Mechatronics & Embedded Microcomputer Control
ME E4058 Fall 2018

Case Study # 4: Stepper Motors

Motors are used for a variety of applications in mechatronic systems. Motors effectively apply torques and forces to mechanical components initiating motion. Mechatronic systems which involve the motion of mechanical components are often called motion control systems. Motion control, in mechatronic terms, means to accurately control the movement of an object based upon either speed, distance, load or a combination of all these factors. There are numerous types of motors used for motion control systems, including: stepper motors, linear step motors, dc brush motors, brushless motors, servo motors, brushless servo motors, linear servo motors, ac motors and more. This case study involves stepper motor technology. Stepper motors are the preferred technology for position control systems such as those in machine tools. They are also used, for example, to control the opening of valves in chemical process control.

Background Information – Stepper Motors

In practice, a stepper motor is a simple device. It has no brushes, or contacts. Basically it's a synchronous motor with the magnetic field electronically switched to rotate the armature around. A stepper motor system consists of three basic elements, often combined with some type of user interface (keypad, host computer, programmable logic controller (PLC) or dumb terminal):

- The Controller (or Indexer) is typically a microcomputer capable of generating step pulses and direction signals for the driver. In addition, the controller is typically required to perform other sophisticated command functions such as fault checking and trajectory planning. The controller may also measure sensors to determine the proper operation of the stepper motor system. Programming an embedded computer as the controller is the goal of this case study.
- The Driver (or Amplifier) converts the controller command signals into the power signals necessary to energize the stepper motor windings. The controller signals are typically low power digital signals. The driver controls the application of power to the stepper motor where the power is delivered from a power supply with the required current capability. There are numerous types of drivers, with different current / power ratings and construction technology. Not all drivers are suitable to run all motors, so when designing a motion control system the driver selection process is critical. Two different types of drivers will be considered in this case study since two different stepper motors are used.
- The Stepper Motor is an electromagnetic device that essentially converts switched digital (i.e. on – off) currents into mechanical shaft rotation.

The advantages of stepper motors are low cost, high reliability, long operating life, high torque at low speeds and a simple, rugged construction that operates in almost any environment. Stepper motors are also used to hold a specific rotational position and to move from one fixed rotational position to another. The main disadvantages in using a stepper motor is the resonance effect often exhibited at low speeds and the decreasing torque with increasing speed.

Types Of Stepper Motors

Stepper motors come in two basic varieties, *permanent magnet* and *variable reluctance* (there are also *hybrid* motors, which are indistinguishable from permanent magnet motors from the controller or indexer point of view). Lacking a label on the motor, you can generally tell the two apart by feel when no power is applied. Permanent magnet motors tend to "cog" as you twist the rotor with your fingers, while variable reluctance motors almost spin freely (although they may cog slightly because of residual magnetization in the rotor). You can also distinguish between the two varieties with an ohmmeter. Variable reluctance motors usually have three (sometimes four) windings, with a common return, while permanent magnet motors usually have two independent windings, with or without center taps. Center-tapped windings are used in unipolar permanent magnet motors.

Stepper motors come in a wide range of angular resolution. The coarsest motors typically turn 90 degrees per step, while high-resolution permanent magnet motors are commonly able to produce 1.8 or even 0.72 degrees per step. With an appropriate controller, most permanent magnet and hybrid motors can be run in half-steps, and some controllers can handle smaller fractional steps or microsteps. Another way to specify a stepper motor is in terms of steps per revolution. Thus a 90 degree per step motor exhibits 4 steps per revolution and a 0.72 degree per step motor exhibits 500 steps per revolution.

For both permanent magnet and variable reluctance stepper motors, if just one winding of the motor is energized, the rotor (under no load) will snap to a fixed angle and hold that angle. If you tried to turn the shaft by hand, the motor will try to hold the angle until the torque you apply to the shaft exceeds the holding torque of the motor, at which point, the rotor will turn, trying to hold again at each successive equilibrium point.

Variable Reluctance Motors

The variable reluctance motor, as indicated by the name, does not use a permanent magnet in its construction. As a result, the motor rotor can usually move without constraint or "detent" torque. This type of construction is good in industrial applications that do not require a high degree of motor torque, such as the positioning of a micro slide. Variable reluctance stepper motors are not used in this case study. The following material is provided as a reference.

If the motor has three windings, typically connected as shown in the schematic diagram in Figure 1, with one terminal common to all windings, it is most likely a variable reluctance stepper motor. In use, the common wire typically goes to the positive voltage power supply and the windings are energized in sequence by grounding the wires. Four wires mean that it is a three-phase variable reluctance stepper motor, the minimum possible. Four and five phase motors also exist having five and six wires respectively.

The cross section shown in Figure 1 is of a 30 degree per step variable reluctance motor. The rotor in this motor has 4 teeth and the stator has 6 poles, with each winding wrapped around two opposite poles. With winding number 1 energized as shown, the rotor teeth marked X are attracted to this winding's poles by a variable reluctance effect (i.e. by the same physical mechanism that caused the solenoid to retract and the magnetic levitation ball to be attracted to the coil). If the current through winding 1 is turned off and winding 2 is turned on, the rotor will rotate 30 degrees clockwise so that the rotor teeth marked Y line up with the poles marked 2. Reversing the procedure (Y to X) would result in a 30 degree counterclockwise rotation.

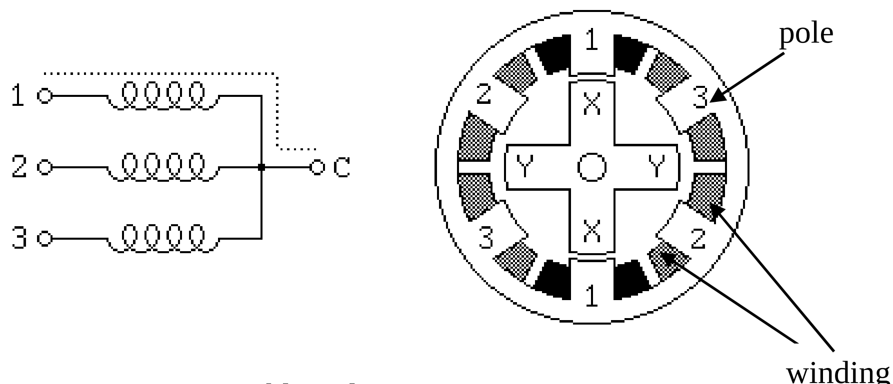


Figure 1. Variable Reluctance Stepper Motor

To rotate this motor continuously, you just apply power to the 3 windings in sequence. Assuming positive logic, where a 1 means turning on the current through a motor winding, the following control sequence will spin the motor illustrated in Figure 1 clockwise 24 steps or 2 revolutions:

Winding 1 -> 1 0 0 1 0 0 1 0 0 1 0 0 1 0 0 1 0 0 1 0 0 1 0 0 1
Winding 2 -> 0 1 0 0 1 0 0 1 0 0 1 0 0 1 0 0 1 0 0 1 0 0 1 0 0
Winding 3 -> 0 0 1 0 0 1 0 0 1 0 0 1 0 0 1 0 0 1 0 0 1 0 0 1 0
time --->

This means that at time step #1, winding 1 is on and windings 2 & 3 are off.

For example, if this motor was being driven by a microcomputer, the above sequence would be the sequence of signals coming from the microcomputer port. Time is required to allow the stepper motor to move so a delay is required between each step of the sequence.

For variable reluctance stepper motors with 4 and 5 windings (requiring 5 or 6 wires), the driving principle is the same as that for the three winding variety, but it becomes important to work out the correct order to energize the windings to make the motor step nicely.

The motor geometry illustrated in Figure 1, giving 30 degrees per step, uses the fewest number of rotor teeth and stator poles that performs this step size satisfactorily. Using more stator poles and more rotor teeth allows construction of motors with smaller step angle. Toothed faces on each pole and a correspondingly finely toothed rotor allows for step angles as small as a few degrees.

Permanent Magnet Motors

A permanent magnet stepper motor referred to as a "canstack" motor, has, as the name implies, a permanent magnet rotor. It is a relatively low speed, low torque device with large step angles of either 45 or 90 degrees. It's simple construction and low cost make it an ideal choice for industrial applications such as the paper feeder for an ink jet printer.

Unlike variable reluctance stepper motors, the permanent magnet motor rotor has no teeth and is designed to be magnetized at a right angle to its axis. Applying current to each phase in sequence will cause the rotor to rotate by rotating a changing magnetic field. Although it also operates at fairly low speed, the permanent magnet motor has a relatively higher torque characteristic than variable reluctance motors. In other words, if you energized a permanent magnet stepper motor phase and then tried to the stepper motor by hand, it would require more torque to move it from its holding position. Both stepper motors used in this case study are of the permanent magnet variety.

Permanent magnet stepper motors can be wound in basically two configurations: unipolar or bipolar. This case study uses one of each winding configuration. These are discussed in more detail below.

Hybrid Stepper Motors

Hybrid motors combine the best characteristics of the variable reluctance and permanent magnet motors. They are constructed with multi-toothed stator poles and a permanent magnet rotor. Standard hybrid motors have 200 rotor teeth and rotate at 1.8 degree step angles. Other hybrid motors are available in 0.9 degree and 3.6 degree step angle configurations. Because they exhibit high static and dynamic torque and run at very high step rates, hybrid motors are used in a wide variety of industrial applications.

Permanent Magnet Stepper Motor Windings

Unipolar Stepper Motors

Unipolar stepper motors have only one winding per stator pole. It is unipolar in the sense of current flow. Stepper motors with a unipolar winding will have more than 4 lead wires. Figure 2 below illustrates a typical unipolar motor.

Unipolar stepper motors (both permanent magnet and hybrid stepper motors with 5 or 6 wires) are usually wired as shown in the figure, with a center tap on each of two windings. In use, the center taps (labeled 1 and 2 in the figure) of the windings are typically connected to the positive voltage power supply, and the two ends of each winding are alternately grounded to reverse the direction of the current and thus the magnetic field provided by that winding. The two center tap terminals can also be connected together inside the motor. The current flow is unipolar in that it is always into the center tap wire.

The motor cross section shown in Figure 2 is of a 30 degree per step permanent magnet motor. Motor winding number 1 is distributed between the top and bottom stator pole, while motor winding number 2 is distributed between the left and right motor poles. The rotor is a permanent magnet with 6 poles, 3 south and 3 north, arranged around its circumference.

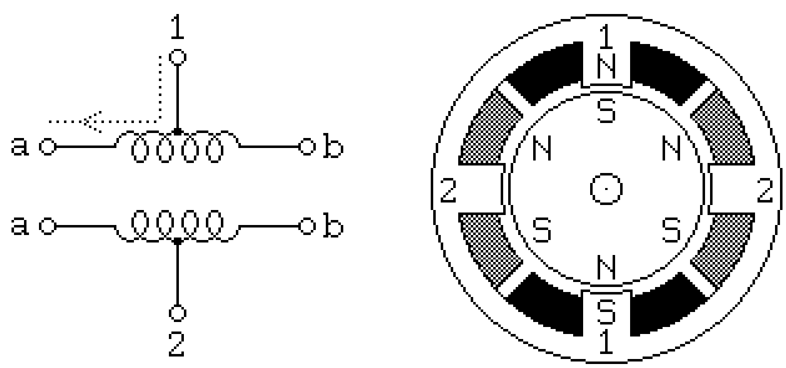


Figure 2. Unipolar Permanent Magnet Stepper Motor

For higher angular resolutions, the rotor must have proportionally more poles. The 30 degree per step motor in the figure is one of the most common permanent magnet motor designs, although 15 and 7.5 degree per step motors are widely available. Permanent magnet motors with resolutions as good as 1.8 degrees per step are also available.

As illustrated in the figure, the current flowing from the center tap of winding 1 to terminal “a” causes (for example) the top stator pole to be a north pole while the bottom stator pole is a south pole. This attracts the rotor into the position shown. If the power to winding 1 is removed and winding 2 is energized by grounding terminal “a” of that winding, the rotor will turn 30 degrees clockwise, or one step. In this case, the left stator pole would be a north pole (attracting the south rotor pole) while the right stator pole is a south pole (attracting the north rotor pole). To continue the rotation, winding 1 is energized by grounding the “b” terminal. This causes current to flow in the opposite direction in the winding and thus the upper stator pole becomes a south pole and the bottom stator pole becomes a north pole. Finally, winding 2 is energized by grounding its “b” terminal. The sequence then repeats to rotate the motor continuously.

The unipolar stepper motor coils are simple lengths of wire wound around the stator poles. The coils are identical and are typically not electrically connected. Each coil has a center tap - a wire coming out from the coil that is midway in length between its two terminals. You can identify the separate coils by touching the terminal wires together. If the terminals of a stator coil are connected, the shaft becomes harder to turn. Because of the long length of the wound wire, it has a measurable resistance (and inductance). You can identify the center tap by measuring resistance with a multimeter capable of measuring low resistance. The resistance from a terminal to the center tap is half the resistance between the two terminals of a coil. The coil resistance of half a coil is usually stamped on the motor. For example, '*5 ohms / phase'* indicates the resistance from center tap to either terminal of a coil. The resistance from terminal to terminal should therefore be 10 ohms.

Permanent magnet stepper motors produce torque by the attraction of unlike magnetic poles. Current flowing through a coil produces a magnet field (by the right hand rule) which attracts an opposite polarity permanent magnet rotor pole connected to the shaft of the motor as shown in Figure 3. The basic principle of a permanent magnet stepper control is to reverse the direction of current through the 2 coils of a stepper motor, in sequence, in order to reverse the magnetic field and therefore influence the rotor rotation. Since there are 2 coils and 2 directions, that gives you a possible 4-phase sequence. All you need to do is get the sequencing right and the motor will turn continuously in the correct direction. You may wonder how the stepper motor can achieve such fine step increments with only a 4 phase sequence. Unlike figure 2, the internal arrangement of the motor is quite complex - the winding and rotor poles repeating around the perimeter of the motor many times. The rotor is advanced only a small angle, either forward or reverse, and the 4-phase sequence is repeated many times before a complete revolution occurs.

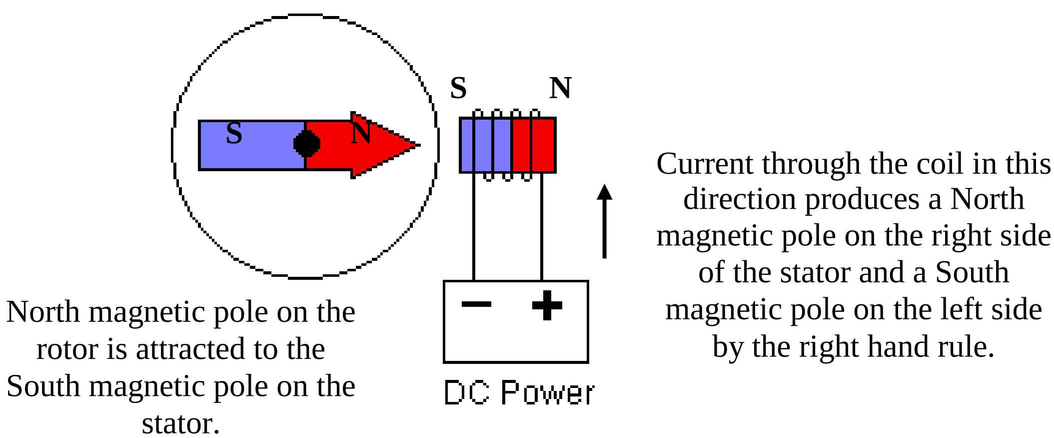


Figure 3. Concept for Controlling Permanent Magnet Stepper Motors

Consider the 4-phase sequence including the reversing of the current though the 2 coils. The unipolar stepper motor controller takes advantage of the center tap to achieve the current reversal with a clever trick -- the center tap is tied to the positive voltage power supply, and one of the 2 terminals of the winding is grounded to get the current flowing in one direction. This is illustrated in Figure 4. When the other winding terminal is grounded, the current is reversed. Current can thus flow in both directions for each pole, but only half coils are energized at a time. Both terminals are never grounded at the same time, which would energize both coils, effectively cancel the magnetic field and achieve nothing but a waste of power. Similar to the circuits used to control the magnetic levitation coil and the solenoid coil, the winding terminals are grounded with transistors and diodes are used to protect the transistors from the inductive voltage spikes. (Note that the center tap terminals can also be connected together at the ends (inside or outside the motor) since they are both connected to the positive terminal of the power supply.)

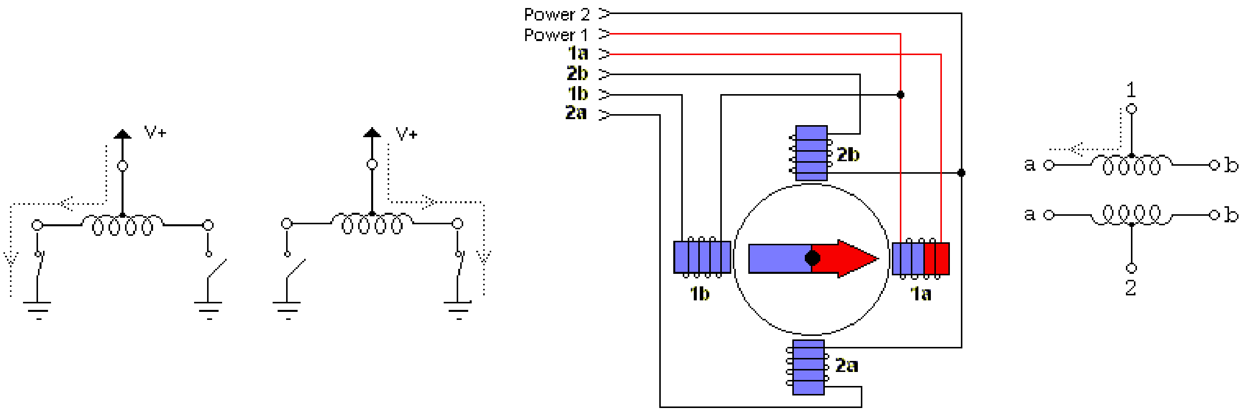
To rotate the motor continuously, you just apply power to the two windings in sequence. Assuming positive logic, where a 1 means turning on the current through a motor winding (by grounding the appropriate terminal), the following control sequence will spin the motor illustrated in Figure 2 clockwise 24 steps or 4 revolutions:

```
Winding 1a ->   1 0 0 0 1 0 0 0 1 0 0 0 1 0 0 0 1 0 0 0 1 0 0 0 1
Winding 2a ->   0 1 0 0 0 1 0 0 0 1 0 0 0 1 0 0 0 1 0 0 0 1 0 0 0
Winding 1b ->   0 0 1 0 0 0 1 0 0 0 1 0 0 0 1 0 0 0 1 0 0 0 1 0 0
Winding 2b ->   0 0 0 1 0 0 0 1 0 0 0 1 0 0 0 1 0 0 0 1 0 0 0 1 0
                                                          time --->
```

Again, each column indicates a step in time. The timing of each step depends on the stepper motor, the driver and the load (but is typically slow in microcomputer time).

“Wave Drive” Step Sequence

In a basic "Wave Drive" clockwise sequence shown above, winding 1a is de-activated and winding 2a is activated to advance to the next phase. The rotor is guided in this manner from one winding to the next, stepping so that the magnetic poles on the rotor line up with the magnetic poles on the stator, producing a continuous cycle. The motion can be relatively smooth depending on the timing of the step sequence but typically has a start-stop step characteristic. Often this is desirable in an industrial product (consider an “analog” clock with a second hand that steps 1/60 of a revolution every second).



(a) schematic (b) concept

Figure 4. Selection of Current Direction in Pole Causes Rotation

Note that if two adjacent windings are activated at the same time in the same direction, the rotor is attracted mid-way between the two windings. (For example, both winding can be energized to produce north magnetic poles on one side of the rotor and south magnetic poles on the other.) This would yield the step sequence shown below. This is called a “Full Step” sequence.

Winding 1a -> 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1
Winding 2a -> 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0
Winding 1b -> 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0
Winding 2b -> 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1
time --->

“Full Step” Step Sequence

Note that in either step sequence, the two halves of each winding are never energized at the same time. Both sequences shown above will rotate a permanent magnet stepper motor one step at a time. The top sequence only powers one winding at a time, as illustrated in Figure 4 above (where only the left winding has power). Thus, it uses less power. The bottom (Full Step) sequence involves powering two windings at a time and generally produces a torque about 1.4 times greater than the top (Wave Drive) sequence while using twice as much power.

The step positions produced by the two sequences above are not the same; as a result, combining the two sequences allows half stepping, with the motor stopping alternately at the positions indicated by one or the other sequence. In other words, the motor stops with the rotor pole aligned with a stator pole (as in Figure 4), then with the rotor pole midway between two stator poles, then with the rotor pole aligned with the second stator pole, etc. The combined sequence is as follows:

```
Winding 1a ->   1 1 0 0 0 0 0 1 1 1 0 0 0 0 0 1 1 1 0 0 0 0 0 1 1 1
Winding 2a ->   0 1 1 1 0 0 0 0 0 1 1 1 0 0 0 0 0 1 1 1 0 0 0 0 0 1
Winding 1b ->   0 0 0 1 1 1 0 0 0 0 0 1 1 1 0 0 0 0 0 1 1 1 0 0 0 0
Winding 2b ->   0 0 0 0 0 1 1 1 0 0 0 0 0 1 1 1 0 0 0 0 0 1 1 1 0 0
                                                          time --->
```

"Half Step" Step Sequence

The following table describes the 3 useful stepping sequences and their relative merits. The sequence pattern is represented with 4 bits such as would be produced from the port of a microcomputer, where a '1' indicates an energized winding (these are the columns in the sequence versus time above). After the last step in each sequence, the sequence repeats and the motor continues to rotate. This produces the stepping sequences versus time described above. Stepping backwards through the sequence (i.e. executing the above sequences from right to left rather than from left to right) reverses the direction of the motor. In the table, this is equivalent to having the microcomputer produce the sequence patterns from the bottom to the top.

Table of Stepping Sequences

Sequence	Name	Description
0001 0010 0100 1000	Wave Drive, One-Phase	Consumes the least power. Only one phase is energized at a time. Assures positional accuracy regardless of any winding or magnetic circuit imbalance in the motor.
0011 0110 1100 1001	Full Step, Two-Phase	High Torque - This sequence energizes two adjacent phases at a time, which offers an improved torque-speed product and greater holding torque but at the expense of more power.
0001 0011 0010 0110 0100 1100	Half-Step, Alternate One-Phase Two-Phase	Half Step - Effectively doubles the stepping resolution of the motor, but the torque is not uniform for each step. (Since you are effectively switching between Wave Drive and Full Step with each step, torque alternates each step.) This sequence reduces motor resonance which can sometimes cause a motor to stall at a particular resonant

1000 1001		frequency. Note that this sequence has 8 steps where the two above have 4 steps.

Bifilar Wound Unipolar Stepper Motors

Bifilar wound motors means that there are two identical sets of windings on each stator pole without a center tap. Current in one direction is produced by one winding; current in the other direction is produced by the other winding. This type of winding configuration simplifies operation in that transferring current from one coil to another one, wound in the opposite direction, will reverse the rotation of the motor shaft. The most common wiring configuration for bifilar wound stepper motors is 8 leads because they offer the flexibility of either a series or parallel connection. There are however, many 6 lead stepper motors available for series connection applications. Note that the only half the winding on each stator pole is used for each step just as with a center tap unifiler winding.

Bipolar Stepper Motor Windings

Bipolar permanent magnet and hybrid stepper motors are constructed with exactly the same magnetic configuration for rotor and stator as is used on unipolar motors, but the two windings are wired more simply, with no center taps. Thus, the motor construction itself is simpler but the drive circuitry needed to reverse the polarity of the current in each pair of motor poles is more complex. Because of this, the bipolar motor requires a different type of driver, one that reverses the current flow through the coils by alternating polarity of the terminals, giving you the name - bipolar. A Bipolar stepper motor of a given size is capable of higher torque than a unipolar motor since entire winding(s) may be energized, not just half-windings. Where 4-wire steppers are strictly 'bipolar', 6 wire motors with center-taps can be used with the bipolar controller (by not connecting the center taps). The schematic in Figure 5 shows how such a motor is wired. Note that the motor cross section shown here on the right is exactly the same as the cross section shown in Figure 2. The difference is in how the stator poles are wound.

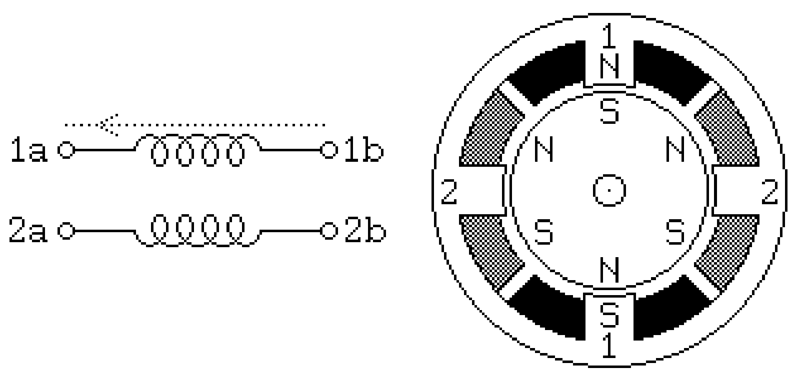
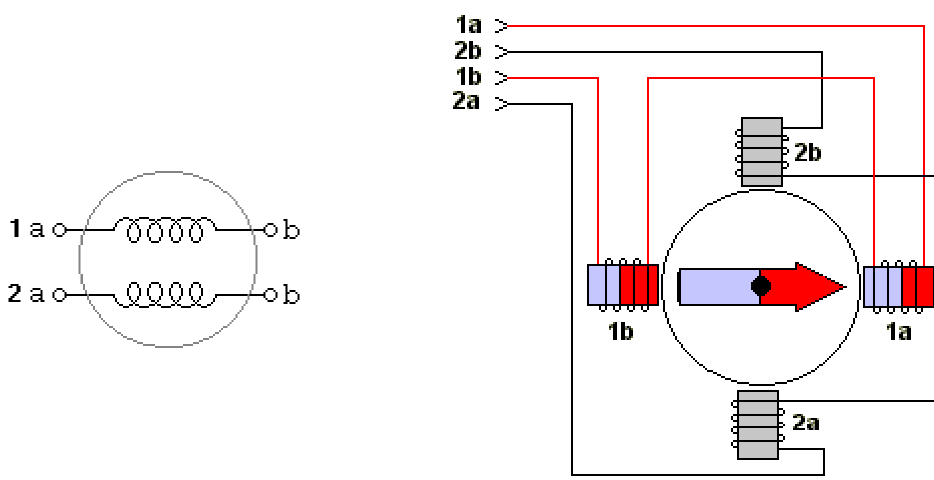


Figure 5. Bipolar Permanent Magnet Stepper Motor

The coils are activated, in sequence, to attract the rotor, which is indicated by the arrow in Figure 6. This conceptual diagram depicts a 90 degree step per phase motor. Assuming Terminal 1b is positive and 1a is negative (or ground), the rotor north pole points to the right in this diagram. If these two terminals were reversed in polarity the rotor north pole would point to the left. Coil 2 is entirely de-activated in the diagram.



(a) schematic (b) concept

Figure 6. Reversal of Current in Pole Winding Causes Rotation

In a basic "Wave Drive" clockwise sequence, winding 1 is de-activated and winding 2 activated to advance to the next phase (similar to the unipolar stepper motor). The rotor is guided in this manner from one winding to the next, producing a continuous cycle. Note that if two adjacent windings are activated, the rotor is attracted mid-way between the two windings producing the “Full Step” sequence.

The drive circuitry for a bipolar stepper motor requires either two power supplies of different polarity or an *H-bridge* control circuit for each winding. For low cost, most industrial applications use the H-bridge. The H-bridge is discussed in more detail in the section on control circuits. Briefly, an H-bridge allows the polarity of the power applied to each end of each winding to be controlled independently. The control sequences for single stepping such a motor are shown below, using + and - symbols to indicate the polarity of the power applied to each motor terminal:

```
Terminal 1a  ->  + - - - + - - - + - - - + - - - + - - - + - - - + - - - + - - -
Terminal 2a  ->  - + - - - + - - - + - - - + - - - + - - - + - - - + - - - + - -
Terminal 1b  ->  - - + - - - + - - - + - - - + - - - + - - - + - - - + - - - + -
Terminal 2b  ->  - - - + - - - + - - - + - - - + - - - + - - - + - - - + - - - +
                                                              time --->
```

```
Terminal 1a  ->  + + - - + + - - + + - - + + - - + + - - + + - - + + - - + + - -
Terminal 2a  ->  - + + - - + + - - + + - - + + - - + + - - + + - - + + - - + + -
Terminal 1b  ->  - - + + - - + + - - + + - - + + - - + + - - + + - - + + - - + +
Terminal 2b  ->  + - - + + - - + + - - + + - - + + - - + + - - + + - - + + - - +
                                                              time --->
```

The first control sequence corresponds to a Wave Drive excitation and the second is the Full Step excitation. Note that these sequences are identical to those for a unipolar permanent magnet stepper motor when you consider that energizing different half windings of the unipolar motor reverses the current. At an abstract level, above the level of the H-bridge power switching electronics, the control logic for the two types of motor can be identical.

Many full H-bridge driver chips have one control input to enable the output and another to control the direction. Given two such bridge chips, one for each winding, the following control sequences will spin the motor identically to the control sequences given above (again, the first is the Wave Drive and the second is the Full Step). In the Wave Drive sequence, since the coil is not enabled, it does not matter which direction is selected. This is indicated by an “x” in the sequence.

```
Enable    1 ->  1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0
Direction 1 ->  1 x 0 x 1 x 0 x 1 x 0 x 1 x 0 x 1 x 0 x 1 x 0 x 1 x 0 x 1 x 0 x
Enable    2 ->  0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1
Direction 2 ->  x 1 x 0 x 1 x 0 x 1 x 0 x 1 x 0 x 1 x 0 x 1 x 0 x 1 x 0 x 1 x 0
                                                                    time --->
```

```
Enable    1 ->  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
Direction 1 ->  1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0
Enable    2 ->  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
Direction 2 ->  0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0
```

time --->

Similar to the unipolar motor, combining the two step sequences produces half step motions.

The following table describes the 3 useful stepping sequences and their relative merits. The polarity of terminals is indicated with + / -. After the last step in each sequence the sequence repeats. Stepping backwards through the sequence reverses the direction of the motor. Note that these sequences are identical to those for a unipolar stepper motor.

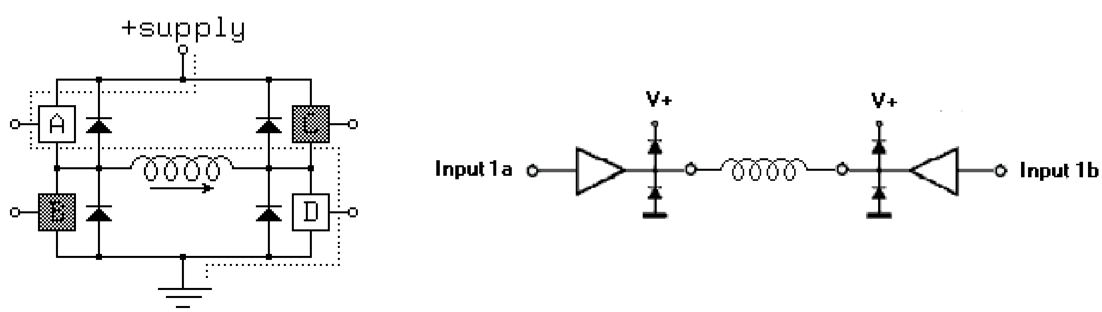
Table of Stepping Sequences

Sequence	Polarity	Name	Description
0001 0010 0100 1000	---+ --+- -+-- +---	Wave Drive, One-Phase	Consumes the least power. Only one phase is energized at a time. Assures positional accuracy regardless of any winding imbalance in the motor.
0011 0110 1100 1001	--++ -++- ++-- +--+	Full Step, Two-Phase	High Torque - This sequence energizes two adjacent phases, which offers an improved torque-speed product and greater holding torque but at the expense of more power.
0001 0011 0010 0110 0100 1100 1000 1001	---+ --++ --+- -++- -+-- ++-- +--- +--+	Half-Step, Alternate One-Phase Two-Phase	Half Step - Effectively doubles the stepping resolution of the motor, but the torque is not uniform for each step. (Since you are effectively switching between Wave Drive and Full Step with each step, torque alternates each step.) This sequence reduces motor resonance which can sometimes cause a motor to stall at a particular resonant frequency. Note that this sequence has 8 steps where the two above have 4 steps.

As discussed above, bifiler permanent magnet stepper motors have 4 independent windings, organized as two sets of two. Within each set, if the two windings are wired in series (with the proper orientation), the result can be used as a high voltage bipolar motor. If they are wired in parallel, the result can be used as a low voltage bipolar motor. If they are wired in series with the center point brought out, the result can be used as a low voltage unipolar motor. (Note the terminology: bifiler stepper motors are not the same as bipolar stepper motors but can be wired in a bipolar configuration.)

To distinguish a bipolar permanent magnet motor from other 4 wire motors, measure the resistances between the different terminals. The bipolar stepper motor has 2 coils. The coils are identical and are not electrically connected. You can also identify the separate coils by touching the terminal wires together. If the terminals of a coil are connected, the shaft becomes harder to turn because of currents generated by the rotating magnet. You can also determine which wires are connected by measuring the resistance with a multimeter.

The bipolar driver must be able to reverse the polarity of the voltage across either coil, so current can flow in both directions. And, it must be able to energize these coils in sequence. Drivers will be discussed in more detail below but consider the following mechanism for reversing the voltage across one of the coils.



(a) conventional (b) as an amplifier

Figure 7. Schematic of H Bridge Driver

The circuit in part (a) is called an H-Bridge, because it resembles a letter "H". The current can be reversed through the coil by closing the appropriate switches – A and D to flow current in one direction then B and C to flow the opposite current. In this way, only one power supply is required. Another way of depicting the H-Bridge is shown in part (b). Since each half of the bridge can both sink and source current, it qualifies as a push-pull type amplifier, and can be drawn with the symbol for the amplifier.

H-bridges are applicable not only to the control of stepper motors, but also for the control of DC motors, permanent magnet solenoids and many other applications, where polarity reversal is needed. The diodes protect the transistor switches from the kickback of the inductive type loads, from the windings of the stepper motor. (Recall that diodes were used in the driver circuits for the magnetic levitation coil and the solenoid.) Two such circuits are needed to drive both coils of the bipolar stepper motor, and is commonly called a "Dual H-Bridge."

Step Modes

Stepper motor "step modes" include Full (which can be either Wave Drive or Full Step), Half and Microstep. The type of step mode output of any motor depends on the design of the driver.

Wave Drive and Full Step

Standard stepper motors produce 200 full steps per revolution of the motor shaft. Dividing the 200 steps into the 360 degrees of rotation equals a 1.8 degree (0.031 radian) full step angle. Normally, full step mode is achieved by energizing either one or both windings while reversing the current alternately. Essentially, one digital input from the driver is equivalent to one step.

For a motor that turns S radians per step, the plot of torque versus angular rotation for the rotor relative to some initial equilibrium position will generally approximate a sinusoid. The actual shape of the curve depends on the pole geometry of both rotor and stator, and neither this curve nor the geometry information is given in the motor data sheets. For permanent magnet and hybrid motors, the actual curve usually looks sinusoidal, but looks can be misleading since higher order shapes are not apparent. For variable reluctance motors, the curve rarely even looks sinusoidal; trapezoidal and even asymmetrical sawtooth curves are not uncommon. More on the shape of the torque in stepper motors is given below when modeling the motors is discussed.

For a three phase (three winding) variable reluctance or permanent magnet motor with S radians per step, the period of the torque versus position curve will be 3S; for a 5-phase permanent magnet motor, the period will be 5S. (In other words, if you energize one phase of a three phase motor and try to turn the shaft by hand, the holding torque repeats every 3S radians of rotation. This is discussed in more detail below. See, for example, Figure 13.) For a two-winding permanent magnet or hybrid motor (the most common type), the period will be 4S, as illustrated in Figure 2 or 5.

Half Step

Half step simply means that the 200 step motor is rotating at 400 steps per revolution. In this mode, one winding is energized and then two windings are energized alternately, causing the rotor to rotate at half the distance, or 0.9 degrees (0.016 radians). (The same effect can be achieved by operating in full step mode with a 400 step per revolution motor. Half stepping is a more practical solution however, in industrial applications for lower cost.) Although it provides slightly less torque, half step mode reduces the amount "jumpiness" inherent in running in a full step mode.

Microstep

Microstepping is a relatively new stepper motor technology that controls the current in the motor windings to a degree that further subdivides the number of positions between poles. Essentially, instead of adjusting the current in two poles equally, the current in one pole can be greater than the other so that the rotor will be attracted to that pole to a greater degree. Some microsteppers are capable of rotating at 1/256 of a step (per step), or over 50,000 steps per revolution. This requires very fine current control for each of the windings. Microstepping is typically used for applications that require accurate positioning and a fine resolution over a wide range of speeds.

Design Considerations

The electrical compatibility between the motor and the driver are the most critical factors in a stepper motor system design. Some general guidelines in the selection of these components are:

- Inductance - Stepper motors are rated with a varying degree of inductance. A high inductance motor will provide a greater amount of torque at low speeds.
- Series, Parallel Connection – There are two ways to connect stepper motor windings, in series or in parallel. A series connection provides a high inductance and therefore greater performance at low speeds. A parallel connection will lower the inductance but increase the torque at faster speeds.
- Driver Voltage - The higher the output voltage from the driver, the higher the level of torque vs. speed. Generally, the driver output voltage should be rated at the motor voltage rating.
- Motor Stiffness - By design, stepper motors attempt to hold a fixed position when energized. If you try to turn an energized stepper motor by hand, you feel a torque which attempts to prevent the rotation. Reducing the current flow to the motor by a small amount will reduce the torque. Likewise, increasing the motor current will increase the torque and thus provide more stiffness. Trade-offs between speed, torque and resolution are a main consideration in designing a step motor system.
- Motor Heat - Step motors are designed to run hot (50º - 90º C). However, too much current may cause excessive heating and damage to the motor insulation and windings.
- Driver Performance - Speed and torque performance of the step motor is based on the flow of current from the driver to the motor winding. The factor that inhibits the flow, or limits the time it takes for the current to energize the winding, is the inductance. The lower the inductance, the faster the current gets to the winding and the better the speed performance of the motor. To reduce the effects of inductance, some types of driver circuits are designed to supply a greater amount of voltage than the motor's rated voltage. When holding a fixed position, the voltage and thus the current to the motor is reduced. This is similar to the drive scheme used for the solenoid in the third case study by using the "reduced" transistor.

Types Of Step Motor Drivers

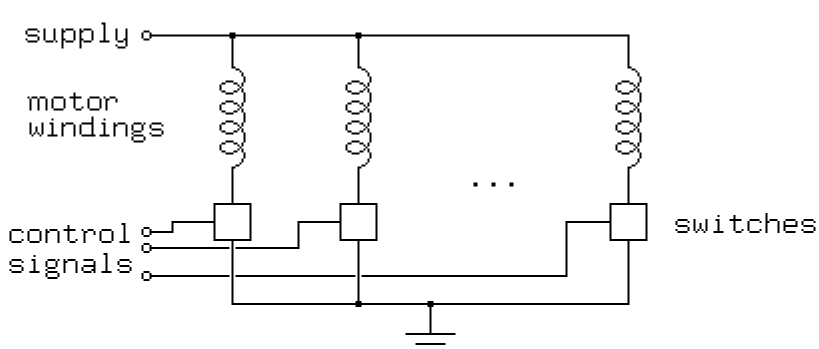
The final stage drive circuitry for stepper motors is discussed next. This circuitry is centered on two issues, switching the current in each motor winding on and off, and controlling its direction. The circuitry discussed in this section is connected directly to the motor windings and the motor power supply, and this circuitry is controlled by the microcomputer (controller) that determines when the switches are turned on or off. Sometimes the microcomputer connects to the final stage drive circuitry through an additional electronic device (as in this case study for the bipolar motor). Other times, the microcomputer connects directly to the transistor switches (as in this case study for the unipolar motor). This section only covers the most elementary control circuitry for each class of motor. All of these circuits assume that the motor power supply provides a drive voltage no greater than the motor's rated voltage. The transistors that directly connect to the stepper motor windings are also called the "switch set".

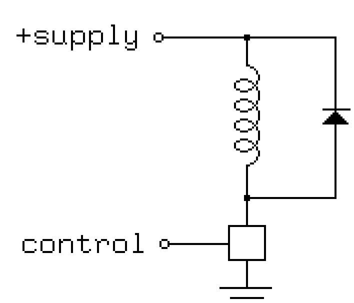
Variable Reluctance Motor Drive Circuitry

Typical controllers for variable reluctance stepper motors are variations on the schematic shown in Figure 8a. In the figure, boxes are used to represent switches (which are generally transistors); a control unit, not shown, is responsible for providing the control signals to open and close the switches at the appropriate times in order to spin the motors. If the transistors are chosen correctly, the microcomputer can directly turn on the transistors from its ports. In this way, the microcomputer generates the outputs needed to control the switches. In other cases, additional control circuitry such as a buffer is introduced.

Stepper motor windings, solenoids and similar devices are all inductive loads. As such, the current through the motor winding cannot be turned on or off instantaneously without involving infinite voltages. When the switch controlling a motor winding is closed, allowing current to flow, the result of this is a slow rise in current. When the switch controlling a motor winding is opened, the result of this is a voltage spike that can seriously damage the switch unless care is taken to deal with it appropriately.

There are two basic ways of dealing with this voltage spike. One is to bridge the motor winding with a diode, and the other is to bridge the motor winding with a capacitor. Diodes are the more traditional approach and shown in Figure 8b.





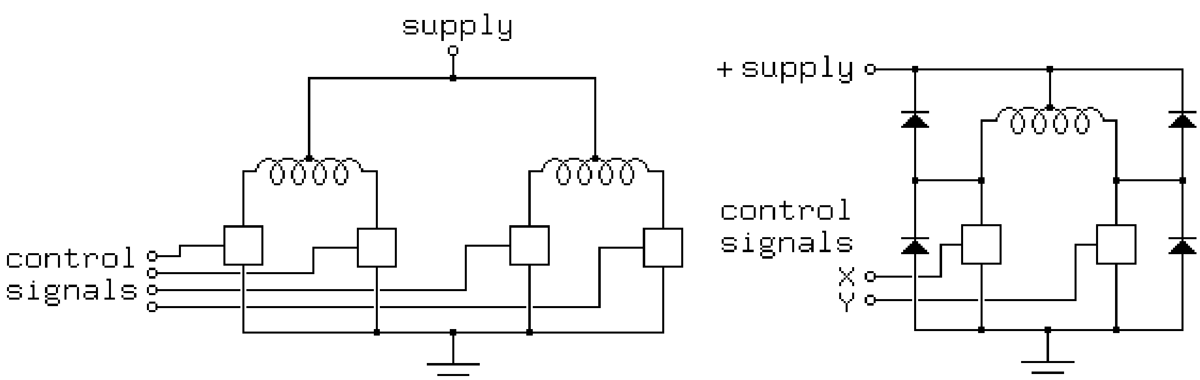
(a) schematic (b) diode protection

Figure 8. Driver for Variable Reluctance Stepper Motors

The diode shown in Figure 8b must be able to conduct the full current through the motor winding, but it will only conduct briefly each time the switch is turned off, as the current through the winding decays. If relatively slow diodes such as the common 1N400X family are used together with a fast switch, it may be necessary to add a small capacitor in parallel with the diode. The FES16JT diodes used in this case study are relatively high-speed diodes.

Unipolar Permanent Magnet Stepper Motor Driver

Typical controllers for unipolar stepper motors are variations on the schematic shown in Figure 9. In Figure 9, as in Figure 8, boxes are used to represent switches; a control unit, not shown, is responsible for providing the control signals to open and close the switches at the appropriate times in order to spin the motor. As with drive circuitry for variable reluctance motors, you must deal with the inductive kick produced when each of these switches is turned off. Again, you may shunt the inductive kick using diodes, but now, four diodes are required for each winding, as shown in Figure 9b.



(a) schematic (b) diode protection

Figure 9. Driver for Unipolar Permanent Magnet Stepper Motors

The extra diodes are required because the motor winding is not two independent inductors, it is a single center-tapped inductor with the center tap at a fixed voltage. This arrangement acts like a transformer. When one end of the motor winding is pulled down, the other end will fly up, and visa versa. When a switch opens, the inductive kickback will drive that end of the motor winding to the positive supply, where it is clamped by the diode. Otherwise, it will be driven above the supply voltage. The opposite end of the winding will fly downward, and if it was not floating at the supply voltage at the time and not clamped by the other diode, it will go to a negative voltage below ground, reversing the voltage across the switch at that end. Some switches are immune to such reversals, but others can be seriously damaged. Providing the extra diodes is a safe design choice.

Bipolar Stepper Motors and H-Bridges

As discussed above, drive circuits are more complex for bipolar permanent magnet stepper motors because these have no center taps on their windings. Therefore, to reverse the direction of the field produced by a motor winding, you need to reverse the current through the winding. You could use a double-pole double throw switch to do this electromechanically; the electronic equivalent of such a switch is an H-bridge and is shown in Figure 10.

As with the variable reluctance and unipolar drive circuits discussed previously, the switches used in the H-bridge must be protected from the voltage spikes caused by turning the power off in a motor winding. Again, this is usually done with diodes, as shown in Figure 10.

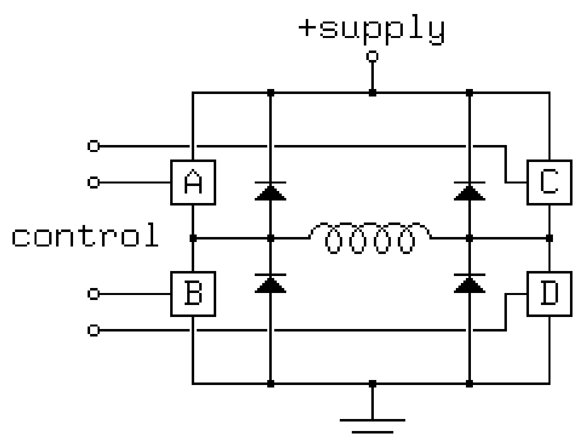


Figure 10. Driver for Bipolar Permanent Magnet Stepper Motors

With 4 switches, the basic H-bridge offers 16 possible operating modes, 7 of which short out the power supply. Care must be taken to avoid the shorting modes. The following operating modes are of interest:

Forward mode, switches A and D closed.
Reverse mode, switches B and C closed.

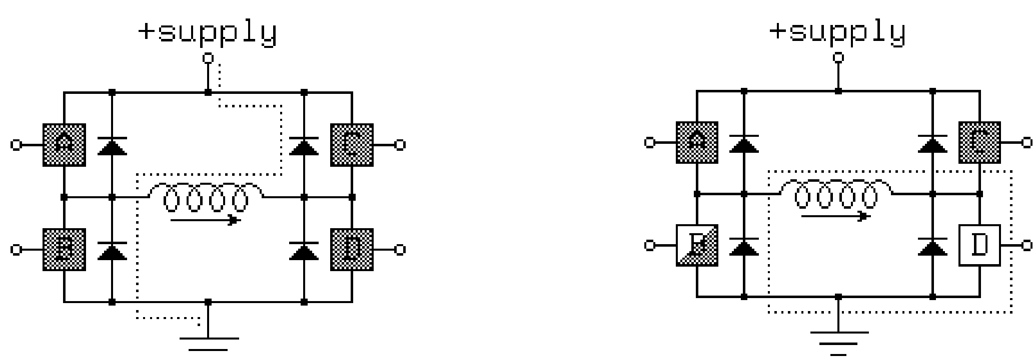
These are the usual operating modes, allowing current to flow from the supply, through the motor winding and onward to ground. Figure 7 above illustrated the forward mode.

Fast current decay mode or *coasting mode*, all switches open.

This mode and the one below are used to stop the stepper motor after it has been rotating for some time if it is not required to hold the motor at a certain position. In the fast decay mode, any current flowing through the motor winding will be working against the supply voltage, plus two diode drops, so current will decay quickly. This mode provides little or no dynamic braking effect on the motor rotor, so the rotor will coast freely if all motor windings are powered in this way. Figure 11a illustrates the current flow immediately after switching from forward running mode to fast decay mode (Note: all the transistor switches are open).

Slow current decay modes or *dynamic braking modes*.

In these modes, current may recirculate through the motor winding with minimum resistance. As a result, if current is flowing in a motor winding when one of these modes is entered, the current will decay slowly, and if the motor rotor is turning, it will induce a current in the winding that will act as a brake on the rotor. Figure 11b illustrates one of the many useful slow-decay modes, with switch D closed; if the motor winding has recently been in forward running mode, the state of switch B may be either open or closed. Another slow decay mode would have switches A and C closed. Some commercial stepper motor drivers have a “Brake” input. When this input is engaged, switches A and C or B and D are closed.



(a) fast decay mode

(b) slow decay mode

Figure 11. Other Operating Modes for a Bipolar Driver

Most H-bridges are designed so that the digital logic necessary to prevent a short circuit is included at a very low level in the design. This digital logic is also typically included in commercial stepper motor drivers. Seldom does a designer rely on the microcomputer code to prevent short circuits. Figure 12 illustrates what is probably the best arrangement using two AND gates.

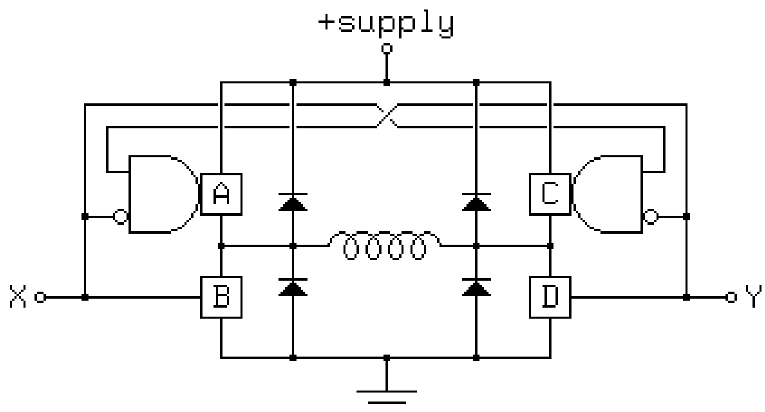


Figure 12. Inclusion of Logic Chips to Prevent Short Circuits

Recall that the dot indicates that one of the inputs to the AND logic gate is inverted. Thus, for this circuit, the following operating modes are available:

XY	ABCD	Mode
00	0000 (all switches off)	fast decay
01	1001 (switch A and D on)	**forward**
10	0110 (switch B and C on)	**reverse**
11	0101 (switch B and D on)	slow decay

The advantage of this arrangement is that all of the useful operating modes are preserved, and they are encoded with a minimum number of bits; the latter is important when using a microcomputer to directly drive the H-bridge because many microcomputers have a limited numbers of bits available for parallel output. Note that there is no combination of outputs XY which could short the power supply (such as by having switch A and B on).

Resistance / Inductance (R/L) or (resistance/limited)

R/L drivers are, by today's standards, old technology but still exist in some (low-power) applications because they are simple and inexpensive. The drawback to using R/L drivers is that they rely on adding a "dropping resistor" in series with the motor to get almost 10 times the amount of motor current rating necessary to maintain a useful increase in speed. As stated above, the inductance limits the application of high speed current. In actuality, it is the time constant of the motor which is the inductance divided by the resistance. By adding resistance in series with the motor, this time constant is reduced. This process also produces an excessive amount of heat and must rely on a larger DC power supply for the current source.

Bipolar Chopper Drives for Microstepping

Recall that in microstepping, you want to control the currents in each winding to a very fine degree. Bipolar chopper drivers are by far the most widely used drivers for industrial applications in these situations. Although they are typically more expensive to design, they offer high performance and high efficiency. Bipolar chopper drivers sometimes use an extra set of switching transistors to control the amount of current in the windings. Additionally, these drivers use a conventional four transistor bridge with recirculating diodes (Figure 10) to control the direction of the current in the windings. A sense resistor produces a feedback voltage proportional to the motor current. The sense resistor is similar to the one used in the magnetic levitation circuit to control the current. Motor windings, using a bipolar chopper driver, are energized to the full supply voltage level by turning on one set (top and bottom) of the control transistors (such as Figure 7a). The sense resistor monitors the linear rise in current until the required level is reached. At this point the top switch or extra switching transistor opens and the current in the motor coil is maintained via the bottom switch and the diode. Current "decay" (current loss over time) occurs until a preset level is reached and the process starts over. This "chopping" effect of the supply is what maintains the correct current and voltage to the motor at all times.

Controller (Indexer) Overview

The controller, or indexer, provides step and direction outputs to the driver. Most applications require that the controller manage other control functions as well, including acceleration, deceleration, steps per second and distance. The controller can also interface to and control, many other external signals.

Microcomputer based controllers offer a great deal of flexibility in that they can operate in either stand-alone mode or interfaced to a host computer. The following highlights the elements of a typical controller:

- Communicated Mode - Communication to the controller is either Bus-based or through a serial port. In either case, the controller is capable of receiving high level commands from a host computer and generating the necessary step and direction pulses to the driver. The controller includes an auxiliary I/O for monitoring inputs from external sources such as a Go, Jog, Home or Limit switch. It can also initiate other machine functions through the I/O output pins. The optical interrupters in this case study illustrate the use of a Home or Limit switch.

- Stand-Alone Operation - In a stand-alone mode the controller can operate independent of the host computer. Different motion programs can be stored in program memory and can be initiated from various types of operator interfaces, such as a keypad or switch, or through the auxiliary I/O inputs. In this way, the stepper motor might execute a sophisticated motion profile after the operator presses a simple switch. A stand-alone stepper motor control system is often packaged with a driver and/or power supply and optional encoder feedback for "closed loop" applications that require stall detection and exact motor position compensation.

- Integrated Control - Integrated control means the controller is embedded within the complete system and accepts commands from the host computer "on-line" throughout the entire motion process. Communication, operator interface and the I/O functions are designed as separate elements of the system. Control and management of the motion sequence is done by the host computer. In this case the controller acts as an intelligent peripheral. CNC (computer numerical control) applications are well suited for integrated control because the data input is "dynamic", or changing frequently. In integrated control applications, the microcomputer acts as a low level motor controller.

- Multi-Axis Control - Many motion applications have more than one motor to control. In such cases a multi-axis control system is available. A PC step motor controller card for example, may have up to four controllers (microcomputers) mounted on it; each one connected to a separate driver and motor. Some serial communication multi-axis controllers control up to 32 axes from a single communication port. Some applications require a high degree of synchronization, such as circular or linear interpolation. Here, it may be necessary to coordinate the movement with the central processor. In multi-axis applications that do not require simultaneous motion, where only one motor moves at a time, it is possible to "multiplex" the step and direction pulse from one controller (microcomputer) to multiple drivers.

The microcomputer is a very effective device for sophisticated control of stepper motors. While some microcomputers have A/D converters to read analog signals and pulse width modulated (PWM) outputs to produce analog signals, all have digital on/off ports for interfacing to the stepper motor system. As in the previous case study in on / off control (the solenoid), these digital outputs are all that are required from the microcomputer to produce the continuous motion from stepper motors. Programming the microcomputer involves setting the properties on the port for the desired operation (reading or writing) and setting internal registers for the desired control. As in digital on / off control, considerations for turning power devices on or off can involve simple timing issues or the state of digital sensors.

Modeling Stepper Motors

The following material is provided as a reference. Stepper motors are modeled as part of the general motion control system. This material also illustrates the considerations that enter into stepper motor selection for motion control applications.

Wave Drive Stepping

As briefly discussed above, for a motor that turns S radians per step, the plot of torque versus angular position for the rotor relative to some initial equilibrium position will generally approximate a sinusoid. The actual shape of the curve depends on the pole geometry of both rotor and stator, and neither this curve nor the geometry information is given in the motor data sheets. This information is also seldom available from the motor manufacturer. For permanent magnet and hybrid motors, the actual curve usually looks sinusoidal. For variable reluctance motors, the curve rarely even looks sinusoidal; trapezoidal and even assymetrical sawtooth curves are not uncommon for variable reluctance motors.

For a three-winding variable reluctance or permanent magnet motors with S radians per step, the period of the torque versus position curve will be 3S as illustrated in Figure 13; for a 5-phase permanent magnet motor, the period will be 5S, etc.

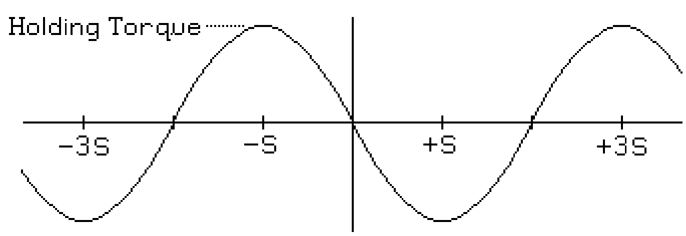


Figure 13. Torque versus Angle for a Stepper Motor (Wave Excitation)

For an ideal 2 winding permanent magnet motor, this can be mathematically expressed as:

$$T = - h \sin(((\pi / 2) / S) \theta)$$

Where: T = torque
h = holding torque
S = step angle, in radians
θ = shaft angle, in radians

Remember, subtle departures from the ideal sinusoid described by this equation are very common. The *single-winding holding torque* of a stepper motor is the peak value of the torque versus angular position curve when the maximum allowed current is flowing through one motor winding. If you attempt to apply a torque greater than this to the motor rotor by hand while maintaining power to one winding, it will rotate.

It is sometimes useful to distinguish between the *electrical shaft angle* and the *mechanical shaft angle*. In the mechanical frame of reference, 2π radians is defined as one full revolution. In the electrical frame of reference, a revolution is defined as one period of the torque versus shaft angle curve. Throughout this section, θ refers to the mechanical shaft angle, and $((\pi / 2) / S)\,\theta$ gives the electrical angle for a motor with 4 steps per cycle of the torque curve.

Assuming that the torque versus angular position curve is a good approximation of a sinusoid, as long as the torque remains below the holding torque of the motor, the rotor will remain within 1/4 period of the equilibrium position. For a two-winding permanent magnet or hybrid motor, this means the rotor will remain within one step of the equilibrium position.

With no power to any of the motor windings, the torque does not always fall to zero. In variable reluctance stepper motors, residual magnetization in the magnetic circuit of the motor may lead to a small residual torque, and in permanent magnet and hybrid stepper motors, the combination of pole geometry and the permanently magnetized rotor may lead to significant torque with no applied power.

The residual (unpowered) torque in a permanent magnet or hybrid stepper motor is frequently referred to as the *cogging torque* or *detent torque* of the motor because a naive observer will frequently guess that there is a detent mechanism of some kind inside the motor. The most common motor designs yield a detent torque that varies sinusoidally with rotor angle, with an equilibrium position at every step and an amplitude of roughly 10 % of the rated holding torque of the motor, but this can vary to values as high as 25 % for a very small motor to a low of 2 % for a mid-sized motor.

Full Stepping, Half Stepping and Microstepping

So long as no part of the magnetic circuit saturates, powering two motor windings simultaneously will produce a torque versus angle curve that is the sum of the torque versus angle curves for the two motor windings taken in isolation. For a two-winding permanent magnet or hybrid motor, the two curves will be S radians out of phase, and if the currents in the two windings are equal, the peaks and valleys of the sum will be displaced S/2 radians from the peaks of the original curves, as shown in Figure 14. This torque curve is also the basis of *half-stepping*.

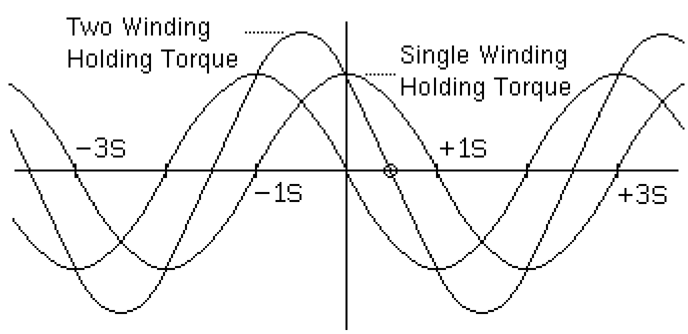


Figure 14. Torque versus Angle for a Stepper Motor (Full Step Excitation)

The *two-winding holding torque* is the peak of the composite torque curve when two windings are carrying their maximum rated current as in full step mode. For common two-winding permanent magnet or hybrid stepper motors, the two-winding holding torque will be:

$$h_2 = \sqrt{2}\ h_1$$

where: h_1 = single-winding holding torque
h_2 = two-winding holding torque

This approximation assumes that no part of the magnetic circuit is saturated and that the torque versus angular position curve for each winding is an ideal sinusoid.

Most permanent-magnet and variable-reluctance stepper motor data sheets quote the two-winding holding torque and not the single-winding figure; in part, this is because it is larger, and in part, it is because the most common full-step controllers always apply power to two windings at once.

If any part of the motor's magnetic circuits is saturated, the two torque curves will not add linearly. As a result, the composite torque will be less than the sum of the component torques and the equilibrium position of the composite may not be exactly S/2 radians from the equilibriums of the original.

Microstepping allows even smaller steps by applying different currents in the two motor windings, as illustrated in Figure 15.

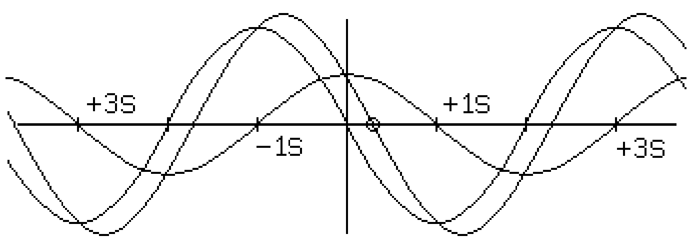


Figure 15. Torque versus Angle for a Stepper Motor (Microstepping)

For a two-winding variable reluctance or permanent magnet motor, assuming non-saturating magnetic circuits, and assuming perfectly sinusoidal torque versus angle curves for each motor winding, the following formula gives the key characteristics of the composite torque curve:

$$h = \sqrt{a^2 + b^2}$$

$$x = (S / (\pi / 2))\ arctan\ (b / a)$$

Where: a = torque applied by winding with equilibrium at 0 radians.
b = torque applied by winding with equilibrium at S radians.
h = holding torque of composite.
x = equilibrium position, in radians.
S = step angle, in radians.

In the absence of saturation, the torques a and b are directly proportional to the currents through the corresponding windings. It is quite common to work with normalized currents and torques, so that the single-winding holding torque or the maximum current allowed in one motor winding is assumed to be unity.

Friction and the Dead Zone

The torque versus position curve shown in Figure 13 does not take into account the torque the motor must exert to overcome friction. Note that frictional torques may be divided into two categories: static or sliding friction, which requires a constant torque to overcome, regardless of motor velocity, and dynamic friction or viscous drag, which offers a resistance to motion that varies with velocity. Consider the impact of static friction. Suppose the torque needed to overcome the static friction on the driven system is 1/2 the peak torque of the motor, as illustrated in Figure 16.

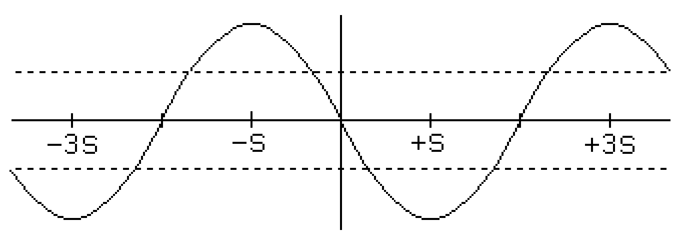


Figure 16. Torque Required to Overcome Static Friction

The dotted lines in Figure 16 show the torque needed to overcome this friction; only that part of the torque curve outside the dotted lines is available to move the rotor. The curve showing the available torque as a function of shaft angle is the difference between these curves, as shown in Figure 17.

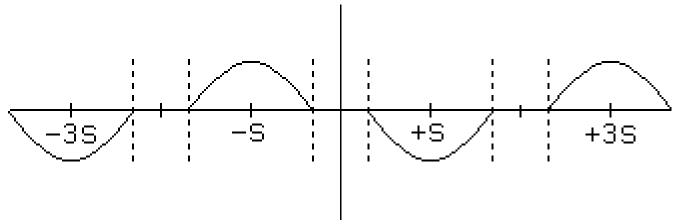


Figure 17. Net Torque Available to Accelerate Rotor

Note that the consequences of static friction are twofold. First, the total torque available to move the load is reduced, and second, there is a *dead zone* about each equilibrium of the ideal motor. If the motor rotor is positioned anywhere within the dead zone for the equilibrium position, the frictional torque will exceed the torque applied by the motor windings, and the rotor will not move. Assuming an ideal sinusoidal torque versus position curve in the absence of friction, the angular width of these dead zones will be:

$$d = 2 \, (S / (\pi / 2)) \, \mathit{arcsin} \, (f / h) = (S / (\pi / 4)) \, \mathit{arcsin} \, (f / h)$$

where: *d* = width of dead zone, in radians
S = step angle, in radians
f = torque needed to overcome static friction
h = holding torque

The important thing to note about the dead zone is that it limits the ultimate positioning accuracy. For the example, where the static friction is 1/2 the peak torque, a 90° per step motor will have dead-zones 60° wide. That means that successive steps may be as large as 150° and as small as 30°, depending on where in the dead zone the rotor stops after each step.

The presence of a dead zone has a significant impact on the utility of microstepping. If the dead zone is x° wide, then microstepping with a step size smaller than x° may not move the rotor at all. Thus, for systems intended to use high-resolution microstepping, it is very important to choose motors with minimal static friction (i.e. good bearings).

Dynamics

Each time you step the motor, you electronically move the equilibrium position S radians. This moves the entire curve illustrated in Figure 13 a distance of S radians, as shown in Figure 18.

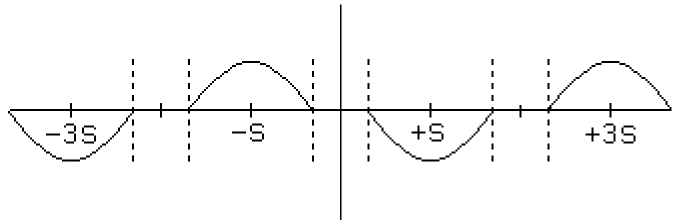


Figure 18. Torque versus Angular Displacement When Turning

The first thing to note about the process of taking one step is that the maximum available torque to accelerate the rotor is at a minimum when the rotor is halfway from one step to the next. This minimum determines the *running torque*, the maximum torque the motor can drive as it steps slowly forward. For common two-winding permanent magnet motors with ideal sinusoidal torque versus angle curves and holding torque h, this will be h / ($2^{1/2}$). If the motor is stepped by powering two windings at a time (i.e. full step excitation), the running torque of an ideal two-winding permanent magnet motor will be the same as the single-winding holding torque.

It should be noted that at higher stepping speeds, the running torque is sometimes called the *pull-out torque*. That is, it is the maximum frictional torque the motor can overcome on a rotating load before the load is pulled out of step by the friction. Some motor data sheets define a second torque figure, the *pull-in torque*. This is the maximum frictional torque that the motor can overcome to accelerate a stopped load to synchronous speed. The pull-in torques documented on stepper motor data sheets are of questionable value because the pull-in torque depends on the moment of inertia of the load used when they were measured, and few motor data sheets document this value.

In practice, there is always some friction, so after the equilibrium position moves one step, the rotor is likely to oscillate briefly about the new equilibrium position and then settle. The resulting trajectory may resemble the one shown in Figure 19.

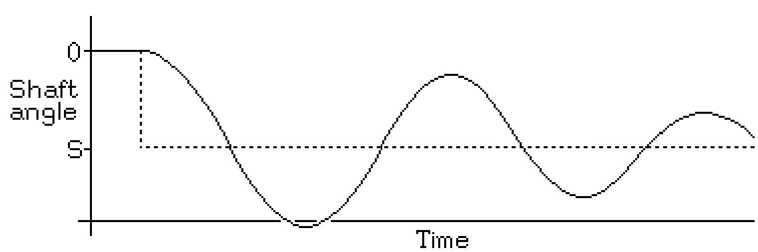


Figure 19. Representative Angular Trajectory versus Time

Here, the trajectory of the equilibrium position (i.e. the final resting point of the rotor if there were no friction) is shown as a dotted line, while the solid curve shows the trajectory of the motor rotor.

Resonance

The resonant frequency of the motor rotor depends on the amplitude of the oscillation; but as the amplitude decreases, the resonant frequency rises to a well-defined small-amplitude frequency. This frequency depends on the step angle and on the ratio of the holding torque to the moment of inertia of the rotor. Either a higher torque or a lower moment will increase the frequency.

Formally, the small-amplitude resonance can be computed as follows. First, recall Newton's second law of motion for angular acceleration:

$$T = J\ A$$

Where: T = torque applied to rotor (N-m)
J = moment of inertia of rotor and load ($kg – m^2$)
A = angular acceleration (rad / sec^2)

It is assumed that, for small amplitudes, the torque on the rotor can be approximated by a linear function of the displacement from the equilibrium position. Therefore, Hooke's law for an ideal torsional spring applies:

$$T = - k\ \theta$$

where: k = the "spring constant" of the system, in torque units per radian
θ = angular position of rotor, in radians

You can equate the two formulas for the torque to get:

$$J\ A = - k\ \theta$$

Recall that acceleration is the second derivitive of position with respect to time:

$$A = d^2\ \theta / dt^2$$

so you can rewrite this above in differential equation form:

$$d^2\ \theta / dt^2 = - (k / J)\theta$$

To solve this, recall that, for:

$$f\ (\ t\ ) = a \sin bt$$

The derivitives are:

$$df(\ t\ )/dt = ab\ cos\ bt$$

$$d^2f(\ t\ )/dt^2 = -ab^2\ sin\ bt = -b^2\ f(t)$$

Note that, throughout this discussion, you assumed that the rotor is resonating. Therefore, it has an equation of motion something like:

$$\theta = a\ sin\ (2\pi\ f\ t)$$

Where: a = angular amplitude of resonance
f = resonant frequency

This is an admissable solution to the above differential equation if you agree that:

$$b = 2\pi\ f$$
$$b^2 = k / J$$

Solving for the resonant frequency f (in rad / sec) as a function of k and J, you get:

$$f = \frac{\sqrt{k / J}}{2\pi}$$

It is important to note that it is the moment of inertia of the rotor plus any coupled load that determines J. The moment of inertia of the motor rotor, in isolation, is irrelevant. Some motor data sheets include information on resonance, but if any load is coupled to the rotor, the resonant frequency will change (decrease).

In practice, this oscillation can cause significant problems when the stepping rate is anywhere near a resonant frequency of the system; the result frequently appears as random and uncontrollable motion.

Resonance and the Ideal Motor

Up to this point, you have dealt only with the small-angle spring constant k for the system. This can be measured experimentally, but if the motor's torque versus position curve is sinusoidal, it is also a simple function of the motor's holding torque. Recall that:

$$T = -\ h\ sin\ (\ ((\pi / 2) / S)\ \theta)$$

The small angle spring constant k is the negative derivitive of T at the origin.

$$k = -\ dT / d\theta = -\ (-\ \boldsymbol{h}\ ((\pi / 2) / S)\ cos\ (\ 0\ )\ ) = (\pi / 2)\ (h / S)$$

Substituting this into the formula for frequency, you get:

$$f = \frac{\sqrt{\frac{(\pi/2)(h/S)}{\square J}}}{2\pi}$$

Given that the holding torque and resonant frequency of the system are easily measured, the easiest way to determine the moment of inertia of the moving parts in a system driven by a stepper motor is indirectly from the above relationship.

$$J = h / (8 \pi f^2 S)$$

For practical purposes, it is usually not the torque or the moment of inertia that matters for a product design, but rather, the maximum sustainable acceleration. Conveniently, this is a simple function of the resonant frequency. Starting again with the Newton's law for angular acceleration:

$$A = T / J$$

You can substitute the above formula for the moment of inertia as a function of resonant frequency, and then substitute the maximum sustainable running torque as a function of the holding torque to get:

$$A = \frac{h/\sqrt{2}}{h/(8\pi f^2 S)} = \frac{(8\pi f^2 S)}{\sqrt{2}}$$

Measuring acceleration in steps per second^2 instead of in radians per second^2, this simplifies to:

$$A_{steps} = \frac{A}{S} = \frac{(8\pi f^2)}{\sqrt{2}}$$

Thus, for an ideal motor with a sinusoidal torque versus rotor position function, the maximum acceleration in steps per second squared is a function of the resonant frequency of the motor with a rigidly coupled load.

Recall that for a two-winding permanent-magnet or variable-reluctance motor, with an ideal sinusoidal torque-versus-position characteristic, the two-winding holding torque is a simple function of the single-winding holding torque:

$$h_2 = \sqrt{2}\ h_1$$

Where: h_1 = single-winding holding torque
h_2 = two-winding holding torque

Substituting this into the formula for resonant frequency, you can find the ratios of the resonant frequencies in these two operating modes:

$$f_1 = (h_1 / \ldots)^{0.5}$$

$$f_2 = (h_2 / \ldots)^{0.5} = (2^{0.5} h_1 / \ldots)^{0.5} = 2^{0.25} (h_1 / \ldots)^{0.5} = 2^{0.25} f_1 = 1.189 f_1$$

This relationship only holds if the torque provided by the motor does not vary appreciably as the stepping rate varies between these two frequencies.

In general, as will be discussed, the available torque will tend to remain relatively constant up until some cutoff stepping rate, and then it will fall. Therefore, this relationship only holds if the resonant frequencies are below this cutoff stepping rate. At stepping rates above the cutoff rate, the two frequencies will be closer to each other.

If a rigidly mounted stepper motor is rigidly coupled to a frictionless load and then stepped at a frequency near the resonant frequency, energy will be pumped into the resonant system, and the result of this is that the motor will literally lose control. There are three basic ways to deal with this problem:

- Controlling resonance in the mechanism

Use of elastomeric motor mounts or elastomeric couplings between motor and load can drain energy out of the resonant system, preventing energy from accumulating to the extent that it allows the motor rotor to escape from control. Viscous damping can be used. Here, the damping will not only draw energy out of the resonant modes of the system, but it will also subtract from the total torque available at higher speeds. Magnetic eddy current damping is equivalent to viscous damping and sometimes used.

Figure 20 illustrates the use of elastomeric couplings and viscous damping in two typical stepper motor applications, one using a lead screw to drive a load, and the other using a cable drive:

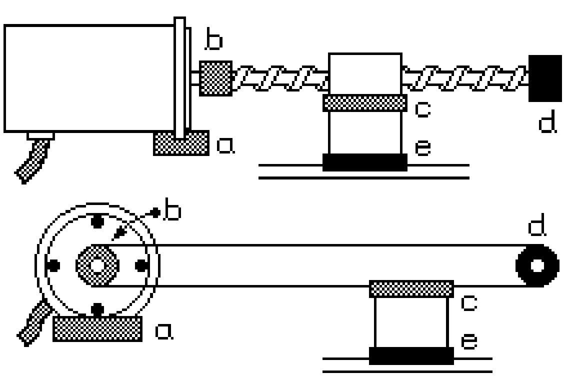


Figure 20. Using Elastomeric Couplings to Control Resonance

In Figure 20, the elastomeric motor mounts are shown at a and elastomeric couplings between the motor and load are shown at b and c. The end bearing for the lead screw or tendon, at d, offers an opportunity for viscous damping, as do the ways on which the load slides, at e. Even the friction found in sealed ball bearings or teflon on steel slide bearings can provide enough damping to prevent resonance problems.

- Controlling resonance in the low-level drive circuitry

A resonating motor rotor will induce an alternating voltage in the motor windings. If some motor winding is not currently being driven, shorting this winding will impose a drag on the motor rotor that is exactly equivalent to using a magnetic eddy current damper.
If some motor winding is currently being driven, the AC voltage induced by the resonance will tend to modulate the current through the winding. Clamping the motor current with an external inductor will counteract the resonance.

- Controlling resonance in the high-level control system

The high-level control system can avoid driving the motor at known resonant frequencies, accelerating and decelerating through these frequencies and never attempting sustained rotation at these speeds. Recall that the resonant frequency of a motor in half-stepped mode will vary by up to 20% from one half-step to the next (since half stepping is a combination of wave drive and full stepping). As a result, half-stepping pumps energy into the resonant system less efficiently than full stepping. Furthermore, when operating near these resonant frequencies, the motor control system may preferentially use only the two-winding half steps when operating near the single-winding resonant frequency, and only the single-winding half steps when operating near the two-winding resonant frequency. Figure 21 illustrates this:

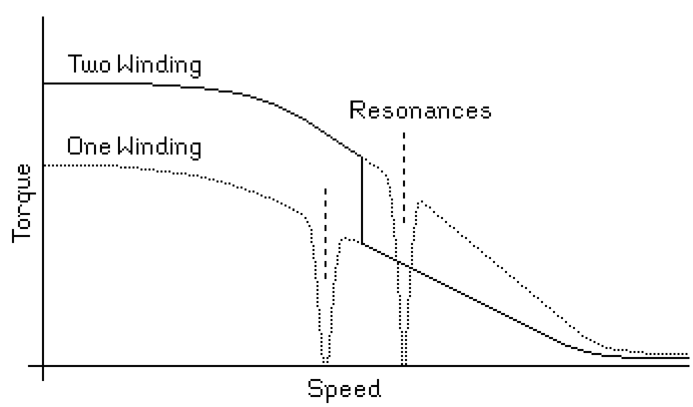


Figure 21. Controlling Resonance by Controlling Stepping Speed

The solid line in Figure 21 shows the operating torque achieved by a control scheme that delivers useful torque over a wide range of speeds despite the fact that the available torque drops to zero at each resonance in the system. This solution is particularly effective if the resonant frequencies are sharply defined and well separated. This will be the case in minimally damped systems operating well below the cutoff speed defined in the next section.

Torque versus Speed

An important consideration in designing high-speed stepper motor controllers is the effect of the inductance of the motor windings. As with the torque versus angle information, this is often poorly documented in motor data sheets, and indeed, for variable reluctance stepper motors, it is not a constant. The inductance of the motor winding determines the rise and fall time of the current through the windings (recall the characteristics of an inductor and resistor in series). While you might hope for a square-wave plot of current versus time, the inductance causes an exponential rise and fall, as illustrated in Figure 22:

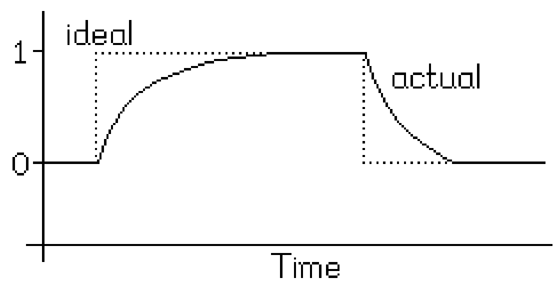


Figure 22. Current versus Time Showing the Effects of Inductance

The details of the current-versus-time function through each winding depend as much on the drive circuitry as they do on the motor itself. It is quite common for the time constants of these exponentials to differ because of the driver. The rise time is determined by the drive voltage and drive circuitry, while the fall time depends on the circuitry used to dissipate the stored energy in the motor winding.

At low stepping rates, the rise and fall times of the current through the motor windings has little effect on the motor's performance, but at higher speeds, the effect of the inductance of the motor windings is to reduce the available torque, as shown in Figure 23:

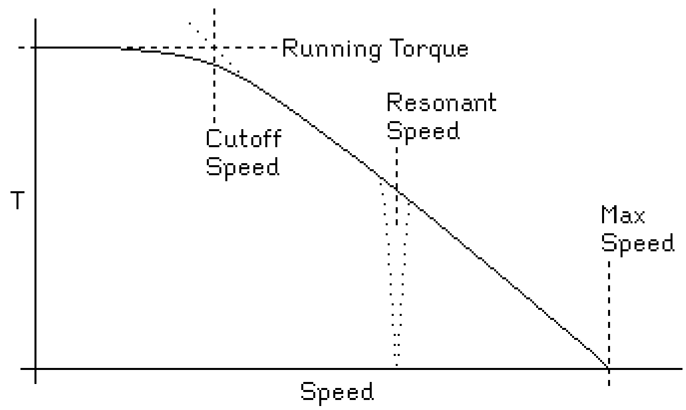


Figure 23. Reduction in Available Torque at High Speeds Because of Inductance Effects

The motor's *maximum speed* is defined as the speed at which the available torque falls to zero. Measuring maximum speed can be difficult when there are resonance problems, because these cause the torque to drop to zero prematurely. The *cutoff speed* is the speed above which the torque begins to fall. When the motor is operating below its cutoff speed, the rise and fall times of the current through the motor windings occupy an insignificant fraction of each step, while at the cutoff speed, the step duration is comparable to the sum of the rise and fall times. Note that a sharp cutoff is rare, and therefore, statements of a motor's cutoff speed are, of necessity, approximate.

The details of the torque versus speed relationship depend on the details of the rise and fall times of the currents in the motor windings, and these depend on the motor control system and driver as well as the motor. Therefore, the cutoff speed and maximum speed for any particular motor depend, in part, on the control system. The torque versus speed curves published in motor data sheets occasionally come with documentation of the motor controller and driver used to obtain that curve, but this is far from universal practice.

Similarly, the resonant speed depends on the moment of inertia of the entire rotating system, not just the motor rotor, and the extent to which the torque drops at resonance depends on the presence of mechanical damping and on the nature of the control system. Some published torque versus speed curves show very clear resonances without documenting the moment of inertia of the hardware that may have been attached to the motor shaft in order to make torque measurements.

The torque versus speed curve shown in Figure 23 is typical of the simplest of control systems. More complex control systems sometimes introduce electronic resonances that act to increase the available torque above the motor's low-speed torque. A common result of this is a peak in the available torque near the cutoff speed.

Electromagnetic Issues

In a permanent magnet or hybrid stepper motor, the magnetic field of the motor rotor changes with changes in shaft angle. The result of this is that turning the motor rotor induces an AC voltage in each motor winding. This is called the *counter EMF* or *back EMF* because the voltage induced in each motor winding is always in phase with and opposes the ideal waveform required to turn the motor in the same direction. Both the frequency and amplitude of the counter EMF increase with rotor speed, and therefore, counter EMF also contributes to the decline in torque with increased stepping rate.

Variable reluctance stepper motors also induce the equivalent of a counter EMF. This is because, as the stator winding pulls a tooth of the rotor towards its equilibrium position, the reluctance of the magnetic circuit declines. This decline increases the inductance of the stator winding, and this change in inductance produces a decrease in the current through the winding in order to conserve energy. This decrease is equivalent to a back EMF.

The reactance (inductance and resistance) of the motor windings limits the current flowing through them. Thus, by Ohm's law, increasing the voltage will increase the current, and therefore increase the available torque. The increased voltage also serves to overcome the back EMF induced in the motor windings, but the voltage cannot be increased arbitrarily. Thermal, magnetic and electronic considerations all serve to limit the useful torque that a motor can produce. The R/L driver discussed above effectively increases the current in the motor winding by increasing the applied voltage and putting an external resistor in series with the motor winding.

The heat expelled by the motor windings is due to both simple resistive losses, eddy current losses, and hysteresis losses. If this heat is not conducted away from the motor adequately, the motor windings will overheat. The simplest failure this can cause is insulation breakdown, but it can also heat a permanent magnet rotor to above its curie temperature, the temperature at which permanent magnets lose their magnetization. This is a particular risk with many modern high strength magnetic alloys.

Even if the motor is attached to an adequate heat sink, increased drive voltage will not necessarily lead to increased torque. Most motors are designed so that, with the rated current flowing through the windings, the magnetic circuits of the motor are near saturation. Increased current will not lead to an appreciably increased magnetic field in such a motor.

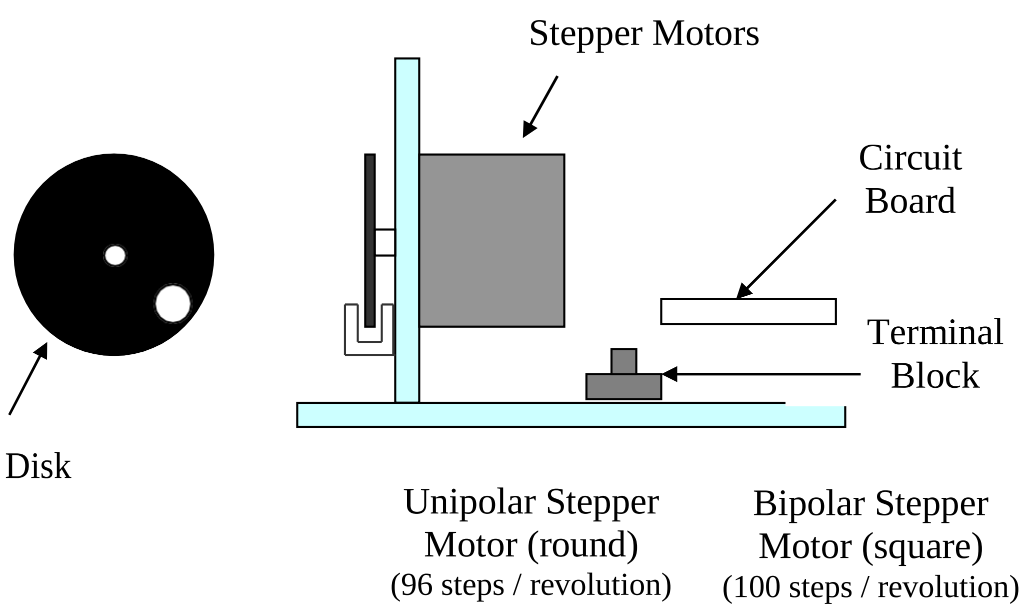
Given a drive system that limits the current through each motor winding to the rated maximum for that winding, but uses high voltages to achieve a higher cutoff torque and higher torques above cutoff, there are other limits that come into play. At high speeds, the motor windings must, of necessity, carry high frequency AC signals. This leads to eddy current losses in the magnetic circuits of the motor, and it leads to skin effect losses in the motor windings. Motors designed for very high speed operation should, therefore, have magnetic structures using very thin laminations or even nonconductive ferrite materials, and they should have small gauge wire in their windings to minimize skin effect losses. Common high torque motors have large-gauge motor windings and coarse core laminations, and at high speeds, such motors can easily overheat and should therefore be derated accordingly for high-speed operation.

It is also worth noting that the best way to demagnetize something is to expose it to a high frequency-high amplitude magnetic field. Running the control system to spin the rotor at high speed when the rotor is actually stalled, or spinning the rotor at high speed against a control system trying to hold the rotor in a fixed position will both expose the rotor to a high amplitude high-frequency field. If such operating conditions are common, particularly if the motor is run near the curie temperature of the permanent magnets, demagnetization is a serious risk and the field strengths (and expected torques) should be reduced accordingly.

The goal in the fourth case study is to provide an understanding of the issues and techniques for stepper motor control using an embedded microcomputer.

Introduction:

This lab will investigate stepper motor control with a microcomputer using a simple laboratory test fixture. The test fixture, shown in Figure 24 below, includes two 12 Volt stepper motors and two sets of optical interrupters. Both stepper motors are of permanent magnet type. The square stepper motor has a bipolar winding and the round motor has a unipolar winding. These should be apparent from the number of wires. When a 12 Volt signal is applied across a stepper motor winding, the stepper motor armature will align with that pole at the proper magnetic polarization. To have each of the motors rotate, the voltage signals must be switched to different windings with the proper sequence and polarization. This was discussed in more detail for each stepper motor previously. We will operate the stepper motors using the high current 13.8 Volt supply.



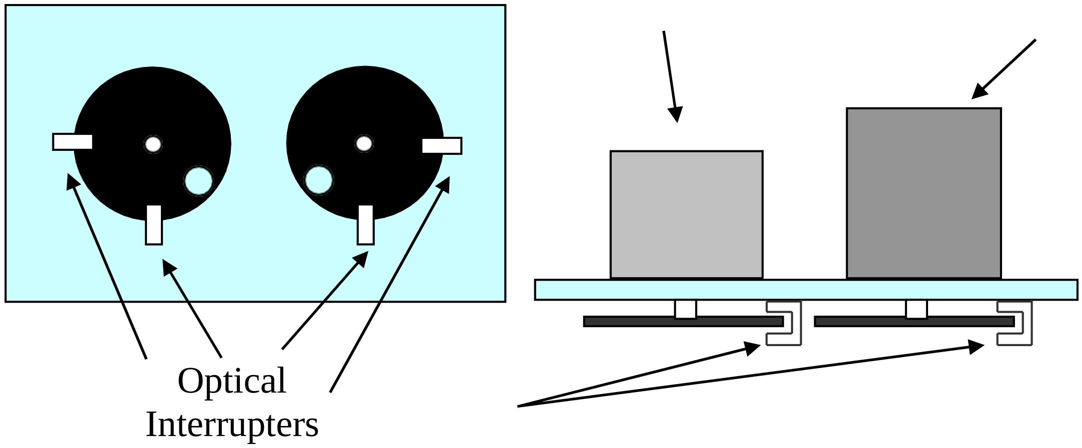


Figure 24. Stepper Motor Test Fixture

The ports assigned to each optical interrupter is shown in Figure 25.

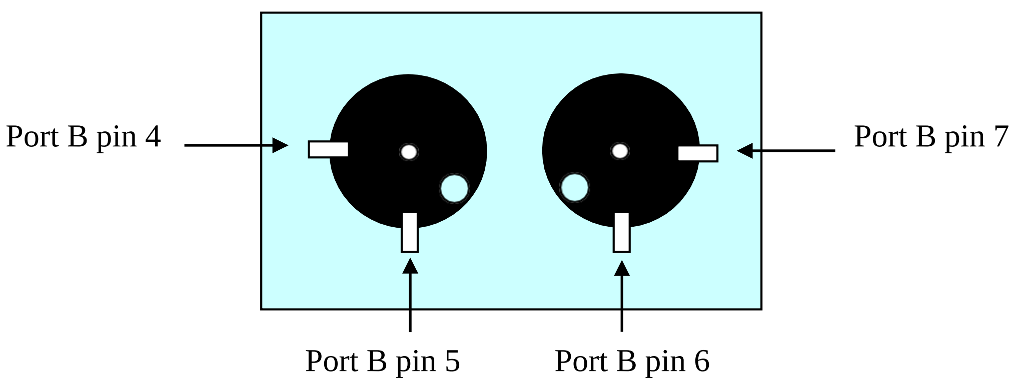


Figure 25. Optical Interrupter Showing Port Pins

An optical interrupter is shown schematically in Figure 26. One leg of the interrupter encases an infrared LED. When current flows through the LED, it emits an infrared light which is directed across the opening of the interrupter. The other leg of the interrupter encases a photodiode. This is similar to the scheme used for the magnetic levitation sensor but the interrupter has both the emitter and detector in a single package. When light enters the photodiode (indicated by the diagonal arrows), the device conducts current between the anode (at the top) and the cathode (at the bottom). The device used in this case study is somewhat more complex as shown in Figure 27. It contains additional circuitry that produces a digital hi output when the interrupter is open and a digital lo output when the interrupter is blocked.

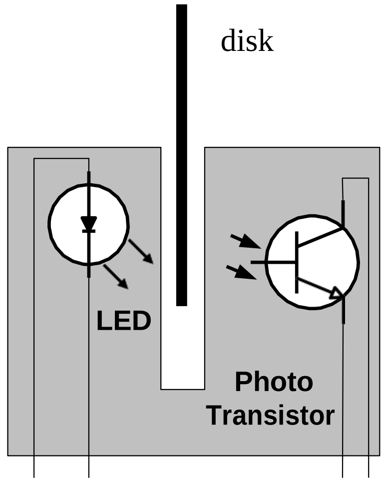


Figure 26. Optical Interrupter

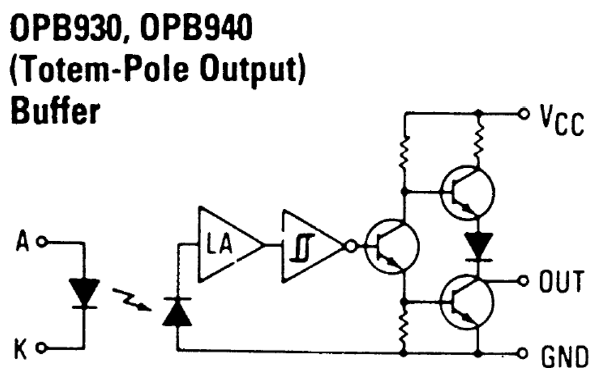


Figure 27. Optical Interrupter Schematic

To use the interrupter, the disk connected to the stepper motor armature typically blocks the path of the light from the LED to the photodiode. This is shown in Figure 24 and 26. When the disk blocks the light, no current passes through the photodiode; when the hole in the disk is positioned in the opening, the light from the LED can pass to the photodiode and the current flows again. The interrupter will operate using 5 Volts (so that it is compatible with the microcomputer which operates on 5 Volts) and requires 1 resistor. The resistor is placed in series with the LED to limit the current flowing through what is effectively a diode. The resistor is chosen to give a sufficient amount of current to operate the device. The device produces a digital output (also called totem-pole) and thus does not require the comparator circuit needed for the digital control (solenoid) case study.

The “user interface” for the program will be the octal switch and green and red pushbutton switches used in the digital control (solenoid) case study. The program will read the octal switches when the green button is pressed and determine the required mode of operation. Three different modes will be programmed. The red pushbutton will determine the operation within a mode. It is expected that much of the code for mode checking used for the digital control case study can be reused.

Laboratory Procedure:

The following circuits have been constructed; nothing additional is required. You will connect to the circuit board attached to the stepper motor system using the ribbon cable from the microcomputer board. For your code, you should understand how each circuit works.

Circuits Constructed

The driver for the unipolar stepper motor is shown in Figure 28. Four transistors will be used to energize the stepper motor. The transistors (MTP 52) are field effect transistors (FETs). They work similar to the bipolar transistors used in the digital control case study except that they switch when a voltage is applied to the gate of the FET rather than a current supplied to the base of a bipolar transistor. FETs are used so that very little current is required to switch the transistor. They are therefore more compatible with microcomputer ports. Bringing the output pin of the microcomputer hi will cause the FET to switch on.

The connection to the microcomputer will be such that if you turn on the Port D pins in order (i.e. pin 0, pin 1, pin 2, pin 3), the unipolar stepper motor will rotate clockwise.

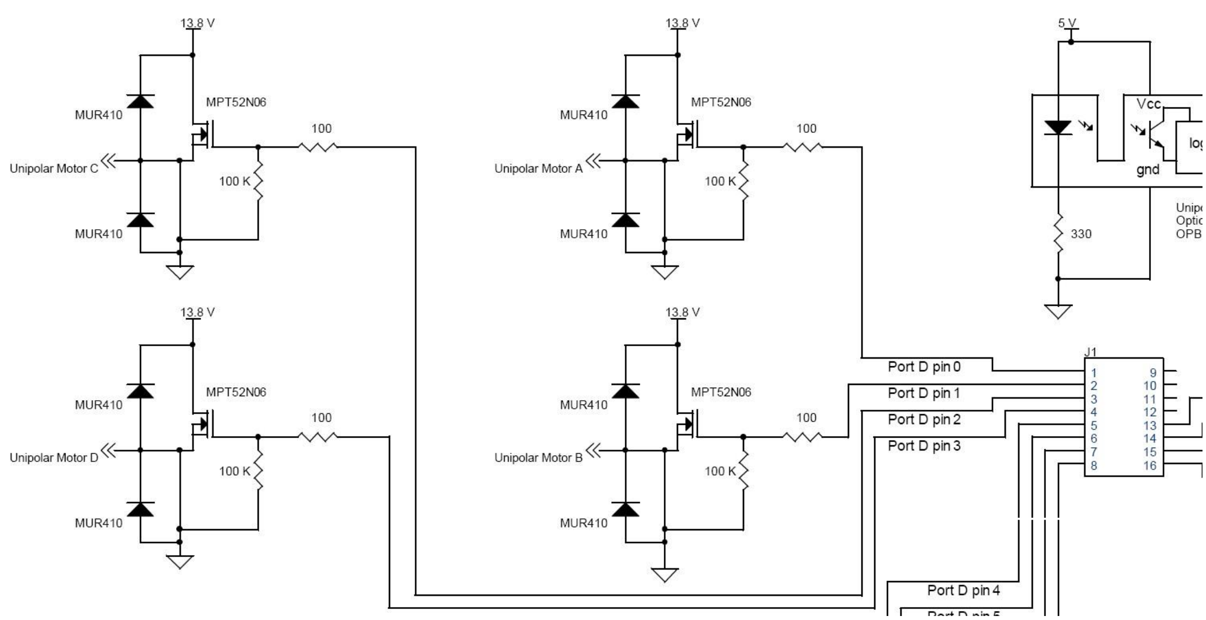


Figure 28. Driver for Unipolar Stepper Motor

The connection for the bipolar stepper motor is shown in Figure 29. A stepper motor driver (UC3770) will be used for each phase of the stepper motor windings. The UC3770 is designed to control and drive the current in one winding of a bipolar stepper motor. The circuit consists of a TTL (transistor-transistor logic) compatible logic input, a current sensor, a monostable oscillator and an output stage with built-in protection diodes. Two UC3770s and a few external components form a complete control and drive unit for a microcomputer controlled stepper motor system. A block diagram for the UC3770 part is shown below in Figure 30.

The connection to the microcomputer will be such that if you turn on the Port D pin 4 hi followed by 6 hi, the stepper motor will rotate clockwise. You should determine the state of pins 5 and 7 from the description below.

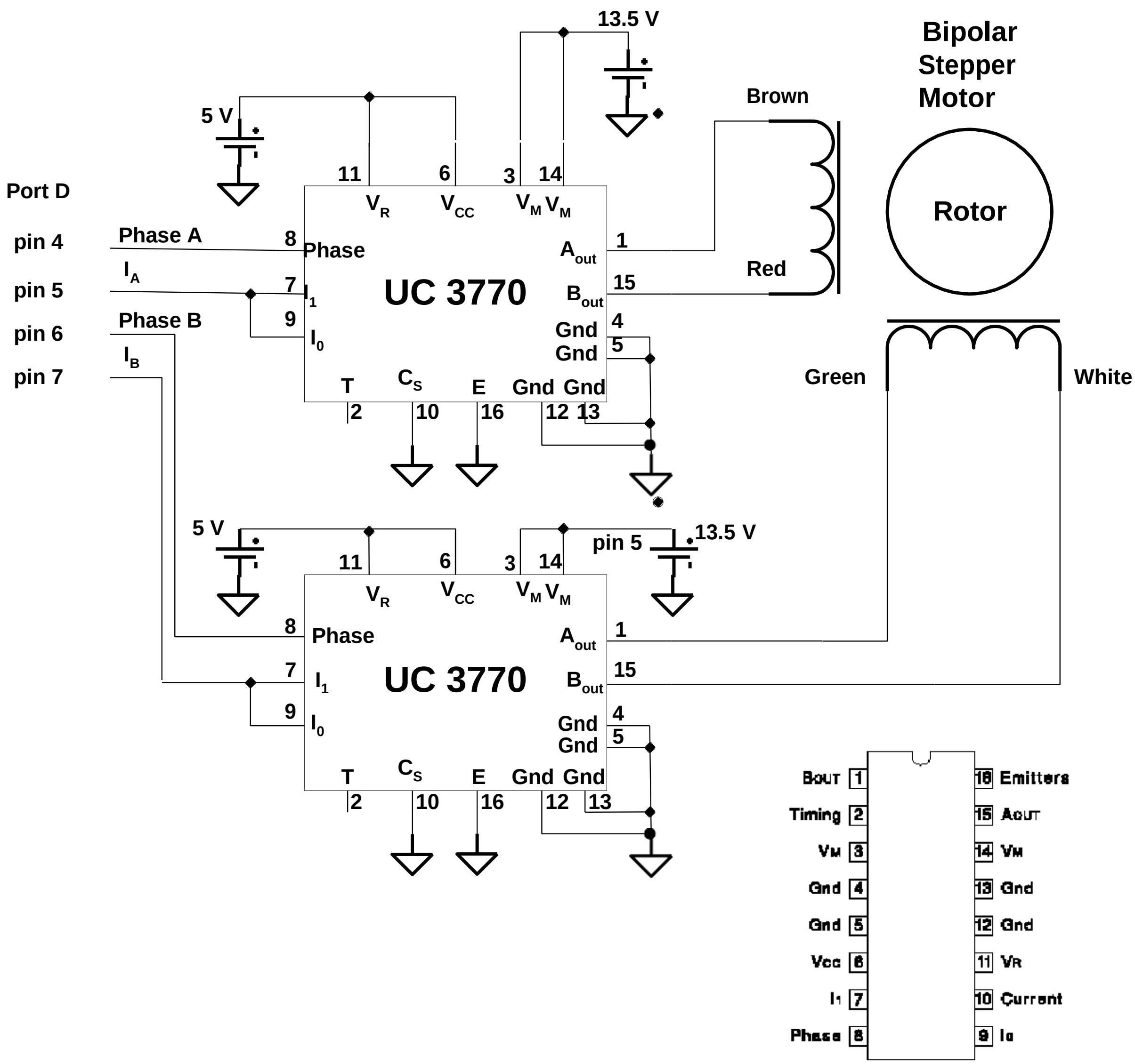


Figure 29. Driver for Bipolar Stepper Motor

The following is a brief description of the capabilities of the UC3770 electronics part. A complete datasheet will be provided. For this case study, only a limited number of these capabilities will be used. The UC3770 drive circuit shown in the block diagram includes the following functions:

- Phase Logic and H-Bridge Output Stage
- Voltage Divider with three Comparators for current control
- Two Logic inputs for Digital current level select
- Monostable oscillator for off time generation

Input Logic: If any of the logic inputs are left open (such as if the port pin is configured as an input), the circuit will treat it as a high level input.

Phase Input: The phase input terminal, pin 8, controls the direction of the current through the motor winding. The Schmidt-Trigger input (a logic circuit which employs positive feedback to provide hysteresis on the input) coupled with a fixed time delay assures noise immunity and eliminates cross conduction (and thus shorting) in the output stage during phase changes. A low level on the phase input will turn Q2 (top right) and Q3 (bottom left) on while a high level will turn Q1 (top left) and Q4 (bottom right) on. (See Figure 31). The logic circuit is similar to Figure 12 in operation, prevent accidentally shorting the power supply.

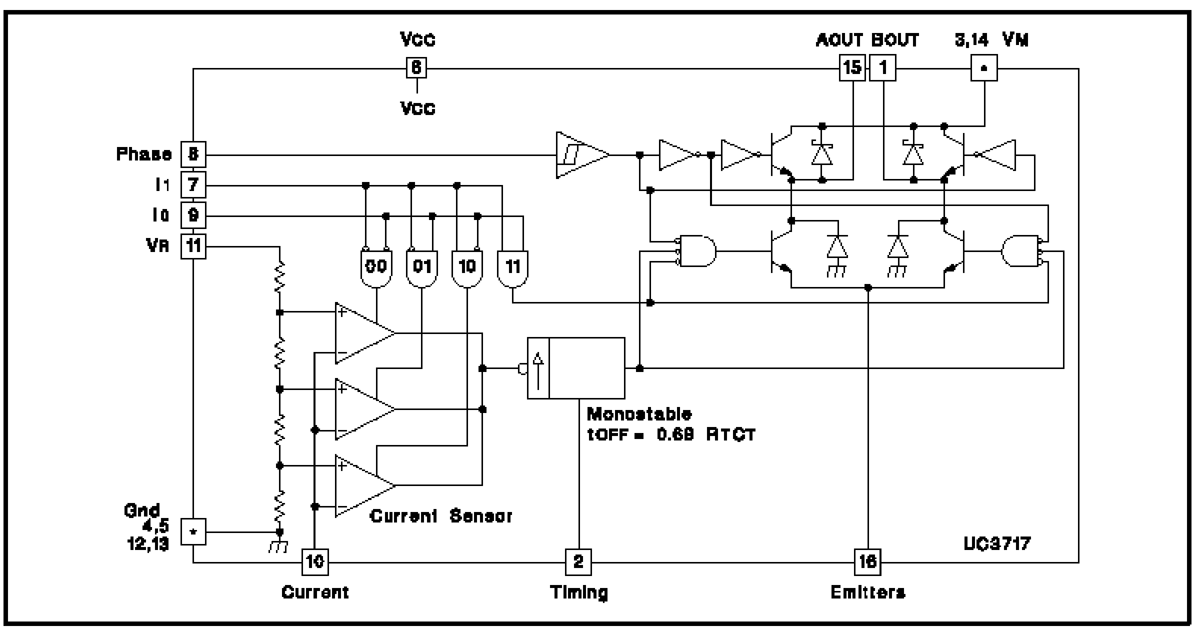


Figure 30. Block Diagram of the UC 3770 Driver

Output Stage: The output stage consists of four Darlington transistors and associated diodes connected in an H-Bridge configuration. The transistors are actually two transistors in a configuration that can be treated like a common transistor. The Darlington configuration is done to increase the effective current gain of the transistor so that very little current into the base of the transistor from the logic gate will cause the transistor to switch on. The diodes are needed to provide a current path when the transistors are being switched. For fast recovery, Schottky type diodes are used across the source transistors. The Schottky diodes allow the current to circulate through the winding while the sink transistors are being switched off. The diodes across the sink transistors in conjunction with the diodes provide the path for the decaying current during phase reversal. (See Figure 31).

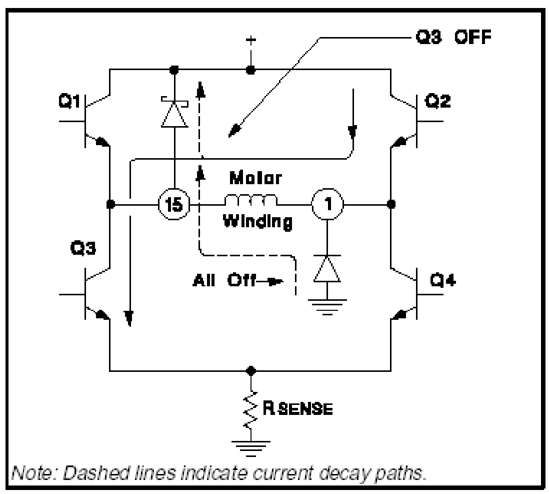


Figure 31. Currents During Phase Reversal

Current Control: The voltage divider, comparators and monostable oscillator provide a means for current sensing and control. This feature is used for microstepping. The two bit input (I0, I1) logic selects the desired comparator and thus the current level. The monostable oscillator controls the off time and therefore the magnitude of the current decrease. The time duration is determined by RT and CT connected to the timing terminal (pin 2). (Note: these are not used for this case study.) The reference terminal (pin 11) provides a means of continuously varying the current for situations requiring microstepping. The relationship between the logic input signals I_0 and I_1 (at pin 7 and 9) in reference to the current level is shown in the table below. The values of the different current levels are determined by the reference voltage together with the value of the external sense resistor R_{SENSE} (pin 16).

I_0	I_1	**Current Level**
0	0	100 %
1	0	60 %
0	1	19 %
1	1	No Current

For this case study, you will be operating the bipolar stepper motor in Full Step mode. From the description given in the previous sections of this case study, you should understand how the microcomputer has to be programmed to provide this. Using the table above and the circuit in Figure 29, you should relate this to the signals that have to be generated at the pins.

Overload Protection: The circuit is equipped with a thermal shutdown function, which will limit the junction temperature by reducing the output current. It should be noted however, that a short circuit of the output is not permitted by the circuit. If your system stops operating it may just be that you are trying to switch the transistors too fast causing them to overheat.

Operation: To turn on the current in a winding, you will use the table above to set the I_0 and I_1 pins so that the current is 100% (full on). The direction of current flow is determined by the phase input (pin 8). By reversing the logic level of the phase input, both active transistors are being turned off and the opposite pair turned on. When this happens the current must first decay to zero before it can reverse. The device takes care of this. The current path is through the two diodes and the power-supply. Refer to Figure 31. To turn off the current in a winding, you will use the table above to set the I_0 and I_1 pins so that the current is 0% (full off). In this case, the logic level on the phase input does not matter.

The inputs are controlled with the microcomputer. The timing diagram in Figure 32 shows the required signal input for a two phase, full step, stepping sequence. Figure 33 shows a one phase, full step, stepping sequence, commonly referred to as wave drive. Figure 34 shows the required input signal for a one phase-two phase stepping sequence called half-stepping.

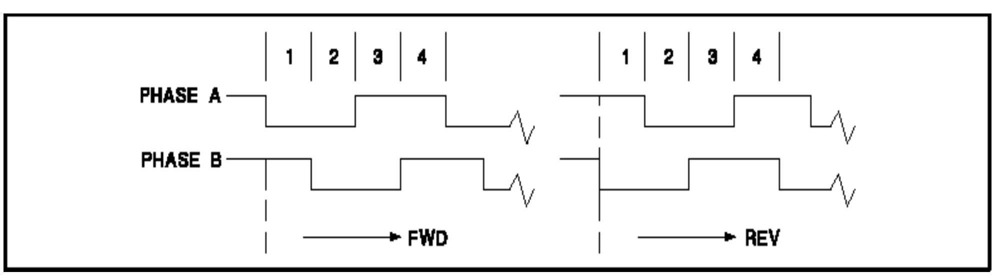


Figure 32. Full Step Sequence

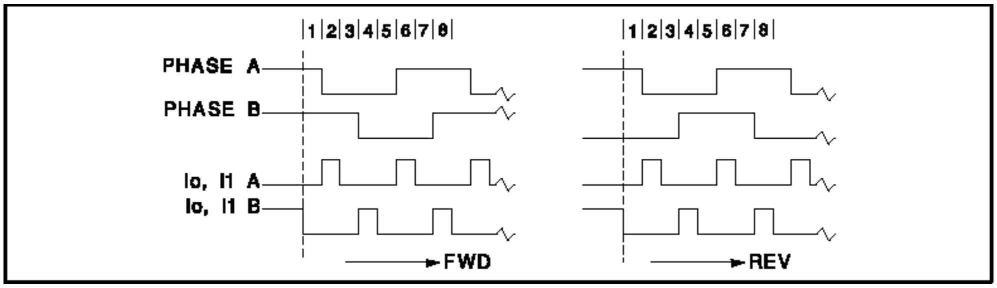


Figure 33. Wave Drive Step Sequence

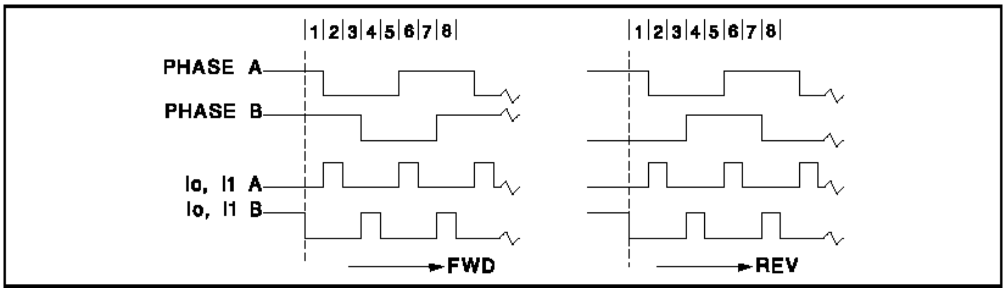


Figure 34. Half Step Sequence

Half-Stepping: In the half step sequence the power input to the motor alternates between one or two phases being energized. In a two-phase motor the electrical phase shift between the windings is 90 degrees. The torque developed is the vector sum of the two windings energized. Therefore when only one winding is energized the torque of the motor is reduced by approximately 30%. This causes a torque ripple and if it is necessary to compensate for this, the VR input can be used to boost the current of the single energized winding.

Ramping: Every drive system has inertia and must be considered in the drive scheme. The rotor and load inertia plays a big role at higher speeds. Unlike the DC motor, the stepping motor is a synchronous motor and does not change its speed due to load variations. Examining typical stepping motors, torque vs. speed curves indicates a sharp torque drop off for the start-stop without error curve, even with a constant current drive. The reason for this is that the torque requirements increase by the square of the speed change, and the power need increases by the cube of the speed change. As it can be seen, for good motor performance controlled acceleration and deceleration should be considered. Alternatively, since time will not be specified in this case study, you should operate the motors at a very low speed step sequence at all times. You may need more than 30 msec between steps to keep synchronization.

General Programming Considerations

In general, the embedded program will operate as follows:

- A memory address will have to be set up. It will hold the state of the program and will be called “**State**”.

- The LED’s connected to Port B will be used to display the State of the program. The lower 4 bits will hold the mode of operation (explained below).

- Upon reset, the program will call an initialization routine called “**init**” (in the function label). Ports will be configured and set for input or output as required. Internal special function registers will be set up as required.

- Initializing the stepper motors requires 2 operations. The two operations have to be done for each motor. For simplicity, they can be done for the motors sequentially.

  - First, the stepper motors have to be synchronized with the step sequence. This is done by simply starting a proper sequence and slowly stepping through it. When the stepper motor rotor lines up with the proper stator pole, it will start to rotate in the proper direction. For the motors, a full step sequence should be used (two poles on at all times). For the bipolar stepper motor, you will need to determine the switching of Phase A and Phase B and I_0 and I_1 to do this (see Figure 32). Begin to rotate the motors in a clockwise direction. **For proper control, once the synchronization is achieved, it is never lost.** This will be discussed in more detail in lecture.

  - Next, the location of the interrupters have to be found. To do this, the program should wait until the horizontal interrupter for each motor goes hi (indicating that the opening in the disk is lined up with the interrupter). The motor should then stop. (Note: the hole in the disk is large and so a number of stepper motor steps will be required to have the interrupter go from low to hi to low again. The home position will be defined as anywhere in this hole.

- The program will then wait until the green pushbutton is pressed. The LED’s will indicate ‘0000’ (status - waiting for start, mode 0) (Note: bit 4 will also be used to indicate an incorrect code as in the solenoid digital control case study. Therefore, the wait state is "correct code, mode 0, no fault" which really is the state of the process since you have not read a mode at this point.) Therefore, nothing happens before the green button is pressed.

- The octal switches connected to Port E can be changed. These three bits will indicate the mode. These will be read when the green pushbutton is pressed and that mode of operation will be started. The LED’s will indicate ‘0bbb’ in binary (status - started, mode bbb). After any change in mode, however, both stepper motors have to be returned to the home position.

- At any time when there is no fault and the motors are in their home position, when the green pushbutton is pressed, the mode bits are read and that mode of operation is engaged. (Remember to display the correct code on the LED's.)

- A fault will be indicated by bit 3 on the LED's. If an incorrect mode (0 or 5 through 7) is indicated on the octal switch, the code will be '1bbb' in binary (status – fault incorrect mode, mode bbb) where bbb will indicate the incorrect mode selected. Only mode faults will be detected. After a fault, pressing the green pushbutton will not cause the bits to be read. The processor must be reset with the reset switch.

- The state of the program should be stored in the "State" internal register. Since the state is essentially the indication on the LED's, the State register can be a copy of the Port B LED's.

Embedded Program Requirements:

The following describes the different modes of operation:

1. **Mode 1 – Basic Incremental Motion**

In mode 1, the microcomputer will rotate the stepper motors between the interrupters sequentially. For this mode, when the red pushbutton is pressed, the microcomputer will cycle a stepper motor between the two interrupters by the shortest path. The motors will then remain at the interrupter position until the red button is pressed again. The two motors will be moved sequentially (i.e. only one motor will move at any time). Full step operation will be used for both motors.

In other words, the motion will look as follows. Both motors start at the horizontal interrupters (the home positions). When the red button is pressed, the unipolar motor will move counterclockwise (the shortest path) to the vertical interrupter and stop. When the red button is pressed again, the bipolar motor will move clockwise (the shortest path) to the vertical interrupter and stop. When the red button is pressed again, the unipolar motor will move clockwise to the horizontal interrupter and stop. Finally, when the red button is pressed one more time, the bipolar motor will move counterclockwise to the horizontal interrupter and stop. The sequence will then start again.

The motion should be smooth. The motors should not back up at any time. This will require you to always keep track of which windings are on.

At any time when the motors have stopped moving, a green button press will switch to another mode. A red button press will continue in this mode.

2. **Mode 2 – Basic Opposed Continuous Motion**

In mode 2, the microcomputer basically controls the motors in full stepping motion continuously with the motors moving in opposite directions (i.e. both motors will be moving at the same time but in opposite directions). Both motors start at the horizontal interrupter position. (Note: depending on the previous state of the motors, you may have to move them to this initial position after a green button press when entering this mode.) After the red button is pressed, both motors are cyclically driven between the two interrupters continuously by the shortest path. This means that the motors are moving in opposite rotational directions (i.e. when the unipolar is moving counterclockwise, the bipolar is moving clockwise). Each of the motors makes a 90^0 rotation of the disk before changing direction. When the rotor indicates that it has reached the correct interrupter, the direction of the motor is switched and it continues to run. If the speeds of the motors are different, the faster motor must wait at the interrupter position until the slower motor reaches it. Full stepping is used for each motor. If the red button is held down as the motors reach the horizontal interrupters (the starting position), the motion is stopped. Otherwise the motion continues. To start the motion again, the red button must be released and then pressed and released again. At any time when the motors have stopped moving, a green button press will switch to another mode. A red button press will continue in this mode.

The bipolar motor has a 3.6^0 step size (100 steps per revolution). Thus it should require about 25 full steps to go between interrupters. The unipolar motor has a 3.75^0 step size (96 steps per revolution). Thus it should require about 24 full steps to go between interrupters. Although not required, the motion will look smoother if, for example, you make a step of the bipolar motor before moving the unipolar. You should then step the motors synchronously and may require an extra step or two of the bipolar after the unipolar has stopped. (To really move synchronously, you would have to adjust the timing between steps so that the bipolar makes 100 steps in the same time that the unipolar makes 96. This is not necessary.)

3. Mode 3 – Basic Synchronous Continuous Motion

In mode 3, the microcomputer basically controls the motors in full stepping continuously with the motors moving in the same direction (again both motors moving at the same time). The bipolar motor starts at the horizontal interrupter position and the unipolar motor starts at the vertical interrupter position. (Note: depending on the previous state of the motors, you may have to move them to this initial position after a green button press.) After the red button is pressed, both motors are cyclically driven between the two interrupters continuously by the longest path. This means that the motors are moving in the same rotational direction at any given time. Each of the motors makes a 270^0 rotation of the disk before changing direction. When the rotor indicates that it has reached one interrupter, the direction of the motor is switched and it continues to run. If the speeds of the motors are different, the faster motor must wait at the interrupter position until the slower motor reaches it. Full stepping is used for each motor. If the red button is held down as the motors reach the starting position, the motion is stopped. Otherwise the motion continues. To start the motion again, the red button must be released and then pressed and released again. At any time when the motors have stopped moving, a green button press will switch to another mode. A red button press will continue in this mode.

4. **Mode 4 – Basic Opposed Continuous Motion – Wave Drive**

In mode 4, the microcomputer basically controls the motors in wave drive motion the same way that it was done in Mode 2 with full step motion. That is, the motors move continuously in opposite directions (i.e. both motors will be moving at the same time but in opposite directions). Both motors start at the horizontal interrupter position. (Note: depending on the previous state of the motors, you may have to move them to this initial position after a green button press when entering this mode.) After the red button is pressed, both motors are cyclically driven between the two interrupters continuously by the shortest path. This means that the motors are moving in opposite rotational directions (i.e. when the unipolar is moving counterclockwise, the bipolar is moving clockwise). Each of the motors makes a 90^0 rotation of the disk before changing direction. When the rotor indicates that it has reached the correct interrupter, the direction of the motor is switched and it continues to run. If the speeds of the motors are different, the faster motor must wait at the interrupter position until the slower motor reaches it. Wave drive is used for each motor. If the red button is held down as the motors reach the horizontal interrupters (the starting position), the motion is stopped. Otherwise the motion continues. To start the motion again, the red button must be released and then pressed and released again. At any time when the motors have stopped moving, a green button press will switch to another mode. A red button press will continue in this mode.

5. **Mode Changes.**

Modes can be changed whenever the motors have stopped by pressing the green pushbutton. Note, in mode 2, 3 and 4, the red button should be held down prior to the motor reaching the horizontal interrupter position. The motor is then stopped. If the red button is pressed and released, the operation continues in the mode selected. If the green button is pressed, the motors can switch to another mode. Note also that if you switch between modes, you have to initialize the motors at the correct interrupters.

This case study will be coded in C.

It is suggested that you think of the operation as if you were programming in Assembler. Once the logic is worked out, programming it in C will not require much time. Please do not shoot the instructor or TA when you realize how easy it is to program a microcomputer in C.

Successful completion of this case study involves:

- Programming and successfully demonstrating each of the modes.

- Submitting successful C code which adheres to the “Software Standard”, is efficient and uses comments liberally. Grading specifics are given in the Software Standard. (Note that the software standard for C allows more flexibility in layout.) Elegance of the program, its efficiency in program size and execution time, will be considered in the grade.

- Answering the following questions.

Questions:

a) Why should there be a difference between the time required for a 200 step per revolution stepper motor to take its first step from a stopped position and the time required to take its 400^{th} step (i.e. after making 2 full revolutions) in a 4 revolution motion?

b) Assuming that the equivalent circuit for the stepper motor winding is simply an inductor and resistor in series, write the differential equation which relates the current to the applied voltage (i.e. assume that the voltage is the input and the current is the output). Write the transfer function for this (i.e. derive the admittance, the inverse of impedance) and the frequency response.

c) List five examples of stepper motor control applications in consumer products or industrial processes (it is fair to check the internet).

d) One possible fault in stepper motor systems is that something is preventing the motors from turning. In words, discuss how you would modify the mode 3 code to detect this fault and stop the process.

e) List sources that you checked outside of the lectures to complete the programs for this case study (such as the Microchip web site or references for C).

High Performance Stepper Motor Drive Circuit

FEATURES

- Full-Step, Half-Step and Micro-Step Capability.
- Bipolar Output Current up to 2A.
- Wide Range of Motor Supply Voltage: 10–50V
- Low Saturation Voltage
- Wide Range of Current Control: 5mA–2A.
- Current Levels Selected in Steps or Varied Continuously.
- Thermal Protection and Soft Intervention.

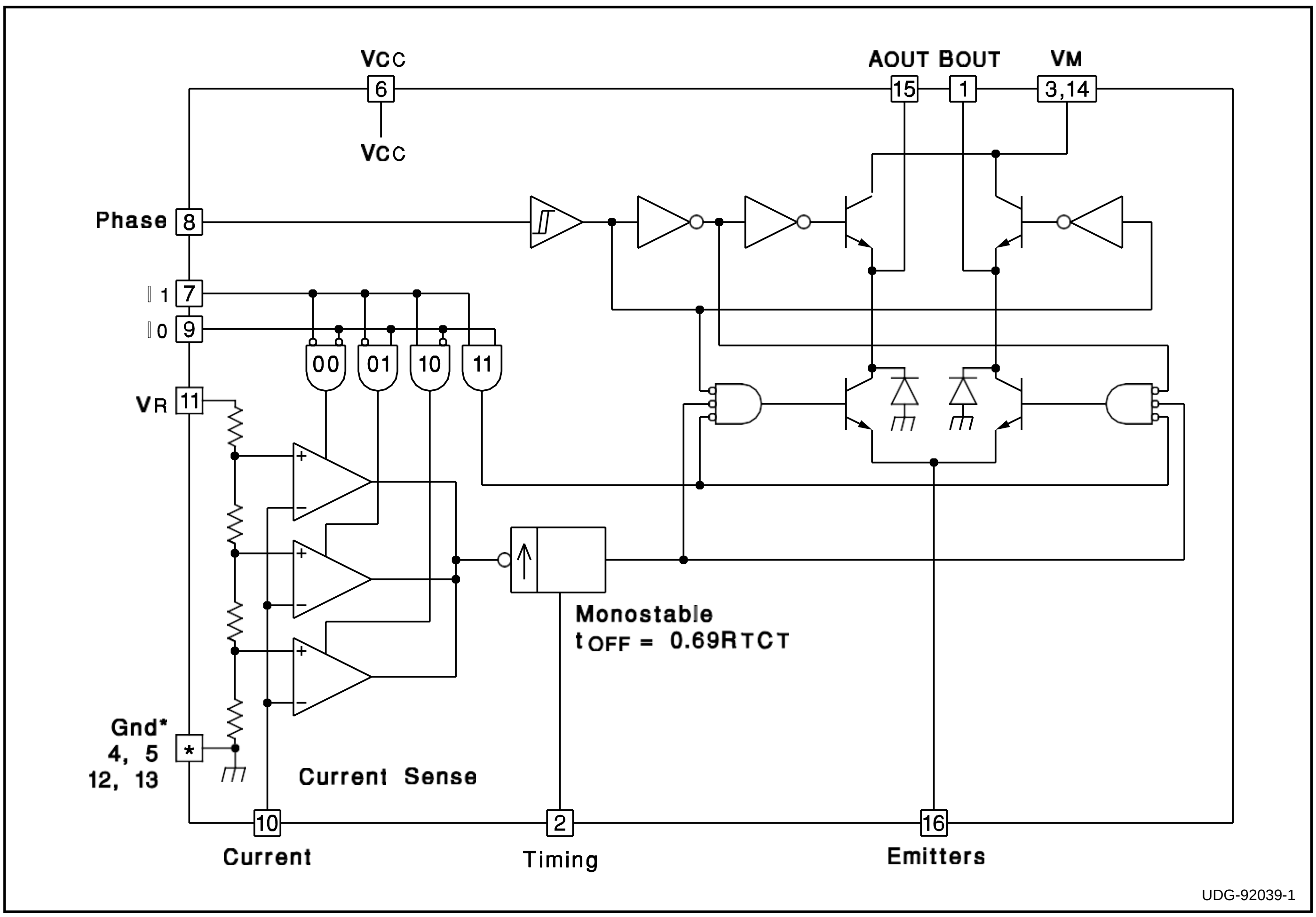
DESCRIPTION

The UC3770A and UC3770B are high-performance full bridge drivers that offer higher current and lower saturation voltage than the UC3717 and the UC3770. Included in these devices are LS-TTL compatible logic inputs, current sense, monostable, thermal shutdown, and a power H-bridge output stage. Two UC3770As or UC3770Bs and a few external components form a complete microprocessor-controllable stepper motor power system.

Unlike the UC3717, the UC3770A and the UC3770B require external high-side clamp diodes. The UC3770A and UC3770B are identical in all regards except for the current sense thresholds. Thresholds for the UC3770A are identical to those of the older UC3717 permitting drop-in replacement in applications where high-side diodes are not required. Thresholds for the UC3770B are tailored for half stepping applications where 50%, 71%, and 100% current levels are desirable.

The UC3770A and UC3770B are specified for operation from 0°C to 70°C ambient.

BLOCK DIAGRAM



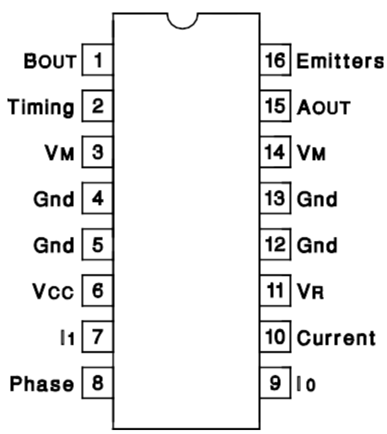
ABSOLUTE MAXIMUM RATINGS

Logic Supply Voltage, VCC 7V
Output Supply Voltage, VMM 50V
Logic Input Voltage (Pins 7, 8, 9) 6V
Analog Input Voltage (Pin 10) VCC
Reference Input Voltage (Pin 11) 15V
Logic Input Current (Pins 7, 8, 9) . . . . –10mA
Analog Input Current (Pins 10, 11) . . . . –10mA
Output Current (Pins 1, 15) . . . . ± 2A
Junction Temperature, TJ . . . . +150°C

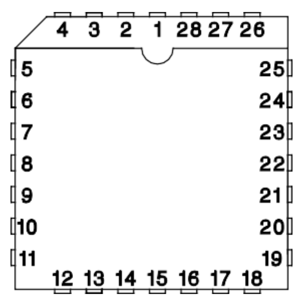
Note 1: All voltages are with respect to Gnd (DIL Pins 4, 5, 12, 13); all currents are positive into, negative out of the specified terminal.
Note 2: Consult Unitrode Integrated Circuits databook for thermal limitations and considerations of packages.

CONNECTION DIAGRAMS

DIL-16 (Top View)
J Or N Package



PLCC-28 (Top View)
Q Package



PACKAGE PIN FUNCTION	
FUNCTION	**PIN**
Gnd	1-3
VM	4
N/C	5
AOUT	6
N/C	7
Emitters	8
Gnd	9
BOUT	10
Timing	11
VM	12
Gnd	13-17
VCC	18
I1	19
Phase	20
I0	21
N/C	22
Current	23
VR	24
N/C	25-27
Gnd	28

ELECTRICAL CHARACTERISTICS: (All tests apply with V_M = 36V, V_{CC} = 5V, V_R = 5V, No Load, and 0°C<T_A<70°C, unless otherwise stated, $T_A = T_J$.)

		UC3770A			UC3770B			
PARAMETER	**TEST CONDITIONS**	**MIN**	**TYP**	**MAX**	**MIN**	**TYP**	**MAX**	**UNITS**
Supply Voltage V_M (Pins 3, 14)		10		45	10		45	V
Logic Supply Voltage V_{CC} (Pin 6)		4.75	5	5.3	4.75	5	5.3	V
Logic Supply Current I_{CC} (Pin 6)	$I_O = I_1$ = H, I_M = 0		15	25		15	25	mA
	$I_O = I_1$ = L, I_M = 0		18	28		18	28	mA
	$I_O = I_1$ = H, I_M = 1.3A		33	40		33	40	mA
Thermal Shutdown Temperature			+170			+170		°C
Logic Threshold (Pins 7, 8, 9)		0.8		2.0	0.8		2.0	V
Input Current Low (Pin 8)	V_I = 0.4V			-100			-100	µA
Input Current Low (Pins 7, 9)	V_I = 0.4V			-400			-400	µA
Input Current High (Pins 7, 8, 9)	V_I = 2.4V			10			10	µA
Comparator Threshold (Pin 10)	V_R = 5V, I_0 = L, I_1 = L	400	415	430	400	415	430	mV
	V_R = 5V, I_0 = H, I_1 = L	240	255	265	290	300	315	mV
	V_R = 5V, I_0 = L, I_1 = H	70	80	90	195	210	225	mV
Comparator Input Current (Pin 10)				±20			±20	µA
Off Time	R_T = 56k, C_T = 820pF	25	30	35	25	30	35	ms

ELECTRICAL CHARACTERISTICS (cont.): (All tests apply with V_M = 36V, V_{CC} = 5V, V_R = 5V, No Load, and 0°C<T_A<70°C, unless otherwise stated, T_A = T_J.)

		UC3770A			UC3770B			
PARAMETER	**TEST CONDITIONS**	**MIN**	**TYP**	**MAX**	**MIN**	**TYP**	**MAX**	**UNITS**
Turn Off Delay				2			2	ms
Sink Driver Saturation Voltage	I_M = 1.0A			0.8			0.8	V
	I_M = 1.3A			1.3			1.3	V
Source Driver Saturation Voltage	I_M = 1.0A			1.3			1.3	V
	I_M = 1.3A			1.6			1.6	V
Output Leakage Current	V_M = 45V			100			100	μA

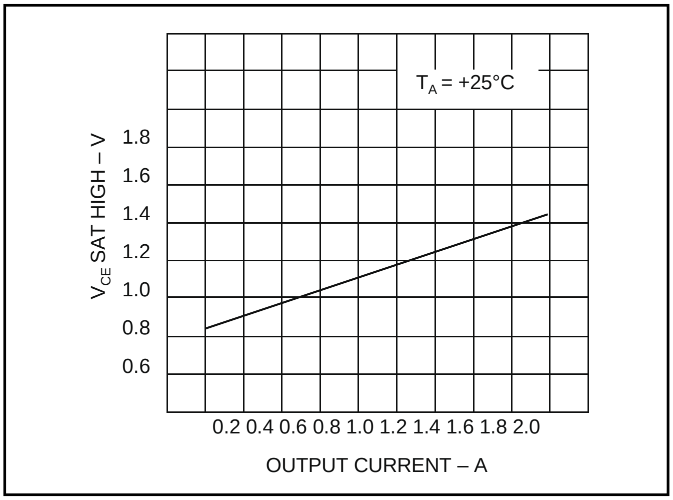


Figure 1. Typical source saturation voltages vs. load current

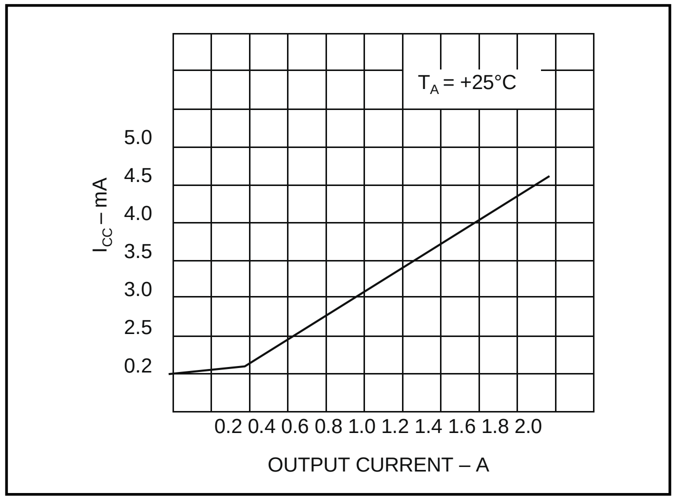


Figure 3. Typical supply current vs. load current.

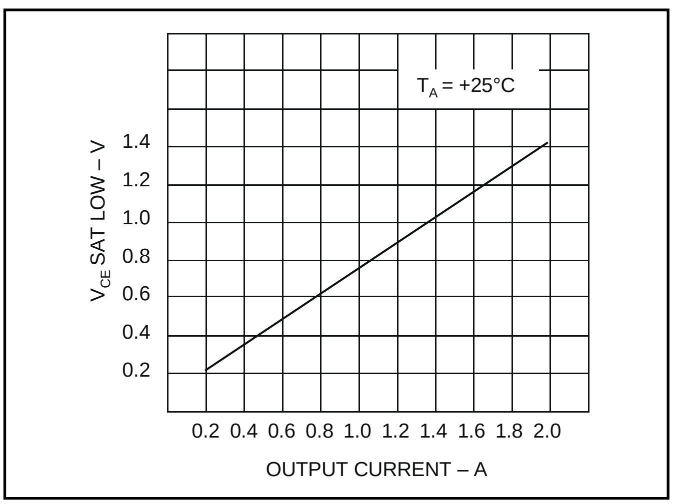


Figure 2. Typical sink saturation voltages vs. load current

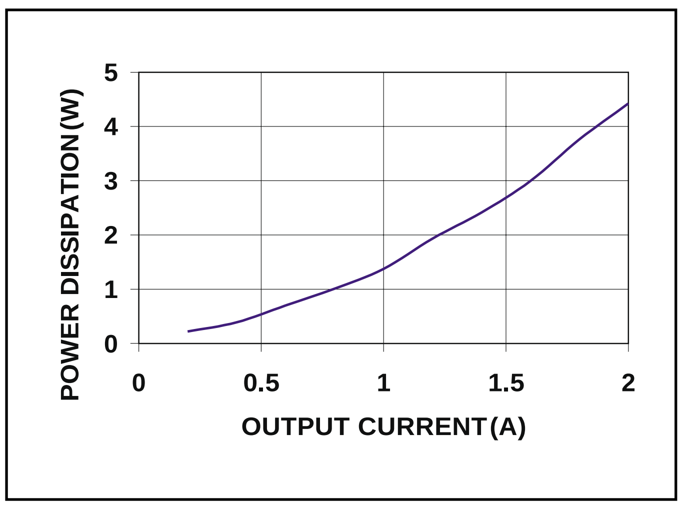


Figure 4. Typical power dissipation vs. output current.

MTP52H06V

Preferred Device

Power MOSFET 52 Amps, 60 Volts

N–Channel TO–220

This Power MOSFET is designed to withstand high energy in the avalanche and commutation modes. Designed for low voltage, high speed switching applications in power supplies, converters and power motor controls, these devices are particularly well suited for bridge circuits where diode speed and commutating safe operating areas are critical and offer additional safety margin against unexpected voltage transients.

- Avalanche Energy Specified
- I_{DSS} and $V_{DS(on)}$ Specified at Elevated Temperature

MAXIMUM RATINGS (T_C = 25°C unless otherwise noted)

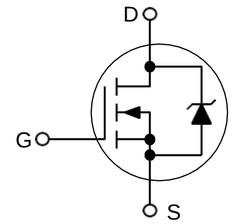
Rating	Symbol	Value	Unit
Drain–Source Voltage	V_{DSS}	60	Vdc
Drain–Gate Voltage (R_{GS} = 1.0 MΩ)	V_{DGR}	60	Vdc
Gate–Source Voltage – Continuous – Non–Repetitive ($t_p \leq$ 10 ms)	 V_{GS} V_{GSM}	 ± 20 ± 25	 Vdc Vpk
Drain Current – Continuous – Continuous @ 100°C – Single Pulse ($t_p \leq$ 10 μs)	I_D I_D I_{DM}	52 41 182	Adc Apk
Total Power Dissipation Derate above 25°C	P_D	188 1.25	Watts W/°C
Operating and Storage Temperature Range	T_J, T_{stg}	–55 to 175	°C
Single Pulse Drain–to–Source Avalanche Energy – Starting T_J = 25°C (V_{DD} = 25 Vdc, V_{GS} = 10 Vdc, I_L = 52 Apk, L = 0.3 mH, R_G = 25 Ω)	E_{AS}	406	mJ
Thermal Resistance – Junction to Case – Junction to Ambient	 $R_{\theta JC}$ $R_{\theta JA}$	 0.8 62.5	°C/W
Maximum Lead Temperature for Soldering Purposes, 1/8″ from case for 10 seconds	T_L	260	°C

ON Semiconductor™

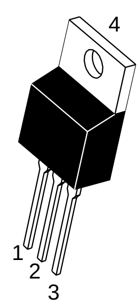
http://onsemi.com

52 AMPERES
60 VOLTS
$R_{DS(on)}$ = 22 mΩ

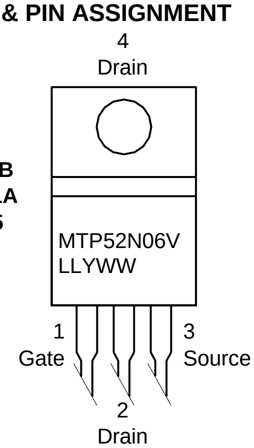
N–Channel



MARKING DIAGRAM & PIN ASSIGNMENT



TO–220AB
CASE 221A
STYLE 5



MTP52N06V	= Device Code
LL	= Location Code
Y	= Year
WW	= Work Week

ORDERING INFORMATION

Device	Package	Shipping
MTP52N06V	TO–220AB	50 Units/Rail

Preferred devices are recommended choices for future use and best overall value.

ELECTRICAL CHARACTERISTICS (T_J = 25°C unless otherwise noted)

Characteristic		Symbol	Min	Typ	Max	Unit
OFF CHARACTERISTICS						
Drain–Source Breakdown Voltage (Cpk ≥ 2.0) (Note 3.) (V_{GS} = 0 Vdc, I_D = 0.25 mAdc) Temperature Coefficient (Positive)		$V_{(BR)DSS}$	 60 –	 – 66	 – –	 Vdc mV/°C
Zero Gate Voltage Drain Current (V_{DS} = 60 Vdc, V_{GS} = 0 Vdc) (V_{DS} = 60 Vdc, V_{GS} = 0 Vdc, T_J = 150°C)		I_{DSS}	 – –	 – –	 10 100	μAdc
Gate–Body Leakage Current (V_{GS} = ± 20 Vdc, V_{DS} = 0)		I_{GSS}	–	–	100	nAdc
ON CHARACTERISTICS (Note 1.)						
Gate Threshold Voltage (Cpk ≥ 2.0) (Note 3.) (V_{DS} = V_{GS}, I_D = 250 μAdc) Temperature Coefficient (Negative)		$V_{GS(th)}$	 2.0 –	 2.7 6.4	 4.0 –	 Vdc mV/°C
Static Drain–Source On–Resistance (Cpk ≥ 2.0) (Note 3.) (V_{GS} = 10 Vdc, I_D = 26 Adc)		$R_{DS(on)}$	–	0.019	0.022	Ohm
Drain–Source On–Voltage (V_{GS} = 10 Vdc, I_D = 52 Adc) (V_{GS} = 10 Vdc, I_D = 26 Adc, T_J = 150°C)		$V_{DS(on)}$	 – –	 – –	 1.4 1.2	Vdc
Forward Transconductance (V_{DS} = 6.3 Vdc, I_D = 20 Adc)		g_{FS}	17	24	–	mhos
DYNAMIC CHARACTERISTICS						
Input Capacitance	(V_{DS} = 25 Vdc, V_{GS} = 0 Vdc, **f = 1.0 MHz)**	C_{iss}	–	1900	2660	pF
Output Capacitance		C_{oss}	–	580	810	
Reverse Transfer Capacitance		C_{rss}	–	150	300	
SWITCHING CHARACTERISTICS (Note 2.)						
Turn–On Delay Time	(V_{DD} = 30 Vdc, I_D = 52 Adc, V_{GS} = 10 Vdc, R_G = 9.1 Ω)	$t_{d(on)}$	–	12	20	ns
Rise Time		t_r	–	298	600	
Turn–Off Delay Time		$t_{d(off)}$	–	70	140	
Fall Time		t_f	–	110	220	
Gate Charge (See Figure 8)	(V_{DS} = 48 Vdc, I_D = 52 Adc, V_{GS} = 10 Vdc)	Q_T	–	125	175	nC
		Q_1	–	10	–	
		Q_2	–	30	–	
		Q_3	–	40	–	
SOURCE–DRAIN DIODE CHARACTERISTICS						
Forward On–Voltage (Note 1.)	(I_S = 52 Adc, V_{GS} = 0 Vdc) (I_S = 52 Adc, V_{GS} = 0 Vdc, T_J = 150°C)	V_{SD}	 – –	 1.0 0.98	 1.5 –	Vdc
Reverse Recovery Time (See Figure 14)	(I_S = 52 Adc, V_{GS} = 0 Vdc, dI_S/dt = 100 A/μs)	t_{rr}	–	100	–	ns
		t_a	–	80	–	
		t_b	–	20	–	
Reverse Recovery Stored Charge		Q_{RR}	–	0.341	–	μC
INTERNAL PACKAGE INDUCTANCE						
Internal Drain Inductance (Measured from contact screw on tab to center of die) (Measured from the drain lead 0.25″ from package to center of die)		L_D	 – –	 3.5 4.5	 – –	nH
Internal Source Inductance (Measured from the source lead 0.25″ from package to source bond pad)		L_S	–	7.5	–	nH

1. Pulse Test: Pulse Width ≤ 300 μs, Duty Cycle ≤ 2%.
2. Switching characteristics are independent of operating junction temperature.
3. Reflects typical values. $C_{pk} = \left| \frac{\text{Max limit – Typ}}{\text{3 x SIGMA}} \right|$

TYPICAL ELECTRICAL CHARACTERISTICS

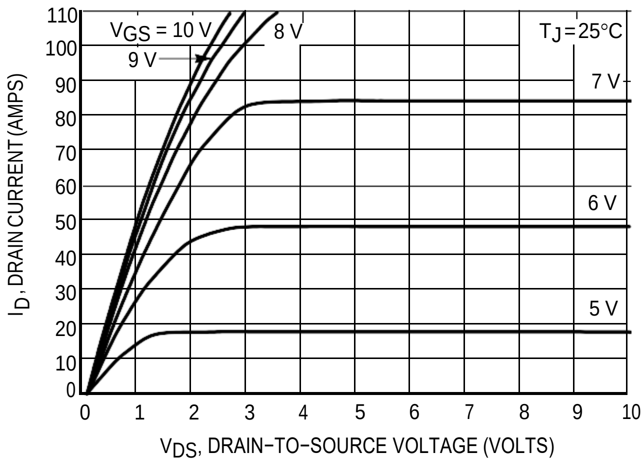


Figure 1. On–Region Characteristics

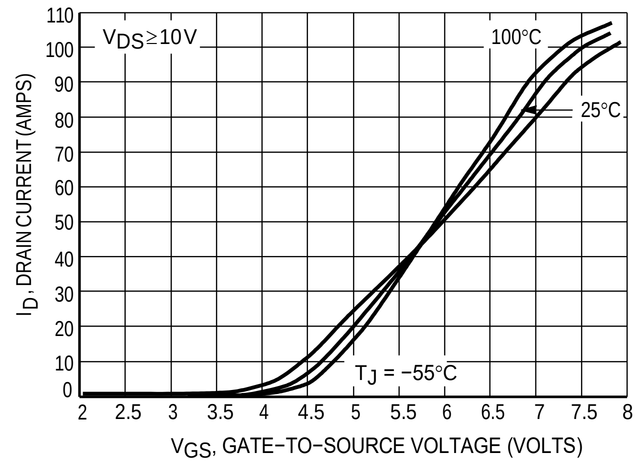


Figure 2. Transfer Characteristics

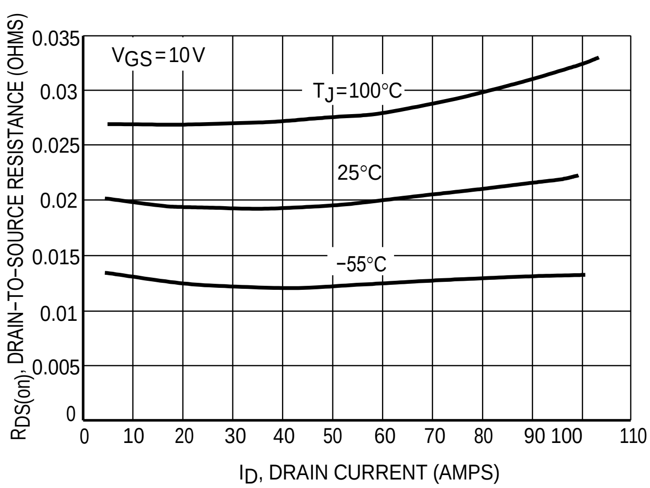


Figure 3. On–Resistance versus Drain Current and Temperature

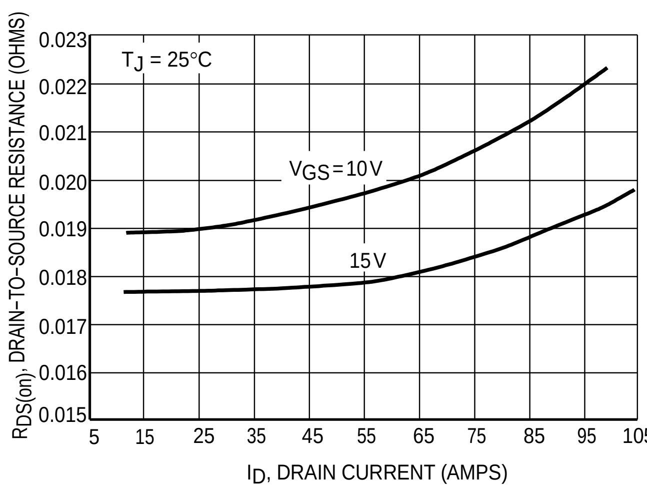


Figure 4. On–Resistance versus Drain Current and Gate Voltage

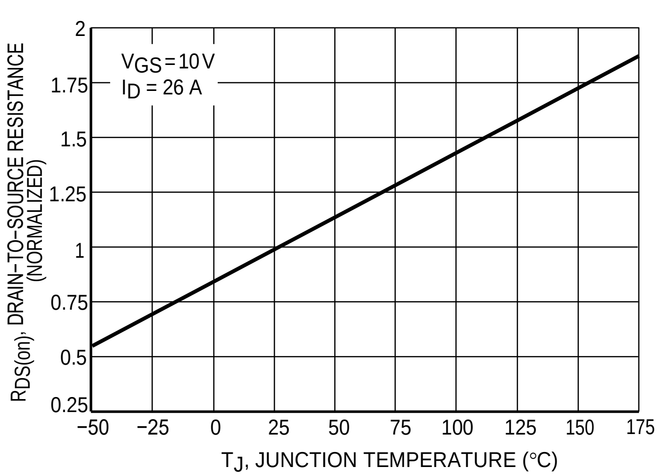


Figure 5. On–Resistance Variation with Temperature

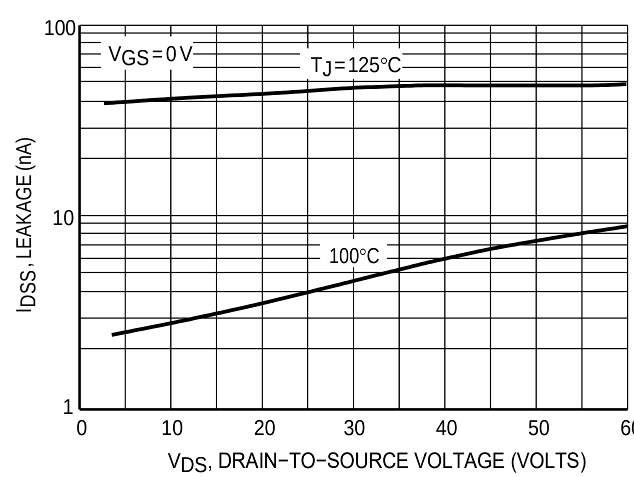


Figure 6. Drain–To–Source Leakage Current versus Voltage

POWER MOSFET SWITCHING

Switching behavior is most easily modeled and predicted by recognizing that the power MOSFET is charge controlled. The lengths of various switching intervals (Δt) are determined by how fast the FET input capacitance can be charged by current from the generator.

The published capacitance data is difficult to use for calculating rise and fall because drain–gate capacitance varies greatly with applied voltage. Accordingly, gate charge data is used. In most cases, a satisfactory estimate of average input current ($I_{G(AV)}$) can be made from a rudimentary analysis of the drive circuit so that

$t = Q/I_{G(AV)}$

During the rise and fall time interval when switching a resistive load, V_{GS} remains virtually constant at a level known as the plateau voltage, V_{SGP}. Therefore, rise and fall times may be approximated by the following:

$t_r = Q_2 \times R_G/(V_{GG} - V_{GSP})$

$t_f = Q_2 \times R_G/V_{GSP}$

where

V_{GG} = the gate drive voltage, which varies from zero to V_{GG}

R_G = the gate drive resistance

and Q_2 and V_{GSP} are read from the gate charge curve.

During the turn–on and turn–off delay times, gate current is not constant. The simplest calculation uses appropriate values from the capacitance curves in a standard equation for voltage change in an RC network. The equations are:

$t_{d(on)} = R_G\ C_{iss}\ \text{In}\ [V_{GG}/(V_{GG} - V_{GSP})]$

$t_{d(off)} = R_G\ C_{iss}\ \text{In}\ (V_{GG}/V_{GSP})$

The capacitance (C_{iss}) is read from the capacitance curve at a voltage corresponding to the off–state condition when calculating $t_{d(on)}$ and is read at a voltage corresponding to the on–state when calculating $t_{d(off)}$.

At high switching speeds, parasitic circuit elements complicate the analysis. The inductance of the MOSFET source lead, inside the package and in the circuit wiring which is common to both the drain and gate current paths, produces a voltage at the source which reduces the gate drive current. The voltage is determined by Ldi/dt, but since di/dt is a function of drain current, the mathematical solution is complex. The MOSFET output capacitance also complicates the mathematics. And finally, MOSFETs have finite internal gate resistance which effectively adds to the resistance of the driving source, but the internal resistance is difficult to measure and, consequently, is not specified.

The resistive switching time variation versus gate resistance (Figure 9) shows how typical switching performance is affected by the parasitic circuit elements. If the parasitics were not present, the slope of the curves would maintain a value of unity regardless of the switching speed. The circuit used to obtain the data is constructed to minimize common inductance in the drain and gate circuit loops and is believed readily achievable with board mounted components. Most power electronic loads are inductive; the data in the figure is taken with a resistive load, which approximates an optimally snubbed inductive load. Power MOSFETs may be safely operated into an inductive load; however, snubbing reduces switching losses.

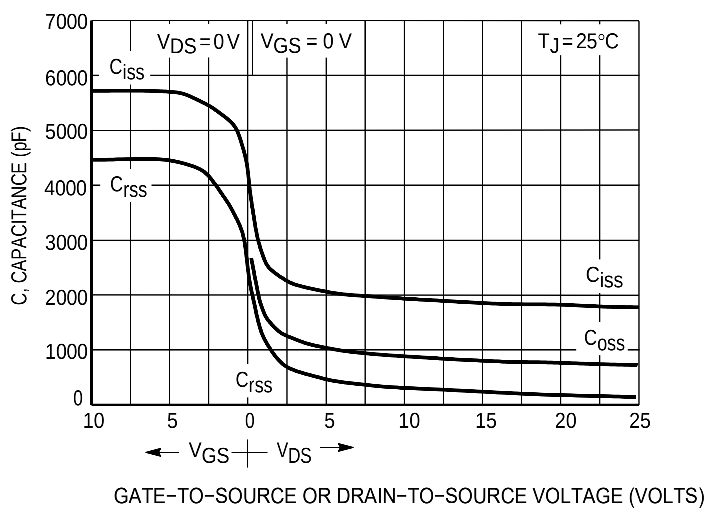


Figure 7. Capacitance Variation

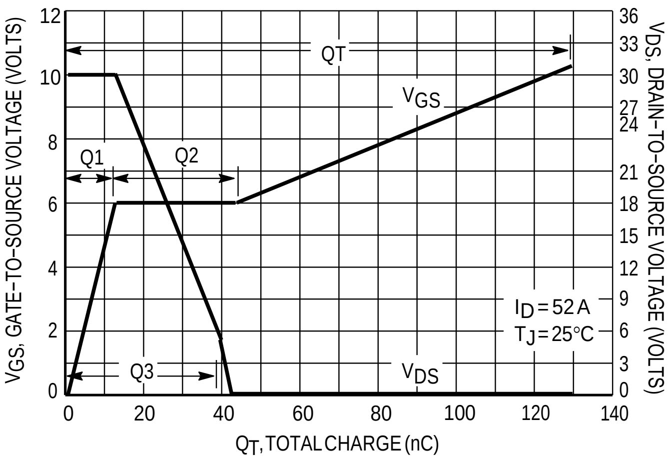


Figure 8. Gate–To–Source and Drain–To–Source Voltage versus Total Charge

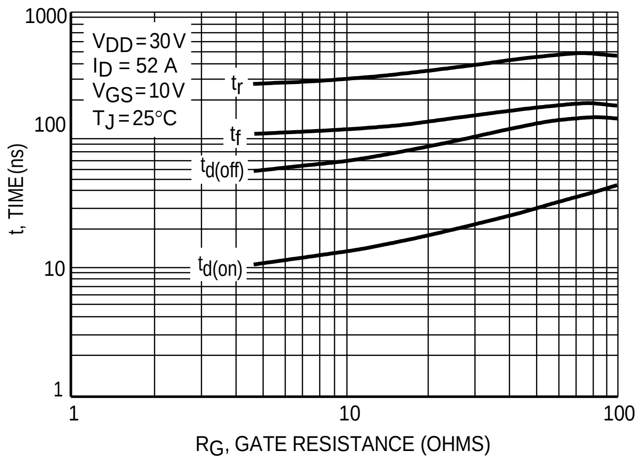


Figure 9. Resistive Switching Time Variation versus Gate Resistance

DRAIN–TO–SOURCE DIODE CHARACTERISTICS

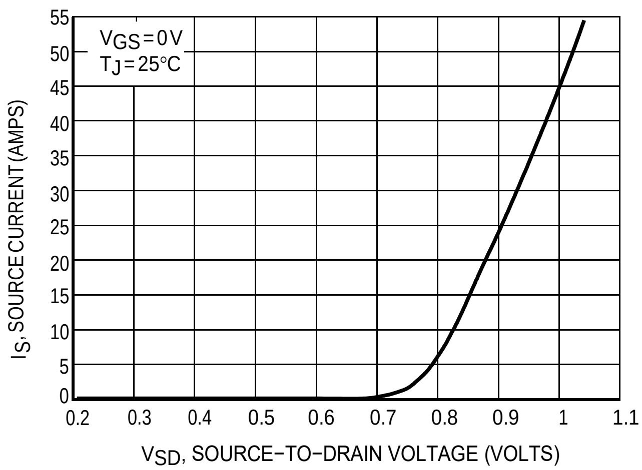


Figure 10. Diode Forward Voltage versus Current

SAFE OPERATING AREA

The Forward Biased Safe Operating Area curves define the maximum simultaneous drain–to–source voltage and drain current that a transistor can handle safely when it is forward biased. Curves are based upon maximum peak junction temperature and a case temperature (T_C) of 25°C. Peak repetitive pulsed power limits are determined by using the thermal response data in conjunction with the procedures discussed in AN569, “Transient Thermal Resistance–General Data and Its Use.”

Switching between the off–state and the on–state may traverse any load line provided neither rated peak current (I_{DM}) nor rated voltage (V_{DSS}) is exceeded and the transition time (t_r,t_f) do not exceed 10 μs. In addition the total power averaged over a complete switching cycle must not exceed ($T_{J(MAX)} - T_C$)/($R_{\theta JC}$).

A Power MOSFET designated E–FET can be safely used in switching circuits with unclamped inductive loads. For reliable operation, the stored energy from circuit inductance dissipated in the transistor while in avalanche must be less than the rated limit and adjusted for operating conditions differing from those specified. Although industry practice is to rate in terms of energy, avalanche energy capability is not a constant. The energy rating decreases non–linearly with an increase of peak current in avalanche and peak junction temperature.

Although many E–FETs can withstand the stress of drain–to–source avalanche at currents up to rated pulsed current (I_{DM}), the energy rating is specified at rated continuous current (I_D), in accordance with industry custom. The energy rating must be derated for temperature as shown in the accompanying graph (Figure 12). Maximum energy at currents below rated continuous I_D can safely be assumed to equal the values indicated.

SAFE OPERATING AREA

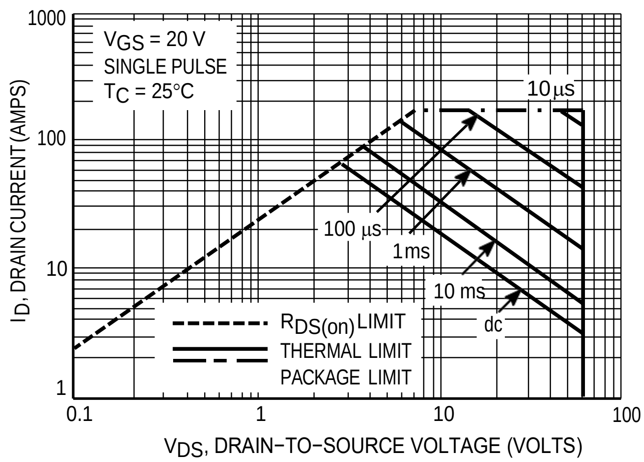


Figure 11. Maximum Rated Forward Biased Safe Operating Area

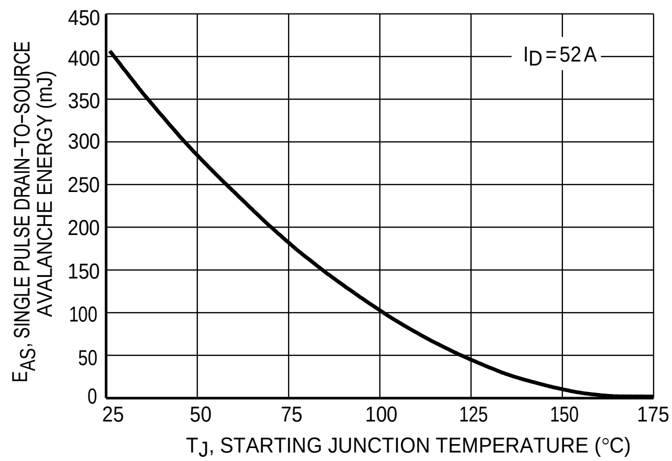


Figure 12. Maximum Avalanche Energy versus Starting Junction Temperature

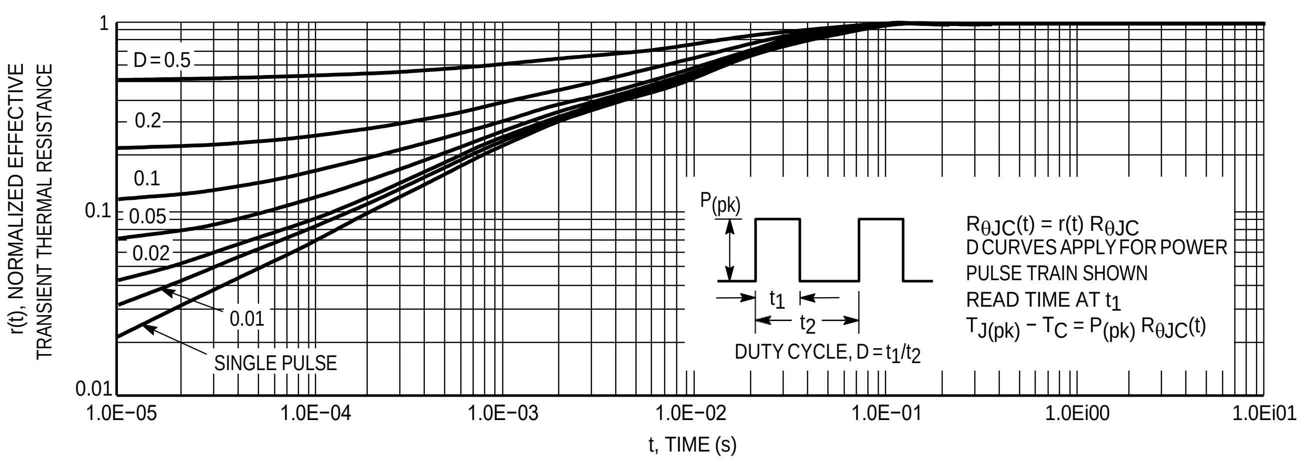


Figure 13. Thermal Response

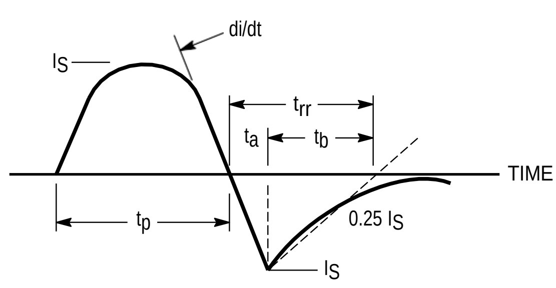
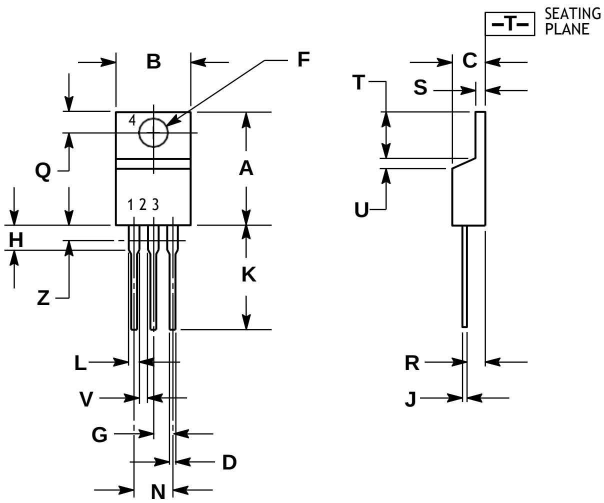


Figure 14. Diode Reverse Recovery Waveform

PACKAGE DIMENSIONS

TO–220 THREE–LEAD
TO–220AB
CASE 221A–09
ISSUE AA



NOTES:
1. DIMENSIONING AND TOLERANCING PER ANSI Y14.5M, 1982.
2. CONTROLLING DIMENSION: INCH.
3. DIMENSION Z DEFINES A ZONE WHERE ALL BODY AND LEAD IRREGULARITIES ARE ALLOWED.

	INCHES		MILLIMETERS	
DIM	MIN	MAX	MIN	MAX
A	0.570	0.620	14.48	15.75
B	0.380	0.405	9.66	10.28
C	0.160	0.190	4.07	4.82
D	0.025	0.035	0.64	0.88
F	0.142	0.147	3.61	3.73
G	0.095	0.105	2.42	2.66
H	0.110	0.155	2.80	3.93
J	0.018	0.025	0.46	0.64
K	0.500	0.562	12.70	14.27
L	0.045	0.060	1.15	1.52
N	0.190	0.210	4.83	5.33
Đ	0.100	0.120	2.54	3.04
R	0.080	0.110	2.04	2.79
S	0.045	0.055	1.15	1.39
T	0.235	0.255	5.97	6.47
U	0.000	0.050	0.00	1.27
V	0.045	---	1.15	---
Z	---	0.080	---	2.04

STYLE 5:
PIN 1. GATE
2. DRAIN
3. SOURCE
4. DRAIN

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MUR405, MUR410, MUR415, MUR420, MUR440, MUR460

MUR420 and MUR460 are Preferred Devices

SWITCHMODE™ Power Rectifiers

. . . designed for use in switching power supplies, inverters and as free wheeling diodes, these state−of−the−art devices have the following features:

- Ultrafast 25, 50 and 75 Nanosecond Recovery Times
- 175°C Operating Junction Temperature
- Low Forward Voltage
- Low Leakage Current
- High Temperature Glass Passivated Junction
- Reverse Voltage to 600 Volts

Mechanical Characteristics:

- Case: Epoxy, Molded
- Weight: 1.1 gram (approximately)
- Finish: All External Surfaces Corrosion Resistant and Terminal Leads are Readily Solderable
- Lead and Mounting Surface Temperature for Soldering Purposes: 220°C Max. for 10 Seconds, 1/16″ from case
- Shipped in plastic bags, 5,000 per bag
- Available Tape and Reeled, 1500 per reel, by adding a “RL’’ suffix to the part number
- Polarity: Cathode indicated by Polarity Band
- Marking: MUR405, MUR410, MUR415, MUR420, MUR440, MUR460

MAXIMUM RATINGS

Please See the Table on the Following Page

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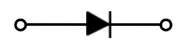
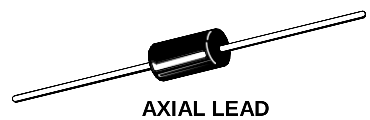
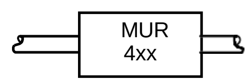
4.0 AMPERES
50−600 VOLTS





AXIAL LEAD
CASE 267−05
(DO−201AD)
STYLE 1

MARKING DIAGRAM



MUR4xx = Device Code
xx = 05, 10, 15, 20, 40, 60

ORDERING INFORMATION

Device	Package	Shipping
MUR405	Axial Lead	5000 Units/Bag
MUR405RL	Axial Lead	1500/Tape & Reel
MUR410	Axial Lead	5000 Units/Bag
MUR410RL	Axial Lead	1500/Tape & Reel
MUR415	Axial Lead	5000 Units/Bag
MUR415RL	Axial Lead	1500/Tape & Reel
MUR420	Axial Lead	5000 Units/Bag
MUR420RL	Axial Lead	1500/Tape & Reel
MUR440	Axial Lead	5000 Units/Bag
MUR440RL	Axial Lead	1500/Tape & Reel
MUR460	Axial Lead	5000 Units/Bag
MUR460RL	Axial Lead	1500/Tape & Reel

Preferred devices are recommended choices for future use and best overall value.

MAXIMUM RATINGS

Rating	Symbol	MUR 405	410	415	420	440	460	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	V_{RRM} V_{RWM} V_R	50	100	150	200	400	600	Volts
Average Rectified Forward Current (Square Wave) (Mounting Method #3 Per Note 2)	$I_{F(AV)}$	4.0 @ T_A = 80°C				4.0 @ T_A = 40°C		Amps
Nonrepetitive Peak Surge Current (Surge applied at rated load conditions, half wave, single phase, 60 Hz)	I_{FSM}	125				110		Amps
Operating Junction Temperature & Storage Temperature	T_J, T_{stg}	—65 to +175						°C

THERMAL CHARACTERISTICS

Maximum Thermal Resistance, Junction to Ambient	$R_{\theta JA}$	See Note 2	°C/W

ELECTRICAL CHARACTERISTICS

		MUR405–420	MUR440–460	
Maximum Instantaneous Forward Voltage (Note 1) (i_F = 3.0 Amps, T_J = 150°C) (i_F = 3.0 Amps, T_J = 25°C) (i_F = 4.0 Amps, T_J = 25°C)	v_F	 0.710 0.875 0.890	 1.05 1.25 1.28	Volts
Maximum Instantaneous Reverse Current (Note 1) (Rated dc Voltage, T_J = 150°C) (Rated dc Voltage, T_J = 25°C)	i_R	 150 5.0	 250 10	μA
Maximum Reverse Recovery Time (I_F = 1.0 Amp, di/dt = 50 Amp/μs) (I_F = 0.5 Amp, i_R = 1.0 Amp, I_{REC} = 0.25 Amp)	t_{rr}	 35 25	 75 50	ns
Maximum Forward Recovery Time (I_F = 1.0 A, di/dt = 100 A/μs, Recovery to 1.0 V)	t_{fr}	25	50	ns

1. Pulse Test: Pulse Width = 300 μs, Duty Cycle Š 2.0%.

MUR405, MUR410, MUR415, MUR420

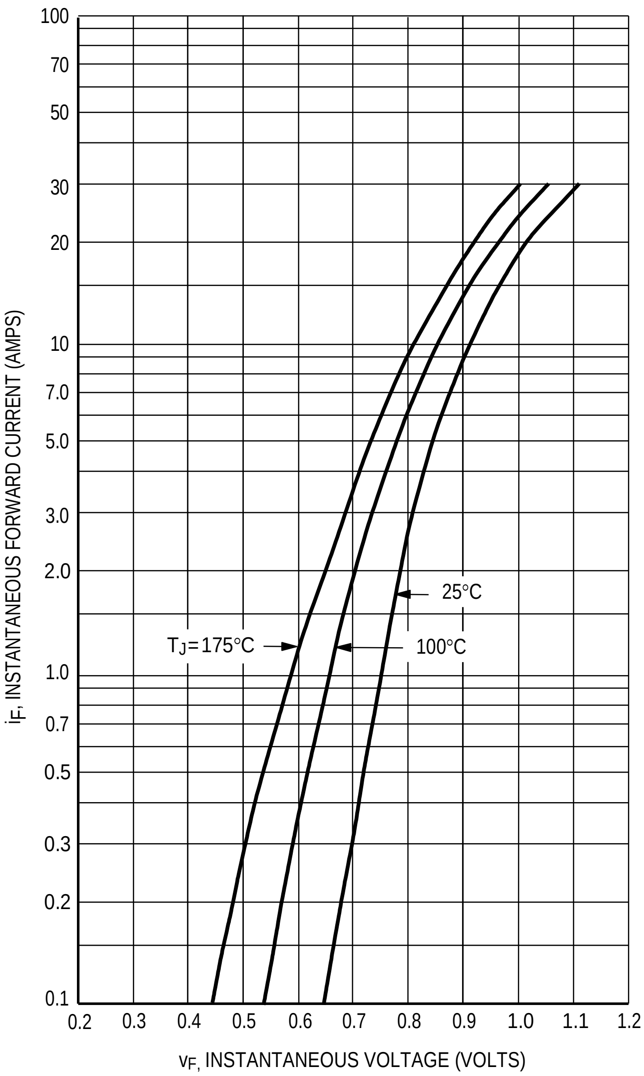


Figure 1. Typical Forward Voltage

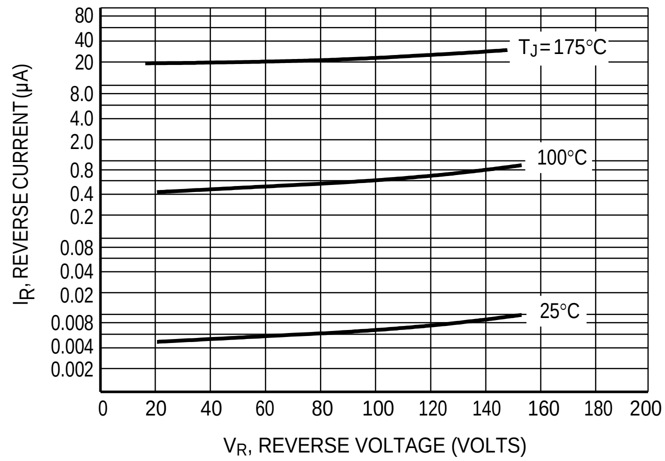


Figure 2. Typical Reverse Current

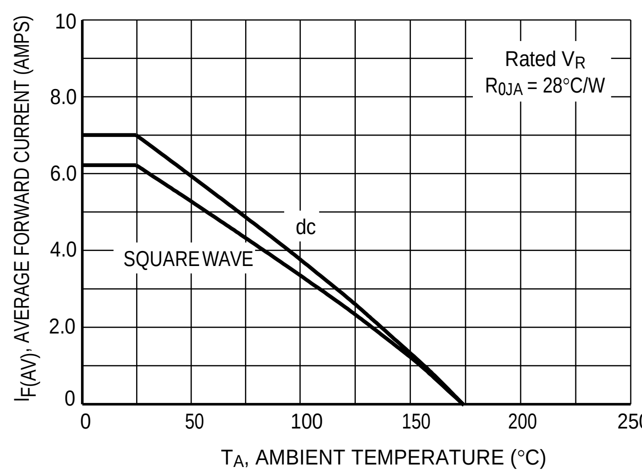


Figure 3. Current Derating (Mounting Method #3 Per Note 2)

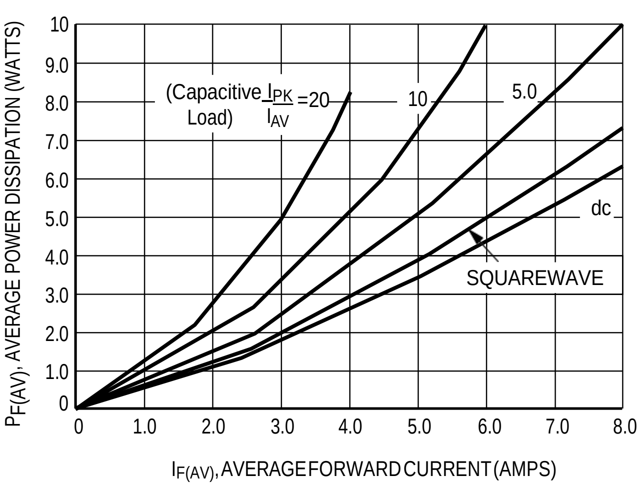


Figure 4. Power Dissipation

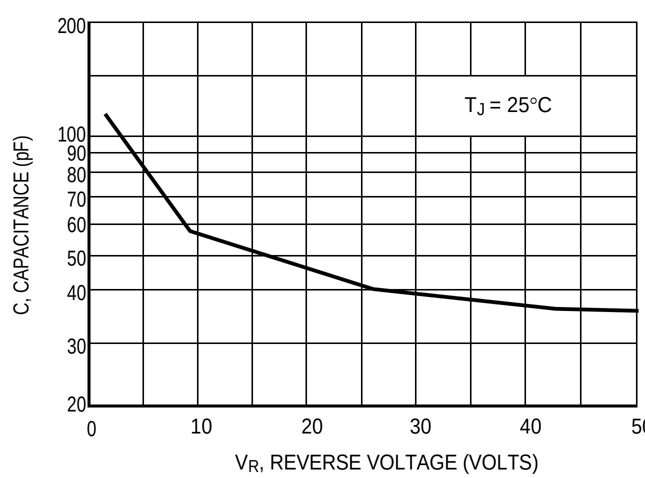


Figure 5. Typical Capacitance

MUR440, MUR460

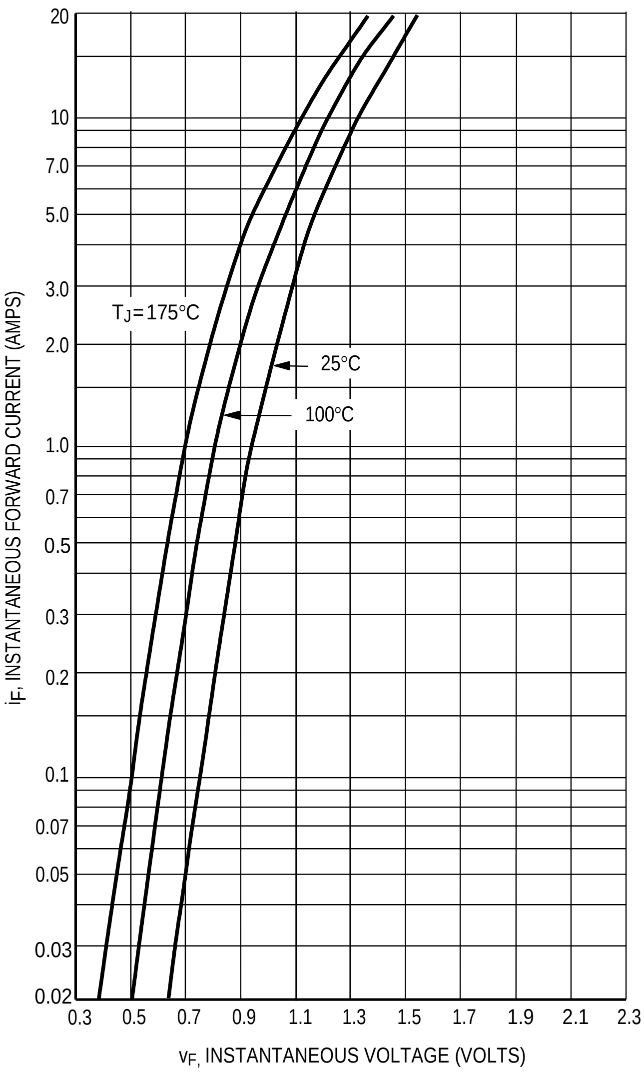


Figure 6. Typical Forward Voltage

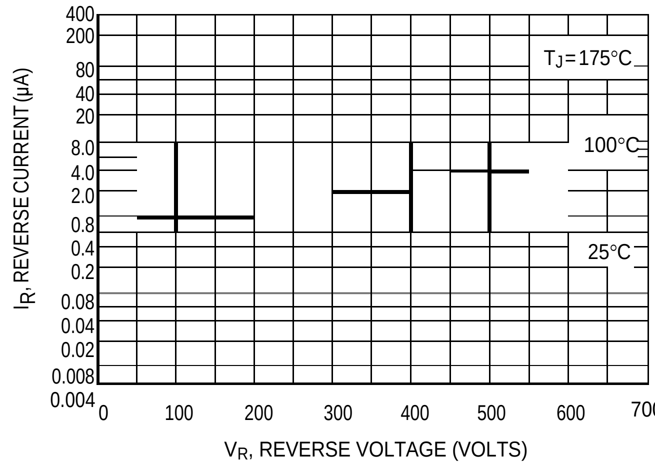


Figure 7. Typical Reverse Current

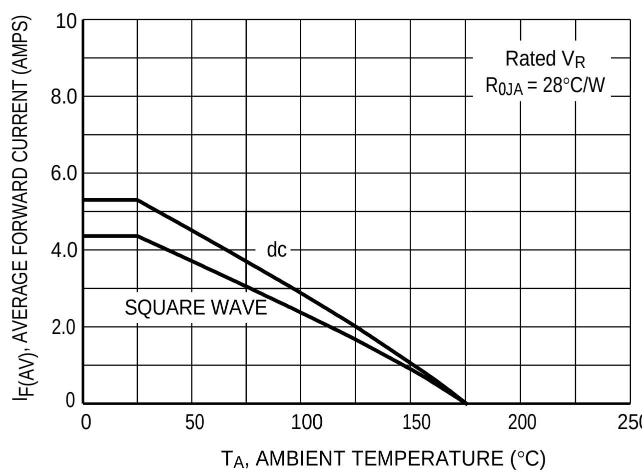


Figure 8. Current Derating (Mounting Method #3 Per Note 2)

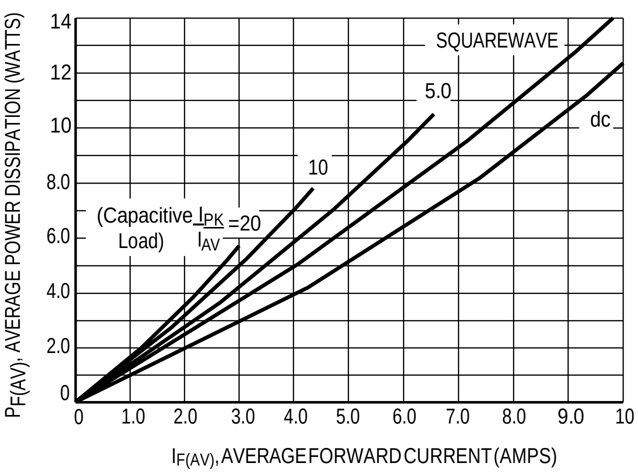


Figure 9. Power Dissipation

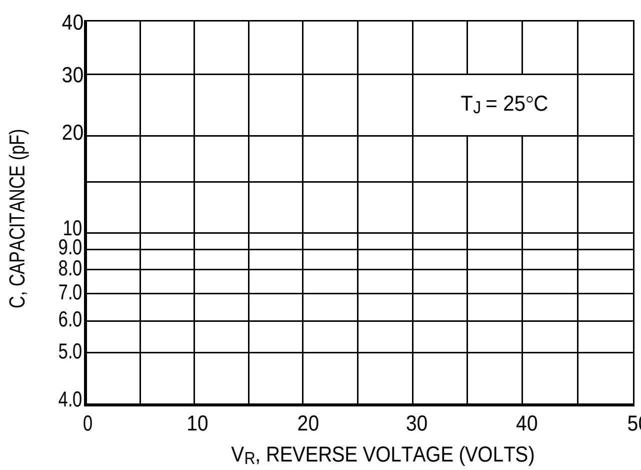


Figure 10. Typical Capacitance

NOTE 2 — AMBIENT MOUNTING DATA

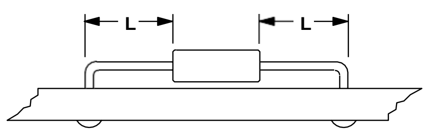
Data shown for thermal resistance junction−to−ambient ($R_{\theta JA}$) for the mountings shown is to be used as typical guideline values for preliminary engineering or in case the tie point temperature cannot be measured.

TYPICAL VALUES FOR $R_{\theta JA}$ IN STILL AIR

Mounting Method		Lead Length, L (IN) 1/8	1/4	1/2	3/4	Units
1	$R_{\theta JA}$	50	51	53	55	°C/W
2		58	59	61	63	°C/W
3		28				°C/W

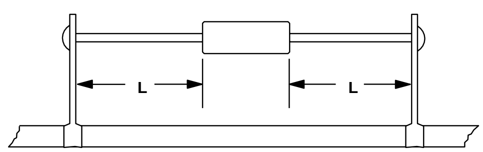
MOUNTING METHOD 1

P.C. Board Where Available Copper Surface area is small.



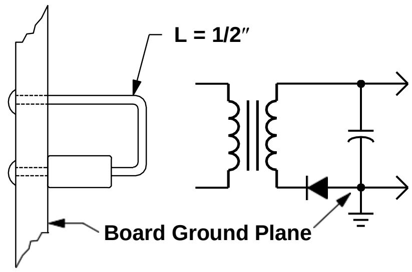
MOUNTING METHOD 2

Vector Push−In Terminals T−28



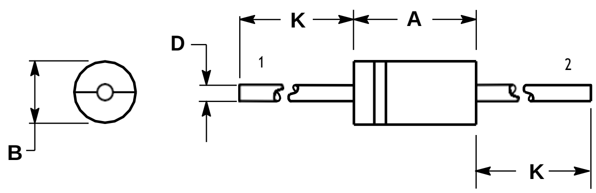
MOUNTING METHOD 3

P.C. Board with 1−1/2″ x 1−1/2″ Copper Surface



PACKAGE DIMENSIONS

AXIAL LEAD
CASE 267−05
(DO−201AD)
ISSUE G



NOTES:
1. DIMENSIONS AND TOLERANCING PER ANSI Y14.5M, 1982.
2. CONTROLLING DIMENSION: INCH.
3. 267−04 OBSOLETE, NEW STANDARD 267−05.

DIM	INCHES MIN	INCHES MAX	MILLIMETERS MIN	MILLIMETERS MAX
A	0.287	0.374	7.30	9.50
B	0.189	0.209	4.80	5.30
D	0.047	0.051	1.20	1.30
K	1.000	---	25.40	---

STYLE 1:
PIN 1. CATHODE (POLARITY BAND)
2. ANODE

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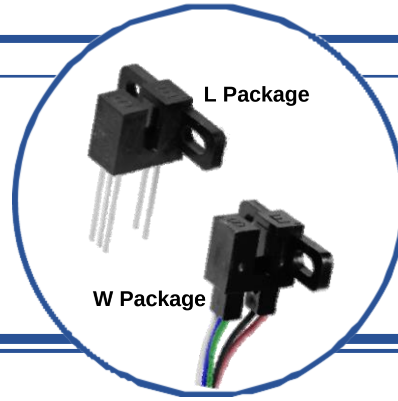
Photologic® Slotted Optical Switch
OPB930 and OPB940 (L and W Series)

TT electronics
OPTEK Technology

Features:
- Choice of aperture size
- Choice of output configurations
- Choice of opaque or IR transmissive shell
- Choice of pins (L) or wires (W)
- 0.125" (3.18 mm) slot width
- 0.320" (8.128 mm) lead spacing for PCBoard (side mounting)
- Data rates to 250 kBaud



Description:
The **OPB930** and **OPB940** series of Photologic® photo integrated circuit switches provide optimum flexibility for the design engineer. Building from a standard housing with a 0.125" (3.18 mm) wide slot, a user can specify the type and polarity of TTL output, discrete shell material, aperture width and either 0.350" (8.9 mm) long pins **(L Series)** or 24" (610 mm) AWG, UL listed wire leads **(W Series)**.

All housings are made from an opaque grade of injection-molded plastic that minimizes the assembly's sensitivity to both visible and near-infrared ambient radiation. Discrete shells (exposed on the parallel faces inside the device throat) are either IR transmissive plastic (for applications where aperture contamination may occur) or opaque plastic (for maximum protection against ambient light).

Electrical output can be specified as either TTL Totem Pole or TTL Open Collector, either of which can be supplied with buffer or inverter output polarity. All devices have the added stability of a built-in hysteresis amplifier.

Custom electrical, wire and cabling and connectors are available. Contact your local representative or OPTEK for more information.

Applications:
- Mechanical switch replacement
- Speed indication (tachometer)
- Mechanical limit indication

Part Number Guide — OPB930 and OPB940 Series

OPB 9 X X X X X Z — **For "W" series only**

Optek Assembly

Photologic® Photo Integrated Circuit Sensor Family

Discrete Shell Material:
3 — Side mount IR transmissive Plastic discrete shell
4 — Side mount opaque Plastic discrete shell

Electrical Specification Variations:
0 = Buffered Totem-Pole Output
1 = Buffered Open-Collector Output
2 = Inverted Totem-Pole Output
3 = Inverted Open-Collector Output

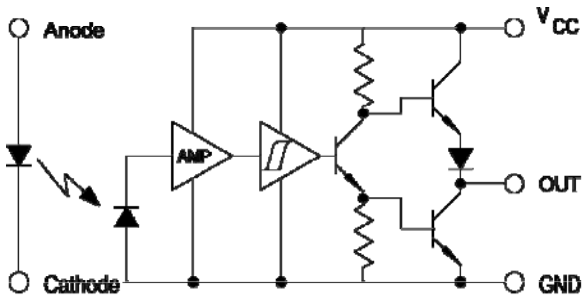
Mounting configurations:
L — Solder leads termination
W — Wire termination

Emitter Aperture:
5 — 0.050" (12.70 mm)

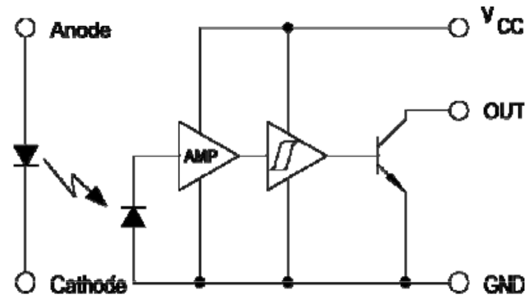
Sensor Aperture:
1 — 0.010" (2.54 mm)
5 — 0.050" (12.70 mm)

RoHS

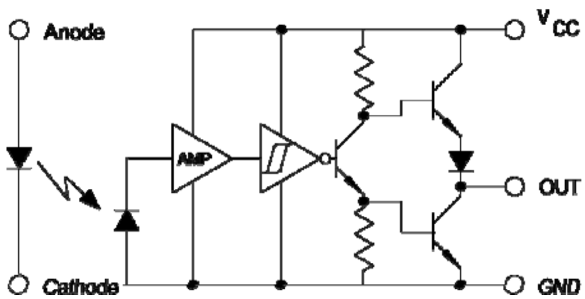
OPB930, OPB940 Buffered Totem-Pole



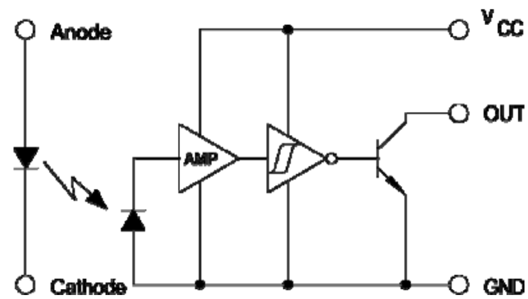
OPB931, OPB941 Buffered Open-Collector



OPB932, OPB942 Inverted Totem-Pole



OPB933 & OPB943 Inverted Open-Collector



Absolute Maximum Ratings (T_A=25°C unless otherwise noted)

Supply Voltage, V_{CC} (not to exceed 3 seconds)	10 V
Operating Temperature Range	-40°C to +70° C
Storage Temperature Range	-40°C to +85° C
Lead Soldering Temperature [1/16 inch (1.6mm) from the case for 5 sec. with soldering iron] (1)	260° C

Input Infrared LED

Input Diode Power Dissipation (2)	100 mW
Output Photologic® Power Dissipation (3)	200 mW
Total Device Power Dissipation (4)	300 mW

Output Photologic®

Voltage at Output Lead (Open Collector Output)	35 V
Diode Forward DC Current	40 mA
Diode Reverse DC Voltage	2 V

Notes:
(1) RMA flux is recommended. Duration can be extended to 10 seconds maximum when flow soldering.
(2) Derate linearly 2.22 mW/°C above 25°.
(3) Derate linearly 4.44 mW/°C above 25°.
(4) Derate linearly 6.66 mW/°C above 25°.
(5) OPB930L/OPB940L series devices are terminated with 0.020” square leads designed for PCBoard mounting.
(6) Methanol and isopropanol are recommended as cleaning agents. Plastic housing is soluble in chlorinated hydrocarbons and ketones.
(7) All parameters tested using pulse technique.

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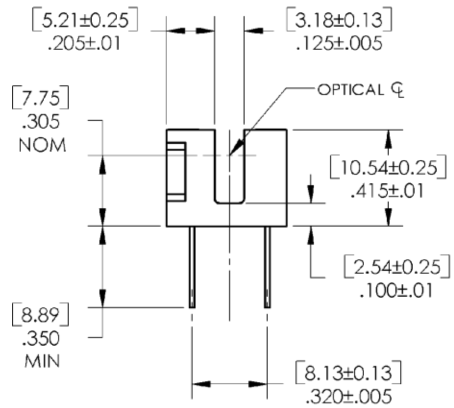
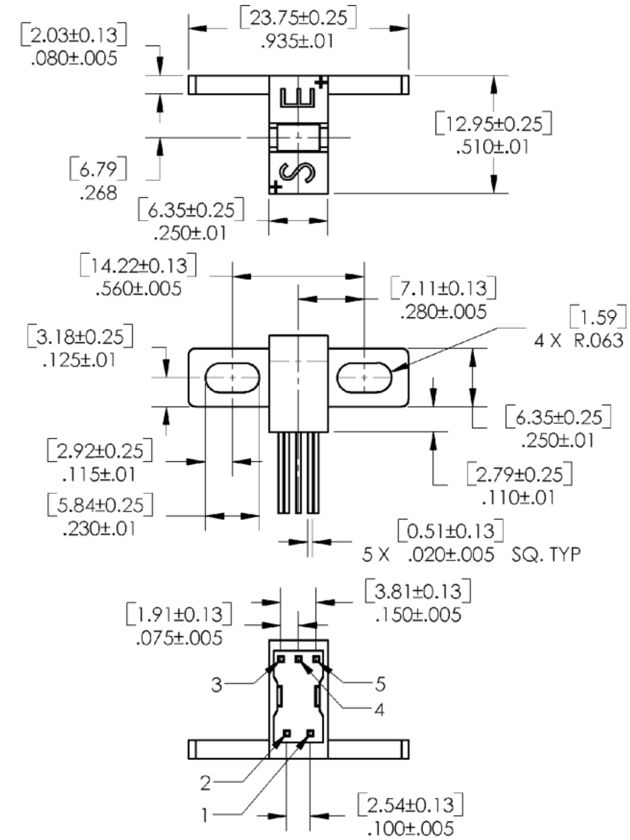
DIMENSIONS ARE IN: [MILLIMETERS] INCHES

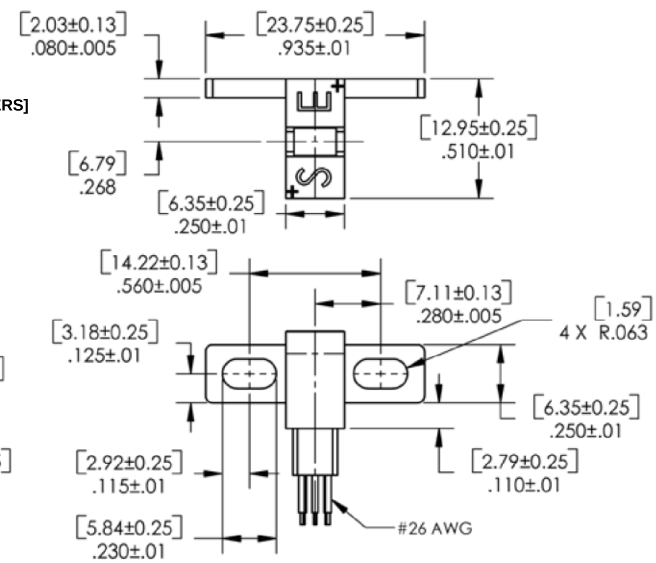


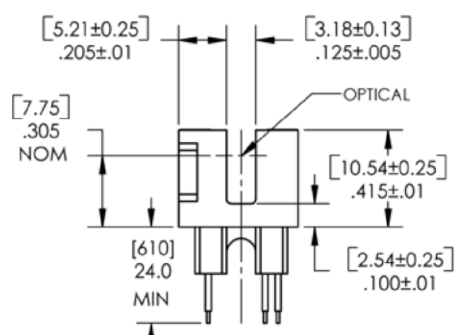


Color- Pin #	Description
Red—1	Anode
Black—2	Cathode
White—3	V_{CC}
Blue—4	Output
Green—5	Ground

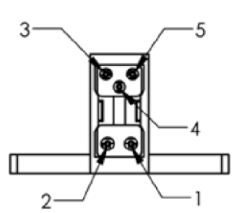
PCBoard (L) version

DIMENSIONS ARE IN: [MILLIMETERS] INCHES





Wired (W) version



The W Series includes wire terminations of 24” (610 mm) 7-strand, 26 AWG UL insulated wire on each terminal. Each device incorporates a wire strain relief at the housing surface. The insulation functions and colors are: anode (red), cathode (black), phototransistor collector (white) and phototransistor emitter (green).

OPTEK reserves the right to make changes at any time in order to improve design and to supply the best product possible.

Electrical Characteristics (T_A = 25°C unless otherwise noted)

SYMBOL	PARAMETER	MIN	TYP	MAX	UNITS	TEST CONDITIONS
Input Diode						
V_F	Forward Voltage	-	-	1.7	V	I_F = 20 mA
I_R	Reverse Current	-	-	100	µA	V_R = 2.0 V
Output Photologic® Sensor						
V_{CC}	Operating D.C. Supply Voltage	4.75	-	5.25	V	-
I_{CCL}	Low Level Supply Current: Totem Pole & Open-Collector	-	-	15	mA	V_{CC} = 5.25, I_F = 0 mA(1)
	Inverted Totem-Pole & Inverted Open-Collector	-	-	15	mA	V_{CC} = 5.25, I_F = 15 mA
I_{CCH}	High Level Supply Current: Totem Pole & Open-Collector	-	-	15	mA	V_{CC} = 5.25, I_F = 15 mA
	Inverted Totem-Pole & Inverted Open-Collector	-	-	15	mA	V_{CC} = 5.25, I_F = 0 mA(1)
V_{OL}	Low Level Output Voltage: Totem Pole & Open-Collector	-	-	0.4	V	V_{CC} = 4.75, I_{OL} = 12.8 mA, I_F = 0 mA(1)
	Inverted Totem-Pole & Inverted Open-Collector	-	-	0.4	V	V_{CC} = 4.75, I_{OL} = 12.8 mA, I_F = 15 mA
V_{OH}	High Level Output Voltage: Totem-Pole & Open-Collector	2.4	-	-	V	V_{CC} = 4.75, I_{OH} = -800 µA, I_F = 15 mA
	Inverted Totem-Pole & Inverted Open-Collector	2.4	-	-	V	V_{CC} = 4.75, I_{OH} = -800 µA, I_F = 0 mA(1)
I_{OH}	High Level Output Current: Totem Pole & Open-Collector	-	-	100	µA	V_{CC} = 4.75, V_{OH} = 30 V, I_F = 15 mA,
	Inverted Totem-Pole & Inverted Open-Collector	-	-	100	µA	V_{CC} = 4.75, V_{OH} = 30 V, I_F = 0 mA(1)
$I_F(+)$	LED Positive-Going Threshold Current	-	-	15	mA	V_{CC} = 5.0 V
$I_F(+)$, $I_F(-)$	Hysteresis	-	2.0	-	V	V_{CC} = 5.0 V
I_{OS}	Short Circuit Output Current: Totem Pole & Open-Collector	-15	-	-60	mA	V_{CC} = 5.25 V, I_F = 15 mA, Output = GND
	Inverted Totem-Pole & Inverted Open-Collector	-15	-	-60	mA	V_{CC} = 5.25 V, I_F = 0 mA(1), Output = GND
$t_r t_f$	Output Rise Time, Output Fall Time	-	70	-	ns	V_{CC} = 5 V, I_F = 0 or 15 mA
T_{PLH}	Propagation Delay Low-High	-	5.0	-	µs	R_L = 8TTL loads (Totem Pole)
T_{PHL}	Propagation Delay High-Low	-	5.0	-	µs	R_L = 360 Ω (Open-Collector)

Notes:
(1) Normal application would be with light source blocked, simulated by I_F = 0 mA.
(2) All parameters are tested using pulse techniques.

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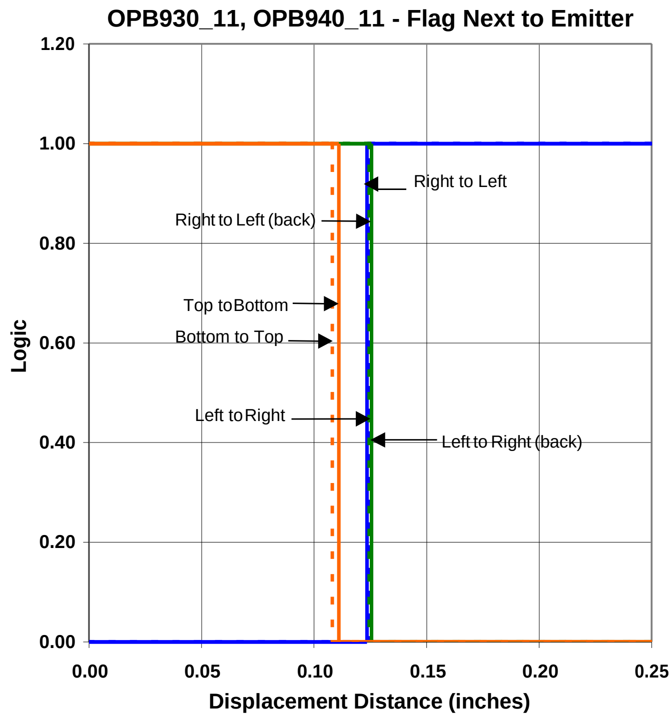
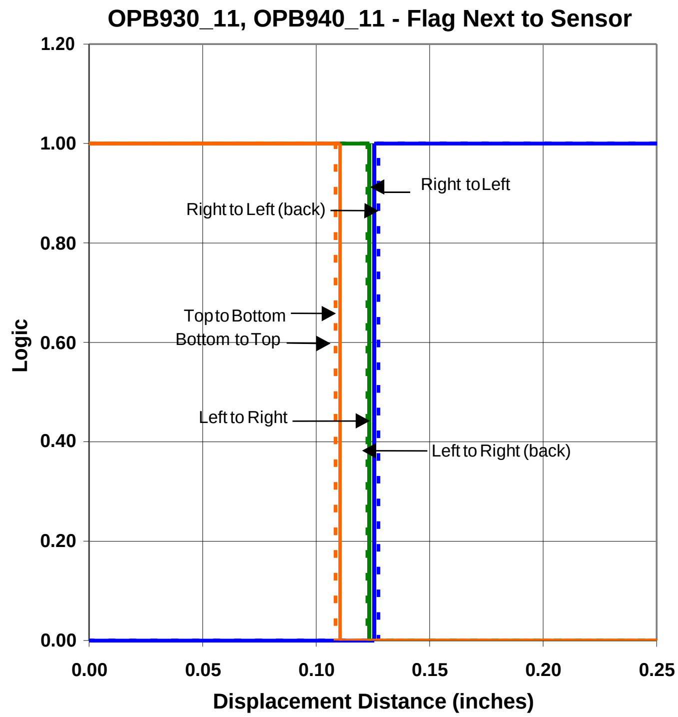
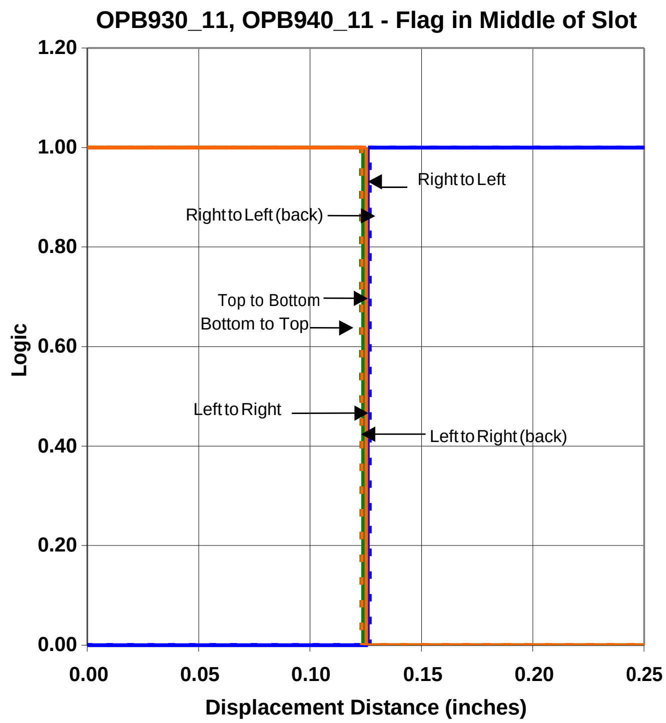
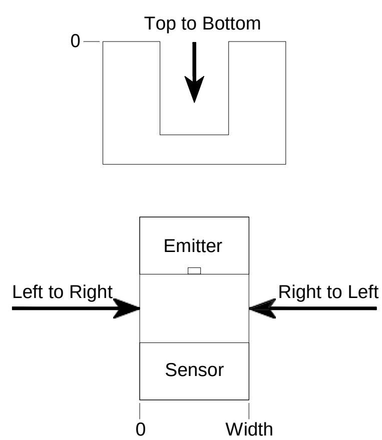
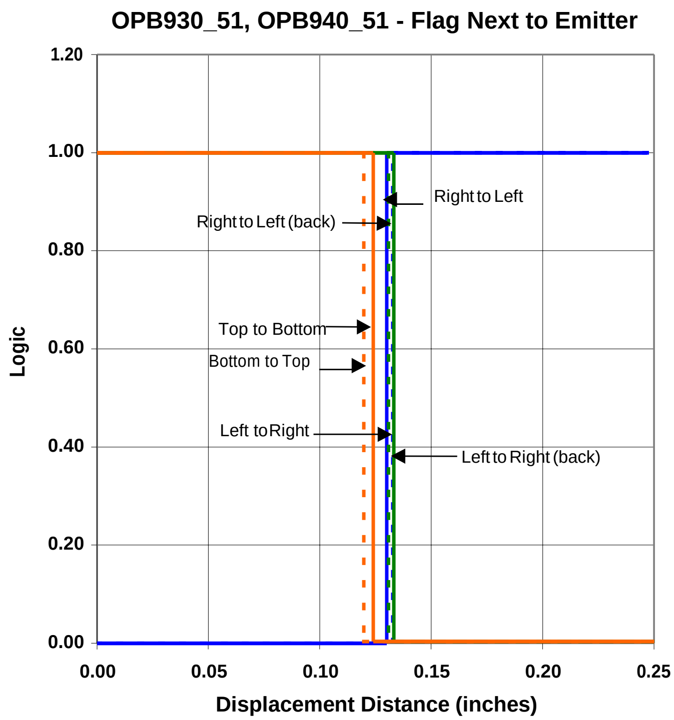
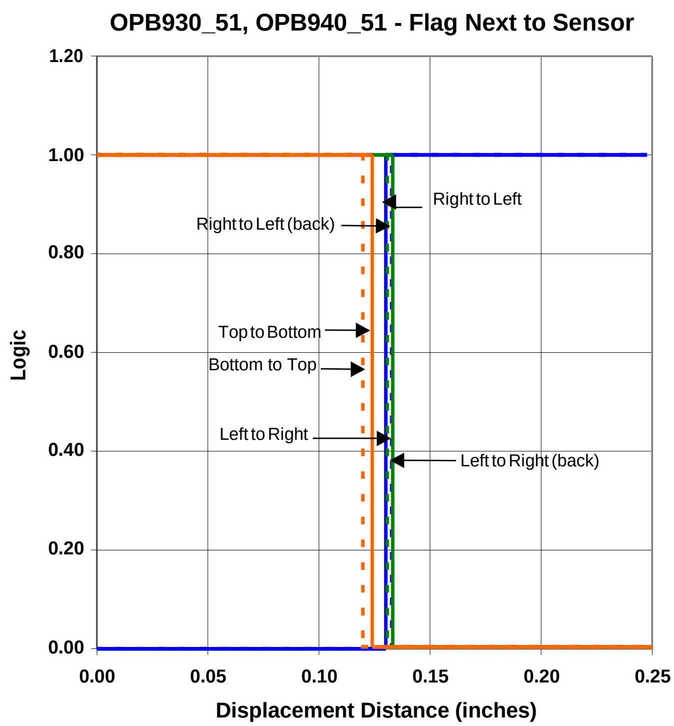

OPB930_11, OPB940_11 - Flag Next to Emitter
Logic
Displacement Distance (inches)
Right to Left
Right to Left (back)
Top to Bottom
Bottom to Top
Left to Right
Left to Right (back)

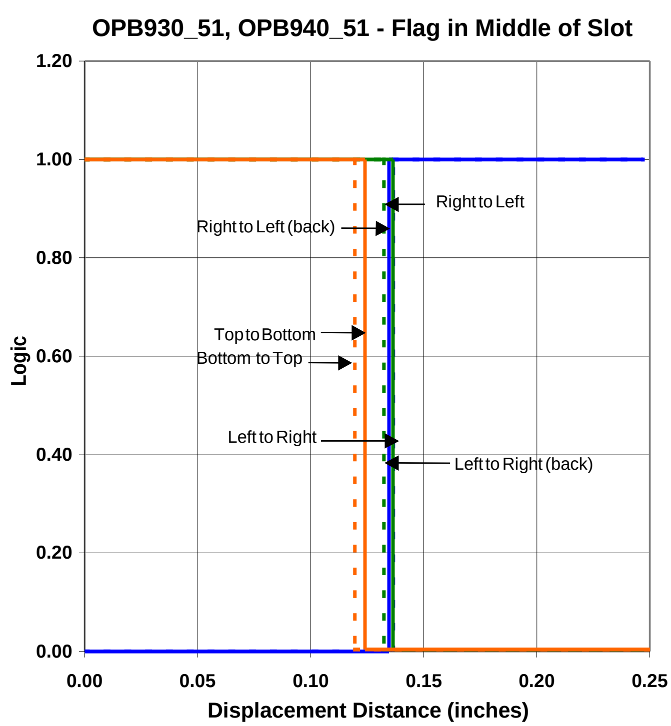

OPB930_11, OPB940_11 - Flag Next to Sensor
Logic
Displacement Distance (inches)
Right to Left
Right to Left (back)
Top to Bottom
Bottom to Top
Left to Right
Left to Right (back)

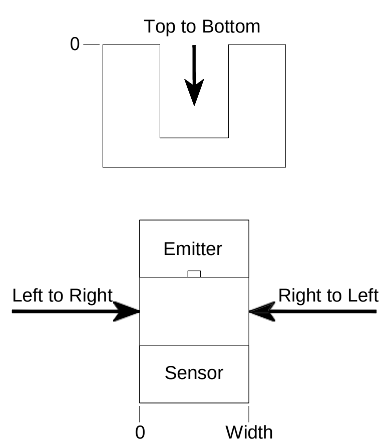

OPB930_11, OPB940_11 - Flag in Middle of Slot
Logic
Displacement Distance (inches)
Right to Left
Right to Left (back)
Top to Bottom
Bottom to Top
Left to Right
Left to Right (back)


Top to Bottom
0
Emitter
Left to Right
Right to Left
Sensor
0
Width









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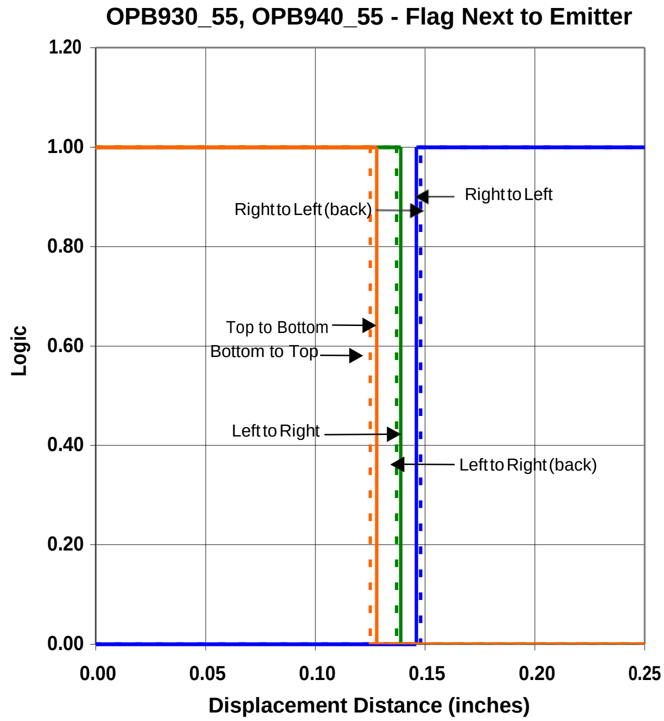

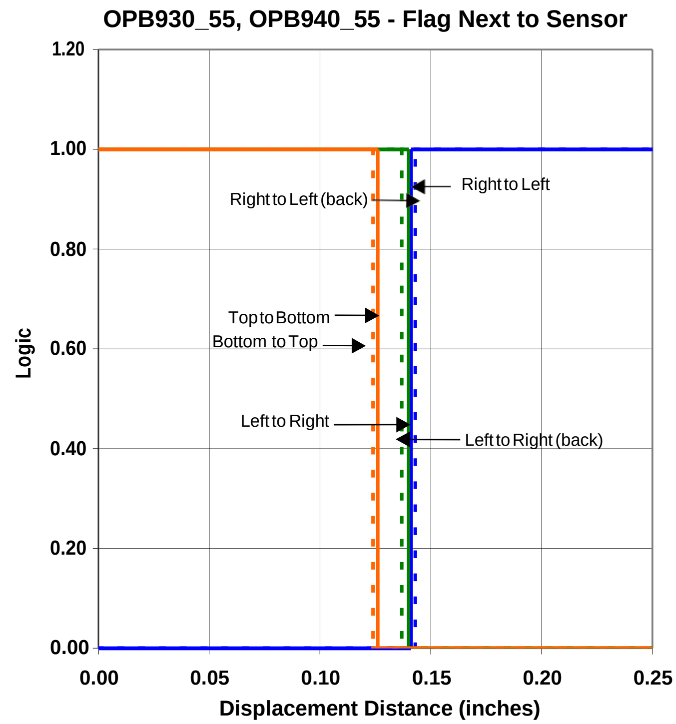

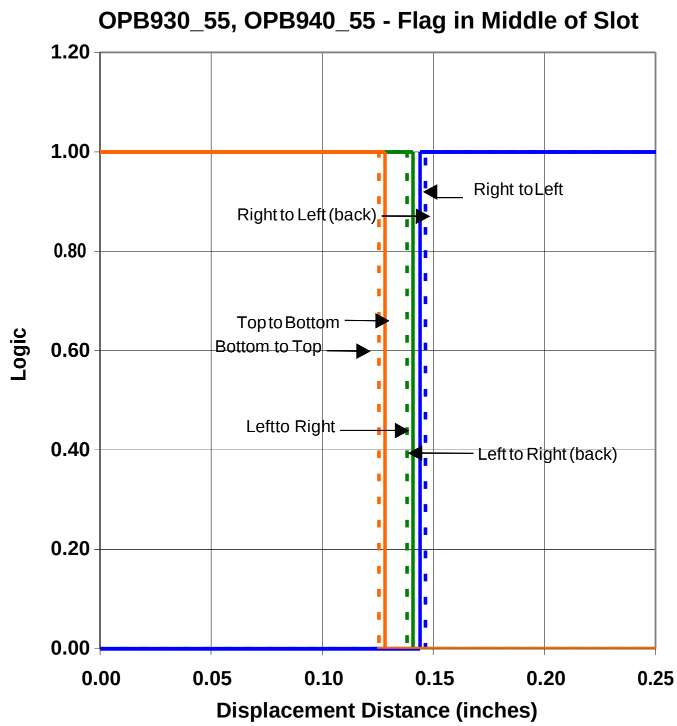

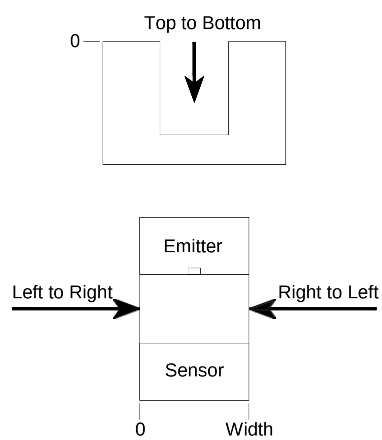

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