

## Stepper Motors

### Stepper Motor Benefits

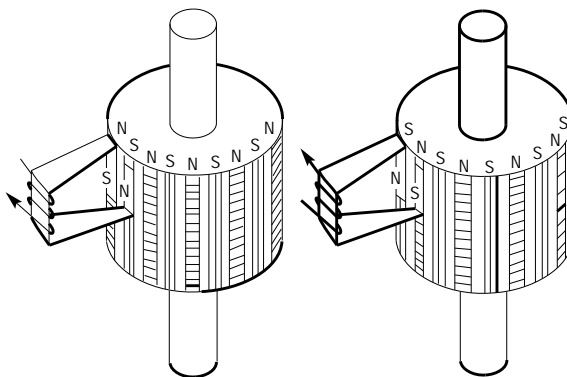
Stepper motors have the following benefits:

- Low cost
- Ruggedness
- Simplicity in construction
- High reliability
- No maintenance
- Wide acceptance
- No tweaking to stabilize
- No feedback components are needed
- They work in just about any environment
- Inherently more failsafe than servo motors.

There is virtually no conceivable failure within the stepper drive module that could cause the motor to run away. Stepper motors are simple to drive and control in an open-loop configuration. They only require four leads. They provide excellent torque at low speeds, up to 5 times the continuous torque of a brush motor of the same frame size or double the torque of the equivalent brushless motor. This often eliminates the need for a gearbox. A stepper-driven system is inherently stiff, with known limits to the dynamic position error.

Permanent Magnet (P.M.) Motors. The tin-can or “canstack” motor shown in Fig. 1.1 is perhaps the most widely-used type in non-industrial applications. It is essentially a low-cost, low-torque, low-speed device ideally suited to applications in fields such as computer peripherals. The motor construction results in relatively large step angles, but their overall simplicity lends itself to economic high-volume production at very low cost. The axial-air gap or disc motor is a variant of the permanent magnet design which achieves higher performance, largely because of its very low rotor inertia. However this does restrict the applications of the motor to those involving little inertia. (e.g., positioning the print wheel in a daisy-wheel printer).

Fig. 1.1 “Canstack” or permanent magnet motor



### Stepper Motor Disadvantages

Stepper motors have the following disadvantages:

- Resonance effects and relatively long settling times
- Rough performance at low speed unless a microstep drive is used
- Liability to undetected position loss as a result of operating open-loop
- They consume current regardless of load conditions and therefore tend to run hot
- Losses at speed are relatively high and can cause excessive heating, and they are frequently noisy (especially at high speeds).
- They can exhibit lag-lead oscillation, which is difficult to damp. There is a limit to their available size, and positioning accuracy relies on the mechanics (e.g., ballscrew accuracy). Many of these drawbacks can be overcome by the use of a closed-loop control scheme.

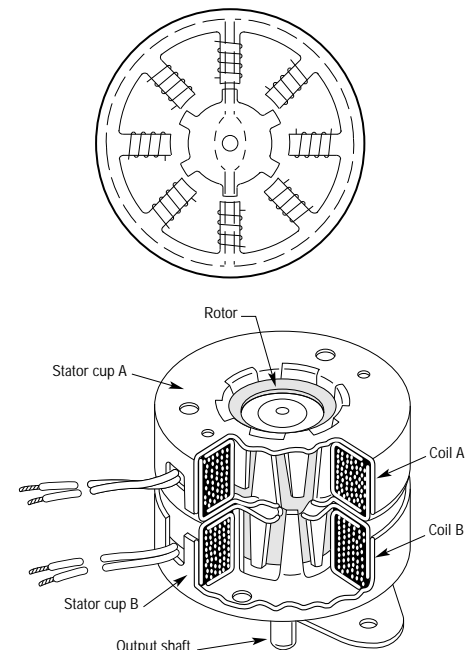
Note: The Compumotor Zeta Series minimizes or reduces many of these different stepper motor disadvantages.

There are three main stepper motor types:

- Permanent Magnet (P.M.) Motors
- Variable Reluctance (V.R.) Motors
- Hybrid Motors

Variable Reluctance (V.R.) Motors. There is no permanent magnet in a V.R. motor, so the rotor spins freely without “detent” torque. Torque output for a given frame size is restricted, although the torque-to-inertia ratio is good, and this type of motor is frequently used in small sizes for applications such as micro-positioning tables. V.R. motors are seldom used in industrial applications (having no permanent magnet). They are not sensitive to current polarity and require a different driving arrangement than the other motor types.

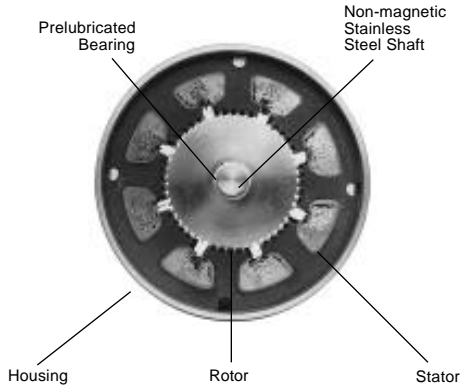
Fig. 1.2 Variable reluctance motor



Courtesy Airpax Corp., USA

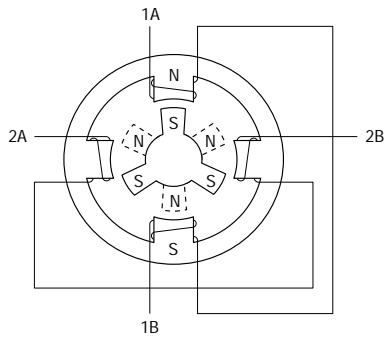
**Hybrid Motors.** The hybrid motor shown in Fig. 1.3 is by far the most widely-used stepper motor in industrial applications. The name is derived from the fact that it combines the operating principles of the other two motor types (P.M. & V.R.). Most hybrid motors are 2-phase, although 5-phase versions are available. A recent development is the “enhanced hybrid” motor, which uses flux-focusing magnets to give a significant improvement in performance, albeit at extra cost.

*Fig. 1.3 Hybrid stepper motor*



The operation of the hybrid motor is most easily understood by looking at a very simple model that will produce 12 steps per rev. (Fig. 1.4).

*Fig. 1.4 Simple 12 step/rev hybrid motor*



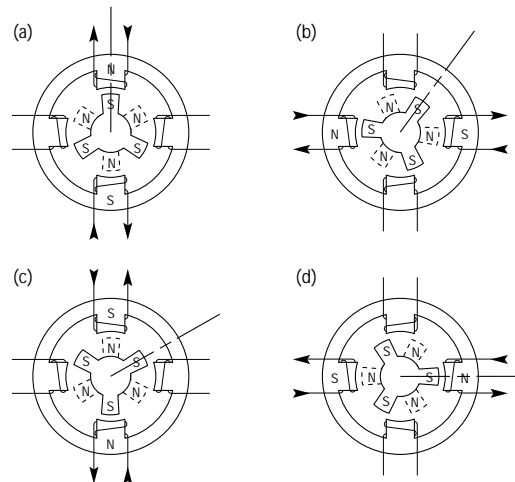
The rotor of this machine consists of two pole pieces with three teeth on each. In between the pole pieces is a permanent magnet that is magnetized along the axis of the rotor, making one end a north pole and the other a south pole. The teeth are offset at the north and south ends as shown in the diagram.

The stator consists of a shell having four teeth that run the full length of the rotor. Coils are wound on the stator teeth and are connected together in pairs.

With no current flowing in any of the motor windings, the rotor will take one of the positions shown in the diagrams. This is because the permanent magnet in the rotor is trying to minimize the reluctance (or “magnetic resistance”) of the flux path from one end to the other. This will occur when a pair of north and south pole rotor teeth are aligned with two of the stator poles. The torque tending to hold the rotor in one of these positions is usually small and is called the “detent torque”. The motor shown will have 12 possible detent positions.

If current is now passed through one pair of stator windings, as shown in Fig. 1.5(a), the resulting north and south stator poles will attract teeth of the opposite polarity on each end of the rotor. There are now only three stable positions for the rotor, the same as the number of rotor teeth. The torque required to deflect the rotor from its stable position is now much greater, and is referred to as the “holding torque”.

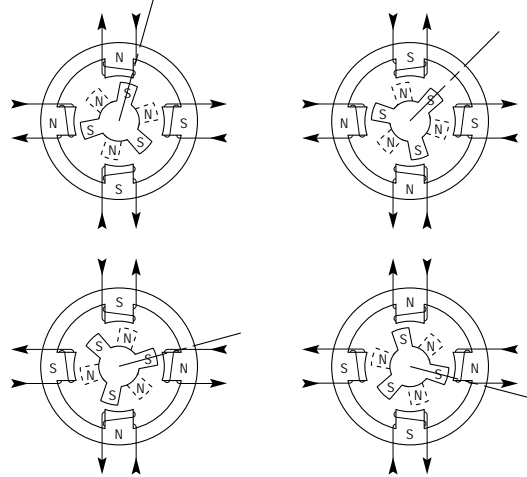
*Fig. 1.5 Full stepping, one phase on*



By changing the current flow from the first to the second set of stator windings (b), the stator field rotates through 90° and attracts a new pair of rotor poles. This results in the rotor turning through 30°, corresponding to one full step. Reverting to the first set of stator windings but energizing them in the opposite direction, we rotate the stator field through another 90° and the rotor takes another 30° step (c). Finally, the second set of windings are energized in the opposite direction (d) to give a third step position. We can now go back to the first condition (a), and after these four steps the rotor will have moved through one tooth pitch. This simple motor therefore performs 12 steps per rev. Obviously, if the coils are energized in the reverse sequence, the motor will go round the other way.

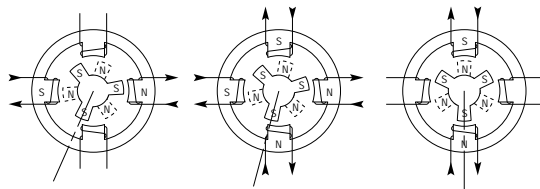
If two coils are energized simultaneously (Fig. 1.6), the rotor takes up an intermediate position since it is equally attracted to two stator poles. Greater torque is produced under these conditions because all the stator poles are influencing the rotor. The motor can be made to take a full step simply by reversing the current in one set of windings; this causes a 90° rotation of the stator field as before. In fact, this would be the normal way of driving the motor in the full-step mode, always keeping two windings energized and reversing the current in each winding alternately.

*Fig. 1.6 Full stepping, two phase on*



By alternately energizing one winding and then two (Fig. 1.7), the rotor moves through only 15° at each stage and the number of steps per rev will be doubled. This is called half stepping, and most industrial applications make use of this stepping mode. Although there is sometimes a slight loss of torque, this mode results in much better smoothness at low speeds and less overshoot and ringing at the end of each step.

*Fig. 1.7 Half stepping*



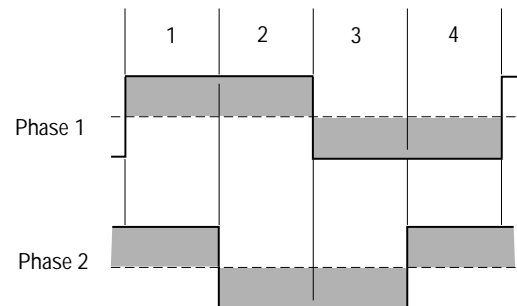
### Current Patterns in the Motor Windings

When the motor is driven in its full-step mode, energizing two windings or “phases” at a time (see Fig. 1.8), the torque available on each step will be the same (subject to very small variations in the

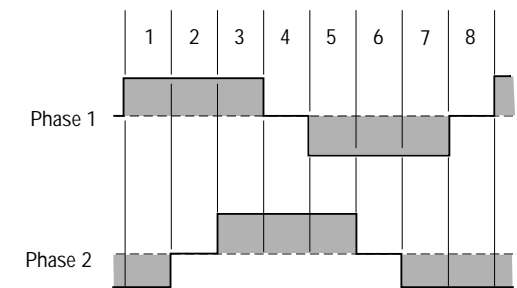
motor and drive characteristics). In the half-step mode, we are alternately energizing two phases and then only one as shown in Fig. 1.9. Assuming the drive delivers the same winding current in each case, this will cause greater torque to be produced when there are two windings energized. In other words, alternate steps will be strong and weak. This does not represent a major deterrent to motor performance—the available torque is obviously limited by the weaker step, but there will be a significant improvement in low-speed smoothness over the full-step mode.

Clearly, we would like to produce approximately equal torque on every step, and this torque should be at the level of the stronger step. We can achieve this by using a higher current level when there is only one winding energized. This does not over-dissipate the motor because the manufacturer’s current rating assumes two phases to be energized (the current rating is based on the allowable case temperature). With only one phase energized, the same total power will be dissipated if the current is increased by 40%. Using this higher current in the one-phase-on state produces approximately equal torque on alternate steps (see Fig. 1.10).

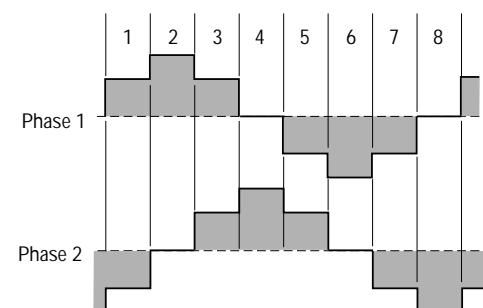
*Fig. 1.8 Full step current, 2-phase on*



*Fig. 1.9 Half step current*

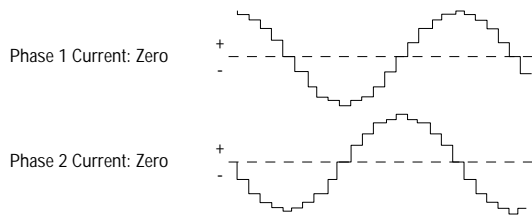


*Fig. 1.10 Half step current, profiled*



We have seen that energizing both phases with equal currents produces an intermediate step position half-way between the one-phase-on positions. If the two phase currents are unequal, the rotor position will be shifted towards the stronger pole. This effect is utilized in the microstepping drive, which subdivides the basic motor step by proportioning the current in the two windings. In this way, the step size is reduced and the low-speed smoothness is dramatically improved. High-resolution microstep drives divide the full motor step into as many as 500 microsteps, giving 100,000 steps per revolution. In this situation, the current pattern in the windings closely resembles two sine waves with a 90° phase shift between them (see Fig. 1.11). The motor is now being driven very much as though it is a conventional AC synchronous motor. In fact, the stepper motor can be driven in this way from a 60 Hz-US (50Hz-Europe) sine wave source by including a capacitor in series with one phase. It will rotate at 72 rpm.

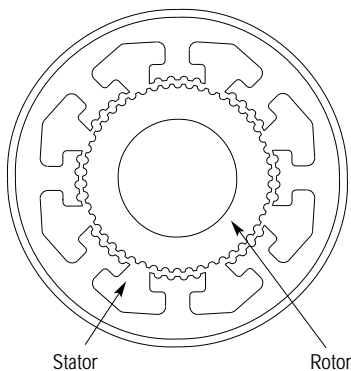
*Fig. 1.11 Phase currents in microstep mode*



## Standard 200-Step Hybrid Motor

The standard stepper motor operates in the same way as our simple model, but has a greater number of teeth on the rotor and stator, giving a smaller basic step size. The rotor is in two sections as before, but has 50 teeth on each section. The half-tooth displacement between the two sections is retained. The stator has 8 poles each with 5 teeth, making a total of 40 teeth (see Fig. 1.12).

*Fig. 1.12 200-step hybrid motor*



If we imagine that a tooth is placed in each of the gaps between the stator poles, there would be a total of 48 teeth, two less than the number of rotor teeth. So if rotor and stator teeth are aligned at 12 o'clock, they will also be aligned at 6 o'clock. At 3 o'clock and 9 o'clock the teeth will be misaligned. However, due to the displacement between the sets of rotor teeth, alignment will occur at 3 o'clock and 9 o'clock at the other end of the rotor.

The windings are arranged in sets of four, and wound such that diametrically-opposite poles are the same. So referring to Fig. 1.12, the north poles at 12 and 6 o'clock attract the south-pole teeth at the front of the rotor; the south poles at 3 and 9 o'clock attract the north-pole teeth at the back. By switching current to the second set of coils, the stator field pattern rotates through 45°. However, to align with this new field, the rotor only has to turn through 1.8°. This is equivalent to one quarter of a tooth pitch on the rotor, giving 200 full steps per revolution.

Note that there are as many detent positions as there are full steps per rev, normally 200. The detent positions correspond with rotor teeth being fully aligned with stator teeth. When power is applied to a stepper drive, it is usual for it to energize in the "zero phase" state in which there is current in both sets of windings. The resulting rotor position does not correspond with a natural detent position, so an unloaded motor will always move by at least one half step at power-on. Of course, if the system was turned off other than in the zero phase state, or the motor is moved in the meantime, a greater movement may be seen at power-up.

Another point to remember is that for a given current pattern in the windings, there are as many stable positions as there are rotor teeth (50 for a 200-step motor). If a motor is de-synchronized, the resulting positional error will always be a whole number of rotor teeth or a multiple of 7.2°. A motor cannot "miss" individual steps – position errors of one or two steps must be due to noise, spurious step pulses or a controller fault.

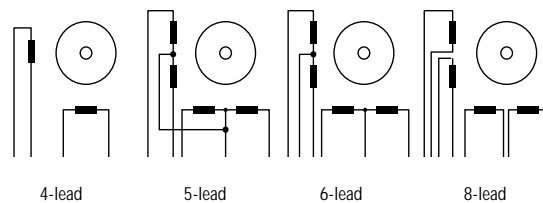
## Bifilar Windings

Most motors are described as being “bifilar wound”, which means there are two identical sets of windings on each pole. Two lengths of wire are wound together as though they were a single coil. This produces two windings that are electrically and magnetically almost identical – if one coil were to be wound on top of the other, even with the same number of turns, the magnetic characteristics would be different. In simple terms, whereas almost all the flux from the inner coil would flow through the iron core, some of the flux from the outer coil would flow through the windings of the coil underneath.

The origins of the bifilar winding go back to the unipolar drive (see Drive Technologies section, page A23). Rather than have to reverse the current in one winding, the field may be reversed by transferring current to a second coil wound in the opposite direction. (Although the two coils are wound the same way, interchanging the ends has the same effect.) So with a bifilar-wound motor, the drive can be kept simple. However, this requirement has now largely disappeared with the widespread availability of the more-efficient bipolar drive. Nevertheless, the two sets of windings do give us additional flexibility, and we shall see that different connection methods can be used to give alternative torque-speed characteristics.

If all the coils in a bifilar-wound motor are brought out separately, there will be a total of 8 leads (see Fig. 1.13). This is becoming the most common configuration since it gives the greatest flexibility. However, there are still a number of motors produced with only 6 leads, one lead serving as a common connection to each winding in a bifilar pair. This arrangement limits the motor’s range of application since the windings cannot be connected in parallel. Some motors are made with only 4 leads, these are not bifilar-wound and cannot be used with a unipolar drive. There is obviously no alternative connection method with a 4-lead motor, but in many applications this is not a drawback and the problem of insulating unused leads is avoided.

*Fig. 1.13 Motor lead configurations*



Occasionally a 5-lead motor may be encountered. These are not recommended since they cannot be used with conventional bipolar drives requiring electrical isolation between the phases.

Looking at the motor longitudinal section (Fig. 1.14), we can see the permanent magnet in the rotor and the path of the flux through the pole pieces and the stator. The alternating flux produced by the stator windings flows in a plane at right angles to the page. Therefore, the two flux paths are at right

angles to each other and only interact in the rotor pole pieces. This is an important feature of the hybrid motor – it means that the permanent magnet in the rotor does not “see” the alternating field from the windings, hence it does not produce a demagnetizing effect. Unlike the DC servo motor, it is generally impossible to de-magnetize a stepper motor by applying excess current. However, too much current will damage the motor in other ways. Excessive heating may melt the insulation or the winding formers, and may soften the bonding material holding the rotor laminations. If this happens and the laminations are displaced, the effects can be the same as if the rotor had been de-magnetized

*Fig. 1.14 Longitudinal section through single stack motor*

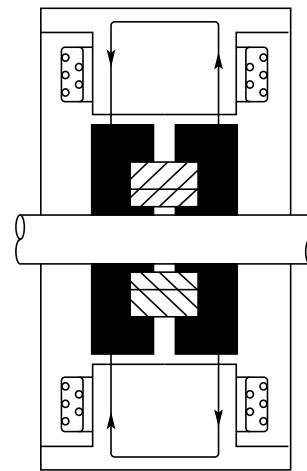


Fig. 1.14 also shows that the rotor flux only has to cross a small air gap (typically 0.1mm or 0.004”) when the rotor is in position. By magnetizing the rotor after assembly, a high flux density is obtained that can be largely destroyed if the rotor is removed. Stepper motors should therefore not be dismantled purely to satisfy curiosity, since the useful life of the motor will be terminated.

Because the shaft of the motor passes through the center of the permanent magnet, a non-magnetic material must be used to avoid a magnetic short-circuit. Stepper shafts are therefore made of stainless steel, and should be handled with care. Small-diameter motors are particularly vulnerable if they are dropped on the shaft end, as this will invariably bend the shaft.

To produce a motor with a higher torque output, we need to increase the strength of both the permanent magnet in the rotor and the field produced by the stator. A stronger rotor magnet can be obtained by increasing the diameter, giving us a larger cross-sectional area. However, increasing the diameter will degrade the acceleration performance of the motor because the torque-to-inertia ratio worsens (to a first approximation, torque increases with diameter squared but inertia goes up by the fourth power). Nevertheless, we can increase torque output without degrading acceleration performance by