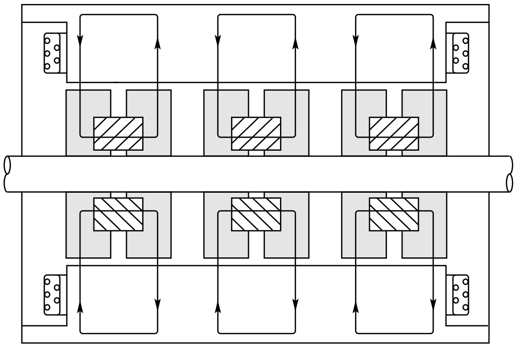
adding further magnet sections or “stacks” to the same shaft (Fig. 1.15). A second stack will enable twice the torque to be produced and will double the inertia, so the torque-to-inertia ratio remains the same. Hence, stepper motors are produced in single-, two- and three-stack versions in each frame size.

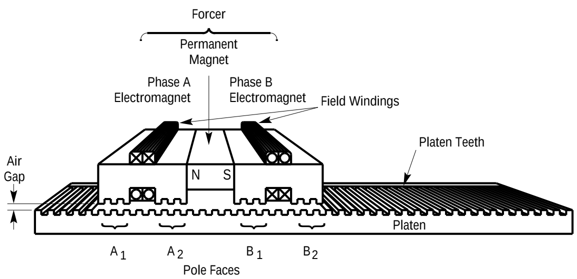
Fig. 1.15 Three-stack hybrid stepping motor



As a guideline, the torque-to-inertia ratio reduces by a factor of two with each increase in frame size (diameter). So an unloaded 34-size motor can accelerate twice as rapidly as a 42-size, regardless of the number of stacks.

Linear Stepping Motors

Fig. 1.16 Linear stepping motor



The linear stepper is essentially a conventional rotary stepper that has been “unwrapped” so that it operates in a straight line. The moving component is referred to as the forcer and it travels along a fixed element or platen. For operational purposes, the platen is equivalent to the rotor in a normal stepper, although it is an entirely passive device and has no permanent magnet. The magnet is incorporated in the moving forcer together with the coils (see Fig. 1.16).

The forcer is equipped with 4 pole pieces each having 3 teeth. The teeth are staggered in pitch with respect to those on the platen, so that switching the current in the coils will bring the next set of teeth into alignment. A complete switching cycle (4 full steps) is equivalent to one tooth pitch on the platen. Like the rotary stepper, the linear motor can be driven from a microstep drive. In this case, a typical linear resolution will be 12,500 steps per inch.

The linear motor is best suited for applications that require a low mass to be moved at high speed. In a leadscrew-driven system, the predominant inertia is usually the leadscrew rather than the load to be moved. Hence, most of the motor torque goes to accelerate the leadscrew, and this problem becomes more severe the longer the travel required. Using a linear motor, all the developed force is applied directly to the load and the performance achieved is independent of the length of the move. A screw-driven system can develop greater linear force and better stiffness; however, the maximum speed may be as much as ten times higher with the equivalent linear motor. For example, a typical maximum speed for a linear motor is 100 in/sec. To achieve this with a 10-pitch ballscrew would require a rotary speed of 6,000 rpm. In addition, the linear motor can travel up to 12 feet using a standard platen.

How the Linear Motor Works

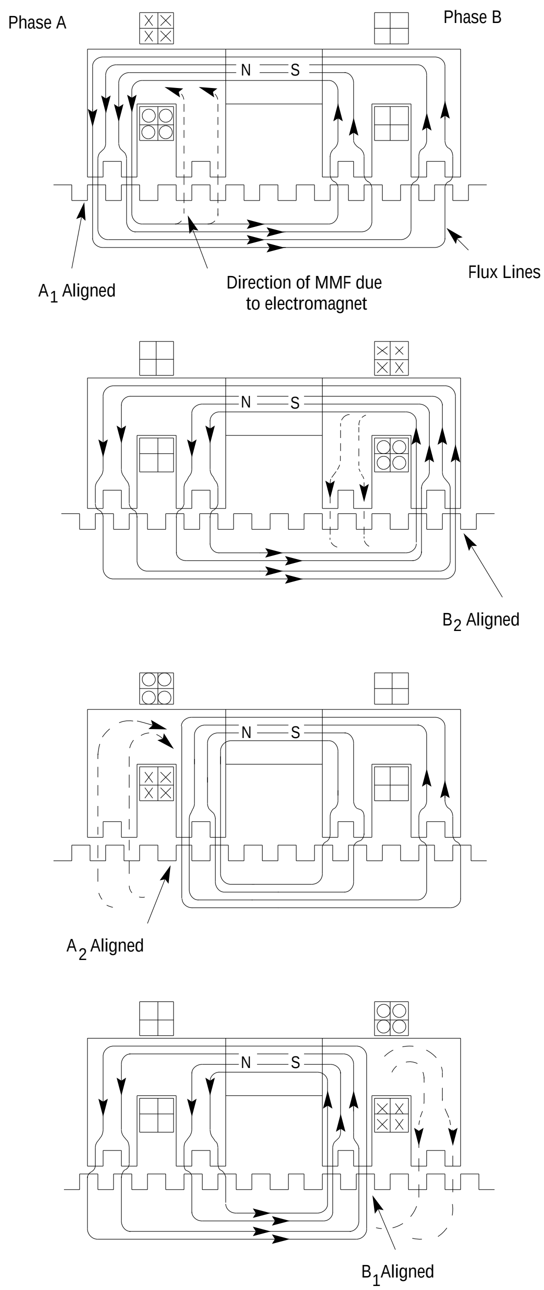
The forcer consists of two electromagnets (A and B) and a strong rare earth permanent magnet. The two pole faces of each electromagnet are toothed to concentrate the magnetic flux. Four sets of teeth on the forcer are spaced in quadrature so that only one set at a time can be aligned with the platen teeth.

The magnetic flux passing between the forcer and the platen gives rise to a very strong force of attraction between the two pieces. The attractive force can be up to 10 times the peak holding force of the motor, requiring a bearing arrangement to maintain precise clearance between the pole faces and platen teeth. Either mechanical roller bearings or air bearings are used to maintain the required clearance.

When current is established in a field winding, the resulting magnetic field tends to reinforce permanent magnetic flux at one pole face and cancel it at the other. By reversing the current, the reinforcement and cancellation are exchanged. Removing current divides the permanent magnetic flux equally between the pole faces. By selectively applying current to phase A and B, it is possible to concentrate flux at any of the forcer’s four pole faces. The face receiving the highest flux concentration will attempt to align its teeth with the platen. Fig. 1.17 shows the four primary states or full steps of the forcer. The four steps result in motion of one tooth interval to the right. Reversing the sequence moves the forcer to the left.

Repeating the sequence in the example will cause the forcer to continue its movement. When the sequence is stopped, the forcer stops with the appropriate tooth set aligned. At rest, the forcer develops a holding force that opposes any attempt to displace it. As the resting motor is displaced from equilibrium, the restoring force increases until the displacement reaches one-quarter of a tooth interval. (See Fig. 1.18.) Beyond this point, the restoring force drops. If the motor is pushed over the crest of its holding force, it slips or jumps rather sharply and comes to rest at an integral number of tooth intervals away from its original location. If this occurs while the forcer is travelling along the platen, it is referred to as a stall condition.

Fig. 1.17 The four cardinal states or full steps of the forcer

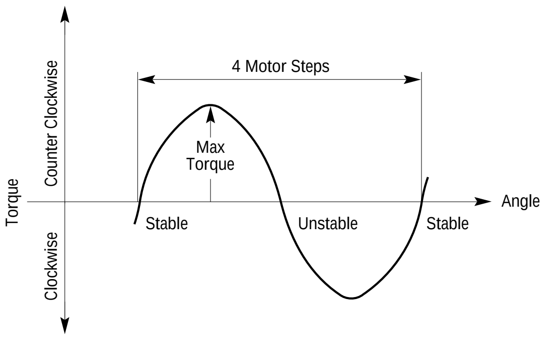


Step Motor Characteristics

There are numerous step motor performance characteristics that warrant discussion. However, we'll confine ourselves to those traits with the greatest practical significance.

Fig. 1.18 illustrates the static torque curve of the hybrid step motor. This relates to a motor that is energized but stationary. It shows us how the restoring torque varies with rotor position as it is deflected from its stable point. We're assuming that there are no frictional or other static loads on the motor. As the rotor moves away from the stable position, the torque steadily increases until it reaches a maximum after one full step (1.8°). This maximum value is called the holding torque and it represents the largest static load that can be applied to the shaft without causing continuous rotation. However, it doesn't tell us the maximum running torque of the motor – this is always less than the holding torque (typically about 70%).

Fig. 1.18 Static torque-displacement characteristic



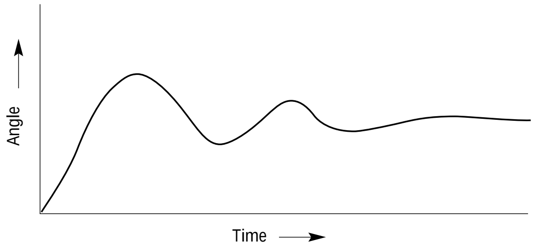
As the shaft is deflected beyond one full step, the torque will fall until it is again at zero after two full steps. However, this zero point is unstable and the torque reverses immediately beyond it. The next stable point is found four full steps away from the first, equivalent to one tooth pitch on the rotor or 1/50 of a revolution.

Although this static torque characteristic isn't a great deal of use on its own, it does help explain some of the effects we observe. For example, it indicates the static stiffness of the system, (i.e., how the shaft position changes when a torque load is applied to a stationary motor). Clearly the shaft must deflect until the generated torque matches the applied load. If the load varies, so too will the static position. Non-cumulative position errors will therefore result from effects such as friction or out-of-balance torque loads. It is important to remember that the static stiffness is not improved by using a microstepping drive—a given load on the shaft will produce the same angular deflection. So while microstepping increases resolution and smoothness, it may not necessarily improve positioning accuracy.

Under dynamic conditions with the motor running, the rotor must be lagging behind the stator field if it is producing torque. Similarly, there will be a lead situation when the torque reverses during deceleration. Note that the lag and lead relate only to position and not to speed. From the static torque curve (Fig. 1.18), clearly this lag or lead cannot exceed two full steps (3.6°) if the motor is to retain synchronism. This limit to the position error can make the stepper an attractive option in systems where dynamic position accuracy is important.

When the stepper performs a single step, the nature of the response is oscillatory as shown in Fig. 1.19. The system can be likened to a mass that is located by a “magnetic spring”, so the behavior resembles the classic mass-spring characteristic. Looking at it in simple terms, the static torque curve indicates that during the step, the torque is positive during the full forward movement and so is accelerating the rotor until the new stable point is reached. By this time, the momentum carries the rotor past the stable position and the torque now reverses, slowing the rotor down and bringing it back in the opposite direction. The amplitude, frequency and decay rate of this oscillation will depend on the friction and inertia in the system as well as the electrical characteristics of the motor and drive. The initial overshoot also depends on step amplitude, so half-stepping produces less overshoot than full stepping and microstepping will be better still.

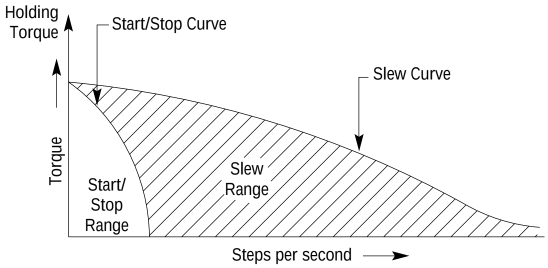
Fig. 1.19 Single step response



Attempting to step the motor at its natural oscillation frequency can cause an exaggerated response known as resonance. In severe cases, this can lead to the motor desynchronizing or “stalling.” It is seldom a problem with half-step drives and even less so with a microstepper. The natural resonant speed is typically 100-200 full steps/sec. (0.5-1 rev/sec).

Under full dynamic conditions, the performance of the motor is described by the torque-speed curve as shown in Fig. 1.20. There are two operating ranges, the start/stop (or pull in) range and the slew (or pull out) range. Within the start/stop range, the motor can be started or stopped by applying index pulses at constant frequency to the drive. At speeds within this range, the motor has sufficient torque to accelerate its own inertia up to synchronous speed without the position lag exceeding 3.6°. Clearly, if an inertial load is added, this speed range is reduced. So the start/stop speed range depends on the load inertia. The upper limit to the start/stop range is typically between 200 and 500 full steps/sec (1-2.5 revs/sec).

Fig. 1.20 Start/stop and slew curves



To operate the motor at faster speeds, it is necessary to start at a speed within the start/stop range and then accelerate the motor into the slew region. Similarly, when stopping the motor, it must be decelerated back into the start/stop range before the clock pulses are terminated. Using acceleration and deceleration “ramping” allows much higher speeds to be achieved, and in industrial applications the useful speed range extends to about 3000 rpm (10,000 full steps/sec). Note that continuous operation at high speeds is not normally possible with a stepper due to rotor heating, but high speeds can be used successfully in positioning applications.

The torque available in the slew range does not depend on load inertia. The torque-speed curve is normally measured by accelerating the motor up to speed and then increasing the load until the motor stalls. With a higher load inertia, a lower acceleration rate must be used but the available torque at the final speed is unaffected.