Sizing of a Right BLDC Motor for CNC Feed Drive

P.Ram Kishore Kumar Reddy, P. Nagasekhara Reddy, M. Ramachandra Rao

Abstract: ***This paper provides a technical aspects and design factors for selection of a right Brushless Direct Current (BLDC) motor for a CNC feed drive.To meet the most demanding requirements of CNC machine tools, robots and transfer lines in terms of productivity, accuracy and dynamic performance, brushless DC drives are very widely used. These drives employ brushless torque motors which are of high torque, low speed direct drive type. The performance and reliability of BLDC motor drivers have been improved because the conventional control and sensing techniques have been improved through sensorless technology. This paper presents a procedure for selecting and sizing a right torque motor for a CNC feed drive when the relevant application data is available. The duty cycle characteristics of the motor are presented to study certain parameters from thermal considerations. Expressions for acceleration torque and acceleration time are developed to study their effect on the high dynamic performance. In this paper the procedure is illustrated in the selection of Z-axis feed motor for CNC lathe with an example.***

Keywords: ***Brushless DC motors, sizing, PWM, CNC Drive, acceleration/deceleration curve, speed and torque.***

I. INTRODUCTION

Since 1980's new design concept of permanent magnet brushless motors has been developed. The Permanent magnet brushless motors are categorized into two types based upon the back EMF waveform, brushless AC (BLAC) and brushless DC (BLDC) motors [1]. BLDC motor has trapezoidal back EMF and quasi-rectangular current waveform. BLDC motors are rapidly becoming popular in industries because of their high efficiency, high power factor, silent operation, compact, reliability and low maintenance [2]. BLDC motor generally utilizes three hall sensors for deciding the commutation sequence.

In BLDC motor the power losses are in the stator where heat can be easily shifted through the frame or cooling systems are utilized in massive machines. BLDC motors have many benefits over DC motors and induction motors. Some of the benefits are better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation, higher speed ranges [3]-[4].

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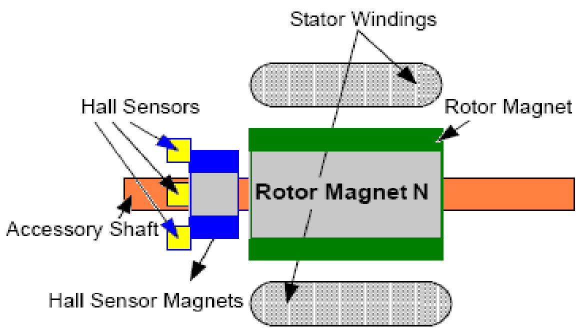
The Brushless DC servo feed drive consists of a synchronous motor and transistor AC PWM regulator. The BLDC motors are permanently excited synchronous motors with rare earth magnetic material. This eliminates the need for a field power supply and reduces the total heat generated in a motor and allows for smaller sizes. The standard version of the motor consists of rotor, stator and a rotor position detector with AC tachometer for sensing motor speed and rotor position [5]. The motors can be coupled directly to the ball screws as well as gear boxes or belt drives. These motors distinguish themselves through high performance features such as fast acceleration response, excellent torque response and short ramp up to maximum rapid traverse speed with low motor inertia. The synchronous motor offers an almost constant overload capacity throughout the entire speed range.



The function of the commutator on the DC motor is accomplished with an AC PWM regulator through the switching of transistors (6 Transistors with 6 anti parallel connected freewheeling diodes). The function of the commutator, specifically the logic decision of the current carrying conductor of the motor with respect to the actual rotor position, is accomplished by using rotor position detector [6]-[7]. The absence of the commutator and the brushes makes these drives virtually maintenance free. Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence [8].

II. PERFORMANCE CHARACTERISTICS:

The BLDC motor is also referred to as an electronically commutated motor. There are no brushes on the rotor and the commutation is performed electronically at certain rotor positions. The stator phase windings are inserted in the slots (a distributed winding), or can be wound as one col on the magnetic pole. The magnetization of the permanent magnets and their displacement on the rotor are chosen in such a way that the back-EMF shape is trapizoidal. This allows the three-phase voltage system, with a rectangular shape, to be used to create a rotational field with low torque ripples. In this respect, the BLDC motor is equivalent to an inverted DC commutator motor in that the magnets rotates while the conductors remain stationary.

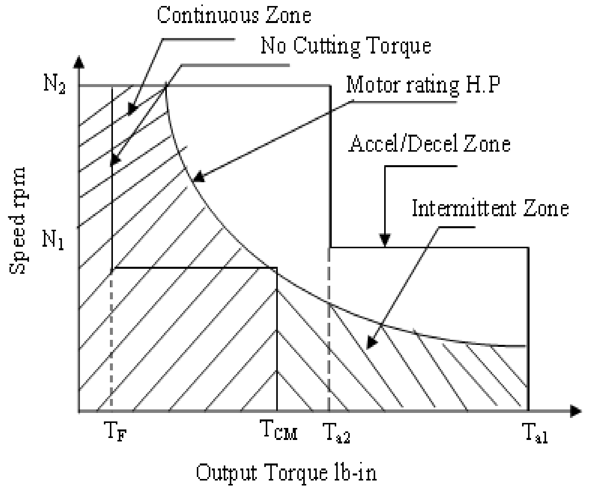


Fig 1.Torque –Speed Characteristic

There are two types of acceleration current profiles in popular use; 2-step current control and HP current control. The rule of thumb for 2-step current control is that the motor is accelerated from zero to half speed at peak torque and then half to full speed at 1/3rd peak torque. For constant HP control, motor is accelerated at peak torque until it reaches the predetermined constant HP acceleration curve. From there acceleration continues at a constant HP until top speed is reached. Operation of the acceleration/deceleration curve is very limited, typically a few 100 milliseconds.

III. SIZING AND SELECTION OF A BLDC MOTOR:

BLDC motors are torque motors designed to be used directly on ball screws without use of gearing. This feature enables a drive with high torque at stall and with high dynamic stiffness without hysteresis. In selecting an optimum torque motor for a specific application, various factors have to be considered with respect to the heat dissipation, position feedback, torque and speed required. The various principal factors to be considered are 1. motor continuous torque 2. load duty cycle characteristics 3. motor speed 4. motor-rotor inertia, 5. acceleration or peak torque, 6. Acceleration time to top speed. These factors are determined from specifications of machine tool.

IV. CALCULATION OF PRINCIPAL MOTOR PARAMETERS:

A.Continuous Torque:

This torque is made up of frictional and cutting load components. Frictional torque, T_F is due to the frictional force between the machine slide and its guide ways and is given by

$$T_F = \frac{\mu W \times pitch}{2\Pi \eta} \quad lb - in \qquad (1)$$

Where W is the weight of slide in lbs,

η is the efficiency of ball screw taken as 0.85,

Pitch in inch/revolution,

μ is the static friction coefficient assumed as 0.15.

B. Cutting Torque, T_C:

Machine tool applications often have loads which do not require continuous operation. They run on duty cycle basis. The thermal equivalent continuous torque T_C is given as

$$T_C = \frac{F_{RMS} \times pitch}{2\Pi \eta} \quad in - lbs \qquad (2)$$

Where F_{rms} is the rms value of the cutting force and is given by

$$F_{RMS} = \sqrt{\frac{\Sigma F_K^2 t_K}{t_{cycle}}} \qquad (3)$$

Where F_K: discreet elements of force # K

t_K: time during which F_K is working

Total torque on screw $T_{Screw} = T_C + T_F$ (4)

This is the torque acting on the motor shaft because of direct drive.

C. Duty Cycle characteristics:

The equation for the temperature rise, θ of a motor is,

$$\theta = \theta_f \left(1 - e^{-t/\tau}\right) \qquad (5)$$

Where τ is the motor thermal time constant

θ_f is the final temperature rise

The output torque $T_P = K_t I_P$ and

the continuous torque $T_c = K_t I_C$

Where, K_t is motor torque constant.

Let Ψ be the duty cycle of the load given by

$$\psi = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{t_{cycle}}$$

The temperature rise is proportional to copper losses.

$$\frac{\text{losses at } T_P}{\text{losses at } T_C} = \frac{I_P^2}{I_C^2} = \frac{\theta_f \left(1 - e^{-t_{cycle}/\tau}\right)}{\theta_f \left(1 - e^{-t_{on}/\tau}\right)}$$

The duty cycle consideration is for the same final temperature rise and

$$\frac{T_P}{T_C} = \sqrt{\frac{1 - e^{-t_{on}/\tau\psi}}{1 - e^{-t_{on}/\tau}}} \qquad (6)$$

Where t_{on} = maximum time ON for maximum armature temperature rise by resistance.

t_{off} = minimum time OFF

For class F insulation $\theta_f = 130^0$ C.

The above equation implies that the DC motor is capable of increased torque on duty cycle basis for loads which do not require continuous operation.

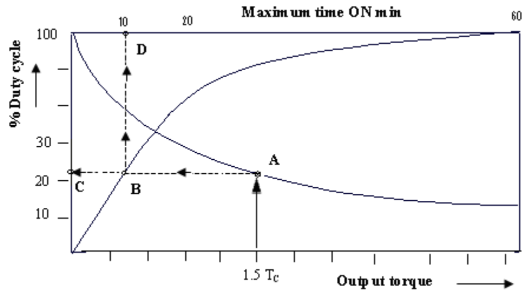


Fig. 2. Information regarding Duty cycle characteristics

Equation (6) is potentially useful in studying parameters of duty cycle and torque T_P associated with heat generation. It enables the motor manufacturers to provide excellent application support and calculation aids in graphical form as shown in figure 2.

For a given T_P/T_C, duty cycle Ψ and t_{on} can be determined. For a given $T_P/T_C = 1.5$ the graphs will enable t_{on} and duty cycle Ψ to be determined. For $T_P = 1.5\ T_C$ on the output torque, follow arrow to point 'A' on the output curve and point on the t_{on} curve corresponding to point 'B'. The percentage duty cycle is given by point 'C' and t_{on} is given by point 'D'.

For most permanent magnet field motors with the exception of those motors which do not use ceramic magnets the following table gives the useful information .

Motor torque Multiplier	Duty cycle (%)	Maximum time t_{on} at torque (min)
1.2	70	45
1.42	50	20
2.0	25	5
3.0	10	1
5.0	4	10 sec
10	1	1 sec

Since the torque required for cutting loads and friction torque when running rarely exceeds 70% duty cycle and 45 min duration, most DC Motor ratings can be increased by 20% when applied on NC machine tools. Accelerating torque required for a high performance contouring often range from 250% to 1000%. Since time for acceleration on these high performance systems usually is 20 to 300 msec, the duty cycle is low and the motor characteristics are ideal to meet the high torque requirements.

Machine tool grade torque motors include provision for liquid cooling to remove heat generated in the stator. The use of liquid cooling effectively increases the continuous torque rating of the motor. The air cooling is also an option, but it is much less effective than liquid for heat transfer.

D. Motor Speed, N:

Motor speed in RPM is obtained from rapid traverse speed (inch/min) and given by,

$$\text{Motor speed, N (RPM)} = \frac{\textit{rapid traverse rate}\left(\textit{inch / min}\right)}{\textit{ball screw pitch}\left(\textit{inch/rev}\right)} \qquad (7)$$

E. Motor Inertia, J_m:

For a direct drive for the case maximum acceleration at the load,

$$J_m = J_L \qquad (8)$$

Where, the load inertia J_L is comprised of ball screw and slide.

F. Peak Torque (T_P) and Acceleration Time:

When an instantaneous change in speed is commanded, the acceleration or deceleration is approximately exponential as shown below.

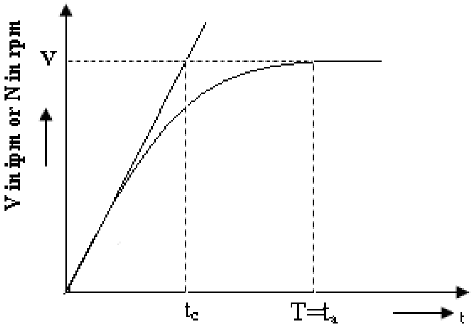


Fig 3. Speed vs Time characteristics

$$v = V\left(1 - e^{-t/t_c}\right) \qquad (9)$$

Where the time constant t_c is the reciprocal of the position loop cross over frequency ω_c in rad/sec .

The maximum slope is essentially the same as that which would permit the full speed change to take place in one time constant, t_c. The acceleration profile is synthesized a). Using two line segment (Linear interpolations) b). Using one line segment and remaining exponential path as shown below.

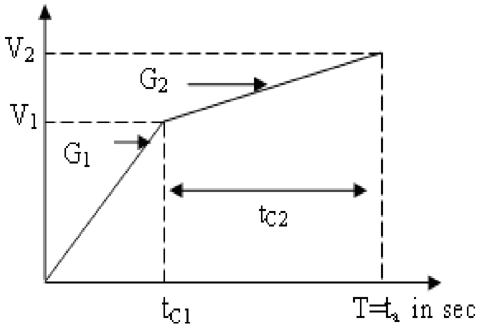


Fig 4a. Two-step acceleration current control

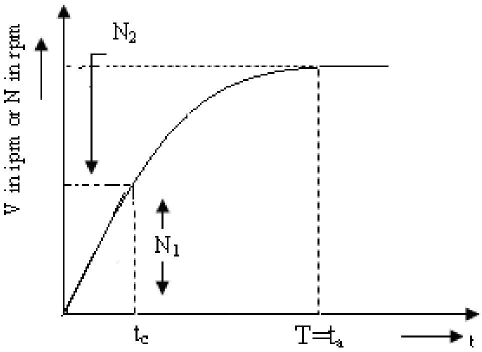


Fig 4b. HP acceleration current control

The above gives rise to 2-step current control and HP current control as mentioned earlier. The two gain circuit provides high gain at low velocities to assume high position accuracy and high static stiffness. A low gain at high velocities avoids in stabilities.

For 2-step current profile, the motor acceleration torque,T_P and T_{a2} are given as,

$$T_{a1} = T_P = J_T \frac{\omega_1}{t_{C1}} + T_F$$

and

$$T_{a2} = J_T \frac{\left(\omega_2 - \omega_1\right)}{\left(t_a - t_C\right)} + T_F$$

(10)

Where $J_T = J_m + J_L$

The rule of thumb for 2-step current control is that $\omega_1 = \omega_2/2$.

Since $t_a \cong 4t_C$,$T_{a2} = T_P/3$.

For the case of constant HP acceleration, the motor torque equation is given as $J_T \frac{d\omega}{dt} + T_F = T_m$ (11)

Since $T_m = 550HP/\omega$, equation (*XI*) gives

$J_T\, \omega \frac{d\omega}{dt} + T_F\, \omega = 550HP$ which gives

$$dt = \frac{J_T}{T_F} \frac{\omega\, d\omega}{\left(\frac{550HP}{T_F} - \omega\right)}$$

With $K=550HP/T_F$

$$dt = \frac{-J_T}{T_F}\left(1 - \frac{K}{K-\omega}\right)d\omega \quad (12)$$

Integrating

$$\int_{t_1}^{t_2} dt = \frac{-J_T}{T_F}\left[\int_{\omega_1}^{\omega_2} d\omega - \int_{\omega_1}^{\omega_2} \frac{K d\omega}{K-\omega}\right]$$

$$= \frac{-J_T}{T_F}\left[(\omega_2 - \omega_1) + K \log\left(\frac{K-\omega_2}{K-\omega_1}\right)\right]$$

$$\text{i.e } t_2 - t_1 = \frac{J_T}{T_F}\left[(\omega_1 - \omega_2) + \frac{550HP}{T_F} \times \log_e\left(\frac{\frac{550HP}{T_F} - \omega_1}{\frac{550HP}{T_F} - \omega_2}\right)\right]$$

The acceleration time t_a is given as,

$t_a = t_c + (t_2 - t_1)$ (13)

A high peak torque at stall entails a lower position loop time constant, t_c and a higher position loop gain, G and high dynamic performance with fast rise time. For good performance consistent with no over shoot in servo and with good positional accuracy, a typical positional loop gain G in terms of normal machine tool language is 1.5 ipm/mil error. However a gain of 1 ipm/mil is almost entirely satisfactory.

V. ILLUSTRATIVE RESULT

The above procedure is applied to select the proper Z axis motor of an inclined bed CNC lathe, the relevant application data for which is furnished below.

Ball screw

Type	Preloaded recirculating ball screw and nuts
Pitch diameter	2.4’’
Lead	o.5’’
Length of preloaded screw	100’’

Slide

Weight, W	2000 lb
Type of slide	Cast iron on steel (Pheripheral ground)
Orientation	(line of horizontal motion)

Speeds

Rapid traverse, V	500 ipm
Max.feed rate	250 ipm
Motor speed, N corresponding to 500 ipm	1000 rpm

Gearbox

Direct drive without gear box.

Axial force on Screw Duty Cycle:

Maximum load of 5500 lbs for a period of 5 minutes followed by continuous load of 3300 lbs for 15 minutes to be followed by idle time of 1 min. The cycle repeats. The total cycle time is 21 minutes.

A. Inertia:

WK^2 of ball screw = $\frac{D^4 L \times 19.4 \times 10^{-5}}{2.7}$ $in.lb.Sec^2$ (D & L in inches) =0.2383 in. lb. Sec^2

WK^2 of slide = $W\left(\frac{V}{N}\right)^2 \times \frac{17.9 \times 10^5}{2.7}$

=0.03 in. lb. sec^2

Load inertia (Screw + slide) J_L = 0.2683 in., lb. sec^2 referred to motor.

$J_M = J_L = 0.2683$ in.lb.sec^2

B. Motor top Speed:

N=500/0.5=1000 rpm

C. **Continuous Torque:**

Friction torque T_F = 30 lb. in.

$F_{RMS} = \sqrt{\frac{5500^2 \times 5 + 3300^2 \times 5}{21}}$ =3850 lbs.

D. ***Cutting torque:*** $T_C = \frac{3850 \times 0.5}{2\pi \times 0.85} = 360.439\, lb.in.$

Motor continuous torque $T_{CM} = T_F + T_C = 30 + 360.439$ = 390.439 lb.in.

$t_{C1} = \frac{1}{16.6 \times G_1}$ = 0.06 Sec.

$t_{C2} = \frac{1}{16.6 \times G_2}$ = 0.12 Sec.

With G_1 = 1ipm/mile, G_2 = 0.5 ipm/mile and V_1= 250 ipm(500 rpm) and V_2 = 500 ipm(1000 rpm)

Total time to accelerate to rapid traverse,

$t_a = \frac{1}{16.6}\left(\frac{1}{G_1} + \frac{1}{G_2}\right) = 0.18\,sec.$

$\omega_1 = \frac{2\pi}{60} \times \frac{250}{0.5} = 52.3\, rad/sec$

$\omega_2 = \frac{2\pi}{60} \times \frac{500}{0.5} = 104.6\, rad/sec$

With $J_T = J_M + J_L = 0.266 + 0.266 = 0.532$ lb.in.

Acceleration torque, $T_{a1} = \left[0.532 \times \frac{52.3}{0.06} + 30\right] = 497.21$ lb.in.

$$T_{a1} = \left[0.532 \times \frac{52.3}{0.12} + 30\right] = 263.60 \text{ lb.in.}$$

VI. CONCLUSION

The Siemens 1FT5108-0AA01 type BLDC motor will meet the requirements. This motor has J_m=0.2638 lb.in.sec^2, (≈ 0.2683 lb.in.sec^2) top speed, N=1200 rpm, continuous torque T_{CM}=486.8 lb.in at 60 k (maximum temperature of stator winding class F insulation) and T_{CM} =601.8 lb.in at 100 K and peak torque T_P is greater than twice the continuous motor torque.

i.e $T_P = \geq 2T_{CM}$=974 lb.in

The above motor meets the feed requirements of the CNC lathe. Acceleration time to rapid traverse speed with constant HP current control t_a= 4t_C=4x0.06=0.24 sec

t_a(in the 2-step current control)=t_{C1}+t_{C2}=0.18 sec.

In this paper, selecting and sizing a right BLDC motor is proposed for a CNC feed drive. The illustrative results demonstrate the selection of various parameters for the drive. As the load torque varies the speed of the BLDC motor remains constant. The mathematical modeling of BLDC motor is done for a CNC feed drive.

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