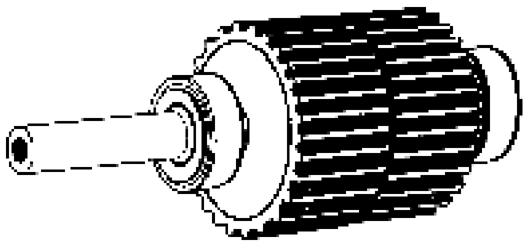
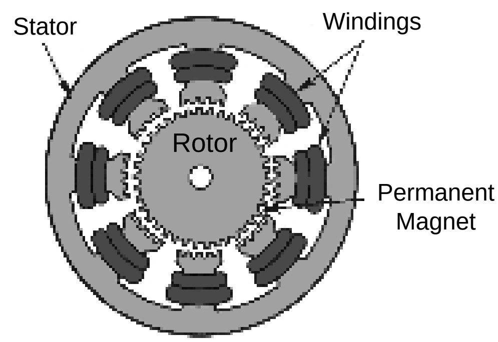
6) Motors and Encoders

Electric motors are by far the most common component to supply mechanical input to a linear motion system. Stepper motors and servo motors are the popular choices in linear motion machinery due to their accuracy and controllability. They exhibit favorable torque-speed characteristics and are relatively inexpensive. The term NEMA refers to the physical size of the motor, and has become an industry standard. All motors of the same NEMA frame size should exhibit the same dimensions. This section will discuss the features associated with each of these types of motors.

Stepper motors convert digital pulse and direction signals into rotary motion and are easily controlled. Although stepper motors can be used in combination with analog or digital feedback signals, they are usually used without feedback (open loop). Stepper motors require motor driving voltage and control electronics.

The rotor of a typical hybrid stepper motor has two soft iron cups that surround a permanent magnet which is axially magnetized. The rotor cups have 50 teeth on their surfaces and guide the flux through the rotor-stator air gap. In most cases, the teeth of one set are offset from the teeth of the other by one-half tooth pitch for a two phase stepper motor.





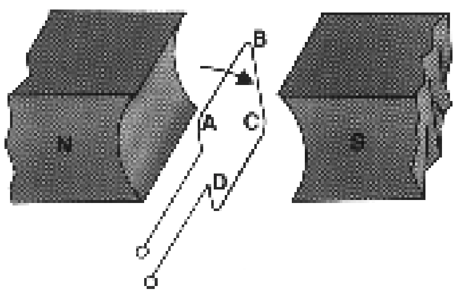
The stator generally has the same number of teeth as the rotor, but can have two fewer depending upon the motor's design. When the teeth on the stator pole are energized with North polarity, the corresponding teeth on the rotor with South polarity align with them. Similarly, teeth on the stator pole energized with South polarity attract corresponding teeth on the rotor that are energized with North polarity. By changing the polarity of neighboring stator teeth one after the other in a rotating sequence, the rotor begins to turn correspondingly as its teeth try to align themselves with the stator teeth. The strength of the magnetic fields can be precisely controlled by the amount of current through the windings, thus the position of the rotor can be precisely controlled by these attractive and repulsive forces.

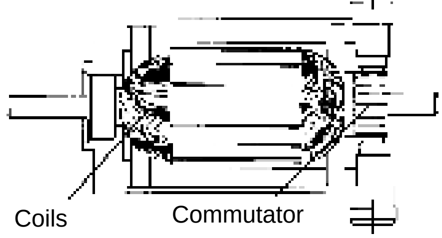
There are many **advantages** to using stepper motors. Since maximum dynamic torque occurs at low pulse rates (low speeds), stepper motors can easily accelerate a load. Stepper motors have large holding torque and stiffness, so there is usually no need for clutches and brakes (unless a large external load is acting, such as gravity). Stepper motors are inherently digital. The number of pulses determines position while the pulse frequency determines velocity. Additional advantages are that they are inexpensive, easily and accurately controlled, and there are no brushes to maintain. Also, they offer excellent heat dissipation, and they are very stiff motors with high holding torques for their size. The digital nature of stepper motors also eliminates tuning parameters.

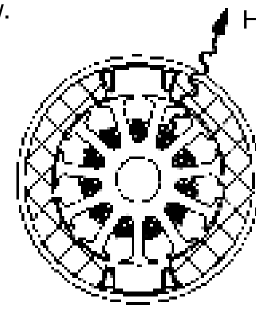
There are **disadvantages** associated with stepper motors. One of the largest disadvantages is that the torque decreases as velocity is increased. Because most stepper motors operate open loop with no position sensing devices, the motor can stall or lose position if the load torque exceeds the motor's available torque. Open loop stepper motor systems should not be used for high-performance or high-load applications, unless they are significantly derated. Another drawback is that damping may be required when load inertia is very high to prevent motor shaft oscillation at resonance points. Finally, stepper motors may perform poorly in high-speed applications. The maximum steps/sec rate of the motor and drive system should be considered, carefully.

Servo motors are more robust than stepper motors, but pose a more difficult control problem. They are primarily used in applications where speed, power, noise level as well as velocity and positional accuracy are important. Servo motors are not functional without sensor feedback; they are designed and intended to be applied in combination with resolvers, tachometers, or encoders (closed loop). There are several types of servo motors, and three of the more common types are described as follows.

The **DC brush** type are most commonly found in low-end to mid-range CNC machinery. The “brush” refers to brushes that pass electric current to the rotor of the rotating core of the motor. The construction consists of a magnet stator outside and a coil rotor inside. A brush DC motor has more than one coil. Each coil is angularly displaced from one another so when the torque from one coil has dropped off, current is automatically switched to another coil which is properly located to produce maximum torque. The switching is accomplished mechanically by the brushes and a commutator as shown below.



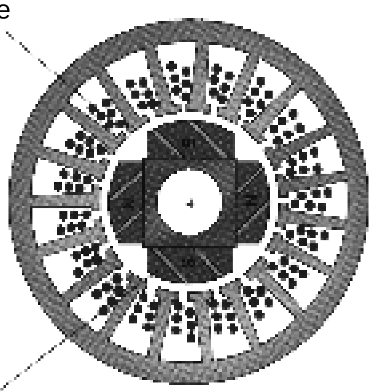


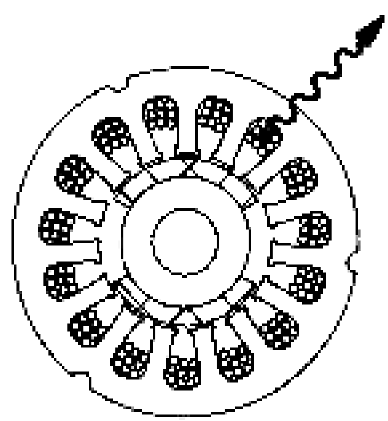


Brushed DC Motor

There are distinct **advantages** to using DC brush servo motors. They are very inexpensive to apply. The motor commutates itself with the brushes and it appears as a simple, two-terminal device that is easily controlled. Among the **disadvantages** is the fact that they are thermally inefficient, because the heat must dissipate through the external magnets. This condition reduces the torque to volume ratio, and the motor performance may suffer inefficiencies. Also, the brushed motor will require maintenance, as the brushes will wear and need replacement. Brushed servo motors are usually operated under 5000 rpm.

The **DC brushless** type offers a higher level of performance. They are often referred to as “inside out” DC motors because of their design. The windings of a brushless motor are located in the outer portion of the motor (stator), and the rotor is constructed from permanent magnets as shown below. DC brushless motors are typically applied to high-end CNC machinery, but the future may see midrange machinery use brushless technology due to the narrowing cost gap.





Brushless Motor

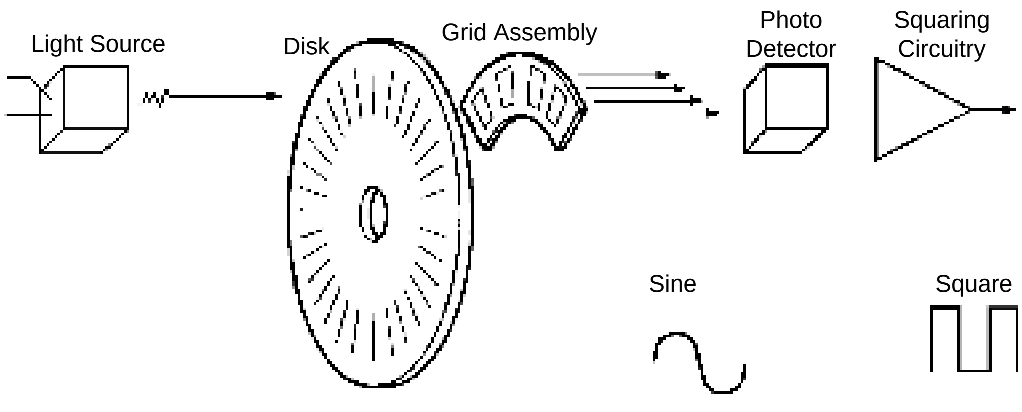
Many **advantages** are realized with brushless DC servo motors. The inside out construction allows for excellent heat dissipation. This results in a higher continuous torque and a higher output rating than found in a comparably sized brushed motor. Also, speeds up to 60000 rpm are not uncommon. Speed torque ripple and cogging torque are both reduced, because there are no mechanical brushes, eliminating the brushed contact. These motors also tend to be maintenance-free. **Disadvantages** are primarily increased cost, increased control complexity, and increased weight.

AC servo motors are another variety that offers high-end performance. Their physical construction is similar to that of the brushless DC motor; however, there are no magnets in the AC motor. Instead, both the rotor and stator are constructed from coils. Again, there are no brushes or contacts anywhere in the motor which means they are maintenance-free. They are capable of delivering very high torque at very high speeds; they are very light and there is no possibility of demagnetization. However, due to the electronic commutation, they are extremely complex and expensive to control.

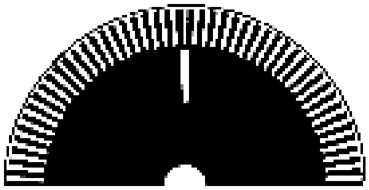
Perhaps the largest **advantage of using servo motors** is that they are used in closed loop form, which allows for very accurate position information and also allows for high output torque to be realized at high speeds. The motor will draw the required current to maintain the desired path, velocity, or torque, and is controlled according to the requirements of the application rather than by the limitations of the motor. Servo motors put out enormous peak torque at or near stall conditions. They provide smooth, quiet operation, and depending upon the resolution of the feedback mechanism, can have very small resolutions.

Among the **disadvantages of servo motors** are the increased cost, the added feedback component, and the increased control complexity. The closed loop feature can be a disadvantage for the case when there is a physical obstacle blocking the path of motion. Rather than stalling, the servo motor will continue to draw current to overcome the obstacle. As a result, the system hardware, control electronics, signal amplifier and motor may become damaged unless safety precautions are taken.

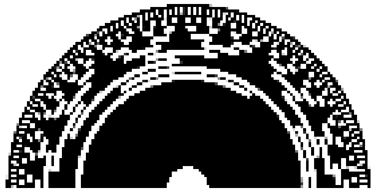
Rotary Optical Encoders are the popular choice to supply signal feedback. They are mounted directly on the shaft of a servo motor. The basic principle of operation is as follows: A disc or plate containing opaque and transparent segments passes between an LED and a detector to interrupt a light beam. All rotary encoders consist of a light source, light detector, code wheel, and signal processor. There are two basic encoder styles: absolute and incremental.



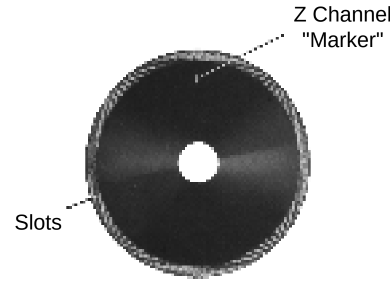
Absolute encoders use multiple detectors and up to 20 tracks of segment patterns. As the encoder disc turns, the binary output changes one bit at a time. For each encoder position, there is a different binary output, therefore shaft position is absolutely determined. The resolution of an absolute encoder is determined by the number of concentric pattern tracks on the wheel. Absolute encoders may be necessary for accuracy critical applications, military applications, or applications requiring accurate position information after power up or power failure, but this level of position detection is not required for typical machining and positioning applications.



Incremental Encoder



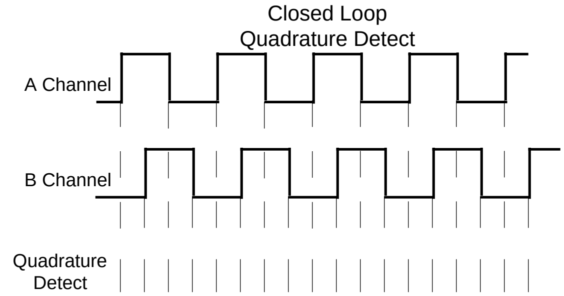
Absolute Encoder



The Encoder Disk

Incremental encoders have only one track (or two) of segment patterns. The resolution of the encoder is equal to the number of bands in the pattern segment. Absolute positioning information cannot be provided since all of the signals are the same. All incremental encoders rely on a counter to determine position and a stable clock to determine velocity. Most incremental encoders provide a single mark on the disc called the Z channel, or indexer. The pulse from this channel provides a reference once per revolution to detect errors within a given revolution.

If a second band of patterns and a second light source were added to an incremental encoder, the result is a **quadrature encoder**, which is very common in machining and positioning applications. Channel B (second band and light source) is spaced one half a slot width apart from the Channel A light source and photo detection. Electrically, the two signals are 90° out of phase from each other as shown.



Quadrature Encoder

The quadrature multiplication results from the two square waves having four unique states at any given moment. Notice that as the waves move in one direction (the disk rotates in one direction), the four states cycle in a specific sequence. As the disk rotates in the opposite direction, the four states cycle in the reverse sequence. Thus, the direction of rotation and the quad multiplying effect (which increases resolution fourfold) can be produced by the second channel.

Sizing Stepper Motors

Before the correct Stepper Motor can be chosen for a particular application, the following information must be determined:

a. operating speed in steps/sec
b. torque in ounce·inches
c. load inertia in $lb \cdot in^2$
d. required step angle
e. time to accelerate in milliseconds
f. time to decelerate in milliseconds
g. type of drive system to be used
h. size and weight considerations

Once this information is known, the best motor/drive combination can be determined using torque vs. speed curves and the formulas given on this and the following pages.

Torque, T (oz·in)

$$T = Fr$$

where

F = Force (in ounces) required to drive the load
r = Radius (in inches)

Moment of Inertia, I ($lb \cdot in^2$)

$$I = \frac{Wr^2}{2} \text{ for a disc}$$

$I = \frac{W}{2}(r_1^2 + r_2^2)$ for a cylinder

where

W = Weight in pounds

r = Radius in inches

Equivalent Inertia

A motor must be able to:

a. overcome any frictional load in the system

b. start and stop all inertial loads including that of its own rotor

The basic rotary relationship is:

$$T = \frac{I\alpha}{24}$$

where:

T = torque (oz·in)

I = moment of inertia (lb·in²)

α = angular acceleration, in radians per square second (rad/sec²)

Angular acceleration (α) is a function of the change in velocity (ω) and the time required for the change.

$$\alpha = \frac{\omega_2 - \omega_1}{t}$$

or, if starting from zero,

$$\alpha = \frac{\omega}{t}$$

where:

ω = angular velocity (rad/sec)

t = time (sec)

since $\omega = \frac{\text{steps per second}}{\text{steps per revolution}} \times 2\pi$,

angular velocity and angular acceleration can also be expressed in steps per second (ω') and steps per square second (α'), respectively.

Sample Calculations

A. Calculating torque required to rotationally accelerate an inertia load:

$$T = 2 \times I_o \frac{\omega'}{t} \times \frac{\pi\theta}{180} \times \frac{1}{24}$$

where:

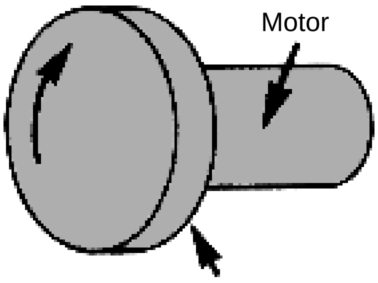
T = torque required (oz·in)

I_o = inertial load (lb·in²)

π = 3.1416

θ = step angle (degrees)

ω' = step rate (steps/sec)



Example:

Assume the following conditions:

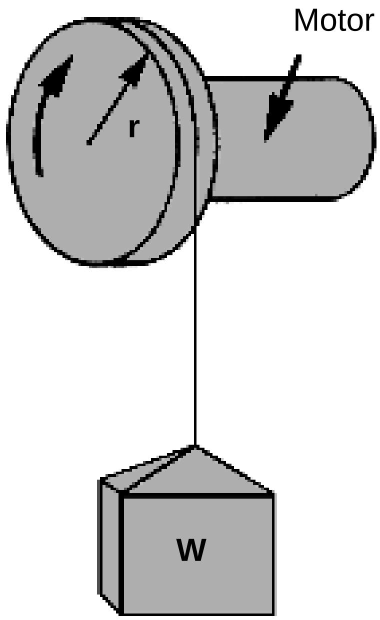
Inertia = 9.2 lb·in²

Step Angle = 1.8°

Acceleration = from 0 to 1000 steps per second in 0.5 seconds

$$T = 2 \times 9.2 \times \frac{1000}{0.5} \times \frac{1.8\,\pi}{180} \times \frac{1}{24}$$

T = 48.2 oz·in to accelerate inertia



B. Calculating torque required to accelerate and raise a weight using a drum and string. The total torque which the motor must supply includes the torque required to:

a. accelerate the weight
b. accelerate the drum
c. accelerate the motor rotor
d. lift the weight

The rotational equivalent of the weight and the radius of the drum is:

$$I_{(eq)} = wr^2$$

where:

$I_{(eq)}$ = equivalent inertia (lb·in²)
w = weight (lb)
r = radius of drum (in)

Example:
Assume the following conditions:

Weight = 5 lbs (80 oz)
Drum = 3" O.D., 1.5" radius
Velocity = 15 ft per second
Time to Reach Velocity = 0.5 seconds
Motor Rotor Inertia = 2.5 lb·in²
Drum Inertia = 4.5 lb·in² (for a 3" dia x 2" long steel drum)

$I_{(eq)} = 5 \times (1.5)^2 = 11.25$ lb·in²
$I_{(drum)} = 4.5$ lb·in²
$I_{(rotor)} = 2.5$ lb·in²
$I_{(total)} = 18.25$ lb·in²

since the velocity is 15 ft/sec using a 3" drum, the velocity in rev/sec can be calculated:

$$\text{speed} = \frac{15 \times 12}{3\,\pi} = 19.1 \text{ rev/sec}$$

The motor step angle is 1.8°, or 200 steps per revolution. Therefore:

ω' = 19.1 x 200 = 3820 steps per second

$$T = 2 \times I_o \times \frac{\omega}{t} \times \frac{\pi\,\theta}{180} \times \frac{1}{24}$$

$$T = 2 \times 18.25 \times \frac{3820}{0.5} \times \frac{3.1416 \times 1.8}{180} \times \frac{1}{24}$$

T = 364 oz·in = torque required to accelerate the system. Torque required to lift weight equals:

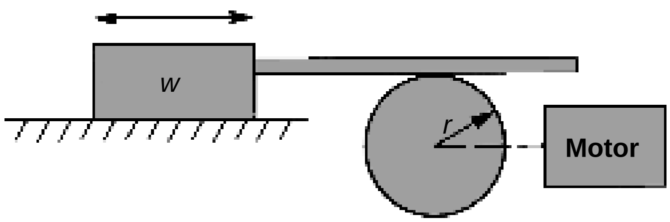
$T = wr$ = 80 x 1.5 = 120 oz·in

Total torque required is, therefore:

364 oz·in (accelerating torque)
120 oz·in (lifting torque)

484 oz·in (total torque)

C. Calculating the torque required to accelerate a mass moving horizontally and driven by a rack and pinion or similar device. The total torque which the motor must provide includes the torque required to:



a. accelerate the weight, including that of the rack
b. accelerate the gear
c. accelerate the motor rotor
d. overcome frictional forces

to calculate the rotational equivalent of the weight:

$$I_{(eq)} = wr^2$$

where:
w = weight (lb)
r = radius (in)

Example:
Assume that:
Weight = 5 lb
Gear Pitch Diameter = 3 in
Gear Radius = 1.5 in
Velocity = 15 ft per second
Time to Reach Velocity = 0.5 seconds
Pinion Inertia = 4.5 lb·in^2 (assumed)
Motor Rotor Inertia = 2.5 lb·in^2

$I_{(eq)} = wr^2 = 5 \times (1.5)^2 = 11.25$ lb·in^2
$I_{(pinion)} = 4.5$ lb·in^2
$I_{(rotor)} = 2.5$ lb·in^2

$I_{(total)} = 18.25$ lb·in^2

Velocity is 15 ft per second with a 3" pitch diameter gear. Therefore:

$$\text{speed} = \frac{15 \times 12}{3\pi} = 19.1 \text{ revolutions per second}$$

The motor step angle is 1.8° (200 steps per revolution). Therefore, the velocity in steps per second is:

$$\omega' = 19.1 \times 200 = 3820 \text{ steps per second}$$

To calculate torque to accelerate system:

$$T = 2 \times I_o \times \frac{\omega}{t} \times \frac{\pi\theta}{180} \times \frac{1}{24}$$

$$T = 2 \times 18.25 \times \frac{3820}{0.5} \times \frac{3.1416 \times 1.8}{180} \times \frac{1}{24}$$

$$T = 364 \text{ oz·in}$$

To calculate torque needed to slide the weight, assume a frictional force of 6 oz:

$$T_{(friction)} = 6 \times 1.5 = 9 \text{ oz·in}$$

Total torque required:

	364 oz·in
+	9 oz·in
=	373 oz·in

Lead Screw Formulas and Sample Calculations

Linear Speed (ipm)

$$\text{Linear Speed} = \frac{\text{steps / second}}{\text{steps / revolution}} \times 60 \times \frac{1}{p}$$

where:

p = lead screw pitch in threads per inch

Axial Force (lb)

$$\text{Force} = \frac{2\pi}{16} \times T \times p \times eff.$$

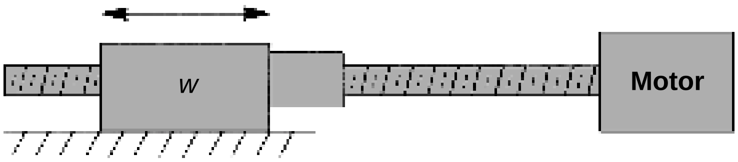
where:

T = torque (oz·in)
p = lead screw pitch in threads per inch
eff. = efficiency expressed as a decimal: 90% = 0.90

Note: Ball screws are generally 85% to 95% efficient. Acme lead screw efficiency is generally 35% to 45%, but can be as high as 85%.

A. Calculating the torque required to accelerate a mass moving horizontally and driven by a ball bearing lead screw and nut. The total torque the motor must provide includes the torque required to:

a. accelerate the weight
b. accelerate the lead screw
c. accelerate the motor rotor
d. overcome the frictional force



To calculate the rotational equivalent of weight ***w*** :

$$I_{(eq)} = w \times \frac{1}{p^2} \times \left(\frac{1}{2\pi}\right)^2$$

where:

w = weight (lb)

p = pitch (threads per inch)

$I_{(eq)}$ = equivalent polar inertia (lb·in^2)

to calculate lead screw inertia (steel screw)

$$I_{(screw)} = D^4 \times \text{length} \times .028$$

Example:

Weight = 1000 lbs
Velocity = 0.15 feet per second
Time to Reach Velocity = 0.1 seconds
Ball Screw Diameter = 1.5"
Ball Screw Length = 48"
Ball Screw Pitch = 5 threads per inch
Motor Rotor Inertia = 2.5 lb·in^2
Friction Force to Slide Weight = 6 oz

$$I_{(eq)} = w \times \frac{1}{p^2} \times .025 = 1000 \times \frac{1}{25} \times .025 = 1.0 \text{ lb·in}^2$$

$$+\ I_{(screw)} = D^4 \times \text{length} \times .028 = 5.06 \times 48 \times .028 = 6.8 \text{ lb·in}^2$$

$$+\ I_{(rotor)} = 2.5 \text{ lb·in}^2$$

$$=\ I_{(total)} = 10.3 \text{ lb·in}^2$$

Velocity is 0.15 feet per second, which is equal to 1800 steps per second (motor steps in 1.8° increments).

Torque to accelerate system:

$$T = 2 \times I_O \times \frac{\omega'}{t} \times \frac{\pi \times 1.8}{180} \times \frac{1}{24} = 2 \times 10.3 \times \frac{1800}{0.1} \times \frac{3.1416 \times 1.8}{180} \times \frac{1}{24} = 484 \text{ oz·in}$$

Torque to overcome friction:

$$F = .393 \times T \times p \times eff.$$

$$T = \frac{F}{.393 \times p \times eff.} = \frac{\frac{6}{16}}{.393 \times 5 \times 0.90} = 0.22 \text{ oz·in}$$

where:

F = frictional force (lb)

T = torque (oz·in)

p = lead screw pitch (threads per inch)

Total torque required = 0.22 oz·in + 484.00 oz·in = 484.22 oz·in

After determining the required motor size, it is recommended to add a 20% factor of safety so that unexpected dynamic loads are easily handled by the motor.

Sizing Servo Motors: Two separate torque figures are needed when selecting a DC motor — a peak torque, being the sum of acceleration and friction torques, and a continuous torque, which is the friction component only. The torque produced by the motor is given by:

$$T = K_\tau I$$

where K_τ is the motor torque constant (e.g., Nm/amp) and I is the drive current (amp). The choice of motor and drive must satisfy the following conditions:

1. The product of K_τ and peak drive current must give the required peak torque
2. The product of K_τ and continuous drive current must produce sufficient continuous torque.
3. The maximum allowable motor current must be greater than the peak drive current.
4. At maximum speed and peak current, the voltage developed across the motor must be less than 80% of the drive supply voltage.

The voltage across the motor is given by:

$$E = K_E\,\omega + R\,I$$

where K_E is the motor voltage constant, ω the speed, R the winding resistance (ohms) and I the peak current (amperes). The speed units should be the same in each case; i.e., if the voltage constant is in volts per radian per second, then ω should also be in radians per second.

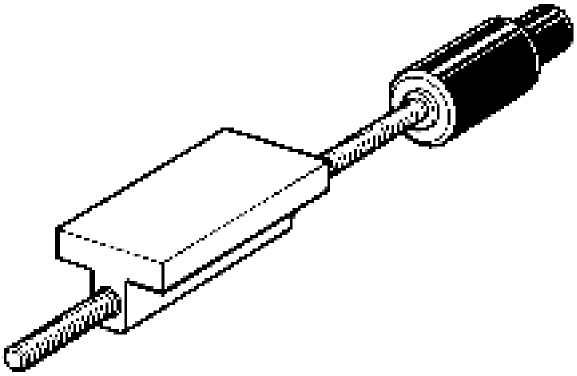
To make the most efficient use of the drive, the chosen solution should utilize most of the peak drive current and most of the available voltage. Motor manufacturers usually offer alternative windings, and care should be taken to select the most appropriate.

Example:
Leadscrew Length: 80 in
Leadscrew Diameter: 1.5 in
Leadscrew Pitch: 2.54 in
Table Weight: 1000 lb
Linear Table Speed Required: 472 inches / min
Acceleration Time: 120 ms

Inertia of Leadscrew: $J = \frac{D^4 L}{36} = 11.25$ lb·in²

Inertia of Table: $J = \frac{W}{40\,p^2} = 3.88$ lb·in²

Total inertia = 15.13 lb·in²



Linear Table Driven by DC Motor

Maximum Speed = 472" / min = 1200 rpm (equivalent to 4000 full steps / sec)

Acceleration Torque:

$$T = \frac{J\,\omega}{764\,t} = 660 \text{ oz·in } (4.65 \text{ N·m})$$

This takes no account of motor inertia, so a suitable motor will be capable of producing around 1000 oz·in torque.

Again, as with stepper selection, it is recommended to add a 20% factor of safety so that unexpected dynamic loads are easily handled by the motor.