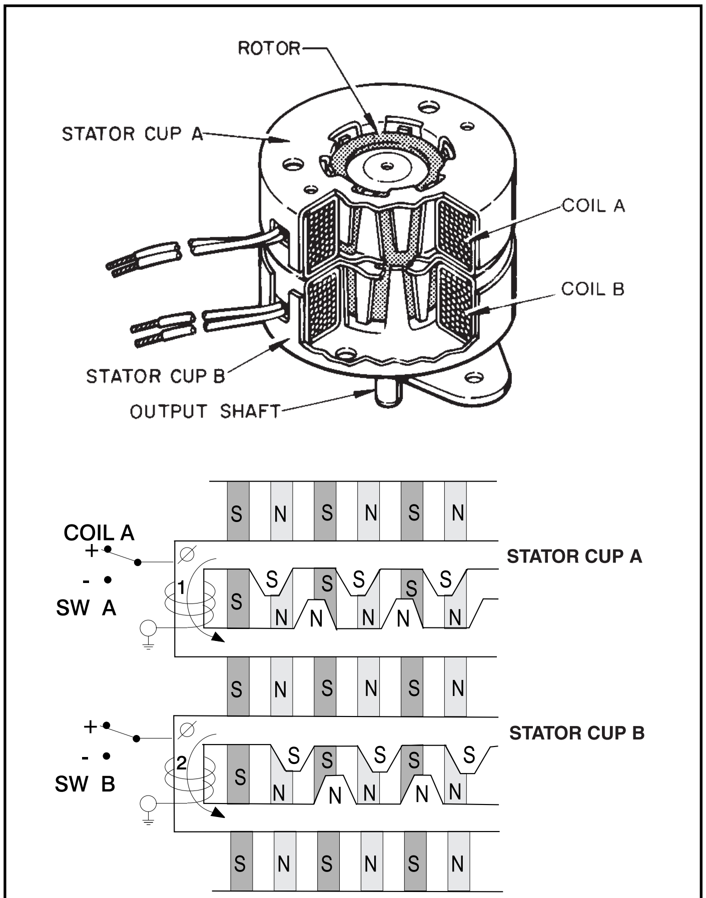
The stepper motor is a device used to convert electrical pulses into discrete mechanical rotational movements.

The Thomson Airpax Mechatronics stepper motors described in this guide are 2-phase permanent magnet (PM) motors which provide discrete angular movement every time the polarity of a winding is changed.

CONSTRUCTION

In a typical motor, electrical power is applied to two coils. Two stator cups formed around each of these coils, with pole pairs mechanically displaced by 1/2 a pole pitch, become alternately energized North and South magnetic poles. Between the two stator-coil pairs, the displacement is 1/4 of a pole pitch.

The permanent magnet rotor is magnetized with the same number of pole pairs as contained by the stator-coil section.



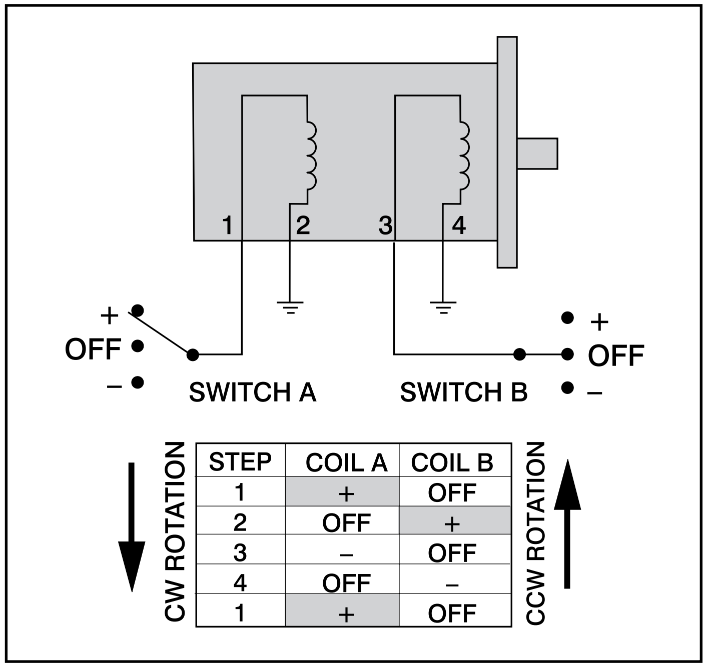
LAYOUT DIAGRAM OF STEP PER MOTOR SHOWING A GIVEN STATOR POLARITY AND ROTOR POSITION.

Figure 1: Cutaway 2∅ — Permanent Magnet Stepper Motor.

Interaction between the rotor and stator (opposite poles attracting and likes repelling) causes the rotor to move 1/4 of a pole pitch per winding polarity change. A 2-phase motor with 12 pole pairs per stator-coil section would thus move 48 steps per revolution or 7.5° per step.

ELECTRICAL INPUT

The normal electrical input is a 4-step switching sequence as is shown in Figure 2.



STEP	COIL A	COIL B
1	+	OFF
2	OFF	+
3	–	OFF
4	OFF	–
1	+	OFF

Figure 2: Schematic — 4-Step Switching Sequence.

Continuing the sequence causes the rotor to rotate forward. Reversing the sequence reverses the direction of rotation. Thus, the stepper motor can be easily controlled by a pulse input drive which can be a 2-flip-flop logic circuit operated either open or closed loop. Operated at a fixed frequency, the electrical input to the motor is a 2-phase 90° shifted square wave as shown below in Fig. 3.

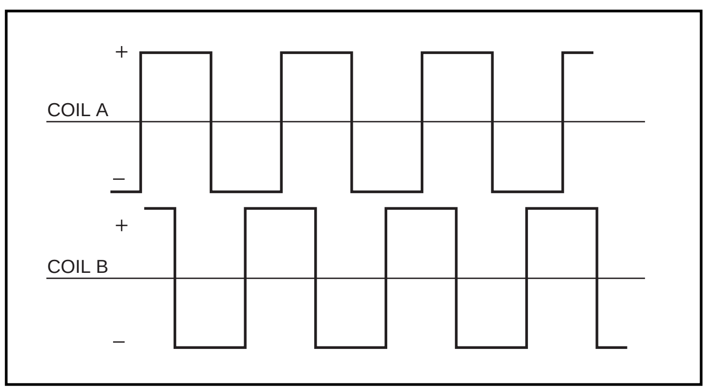


Figure 3: Voltage Wave Form — Fixed Frequency — 4-Step Sequence.

Since each step of the rotor can be controlled by a pulse input to a drive circuit, the stepper motor used with modern digital circuits, microprocessors and transistors provides accurate speed and position control along with long life and reliability.

STEP ANGLE

Step angles for steppers are available in a range from .72° to 90°. Standard step angles for Thomson Airpax steppers are:

3.6º — 100 steps per rev.
7.5° — 48 steps per rev.
15° — 24 steps per rev.
18° — 20 steps per rev.

A movement of any multiple of these angles is possible. For example, six steps of a 15° stepper motor would give a movement of 90°.

ACCURACY

A 7.5° stepper motor, either under a load or no load condition, will have a step-to-step accuracy of 6.6% or 0.5º. This error is non-cumulative so that even after making a full revolution, the position of the rotor shaft will be 360º ± 0.5º.

The step error is noncumulative. It averages out to zero within a 4-step sequence which corresponds to 360 electrical degrees. A particular step characteristic of the 4-step is to sequence repeatedly using the same coil, magnetic polarity and flux path. Thus, the most accurate movement would be to step in multiples of four, since electrical and magnetic imbalances are eliminated. Increased accuracy also results from movements which are multiples of two steps. Keeping this in mind, positioning applications should use 2 or 4 steps (or multiples thereof) for each desired measured increment, wherever possible.

TORQUE

The torque produced by a specific stepper motor depends on several factors:

1/ The Step Rate
2/ The Drive Current Supplied to the Windings
3/ The Drive Design

HOLDING TORQUE

At standstill (zero steps/sec and rated current), the torque required to deflect the rotor a full step is called the *holding torque*. Normally, the holding torque is higher than the running torque and, thus, acts as a strong brake in holding a load. Since deflection varies with load, the higher the holding torque the more accurate the position will be held. Note in the curve below in Fig. 4, that a 2-step deflection corresponding to a phase displacement of 180, results in zero torque. A 1-step plus or minus displacement represents the initial lag that occurs when the motor is given a step command.

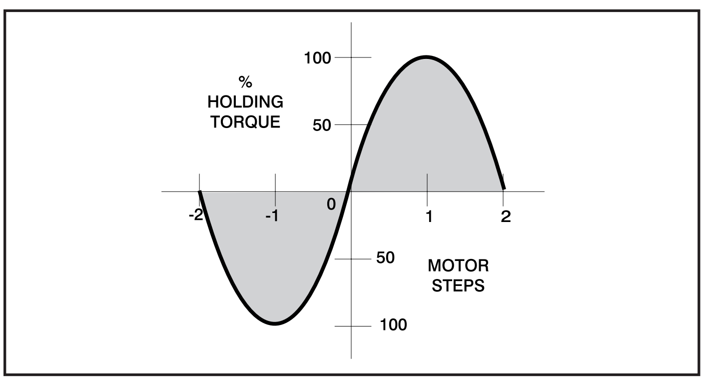


Figure 4: Torque Deflection.

RESIDUAL TORQUE

The non-energized detent torque of a permanent magnet stepper motor is called *residual torque*. A result of the permanent magnet flux and bearing friction, it has a value of approximately 1/10 the holding torque. This characteristic of PM steppers is useful in holding a load in the proper position even when the motor is de-energized. The position, however, will not be held as accurately as when the motor is energized.

DYNAMIC TORQUE

A typical torque versus step rate (speed) characteristic curve is shown in Figure 5.

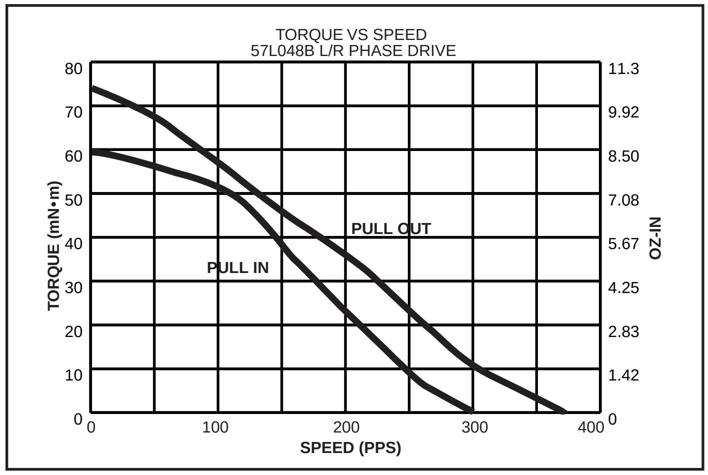


Figure 5: Torque/Speed — (Thomson Airpax 57L048B L/R Stepper).

The *PULL IN* curve shows what torque load the motor can start and stop without loss of a step when started and stopped at a constant step or pulse rate.

The *PULL OUT* curve is the torque available when the motor is slowly accelerated to the operating rate. It is thus the actual dynamic torque produced by the motor.

The difference between the *PULL IN* and *PULL OUT* torque curves is the torque lost due to accelerating the motor rotor inertia.

The torque/speed characteristic curves are key to selecting the right motor and control drive method for a specific application.

Note: In order to properly analyze application requirements, the load torque must be defined as being either *Frictional* and/*or Inertial*. (See Handy Formula Section in this engineering guide on pages 12 and 13 for resolving the load torque values. Also, an additional "Application Notes" section is located on pages 10 and 11.)

Use the *PULL IN* curve if the control circuit provides no acceleration and the load is frictional only.

Example: Frictional Torque Load.
Using a torque wrench, a frictional load is measured to be 25 mN•m (3.54 oz-in). It is desired to move this load 67.5° in .06 sec or less.

Solution:

1. If a 7.5° motor is used, then the motor would have to take nine steps to move 67.5°.
   A rate of $v = \dfrac{9}{.06}$ = 150 steps/sec or higher is thus required.
2. Referring to Fig. 6, the maximum *PULL IN* error rate with a torque of 25 mN•m is 185 steps/sec. (It is assumed no acceleration control is provided.)
3. Therefore, a 57L048B motor could be used at 150 steps per second — allowing a safety factor.

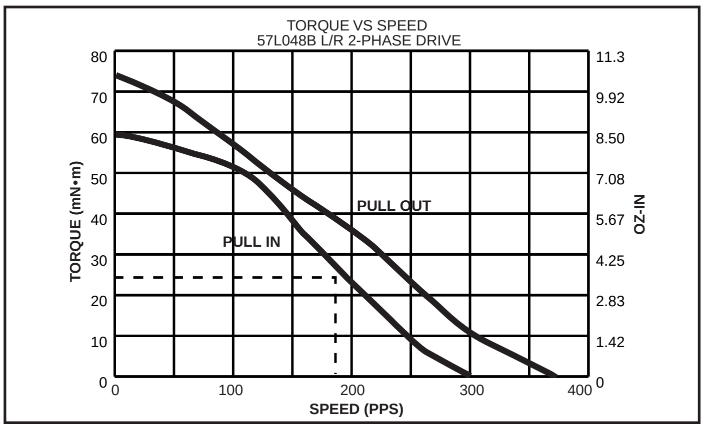


Figure 6: Torque/Speed — Frictional Load.

Use the *PULL OUT* curve, in conjunction with a Torque = Inertia x Acceleration equation (T= Jα), when the load is inertial and/or acceleration control is provided.

In this equation, acceleration or ramping $\alpha = \dfrac{\Delta v}{\Delta t}$ is in radians/sec^2.

RAMPING

Acceleration control or *ramping* is normally accomplished by gating on a voltage controlled oscillator (VCO) and associated charging capacitor. Varying the RC time constant will give different ramping times. A typical VCO acceleration control frequency plot for an incremental movement with equal acceleration and deceleration time would be as shown in Fig. 7.

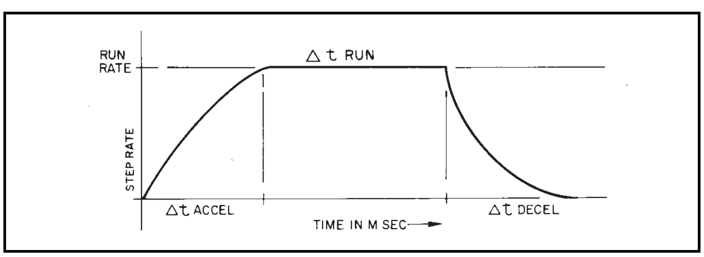


Figure 7: Step Rate/Time.

Acceleration also may be accomplished by changing the timing of the input pulses (frequency). For example, the frequency could start at a 1/4 rate, go to a 1/2 rate, 3/4 rate and finally the running rate.

A. Applications where:
Ramping acceleration or deceleration control time is allowed.

$$T_J(\text{Torque mN}\bullet\text{m}) = J_T \times \frac{\Delta v}{\Delta t} \times K$$

Where J_T = Rotor Interia (g•m^2) plus Load Inertia (g•m^2)

Δv = Step rate change

Δt = Time allowed for acceleration in seconds

$K = \dfrac{2\pi}{\text{steps/rev}}$ (converts steps/sec to radians/sec)

K = .13 for 7.5° — 48 steps/revolution
K = .26 for 15° — 24 steps/revolution
K = .314 for 18° — 20 steps/revolution

In order to solve an application problem using acceleration ramping, it is usually necessary to make several estimates according to a procedure similar to the one used to solve the following example:

Example: Frictional Torque Plus Inertial Load with Acceleration Control. An assembly device must move 4 mm in less than 0.5 sec. The motor will drive a lead screw through a gear ratio. The lead screw and gear ratio were selected so that 100 steps of a 7.5° motor = 4 mm. The total Inertial Load (rotor + gear + screw) = 25 x 10^{-4} g•m^2. The Frictional Load = 15 mN•m

Solution:

1. Select a stepper motor *PULL OUT* curve which allows a torque in excess of 15 mN•m at a step rate greater than

$$v = \frac{100\ \text{steps}}{0.5\ \text{sec}} = 200\ \text{steps/sec}$$

Referring to Fig. 8, determine the maximum possible rate (vF) with the frictional load only.

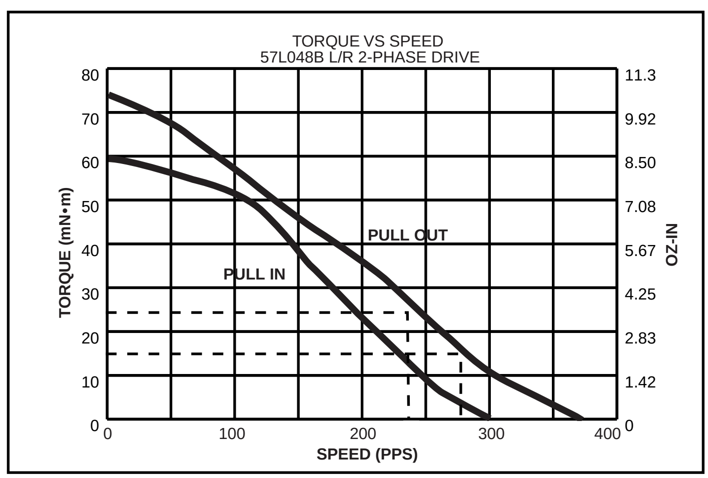


Figure 8: Torque/Speed — Friction Plus Inertia. (Thomson Airpax 57L048B L/R Stepper).

For information or to place an order in North America: 1 (203) 271-6444 Europe: (44) 1276-691622 Asia: (65) 7474-888

THOMSON AIRPAX MECHATRONICS

2. Make a first estimate of a working rate (a running rate less than the maximum) and determine the torque available to accelerate the inertia (excess over T_F).

$$T_1 - T_F = 23 - 15 = 8 \text{ mN}\bullet\text{m}$$

(torque available for acceleration at 240 steps/sec)

3. Using a 60% safety factor

$8 \text{ mN}\bullet\text{m} \times .6 = 4.8 \text{ mN}\bullet\text{m}$,

calculate Δt to accelerate. (Refer to Fig. 7).

From the $T_J = J_T \times \frac{\Delta v}{\Delta t} \times K$ equation,

$$4.8 \text{ mN m} = \frac{25 \times 10^{-4} \times 240 \times .13}{\Delta t}$$

Therefore, to accelerate $\Delta t = .016$ sec.

Note: The same amount of time is allowed to decelerate.

4. The number of steps used to accelerate and decelerate,

$$N_A + N_D = \frac{v}{2} \Delta t \times 2$$

or

$$N_A + N_D = v\Delta t$$

$$= 240\ (.016) = 4 \text{ steps}$$

5. The time to move at the run rate

$$\Delta t_{run} = N_T - (N_A + N_D) = \frac{100-4}{240} = .4 \text{ sec}$$

Where N_T = Total move of 100 steps

6. The total time to move is thus

$$\Delta t_{run} + \Delta t_{accel} + Dt_{decel}$$

$$.4 + .016 + .016 = .43 \text{ sec}$$

This is the first estimate. You may make the motor move slower if more safety is desired, or faster if you want to optimize it. At this time, you may wish to consider a faster motor drive combination as will be discussed on page 8.

B. Applications where:
No ramping acceleration or deceleration control time is allowed.

Even though no acceleration time is provided, the stepper motor can lag a maximum of two steps or 180 electrical degrees. If the motor goes from zero steps/sec to v steps/sec, the lag time Δt would be

$$\frac{2}{v} \text{ sec}$$

Thus, the torque equation for no acceleration or deceleration is:

$$\mathbf{T\ (Torque\ mN\bullet m) = J_T \times \frac{v^2}{2} \times K}$$

Where:

J_T = Rotor Inertia ($g\bullet m^2$) plus Load Inertia ($g\bullet m^2$)

v = steps/sec rate

$$K = \frac{2\pi}{\text{step/rev}}$$

("K" values as shown in application A on page 4)

Example: Friction Plus Inertia – No Acceleration Ramping.
A tape capstan is to be driven by a stepper motor. The frictional drag torque (T_F) is 15.3 mN•m and the inertia of the capstan is 10 x 10^{-4} $g\bullet m^2$. The capstan must rotate in 7.5° increments at a rate of 200 steps per second.

Solution:
Since a torque greater than 15.3 mN•m at 200 steps per second is needed, consider a 57L048B motor.

The Total Inertia = Motor Rotor Inertia + Load Inertia.

$$J_T = J_R + J_L$$

$$= (34 \times 10^{-4} + 10 \times 10^{-4})\ g\bullet m^2$$

$$= 44 \times 10^{-4}\ g\bullet m^2$$

1. Since there is no acceleration ramping, use the equation:

$$T_J = J_T \times \frac{v^2}{2} \times K \quad (K = .13)$$

$$T_J = 44 \times 10^{-4} \times \frac{200^2}{2} \times .13$$

$$T_J = 11.4 \text{ mN}\bullet\text{m}$$

2. Total Torque $= T_F + T_J$

$$= 15.3 + 11.4$$

$$= 26.7 \text{ mN}\bullet\text{m}$$

3. Refer to the *PULL OUT* curve Fig. 9, at speed of 200 pulses per second, where the available torque is 35 mN•m. Therefore, the 57L048B motor can be selected with a safety factor.

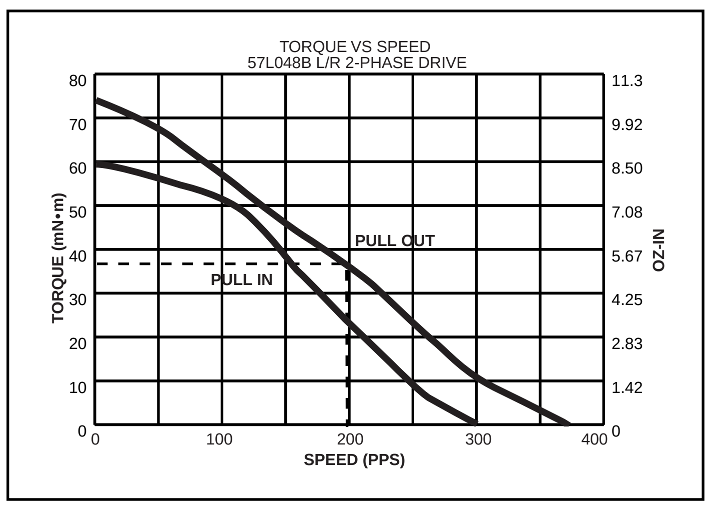


Figure 9: Torque/Speed — Friction Plus Inertia. (Thomson Airpax 57L048B L/R Stepper).

STEP FUNCTION - SINGLE STEP

When a single step of a motor is made, a typical response is as shown in Figure 10.

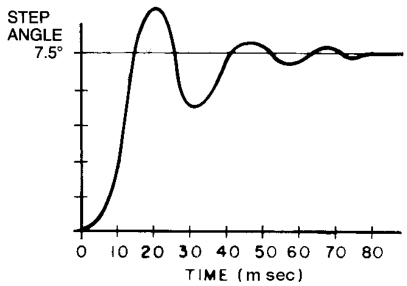


Figure 10: Single Step Response.

The actual response for a given motor is a function of the power input provided by the drive and the load. Increasing the frictional load or adding external damping can thus modify this response, if it is required.

Mechanical dampers (e.g., slip pads or plates), or devices such as a fluid coupled flywheel can be used, but add to system cost and complexity. Electronic damping also can be accomplished. Step sequencing is altered to cause braking of the rotor, thus minimizing overshoot.

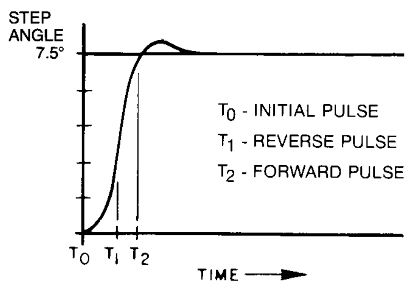


Figure 11: Electronically Damped Response.

STEP FUNCTION - MULTIPLE STEPPING

Multiple stepping can offer several alternatives. A 7.5° motor moving 12 steps (90º), or a 15° motor moving six steps (90º) to give a 90° output move would have less overshoot, be stiffer, and relatively more accurate than a motor with a 90° step angle. Also, the pulses can be timed to shape the velocity of the motion; slow during start, accelerate to maximum velocity, then decelerate to stop with minimum ringing.

RESONANCE

If a stepper motor is operated no load over the entire frequency range, one or more natural oscillating resonance points may be detected, either audibly or by vibration sensors. Some applications may be such that operation at these frequencies should be avoided. External damping, added inertia, or a microstepping drive can be used to reduce the effect of resonance. A permanent magnet stepper motor, however, will not exhibit the instability and loss of steps often found in variable reluctance stepper motors, since the PM has a higher rotor inertia and a stronger detent torque.

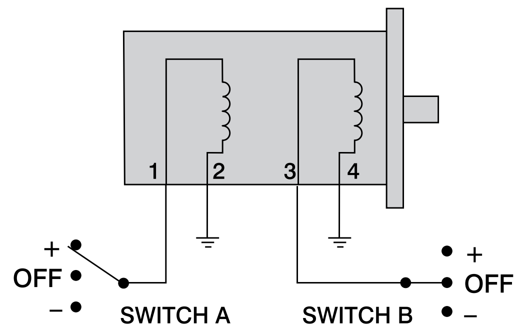
DRIVE METHODS

The normal drive method is the 4-step sequence shown in Fig. 2, (page 2); however, the following methods are also possible.

WAVE DRIVE

Energizing only one winding at a time, as indicated in Fig. 12 is called *Wave Excitation*. It produces the same increment as the 4-step sequence.

Since only one winding is on, the hold and running torque with rated voltage applied will be reduced 30%. Within limits, the voltage can be increased to bring output power back to near rated torque value. The advantage of this type of drive is increased efficiency, while the disadvantage is decreased step accuracy.



CW ROTATION

STEP	COIL A	COIL B
1	+	OFF
2	OFF	+
3	–	OFF
4	OFF	–
1	+	OFF

CCW ROTATION

Figure 12: Schematic — Wave Drive Switching Sequence.

HALF STEP

It is also possible to step the motor in an 8-step sequence to obtain a half step — such as a 3.75° step from a 7.5° motor, as in Fig. 13.

For applications utilizing this, you should be aware that the holding torque will vary for every other step, since only one winding will be energized for a step position; but, on the next step two windings are energized. This gives the effect of a strong step and a weak step. Also, since the winding and flux conditions are not similar for each step when 1/2 stepping, accuracy will not be as good as when full stepping.

CW ROTATION

STEP	COIL A	COIL B
1	+	+
2	+	OFF
3	+	-
4	OFF	-
5	-	-
6	-	OFF
7	-	+
8	OFF	+
1	+	+

CCW ROTATION

Figure 13: Half Step or 8-Step Switching Sequence.

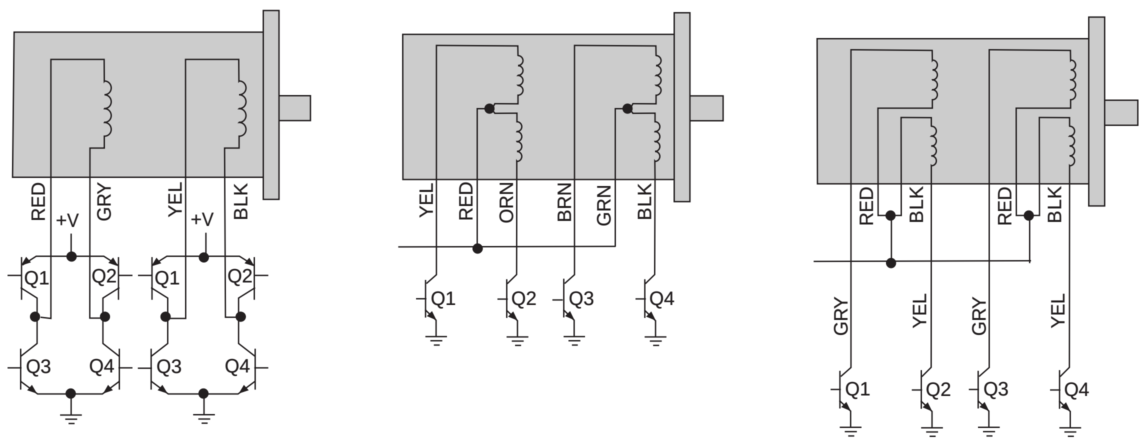
BIPOLAR AND UNIPOLAR OPERATION

All Thomson Airpax stepper motors are available with either 2-coil *Bipolar*, or 4-coil *Unipolar* windings.

The stator flux with a Bipolar winding is reversed by reversing the current in the winding. It requires a push-pull Bipolar drive as shown in Fig. 14. Care must be taken to design the circuit so that the transistors in series do not short the power supply by coming on at the same time. Properly operated, the Bipolar winding gives the optimum motor performance at low-to-medium step rates.

A Unipolar winding has two coils wound on the same bobbin (one bobbin resides in each stator half) per stator half. Flux is reversed in each coil bobbin assembly by sequentially grounding ends of each half of the coil winding. The use of a Unipolar winding, sometimes called a *bifilar winding*, allows the drive circuit to be simplified. Not only are half as many power switches required (4 vs. 8), but the timing is not as critical to prevent a current short through two transistors as is possible with a Bipolar drive.

For a Unipolar motor to have the same number of turns per winding as a Bipolar motor, the wire diameter must be decreased and the resistance increased. As a result, Unipolar motors have 30% less torque at low step rates. However, at higher rates the torque outputs are equivalent.



BIPOLAR

UNIPOLAR

Normal
4-Step Sequence

CW ROTATION / CCW ROTATION

Step	Q_1-Q_4	Q_2-Q_3	Q_5-Q_8	Q_6-Q_7
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	ON
3	OFF	ON	OFF	ON
4	OFF	ON	ON	OFF
1	ON	OFF	ON	OFF

CW ROTATION / CCW ROTATION

Step	Q_1	Q_2	Q_3	Q_4
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	ON
3	OFF	ON	OFF	ON
4	OFF	ON	ON	OFF
1	ON	OFF	ON	OFF

½ Step
8-Step Sequence

CW ROTATION / CCW ROTATION

1	ON	OFF	ON	OFF
2	ON	OFF	OFF	OFF
3	ON	OFF	OFF	ON
4	OFF	OFF	OFF	ON
5	OFF	ON	OFF	ON
6	OFF	ON	OFF	OFF
7	OFF	ON	ON	OFF
8	OFF	OFF	ON	OFF
1	ON	OFF	ON	OFF

CW ROTATION / CCW ROTATION

1	ON	OFF	ON	OFF
2	ON	OFF	OFF	OFF
3	ON	OFF	OFF	ON
4	OFF	OFF	OFF	ON
5	OFF	ON	OFF	ON
6	OFF	ON	OFF	OFF
7	OFF	ON	ON	OFF
8	OFF	OFF	ON	OFF
1	ON	OFF	ON	OFF

Wave Drive
4-Step Sequence

CW ROTATION / CCW ROTATION

1	ON	OFF	OFF	OFF
2	OFF	OFF	OFF	ON
3	OFF	ON	OFF	OFF
4	OFF	OFF	ON	OFF
1	ON	OFF	OFF	OFF

CW ROTATION / CCW ROTATION

1	ON	OFF	OFF	OFF
2	OFF	OFF	OFF	ON
3	OFF	ON	OFF	OFF
4	OFF	OFF	ON	OFF
1	ON	OFF	OFF	OFF

Figure 14: Schematic Bipolar and Unipolar Switching Sequence. Direction of Rotation Viewed from Shaft End.

HIGHER PERFORMANCE

A motor operated at a fixed rated voltage has a decreasing torque curve as the frequency or step rate increases. This is due to the fact that the rise time of the coil limits the percentage of power actually delivered to the motor. This effect is governed by the inductance to resistance ratio of the circuit (L/R).

Compensation for this effect can be achieved by either increasing the power supply voltage to maintain a constant current as the frequency increases, or by raising the power supply voltage and adding a series resistor in the L/4R drive circuit (See Fig. 15). Note that as the L/R is changed, more total power is used by the system.

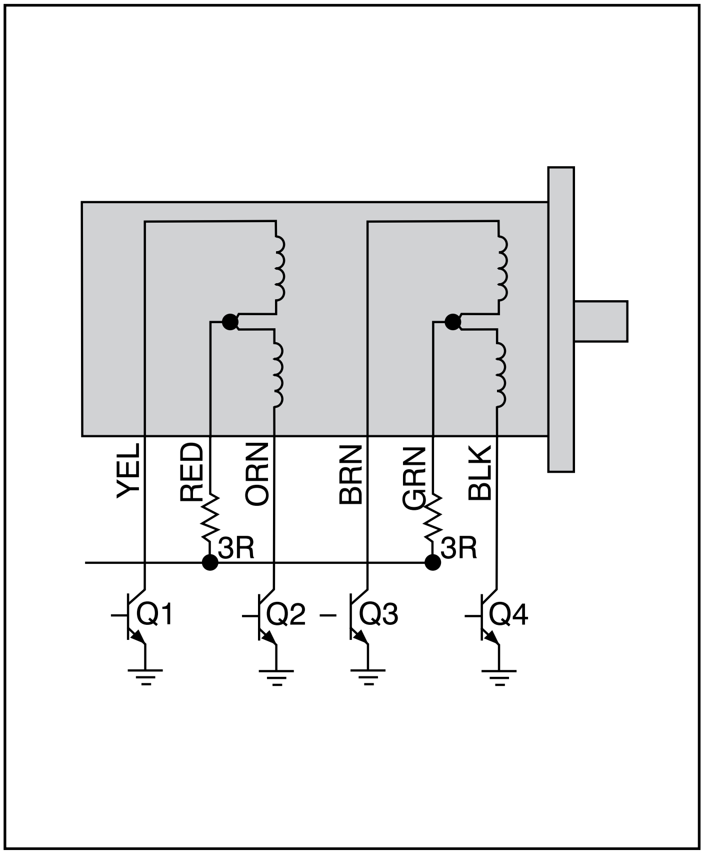


Figure 15: L/4R Drive

The series resistors, R, are selected for the L/R ratio desired. For L/4R they are selected to be three times the motor winding resistance with a wattage rating = (current per winding)^2 x R.

The power supply voltage is increased to four times motor rated voltage so as to maintain rated current to the motor. The power supplied will thus be four times that of a L/R drive.

Note, the Unipolar motor which has a higher coil resistance, thus has a better L/R ratio than a Bipolar motor.

To minimize power consumption, various devices such as a bi-level power supply or chopper drive may be used.

BI-LEVEL DRIVE

The bi-level drive allows the motor at zero steps/sec to hold at a lower than rated voltage. When stepping, it runs at a higher than rated voltage. It is most efficient when operated at a fixed stepping rate. The high voltage may be switched on through the use of a current sensing resistor, or by a circuit (See Fig. 16) which uses the inductively generated turnoff current spikes to control the voltage.

At zero steps/sec the windings are energized with the low voltage. As the windings are switched according to the 4-step sequence, the suppression diodes D_1, D_2, D_3 and D_4 are used to turn on the high voltage supply transistors S_1 and S_2.

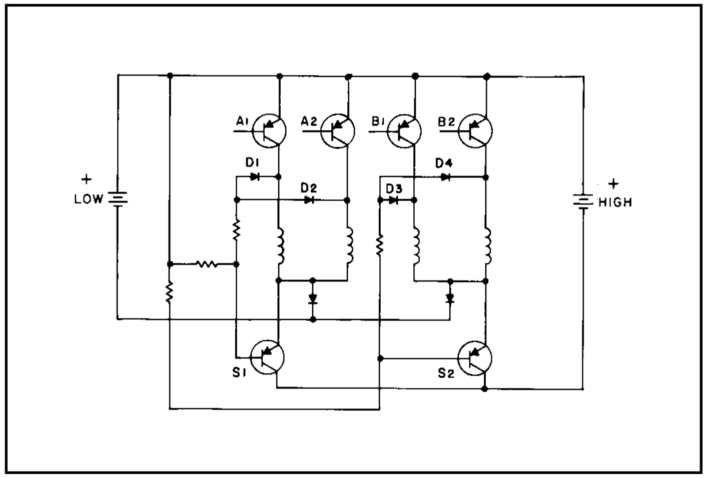


Figure 16: Unipolar Bi-Level Drive.

CHOPPER DRIVE

A chopper drive maintains an average current level through the use of a current sensor, which turns on a high voltage supply until an upper current value is reached. It then turns off the voltage until a low level limit is sensed, when it turns on again. A chopper is best for fast acceleration and variable frequency applications. It is more efficient than a constant current amplifier regulated supply. The V+ in the chopper shown in Fig. 17 typically would be five to six times the motor voltage rating.

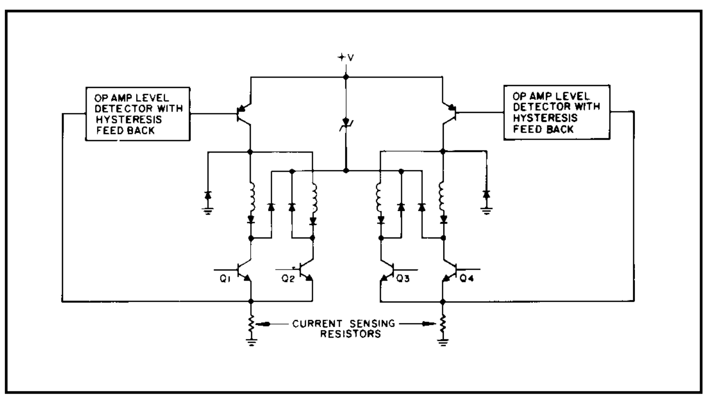


Figure 17: Unipolar Chopper Drive.

VOLTAGE SUPPRESSION

Whenever winding current is turned off, a high voltage inductive spike will be generated, which can damage the drive circuit. The normal method used to suppress these spikes is to put a diode across each winding. This, however, will reduce the torque output of the motor, unless the voltage across the switching transistors is allowed to build up to at least twice the supply voltage. The higher this voltage, the faster the induced field, and current will collapse, and thus the better performance. For this reason, a zener diode or series resistor is usually added as shown in Figure 18.

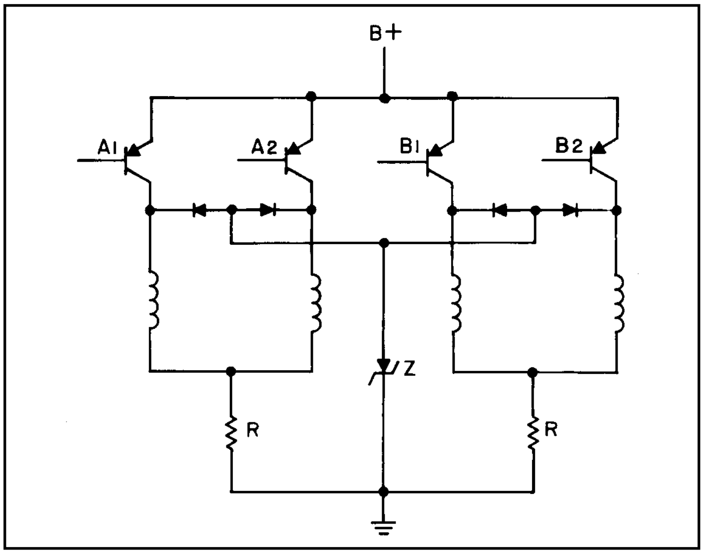


Figure 18: Voltage Suppression Circuit.

PERFORMANCE LIMITATIONS

Increasing the voltage to a stepper motor at standstill or low stepping rates will produce a proportionally higher torque until the magnetic flux paths within the motor saturate. As the motor nears saturation, it becomes less efficient and thus does not justify the additional power input.

The maximum speed a stepper motor can be driven is limited by hysteresis and eddy current losses. At some rate, the heating effects of these losses limit any further effort to get more speed or torque output by driving the motor harder.

TORQUE MEASUREMENT

The output torque of a stepper motor and drive can best be measured by using a bridge type strain gage coupled to a magnetic particle brake load. A simple pulley and pull spring scale also can be used, but is difficult to read at low and high step rates.

MOTOR HEATING AND TEMPERATURE RISE

Operating continuous duty at rated voltage and current will give an approximate 40°C motor winding a temperature rise. If the motor is mounted on a substantial heat sink, however, more power may be put into the windings. If it is desired to push the motor harder, a maximum motor winding temperature of 100°C should be the upper limit. Motor construction can be upgraded to allow for a winding temperature of 120°C (60°C rise).

SUMMARY OF KEY TORQUE EVALUATIONS

The torque-speed characteristic curves are key to selecting the right motor and the control drive method for a specific application.

Define your application load.

Use the PULL IN curve if the control circuit provides no acceleration and the load is frictional only.

Use the PULL OUT curve, in conjunction with a Torque = Inertia x Acceleration equation ($T = J\alpha$), when the load is inertial and/or acceleration control is provided.

When acceleration ramping control is provided, use the PULL OUT curve and this torque equation:

$$T_J \text{ (Torque mN}\bullet\text{m)} = J_T \times \frac{\Delta V}{\Delta t} \times K$$

When no acceleration ramping control is provided, use the PULL OUT curve and this torque equation:

$$T \text{ (Torque mN}\bullet\text{m)} = J_T \times \frac{v^2}{2} \times K$$

Motor Selection Guidelines

1. **Based on frictional torque and speed, make a first estimate motor selection.**
2. **Use torque equations and motion plot to evaluate.**
3. **If necessary, select another motor and/or modify the drive.**
4. **Secure prototype and test.**

Formula for determining temperature rise of a motor (using coil resistance) is:

Motor T rise °C =

$$\frac{R\ hot}{R\ cold}(234.5 + T\ amb\ cold) - (234.5 + T\ amb\ hot)$$

Applying a stepper motor can be relatively easy or it can be complex. As a designer gains experience, the versatility and ways to use a stepper motor become more obvious. These application notes should be an aid to you in gaining this experience.

SELECTION GUIDE

The following elements should be considered in selecting a stepper motor:

1. Frictional torque required in mN•m
2. Load inertia in g•m^2
3. Move required in degrees
4. Time to complete move in sec
5. Number of steps and step angle in movement
6. Step rate in steps per sec
7. Acceleration - Deceleration time in sec
8. Power available
9. Drive System (Unipolar and/or Bipolar)
10. Size; Weight; Shaft and Mounting considerations

The importance of any of the above elements will, of course, depend on system and budget considerations. Some apply only to positioning type applications. Other considerations should be taken into account for fixed speed or variable speed applications. These might include:

1. RPM required
2. Maximum/Minimum pulse rate required
3. Pulse or frequency source accuracy
4. Allowable velocity variations
5. Resonance

OPEN LOOP

The features of a stepper motor make it an ideal open loop device for providing precise pulse-to-step movements in a variety of positioning applications from printer paper feeds to small clocks. Most applications are open loop. When operated open loop, always assume worst case values in calculating loads. If you measure average values, allow at least a 20% safety factor. Some applications run open loop with a periodic verification. For example, an electronic typewriter may be character advanced open loop with the line return end position verified by a sensor.

Variable speed or fixed speed applications such as chart drives or reagent pumps take advantage of the fact that variations in torque do not effect the output speed, which is as accurate as the pulse source. For applications such as these you should avoid running at certain frequencies because of resonance.

CLOSED LOOP

Various devices such as optical encoders or magnetic Hall effect sensors may be used to close the control loop in order to obtain the maximum torque and/or acceleration from a given stepper motor.

In a typical closed loop system, a 2-quadrature track encoder capable of detecting direction could be used to sense that a step has been made before allowing the next pulse to step the motor.

Obviously, the closed loop system will be more complicated and expensive than open loop, but it will have the ability to handle a wide variation in load conditions with optimum acceleration and reliability. Closed loop operation also can be used to stabilize resonance in variable speed applications.

A more detailed analysis of both open and closed loop performance is beyond the scope of this guide; however, it can be obtained by referring to the proceedings from *Incremental Motion Control Systems and Devices, University of Illinois*, 1972 to 1998 issues.

LOAD COUPLING, GEARS AND PULLEYS, LEAD SCREWS

Other than the added inertia of the coupling, a properly aligned direct coupling will present the load as it is.

Gears, however, will increase or decrease the load by the gear ratio as is shown in the *Handy Formula Section (pages 12-13)*. It is not recommended to gear up, such as to make a 30° movement with a 15° stepper motor. The torque reflected to the motor in this case would be twice the frictional load torque and the inertia would be four times the inertia load.

It would be better to take two motor steps to get the 30° movement, or if the motor load were high, take four motor steps of 7.5° and gear down 2:1 speed torque curve permitting. In this instance, the motor would see only 1/2 the frictional load and 1/4 the inertial load.

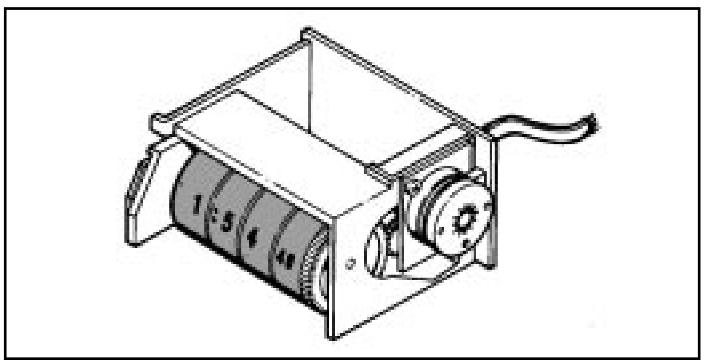
Equations using lead screws also are given in the *Handy Formula Section*. Note how the load to the motor is reduced when the lead of the screw is small.

The following examples show how three typical systems were designed.

1. FIXED SPEED APPLICATION

A stepper motor being run at a fixed speed is in reality a synchronous motor running on square waves.

Typical applications running at fixed frequencies are timing devices, recorders, meters and clocks.



One such system, a DC operated clock, uses a small stepper motor and drive with signal pulses supplied by a 240 Hz crystal oscillator module. The 240 Hz signal generates the equivalent of 60 Hz 2-phase operation. When operated at this pulse rate, a 15° stepper rotates at 600 RPM and will be as accurate as the crystal rate.

2. POSITIONING TYPE APPLICATION

A computer peripheral type serial character printer is a typical positioning application. The stepper motor is used to advance the paper for line feed.

The printer prints either six or eight lines per inch.

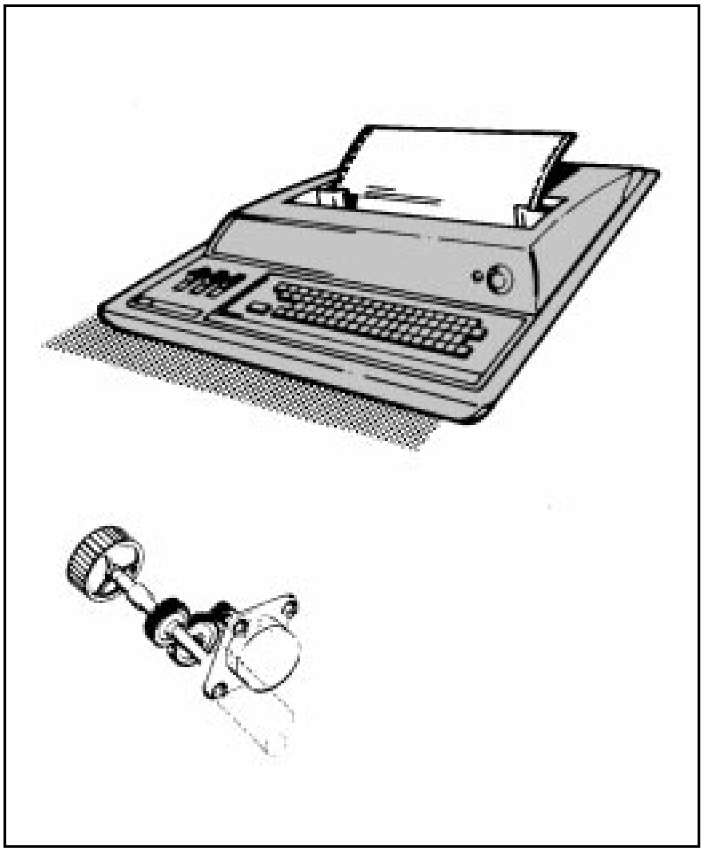
A 4.5:1 gear ratio is used between the paper roller and the motor. A 7.5° stepper motor taking eight steps per incremental movement will advance the paper at six lines per inch. A simple control logic change makes the motor take six steps per movement giving eight lines per inch.

The reflected frictional load to the motor is 22% of the frictional load of the roller and paper and only 5% of the inertial load because of the gear ratio.

Since the motor always takes at least six pulses to move a line, the timing of the pulses is spaced or ramped so as to accelerate and decelerate the motor in the fastest time with minimum ringing.

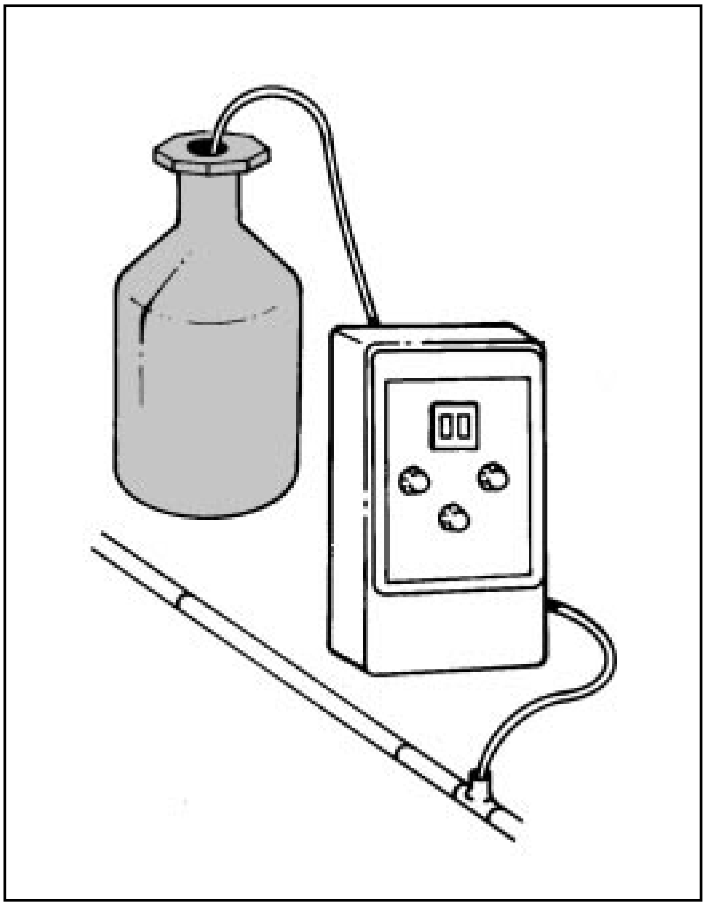
In order to get the maximum line feed rate, the motor is driven by a a bi-level supply which puts five times rated voltage on the motor when stepping and drops down to 25% rated voltage when not being stepped. This allows maximum input power during stepping and minimum dissipation during standstill.

Additionally, the accuracy of the spacing between lines is optimum, since the motor is stepped in multiples of four or two.



3. VARIABLE SPEED APPLICATION

Many variable speed applications use DC motors with the speed of the motor being controlled by velocity feedback devices. Since problems of life, noise and complexity of feedback servo make the use of a DC motor unsatisfactory, it is more advantageous to use stepper motors in applications such as a reagent pump.



Reagent pumps are used to dispense various solutions at preselected rates. A crystal oscillator is used as the base frequency. Sub-multiples of this frequency are obtained by dividing the base frequency to get the desired feed rates.

A 4:1 ratio pulley and belt couple the 7.5° stepper motor to the pump. The stepper motor was selected on the basis of the maximum running rate torque required with a 50% safety factor. Since the feed rates are fixed by the crystal, torque load variations within the range have no effect on the rate the fluid is dispensed.

The relative low shaft speed of the motor and the absence of brushes provide the long motor life required of the pump. Also, the stepper motor has the ability to be pulsed from very low rates to very high rates, thus giving the pump a possible flow rate range of 1000:1. A practical open loop DC system speed range is only about 10:1.

Primary units in this guide are metric (SI – the International System of units):

Length - m - (meter)
Mass - g - (gram)
Force - mN - (millinewton)
Torque - mN•m - (millinewton meter)
Inertia - g•m^2 - (gram meter^2)

In this system, mass is always in kilograms or grams. Force, or weight, is always in newtons or millinewtons.

Force (or weight) = Mass x Acceleration

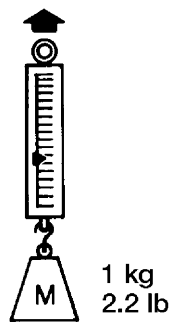
F = ma

when a = 9.81 m/sec^2 (acceleration due to gravity), then F would be the weight in newtons.

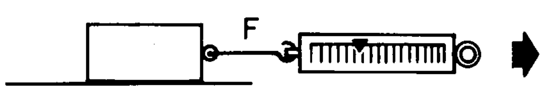
How to measure Mass or Force.

A spring scale reading of 1 kg means that you are measuring a mass of 1 kg.

A spring scale reading of 2.2 lb also is measuring a mass of 1 kg.



If you use that same spring scale to measure a force, the 1 kg reading must be multiplied by 9.8 to give a force of 9.8 newtons.



The reading of 2.2 lb is a force and is equal to 9.8 newtons.

If the same scale is used to measure torque (T = FR) at a one meter radius, the reading of

1 kilogram x 1 meter = 1 kgm

must be multiplied by 9.8 to give a torque of 9.8 newton meters (N•m).

	Given Unit				Units Used in this Manual (Metric SI)
Length	1 inch	=	2.54 cm	=	2.54 X 10^{-2}m
Force	1 oz	=		=	278 mN
	1 lb	=	4.45 N	=	4,450 mN
	1 g•cm	=		=	9.8 mN
Mass	1 lb	=		=	454g
	1oz	=		=	28.4g
	1kg	=		=	1,000g
	1 slug	=	14.6 kg	=	14,600g
Inertia	1 g•cm^2	=		=	10^{-4} g•m^2
	1 oz-in-sec^2	=		=	7.06 g•m^2
	1 slug ft^2	=		=	.29 g•m^2
Torque	1 oz-in	=	72.01 g•cm	=	7.06 mN•m
	1 lb-ft	=		=	1.356 x N•m
	1 g•cm	=		=	9.8 x 10^{-2} mN•m
			10.2 g•cm	=	1 mN•m
			141.6 oz-in	=	1 N•m

1. Torque (mN•m) = Force (mN) x Radius (m)

Torque = FR

2. Torque required to accelerate inertial load

$$\mathbf{T\ (mN \bullet m) = J\ \alpha}$$

J = Inertia in g•m^2

α = Acceleration in radians/sec^2

EXAMPLE:
If a rotor inertia plus load inertia = J = 2 x 10^{-3} g•m^2, and the motor is to be accelerated at 6,000 radians per sec, what torque is required?

$T = J\alpha = 2 \times 10^{-3} \times 6000$
$T = 12$ mN•m

For stepper motors, α can be converted to radians/sec^2 from steps/sec^2.

$$\alpha \text{ (radians/sec)} = \frac{\Delta v \text{ (steps/sec)}}{\Delta t \text{ (accel. time)}} \times \frac{2\pi}{\text{steps/rev}}$$

$$\mathbf{TORQUE = J\ \frac{\Delta v}{\Delta t} \times \frac{2\pi}{steps/rev}}$$

EXAMPLE:
For a 48-step per revolution motor accelerating from zero to steps/sec running rate v in Δt seconds.

$$\text{TORQUE} = J\ \frac{v}{\Delta t} \times \frac{\pi}{24}$$

For information or to place an order in North America: 1 (203) 271-6444 Europe: (44) 1276-691622 Asia: (65) 7474-888

THOMSON AIRPAX MECHATRONICS

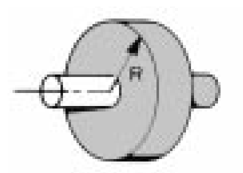
If no *acceleration time* is provided, then a maximum 2-step lag can occur.

Δt (sec) $= \dfrac{2 \text{ (steps)}}{v \text{ (steps/sec)}}$ giving the following equation.

$$\textbf{TORQUE} = J\,\frac{V^2}{2} \times \frac{2\pi}{\text{steps/rev}}$$

3. Moment of Inertia

Disc or shaft

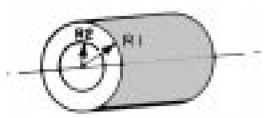


M = Mass in grams

R = Radius in meters

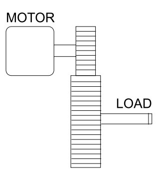
$$J\ (g\bullet m^2) = \frac{MR^2}{2}$$

Cylinder



$$J\ (g\bullet m^2) = \frac{M^2}{2}\,(R^2_1 + R^2_2)$$

4. Reflected loads when using gears or pulleys

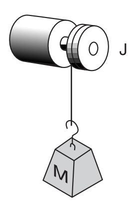


$$\textbf{Torque required of motor} = \frac{\textbf{Load Torque}}{\textbf{GR}}$$

$$\text{gear or pulley ratio GR} = \frac{\text{motor shaft revolutions}}{\text{load shaft revolutions}}$$

$$\textbf{Inertia reflected to motor} = \frac{\textbf{Load intertia}}{(\textbf{GR})^2}$$

5. Equivalent Inertial Load
   For a pulley and weight or a rack and pinion



J eqv. $(g\bullet m^2) = MR^2$

M = Mass of load in grams
R = Radius of pulley in meters

6. Total Load
   Note: Be sure to include all load components.

   J_T = Rotor Inertia + all J Loads

   T_F = Frictional and Forces

   Note: In the pulley example above, the total load would be:

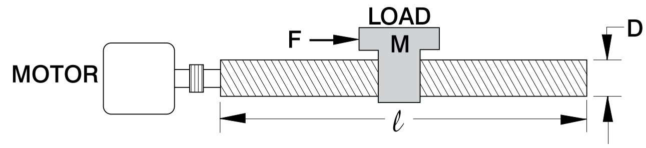
   J_T = J rotor + J pulley + J eqv.

   T_F = T frictional + Load Weight x Radius

   Total T = $J_T\,\alpha + T_F$

   The load weight = mass x 9.8 millinewtons.

7. Axial Force of Lead Screw



$$F = \frac{2\pi \times T}{L} \times \text{eff.}$$

F (mN) when T = Torque in mN•m

L = Lead of screw in meters

F (oz) when T = Torque in oz-in

L = Lead of screw in inches

efficiency = from .9 for ballnut to .3 for Acme

Inertia of lead screw load

J = J rotor + J steel screw + J reflected

J steel screw $= D^4 \times \ell \times \dfrac{\pi}{32} \times$ Density

Density for steel = 7.83 x 106 g/m³

then:

$$\mathbf{J\ (g\bullet m^2) = D^4\ \ell \times 7.7 \times 10^5}$$

The reflected inertia of the load is:

$$\mathbf{J\ reflected\ (g\bullet m^2) = M\ (load)\ L^2 \times .025}$$

Total Torque Load from lead screw (T) in mN•m

T = (J rotor + J screw + J reflected) α + T friction

8. Motor watts output

   Watts out = Torque output x speed in radians/sec

   1 watt = 1 Nm/sec

For a given output Torque (mN•m) and converting v (steps/sec) to radians/sec

$$\textbf{Watts out} = \textbf{Torque (mN•m)} \times v\,\frac{\textbf{(motor step angle)}}{\textbf{57.3}} \times 10^{-3}$$

If the speed is in RPM then:

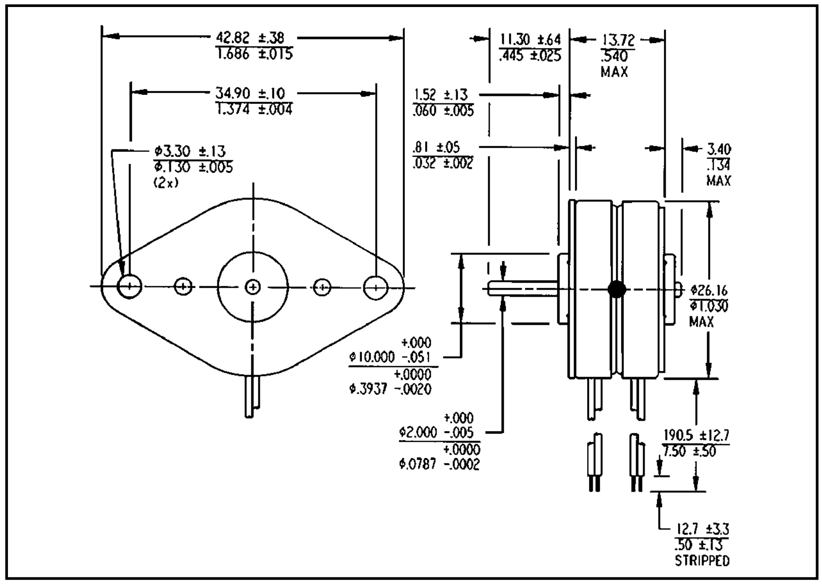
Watts out = 1.05 x 10^{-4} x torque (mN•m) x RPM

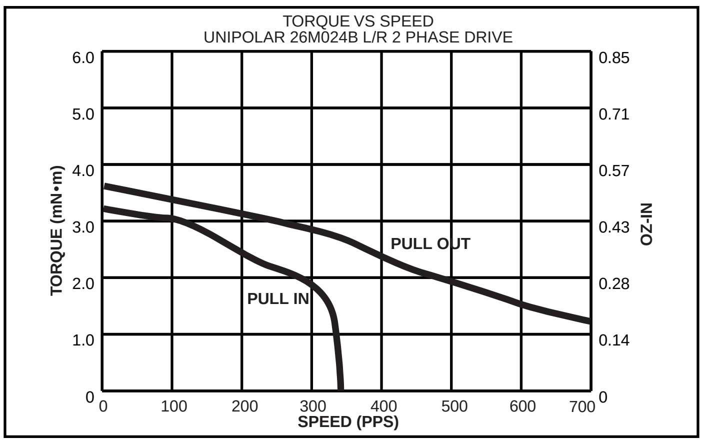
9. Steps/sec to RPM

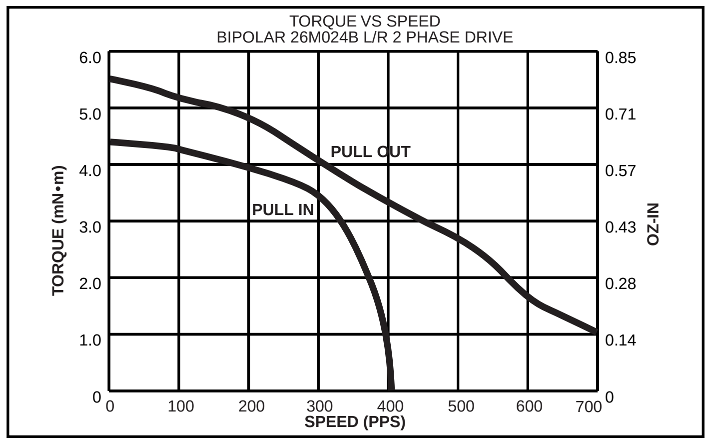
$$\textbf{RPM} = \frac{\textbf{v (steps/sec) x 60}}{\textbf{motor steps/rev}}$$

For information or to place an order in North America: 1 (203) 271-6444 Europe: (44) 1276-691622 Asia: (65) 7474-888

Dimensions: mm/inches







Specifications

NOTE: Refer to page 7 for switching sequence

Part Number	Unipolar		Bipolar	
	26M024B1U	26M024B2U	26M024B1B	26M024B2B
DC Operating Voltage	5	12	5	12
Res. per Winding Ω	20.4	118	19.6	113
Ind. per Winding mH	6.4	33.8	13.8	72.9
Holding Torque mN•m/oz-in†	4.9/0.7		7.1/1.0	
Rotor Moment of Inertia g•m²	1.1 x 10^{-4}			
Detent Torque mN•m/oz-in	1.06/0.15			
Step Angle	15°			
Step Angle Tolerance†	±1°			
Steps per Rev.	24			
Max Operating Temp.	100°C			
Ambient Temp Range				
Operating	-20°C to 70°C			
Storage	-40°C to 85°C			
Bearing Type	Bronze sleeve			
Insulation Res. at 500Vdc	100 megohms			
Dielectric Withstanding Voltage	650 ±50 VRMS 60 Hz for 1 to 2 seconds			
Weight g/oz	28 g/1 oz			
Lead Wires	28 AWG			

† Measured with 2 phases energized.

For information or to place an order in North America: 1 (203) 271-6444 Europe: (44) 1276-691622 Asia: (65) 7474-888

THOMSON AIRPAX MECHATRONICS