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A Study of Stepper Motors for Performance Improvement of the CNC Machines

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Abstract—*Computerized Numerical Control (CNC) Machines have been historically and primarily developed to achieve accurate and precise positioning of tool and work-piece in relation to each other. This whole positioning system is simply based on the coordinates of the machine work space or envelop. In order to achieve these coordinates for the positioning or movement of the tool and / or machine table (or work-piece), a CNC machine provide commands to the various electrical drives through various CNC codes and data supplied by the operator in the form a part-program. Thus, the accuracy and precision of these CNC machines and hence the performance of the CNC machines is primarily dependent on the accurate and precise movement of the tool and/or machine table (or work-piece) generated by these electrical drives and associated mechanisms. These movements of tool or work-piece takes place along some axis of the CNC machine and thus the various electrical drives affecting these movements are referred as axes drives. For axes drives, the CNC machines mainly use two types of motors viz. Stepper Motors and Servo Motors. Each of these classes of motors has several variants and each have their advantages and disadvantages. 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. A stepper motor is a pulse-driven motor that changes the angular position of the rotor in steps and is widely used in low cost, open loop position control systems that require no feedback mechanisms. This study provides an understanding of the technology and operations of stepper motors that shall assist in their selection and possibly advancement to further improve the performance of CNC machines.*

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

1. INTRODUCTION

One of the most important decisions that have significant bearing on the performance of a CNC machine is the appropriate type and rating of the electric motors employed to power its many elements. Of these, electric motors required to power spindle and various axes of the CNC machines are critical to the accuracy and precision of these machines and hence deserve special care and attention while making a selection for these motors. Basically, there are two categories of motors that are in practical applications for such purposes on CNC machines. The two broad categories are Stepper Motors and Servo Motors. Each of these classes has several variants and each have their advantages and disadvantages. Servomotors are not a specific class of motor although the term servomotor is often used to refer to a motor suitable for use in a closed-loop control system. Thus, for most practical applications, servo motor is a DC or AC or brushless DC motor combined with a position / velocity sensing device. In control engineering a servomechanism, sometimes shortened to servo, is an automatic device that uses error-sensing negative feedback to correct the action of a mechanism. It usually includes a built-in encoder or other position feedback mechanism to ensure the output is achieving the desired effect. The term correctly applies only to systems where the feedback or error-correction signals help control mechanical position, speed or other parameters. This is why servo motors are also known as Control Motors [1,2,3].

A stepper motor is a pulse-driven motor that changes the angular position of the rotor in steps. The size of the increment or steps is measured in degrees and can vary depending on the application. Due to this nature of a stepper motor, it is widely used in low cost, open loop position control systems that require no feed back mechanisms. But, there are limitations of stepper motors too, such as the revolution of the rotor becomes oscillatory and unstable in certain speed ranges, and due to this behavioural characteristic, the speed and acceleration of a stepping motor controlled using an open loop system can not be as fast as a DC motor driven in a closed loop control. Hence, in order to expand their applicability, it is necessary to tackle the issue of such oscillations in stepper motors. One such remedy is to operate the stepper motors under closed loop control that improves its stability and provides a quick acceleration capability. Moreover, In order to achieve superior torque characteristics over a wide speed range, the speed of the rotors rotation in a stepper motor may be controlled in a variety of ways. Three such possibilities are through a series resistance, gearbox and voltage regulation. Each type has advantages over each other, and a methods implementation depends on the motor application and functionality [4,5].

Stepper motor requires sequencers and driver to operate as per the operation data received from the programmable controllers which in turn is input by the operators. Sequencer generates sequence for switching which determines the direction of rotation and mode of operation. Driver is required to change the flux direction in the phase windings [6]. The block diagram of stepper motor system is shown in Figure 1.

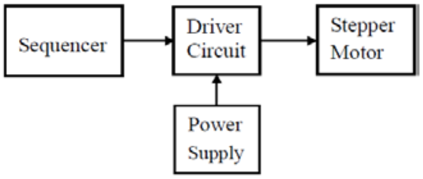

Figure 1: Block diagram of a Stepper Motor System [6]

There are three types of stepper motor. The first category of stepper motors known as Permanent Magnet Stepper Motors (PMSM); the second category of stepper motors are known as Variable Reluctance Stepper Motors (VRSM) and these does not employ permanent magnet; and the third category of stepper motors known as Hybrid Stepper Motors (HSM) are designed to provide features of both the variable reluctance and permanent magnet motors together [2,4].

Stepper motor can be selected based on the following Electrical and Mechanical specifications [7]. Electrical specifications include number of phases, step angle, winding voltage, winding resistance/ inductance, holding torque, pull-out torque, maximum slew rate, positional accuracy, temperature rise and power supply & drive circuits. Mechanical specifications includes shaft length & shape, motor length, shape of flange face, lead wire length and connector type. Some of the features common to all stepper motors that make them ideally suited for such type of applications are High Accuracy, Reliability, Holding Torque, and Load Independent Speed Characteristics provided that rated torque is maintained [6,7]. Owing to these and many more features, stepper motors are commonly used in medical equipment, satellites, robotic, CNC machines and other control applications, and this warrants a further detailed study and analysis of stepper motors.

2. BRIEF LITERATURE REVIEW

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. Traditionally, the precision control for linear movement is enhanced by feedback loops as it is presented. The conventional PID controllers (Proportional-Integral- Derivative) provide good precision in position loops and they are easy to implement and adjust. Besides, the interpolator is one of the key components in the control loop since it sends the command positions to the electric drive. If the position close loop is not working with efficient conditions, the electric drive will generate bigger position errors between the real position and the command one [8].

Most CNC machine tools nowadays have an electronic compensation feature built in within the controller system. This feature can be used to compensate electronically the geometric errors of the machine such as the positioning and backlash errors. The accuracy of machined parts depends on the machine accuracy. The state of machine tool accuracy has a huge impact on the quality of the end products. However, errors in machining can cause inaccuracies to the process which directly affect the quality of the end products. 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 [9].

In recent decades, numerous research efforts to develop machine tools with positioning performances at the nanometre level or better have been undertaken [10]. 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 [11].

Feed drive mechanical characteristics such as overall resilience, pre-loading, friction and inertia also have significant effect on the design optimization and it is important to achieve optimum parameterization in this regard. 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 [12,13]. Previous studies employing only constant acceleration bounds (an assumption that incurs arbitrarily high speeds if the path contains extended linear segments) are not sufficient, and 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 [14].

3. STEPPER MOTORS

Stepper or stepping motor is a special type of electric motor that moves in precisely defined increments of rotor position (Steps). Stepping motors are attractive because they can be controlled directly by computers or microcontrollers. Their unique feature is that the output shaft rotates in a series of discrete angular intervals, or steps, one step being taken each time a command pulse is received. When a definite number of pulses have been supplied, the shaft will have turned through a known angle, and this makes the motor ideally suited for open-loop position control that is where no feed back mechanism in place. Each step is completed very quickly, usually in a few milliseconds; and when a large number of steps are called for the step command pulses can be delivered rapidly, sometimes as fast as several thousand steps per second. At these high stepping rates the shaft rotation becomes smooth, and the behaviour resembles that of an ordinary motor. In order to understand the working of stepper motors, it is required to study the generation of step pulses and the resultant motor response. The step pulses may be produced by an oscillator circuit, which itself is controlled by an analogue voltage, digital controller or microprocessor [15].

Three important general features can be identified when step command pulses are supplied at a constant rate, and with sufficiently long intervals between the pulses to allow the rotor to come to rest between steps. Firstly, although the total angle turned through is governed only by the number of pulses, the average speed of the shaft depends on the oscillator frequency. The higher the frequency, the shorter the time taken to complete the requisite steps. Secondly, the stepping action is not perfect. The rotor takes a finite time to move from one position to the other, and then overshoots and oscillates before finally coming to rest at the new position. Overall single-step times vary with motor size, step angle and the nature of the load, but are commonly within the range 5–100 ms. Thirdly, in order to be sure of the absolute position at the end of a stepping sequence, the absolute position must be known at the beginning. This is because a stepping motor is an incremental device. Normally the step counter will be ‘zeroed’ with the motor shaft at the datum position, and will then count up for clockwise direction, and down for anticlockwise rotation. Provided no steps are lost the number in the step counter will then always indicate the absolute position [15].

But most commercial and industrial applications call for a more exacting and varied performance where a stepping rate of perhaps 2000 steps per second (or even higher), may be called for and where it cannot possibly come to rest between successive steps, as it does at low stepping rates. Instead, in practice, at these high stepping rates, the rotor velocity of the stepper motors becomes quite smooth as if moving continuously and not in steps. Nevertheless, the vital one-to-one correspondence between step command pulses and steps taken by the motor is maintained throughout, and the open-loop position control feature is preserved. This extraordinary ability to operate at very high stepping rates (up to 20 000 steps per second in some motors), and yet to remain fully in synchronism with the command pulses, is the most striking feature, referred to as “slewing”, of stepping motor systems. The transition from single stepping to high-speed slewing is a gradual one. Roughly speaking, the motor will ‘slew’ if its stepping rate is above the frequency of its single-step oscillations. When motors are in the slewing range, they generally emit an audible whine, with a fundamental frequency equal to the stepping rate. For slewing to be in effect, the stepper motor has to be started at a more modest stepping rate, before being accelerated (or ‘ramped’) up to high speeds, and if the stepping rate is increased too quickly, the motor will not be able to remain ‘in step’ and will stall. The stepper motor will meet the same fate when it is slewing and the train of step pulse is suddenly stopped, instead of being progressively slowed. Failures of this sort are prevented by the use of closed-loop control [15].

The construction of stepping motors is simple, the only moving part being the rotor, which has no windings, commutator or brushes: they are therefore robust and reliable. The rotor is held at its step position solely by the action of the magnetic flux between stator and rotor. The step angle is a property of the tooth geometry and the arrangement of the stator windings, and accurate punching and assembly of the stator and rotor laminations is therefore necessary to ensure that adjacent step positions are exactly equally spaced [15].

Step angle of a stepper motor is given by:

Step angle = 360° / Number of poles

The main benefits of stepper motors are: Low cost; Ruggedness; Simple construction; Low maintenance; Less likely to stall or slip; Excellent start-stop and reversing responses. Some of the limitations of the stepper motors are: Low torque capacity compared to DC motors; Limited speed; during overloading, the synchronization will be broken; Vibration and noise occur when running at high speed [2].

The stepper motors are of the following three types [2,4,6]:

3.1. Variable Reluctance Stepper Motor (VRSM)

Figure 2 shows the construction of Variable Reluctance stepper motor. In order to be efficient and effective, both the stator and rotor materials must have high permeability and be capable of allowing high magnetic flux to pass through even if a low magneto motive force is applied. The cylindrical rotor is made of soft steel and has four poles as shown in Figure 2. It has four rotor teeth, 90^0 apart and six stator poles, 60^0 apart. Electromagnetic field is produced by activating the stator coils in sequence. It attracts the metal rotor. When the stator windings are energized in a reoccurring sequence of 2, 3, 1, and so on, the motor will rotate in a 30^0 step angle, and this energizing sequence shall also determine the direction of rotation of the rotor.

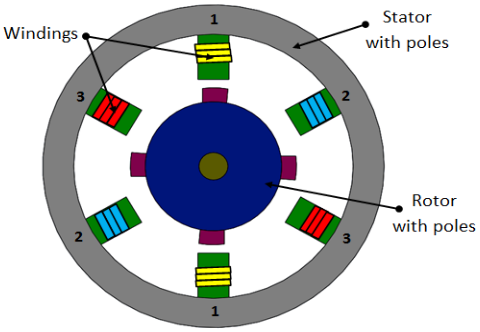

Figure 2: Variable reluctance stepper motor [2]

Rotation occurs when the rotor teeth are attracted to the energized stator poles in order to create a new position of minimum reluctance for the rotor as when the rotor teeth are directly lined up with the stator poles, the rotor is in a position of minimum reluctance to the magnetic flux. Thus, to achieve a rotor ‘step’, a stator phase is de-energized and the next phase in sequence is energized.

In the non-energized condition, there is no magnetic flux in the air gap, as the stator is an electromagnet and the rotor is a piece of soft iron; hence, there is no detent torque which is available only with the motors having permanent magnet. This type of stepper motor is called a variable reluctance stepper.

3.2. Permanent Magnet (PM) Stepper Motor (PMSM)

In this type of motor, the rotor is a permanent magnet with alternating north and south poles situated in a straight line parallel to the rotor shaft. These magnetized rotor poles provide an increased magnetic flux intensity and, because of this the PM motor exhibits improved torque characteristics when compared with the VRSM type. Unlike the other stepping motors, the PM motor rotor has no teeth and is designed to be magnetized at a right angle to its axis.

Figure 3 shows a simple, 90^0 PM stepper motor that employs a cylindrical permanent magnet as the rotor and possesses four poles in its stator carrying four phases (A-D). Two overlapping windings are wound as one winding on poles A and C and these two windings are separated from each other at terminals to keep them as independent windings. The same is true for poles B and D. Applying current to each phase in sequence will cause the rotor to rotate by adjusting to the changing magnetic fields and the energizing sequence of these phases shall also determine the direction of rotation of the rotor. Moreover, if the number of stator teeth and magnetic poles on the rotor are both doubled, a two-phase motor with a step length of 45^0 will be realized. Although, these motors operate at fairly low speed, the PM motor has a relatively high torque characteristic.

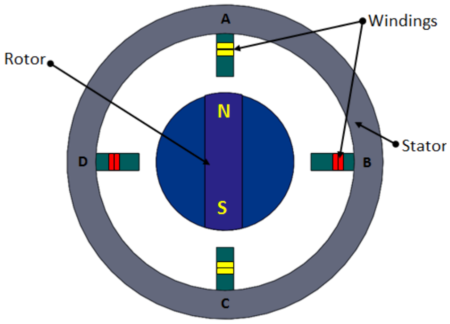

Figure 3: Permanent magnet stepper motor [2]

3.3. Hybrid Stepper Motor (HSM)

Hybrid stepping motors combine a permanent magnet and a rotor with metal teeth to provide features of the variable reluctance and permanent magnet motors together. In a hybrid stepper motor, the stator core structure is similar to that of a variable reluctance (VR) stepper motor but the windings and coil connections are different from that of a VR stepper motor. In the VR stepper motor only one of the two coils of one phase is wound on one pole, while in the four-phase hybrid motor, coils of two different phases are wound on the same pole. Therefore, one pole does not belong to only one phase. This arrangement of two coils of different phases on a single pole is to generate different magnetic polarities when these different coils are energized as per a scheme. Another feature that differentiates it from permanent magnet (PM) stepper motor is its rotor structure. Although both the PM motor and hybrid motors have a cylindrically shaped magnet in the core of the rotor, but this cylindrical shaped magnet in hybrid motors is magnetized lengthwise to produce a unipolar field. Each pole of the magnet is covered with uniformly toothed soft steel and thereby giving an impression that two different rotors are mounted on a shaft whereas they represent the two different poles of the same magnet or two sections of the same rotor. The teeth on these two sections are misaligned with respect to each other by a half tooth pitch. In some hybrid motors, the rotor teeth on both the sections are aligned with each other but the stator core has a misalignment.

The number of rotor pole pairs is equal to the number of teeth on one of the rotor’s parts. The hybrid motor stator has teeth creating more poles than the main poles windings (Figure 4).

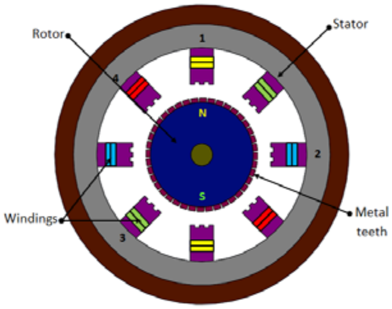

Figure 4: Hybrid stepper motor [2]

Rotation of a hybrid stepping motor is produced in the similar fashion as a permanent magnet stepping motor, by energizing individual windings in a positive or negative direction. When a winding is energized, north and south poles are created, depending on the polarity of the current flowing. These generated poles attract the permanent poles of the rotor and also the finer metal teeth present on rotor. The rotor moves one step to align the offset magnetized rotor teeth to the corresponding energized windings. This step is equal to quarter tooth-pitch or half of the misalignment in the teeth to nullify the driving forces and equilibrium is reached. When this excitation is turned off and new poles are excited to produce fresh north and south poles, the rotor will make another step to nullify the driving forces created as a result of fresh misalignment of teeth. It is evident from the working of these hybrid motors that the design and arrangement of teeth in both rotor and stator play a decisive role to realize a small step angle. Hybrid motors are more expensive than motors with permanent magnets, but they use smaller steps, have greater torque and maximum speed.

4. DISCUSSION AND SCOPE OF FUTURE RESEARCH

This work mainly concentrated on the understanding of the working of the stepper motors which are vital for the performance of the open loop CNC machines. This understanding shall be helpful in further advancement of this stepper motor technology to contain its disadvantages and enhance its usefulness with an objective to further improve the performance of the CNC machines. However, much more elaborate understanding of this stepper motor technology is still pending which shall be the subject of our next study. This study has provided a better platform for our planned next study and we are sure that both these studies shall pave a way for real advancement of this stepper motor technology. It is planned to put special emphasis on some aspects among others in our future study. These aspects are: different types of excitation mechanisms of stepper motors i.e. Full, Half and Micro steps; types of drivers i.e. Unipolar and Bi-polar drivers; Static Characteristics of stepper motors like Torque – Angle Curve, Holding Torque, Detent Torque; etc.; and Dynamic characteristics of stepper motors like Torque vs. Speed characteristics, etc.; and Closed-loop control of stepper motors.

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