepper Motors, Servo Motors and their associated control mechanisms which are the major power drive systems having significant bearing on the performance of CNC machines especially during contouring operations.

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