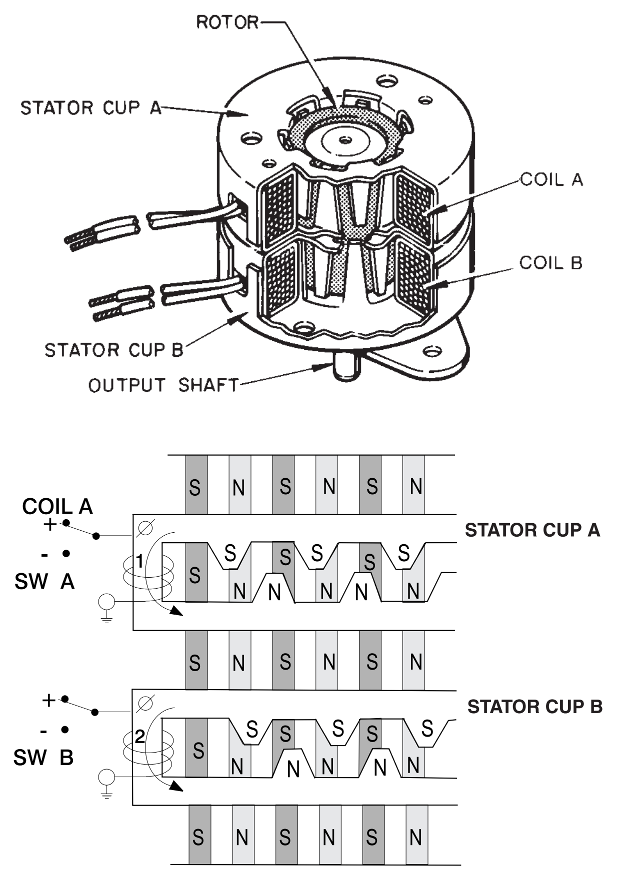
The stepper motor is a device used to convert electrical pulses into discrete mechanical rotational movements.

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.



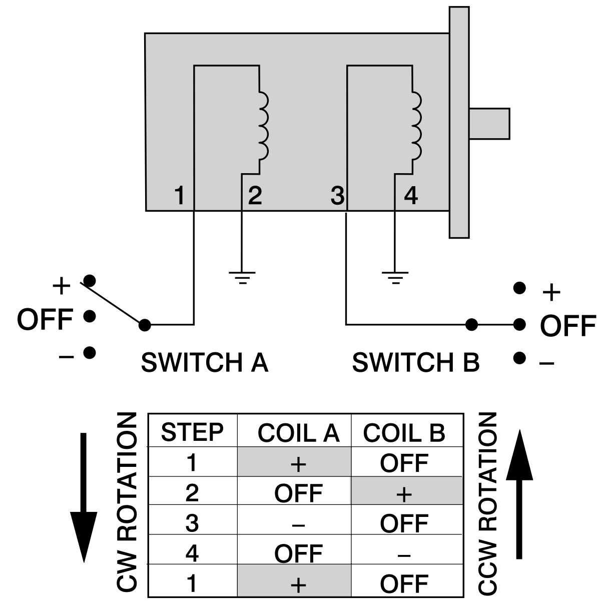
LAYOUT DIAGRAM OF STEP PER MOTOR SHOWING A GIVEN STATOR POLARITY AND ROTOR POSITION.

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.

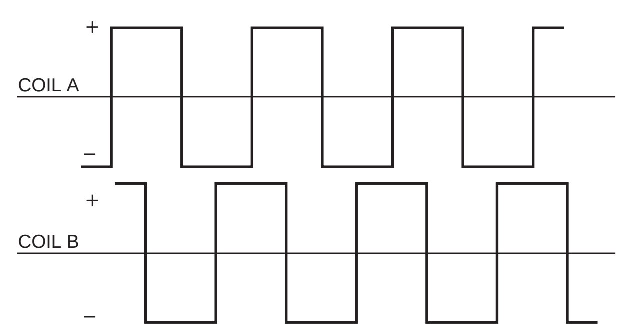


Figure 3: Voltage Wave Form — Fixed Frequency — 4-Step Sequence.

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.

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THOMSON AIRPAX MECHATRONICS

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.

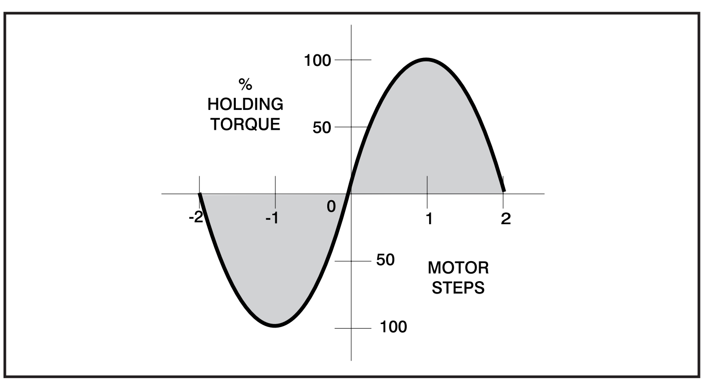

Figure 4: Torque Deflection.

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.

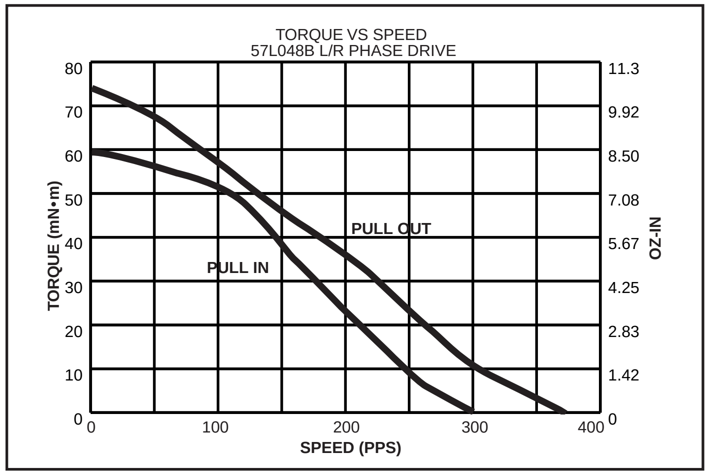

Figure 5: Torque/Speed — (Thomson Airpax 57L048B L/R Stepper).

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.)

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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 $v = \frac{9}{.06}$ = 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.

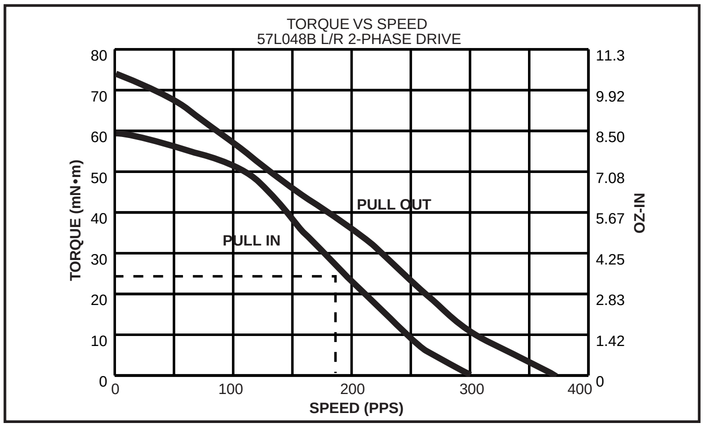

Figure 6: Torque/Speed — Frictional Load.

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 $\alpha = \frac{\Delta v}{\Delta t}$ 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.

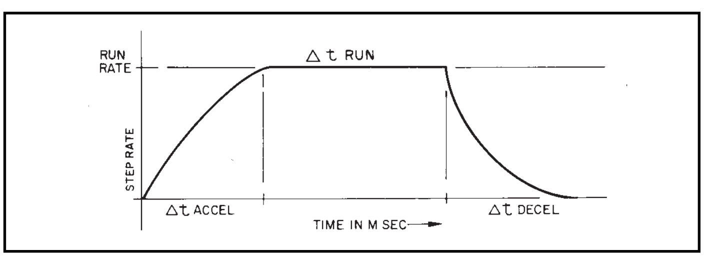

Figure 7: Step Rate/Time.

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.

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

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

$K = \frac{2\pi}{\text{steps/rev}}$ (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.

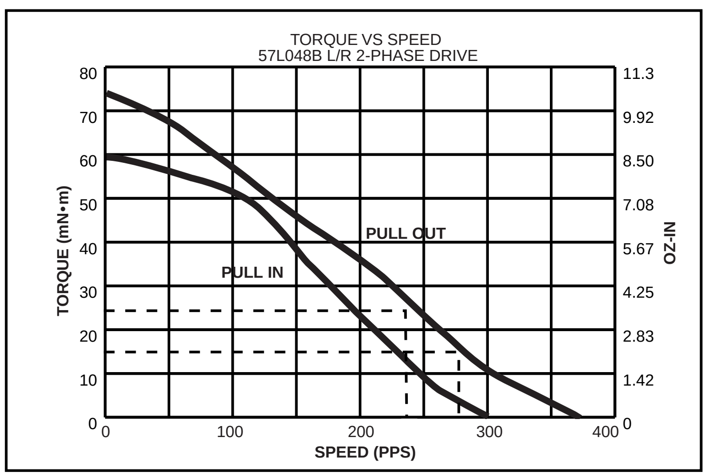

Figure 8: Torque/Speed — Friction Plus Inertia. (Thomson Airpax 57L048B L/R Stepper).

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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 mN•m x .6 = 4.8 mN•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 Δt = .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

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

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•m²) plus Load Inertia (g•m²)

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•m². 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.

$$J_T = J_R + J_L$$

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

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

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.

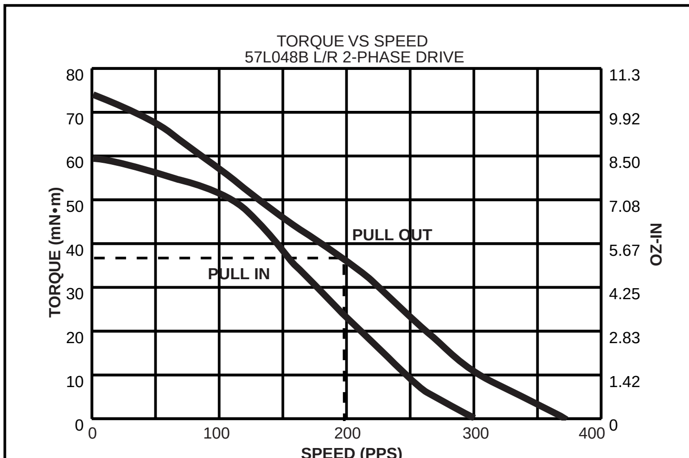


Figure 9: Torque/Speed — Friction Plus Inertia. (Thomson Airpax 57L048B L/R Stepper).

STEP FUNCTION - SINGLE STEP

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

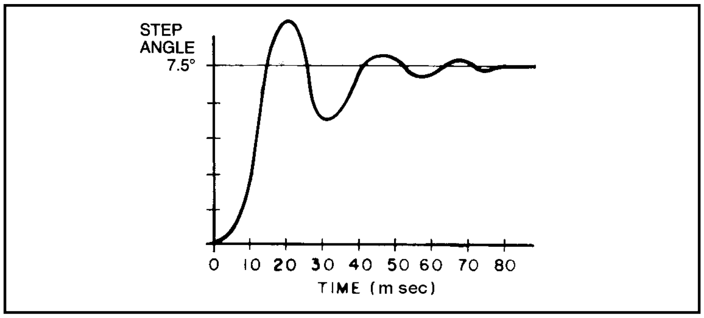


Figure 10: Single Step Response.

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.

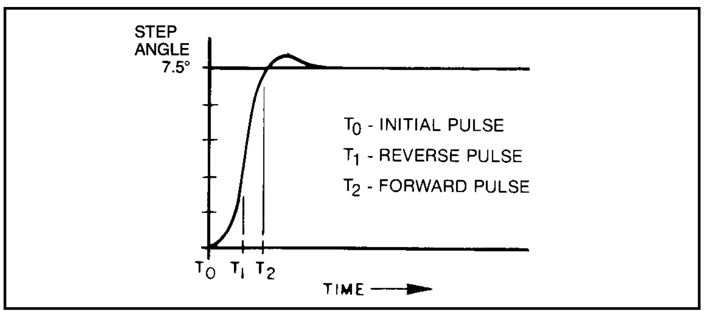


Figure 11: Electronically Damped Response.

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.

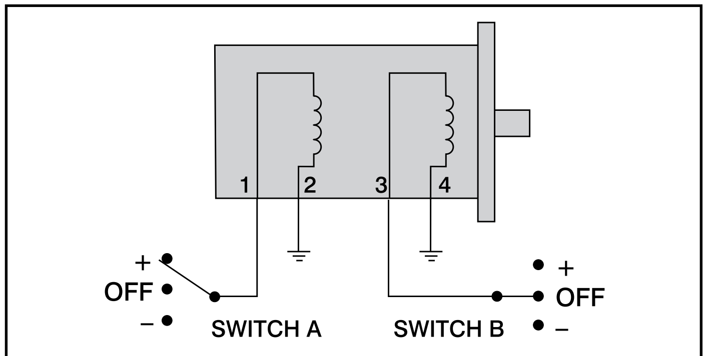
DRIVE METHODS

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.



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

CW ROTATION ↓ 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.

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

CW ROTATION ↓ CCW ROTATION ↑

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

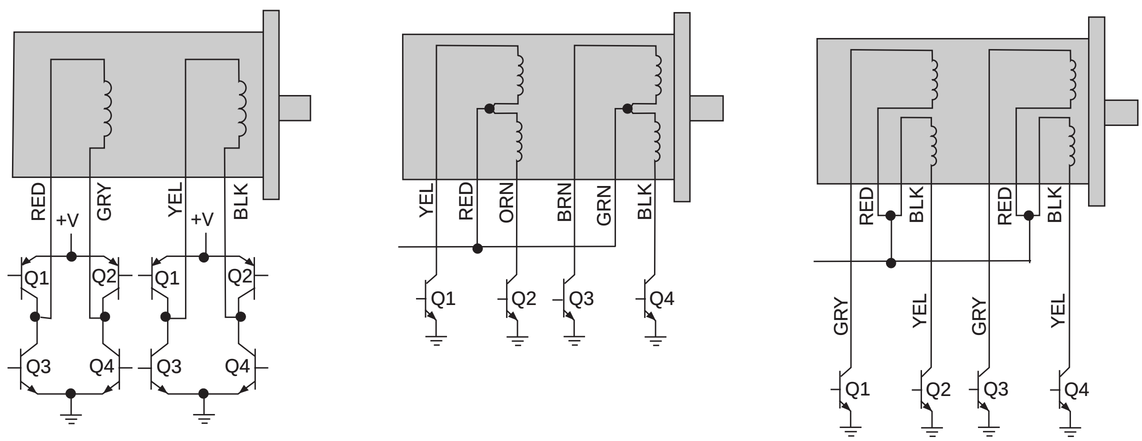
BIPOLAR AND UNIPOLAR OPERATION

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

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

1/2 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

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

UNIPOLAR

Normal 4-Step Sequence (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

1/2 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

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

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.

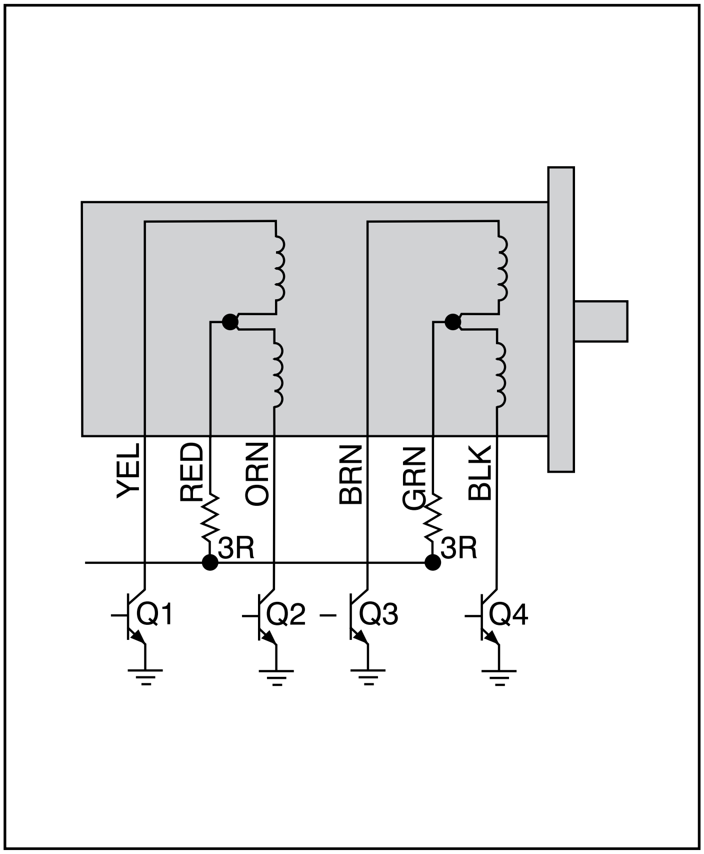


Figure 15: L/4R Drive

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.

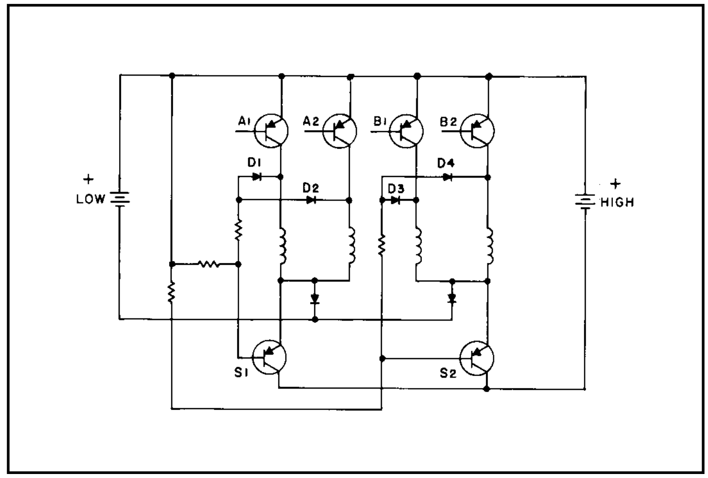


Figure 16: Unipolar Bi-Level Drive.

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.

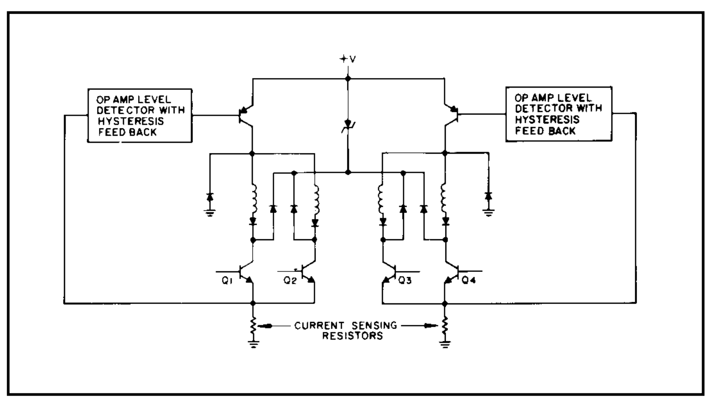


Figure 17: Unipolar Chopper Drive.

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.

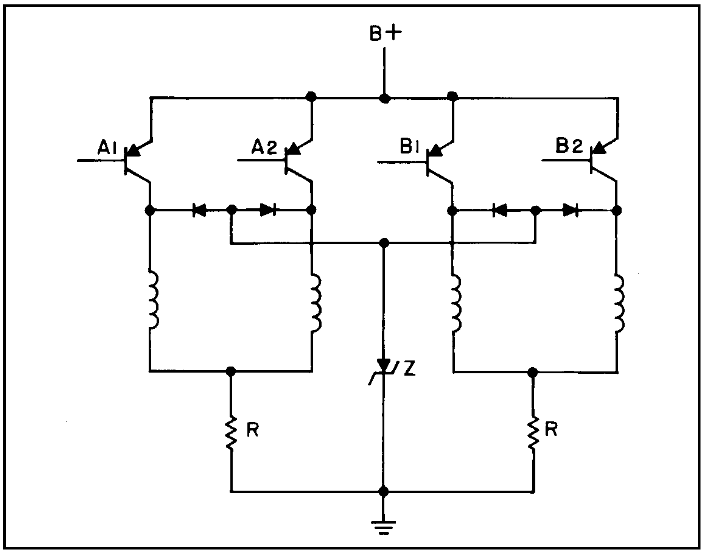


Figure 18: Voltage Suppression Circuit.

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 = Jα), 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 =

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

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