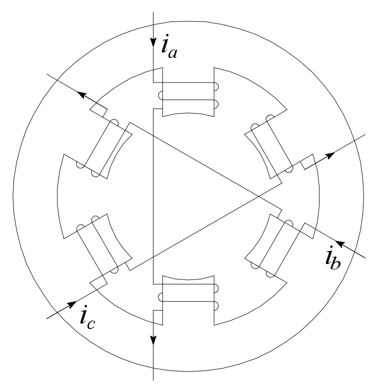
Chapter 11

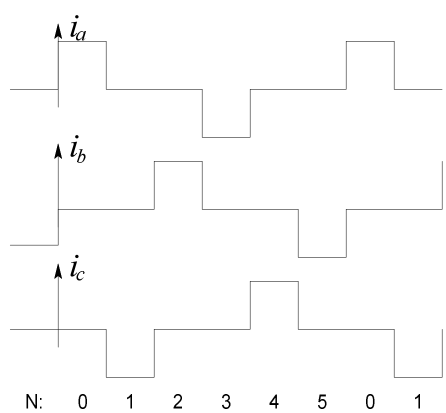
Stepping Motors

In the synchronous motor, the combination of sinusoidally distributed windings and sinusoidally time varying current produces a smoothly rotating magnetic field. We can eliminate "sinusoidally" from this description if we also eliminate "smoothly," i.e. we can still get a rotating field, but it will be "jerky."

For example, if we replaced the stator of a synchronous motor with the structure on the right, it would still work, but the torque would no longer be uniform.



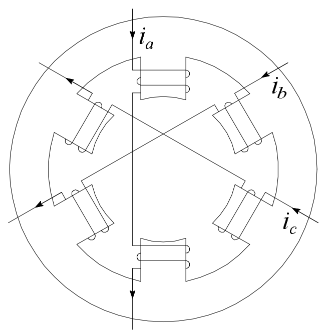
We could also replace the sinusoidal drive currents with the "binary approximation" of the pulse waveform on the right. In this case the field would rotate in discrete jumps or *steps*.

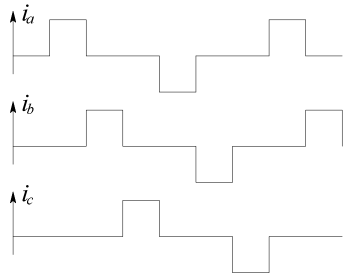


We can represent this pulse waveform as a state table where each of the six directions of the field corresponds to a different pattern of current values.

N	i_a	i_b	i_c
0	+I	0	0
1	0	0	-I
2	0	+I	0
3	-I	0	0
4	0	0	+I
5	0	-I	0

A simpler state sequence results if we place the windings 60° apart instead of 120°.





N	i_a	i_b	i_c
0	+I	0	0
1	0	+I	0
2	0	0	+I
3	-I	0	0
4	0	-I	0
5	0	0	-I

If we insert a permanent magnet rotor into this structure, the alignment torque will cause it to follow the rotating field, as in a synchronous motor. If all we did was run it at a constant speed, it would have no advantages over the synchronous motor, and its torque would not be as smooth. Its advantage lies in situations where we want to vary the speed, down to and including zero.

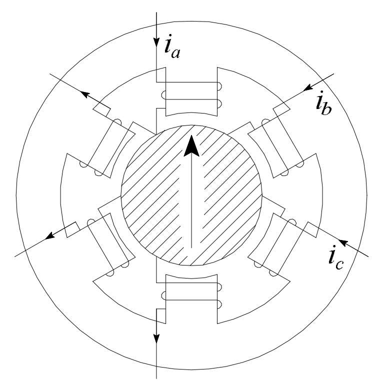


Figure 11.1:

To change the speed of a synchronous motor, we must change the driving frequency. Since the HL&P is unlikely to be agreeable to changing the line frequency to suit our requirements, we will have to generate our own variable frequency, and generating square waves is easer than generating sine waves, especially at high power levels.

But the major advantage of the stepper motor is its ability to control *position*. If we stop the pulse sequence in one of its six states, the rotor will come to rest pointing in the corresponding direction, held in place by the alignment torque. If we then change the excitation currents to the next pattern in the sequence, the field will point in a new direction, 60° away from the previous one. The alignment torque will pull the rotor into alignment with the new direction, advancing it by one *step*. By sequencing through the states we can advance the rotor by any desired number of steps, stopping at any desired point.

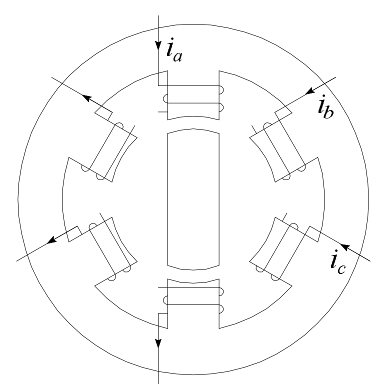
11.1 Types of Stepping Motors

11.1.1 Permanent Magnet

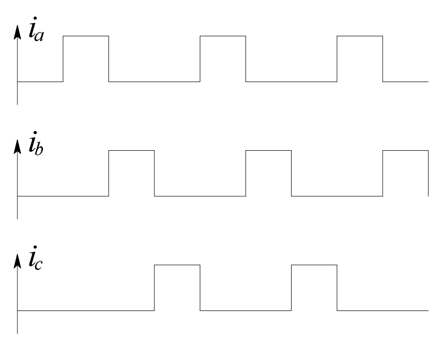
The structure in Figure 11.1 is called a *permanent magnet stepper motor*. The torque required to move from one position to another is due entirely to alignment torque. Because of the *salient poles* of the stator, there is some amount of reluctance torque (called *detent torque*) tending to hold the rotor in its current position. This torque is present even with no current flowing in any of the windings, and must be overcome by the alignment torque before motion will occur.

11.1.2 Variable Reluctance

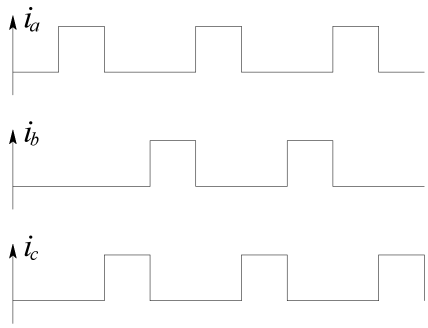
If we replace the permanent magnet rotor by a smooth, soft iron rotor, no torque will be produced. However, if we flatten the sides of the soft iron rotor, we get a structure similar to the rotary reluctance machine in Figure 9.1, and the resulting reluctance torque will align the rotor with whichever pair of stator poles is carrying current. This gives us a *variable reluctance stepper motor*.



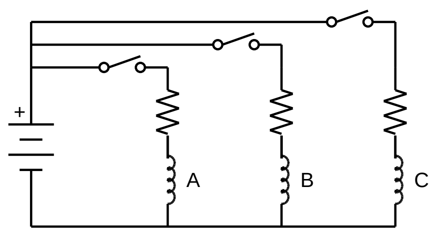
Since the reluctance torque doesn't depend on the sign of the current, we can use a full-wave rectified version of the drive sequency for a permanent magnet stepper.



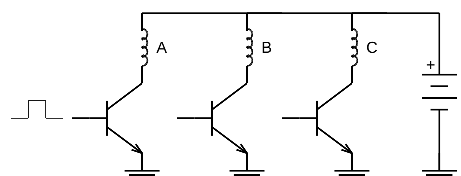
Again, we can reverse the direction of rotation by exchanging two phases.



Since only unipolar current is required, a much simpler drive circuit results. Because of the non-zero resistance of the coil windings, we can drive them from a voltage source. The steady state current will be $I = \frac{V_{drive}}{R_{coil}}$.

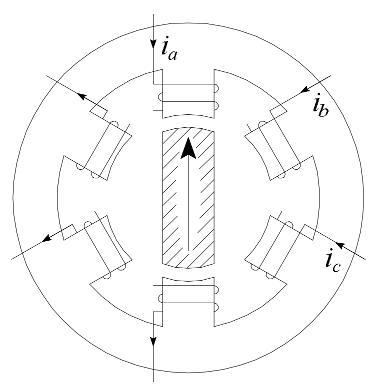


In actual practice, the switching of the current in the windings would be performed by transistors.



11.1.3 Hybrid

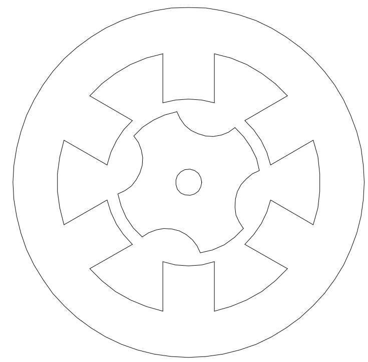
By using a salient pole, magnetized rotor, we can utilize both alignment and reluctance torque. This is called a *hybrid stepper motor*.



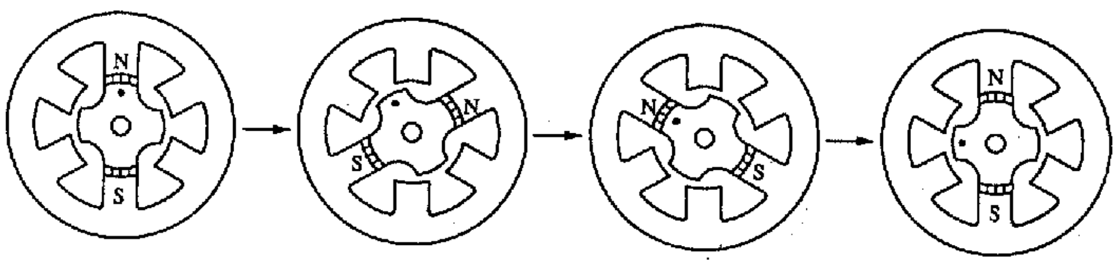
11.2 Increasing Angular Resolution

So far the number of steps per revolution has been equal to the number of poles on the stator, six in the previous examples. As with AC motors, it is possible to increase the number of poles without increasing the number of phases, so we could have, for example, a 3-phase, 12-pole stepper. This would give 12 steps per revolution with the same drive signals as the 6-pole motor.

A simpler approach is to change the number of poles on the rotor. For example, with a 4-pole rotor in a 6-pole stator, there are 12 unique alignment states.

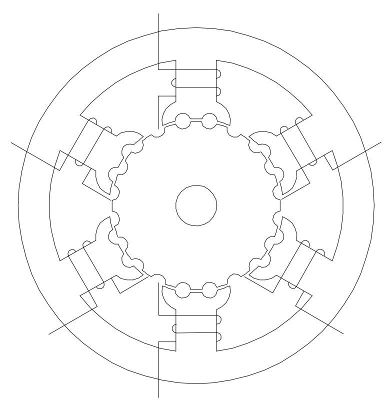


Note that as the field steps in a clockwise direction, the rotor moves in a counterclockwise direction.



We can't go very far with this idea. A six pole rotor in a six pole stator won't rotate at all.

However, we can put *more* poles on the rotor than on the stator if we groove the stator pole pieces, producing so called *castellated poles*. The structure on the right has 60 steps/revolution using a rotor with 20 grooves.



11.2.1 Half Stepping and Microstepping

In the excitation waveforms we've seen so far, only a single phase has been energized at any one time, the current in all other phases being zero. If we simultaneously excite two adjacent phases (with current of the same polarity) then the total stator field will be the sum of the two individual fields and will point in a direction *between* the two poles. In particular, if the two currents are equal, the field will point midway between the two poles. This is called *half-stepping.*

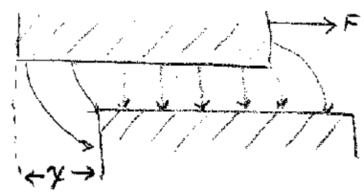
Any direction between the two poles is possible by proper choice of the relative values of the currents in the two phases. It is possible to divide a single physical step into an arbitrary number of sub-steps, a process called *microstepping.*

11.3 Static Behavior

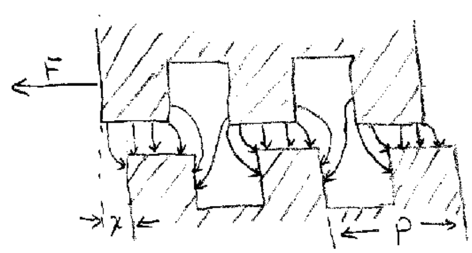
In a typical stepper motor application, the load is moved from one position to another, and then held in the new position. In moving between positions, we are interestested in the dynamic behavior, while in holding a position, we are interested in static (T vs. θ) behavior.

From the results in Section 9.2.3, we would expect the torque to be zero with the rotor and stator poles aligned and to quickly rise to a constant value as it is disturbed away from the equilibrium position.

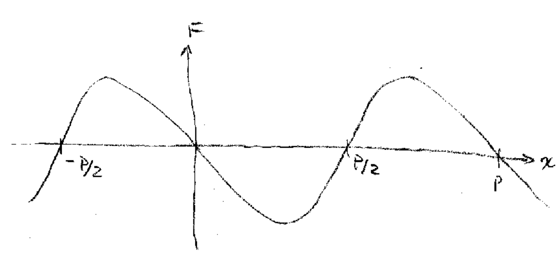
Indeed if the pole faces were wide compared to the gap the approximations used to obtain this result would be valid.



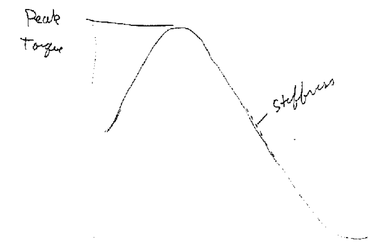
However, because the poles are narrow and periodic, a more complex torque vs. displacement curve results.



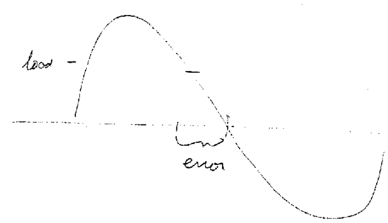
The torque will increase smoothly with angle, perhaps reaching a plateau, and then begin to decrease, reversing direction when the next active pole becomes closer than the original one. This results in a periodic T vs. θ curve.



This has a number of consequences with regard to static behavior. First of all, near the equilibrium point the stepper acts like a spring whose stiffness is determined by the stator current. If the torque exceeds the peak value of the $T - \theta$ curve (called the *holding torque*), the rotor will slip, loosing the desired position.



When holding a static position, the interaction between the load torque and the sloping $T - \theta$ curve will result in a *position error* between the equilibrium state and the desired direction.



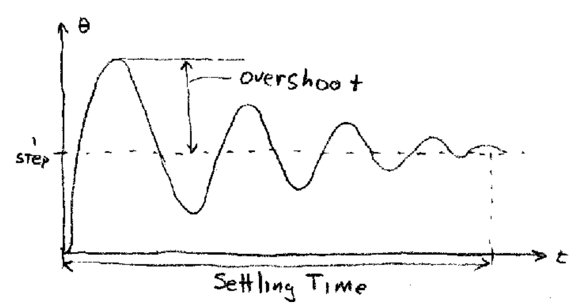
11.4 Dynamic Behavior

Static behavior describes how accurately a stepper motor can *hold* a desired position. If we try to analyze how it can move to a new target position we find a complex interaction between the stepper's $T - \theta$ curve, the dynamic characteristics of the load, and the θ vs. t profile of the move.

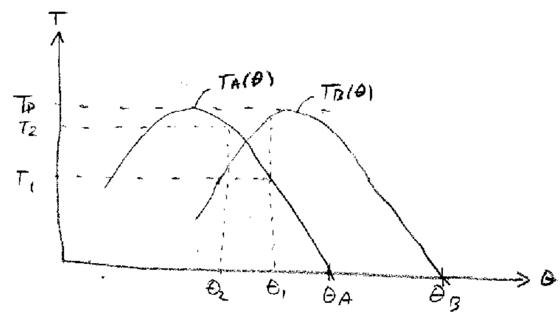
11.4.1 Single Step

The simplest and safest (but slowest and noisest) way to move to a new position is to take one step at a time, allowing sufficient time for the load to come to rest at the new position before moving to the next.

An inertial load will combine with the spring-like behavior of the stepper's $T - \theta$ curve to produce a second order system. The amount of friction will determine the damping characteristics, and since good design practice usually calls for minimizing friction, it is likely to be underdamped, resulting in overshoot and long settling times.

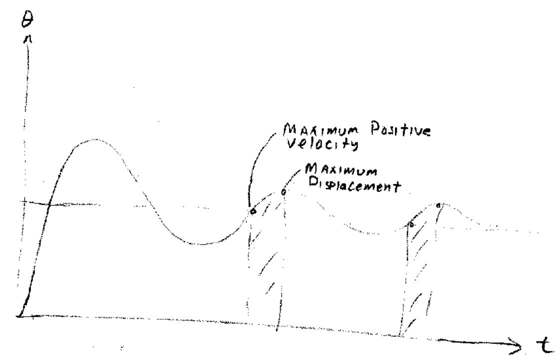


One unfortunate consequence of the shape of the $T-\theta$ curve is that the torque available to step to a new position is less than the peak torque available to hold the current step. With a load torque of T_1 the rotor equilibrium point will be θ_1 with phase A energized. If phase is turned off and phase B turned on, the torque available to move the load to the next step will be $T_B(\theta_1) - T_1$, which is greater than zero. On the other hand, for a load torque of T_2, $T_B(\theta_2) - T_2$ is negative, so the rotor will move backwards, loosing synchronization.

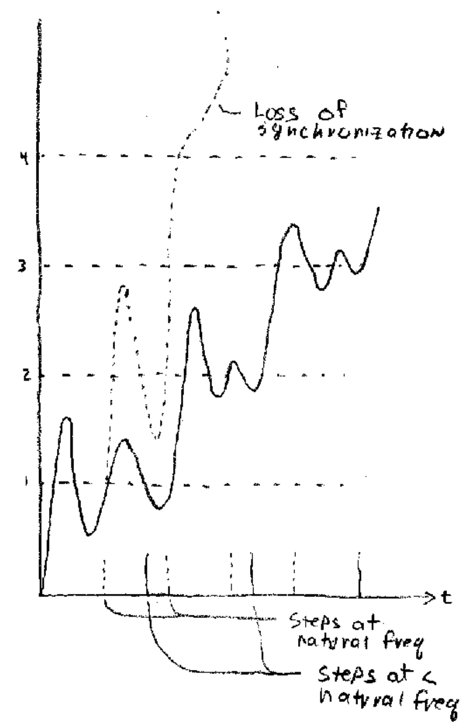


11.4.2 Multiple Steps

If we don't wait for the previous step to settle before beginning the next, we face potential problems with resonance. When the rotor overshoots the new equilibrium position, it is moving with a positive velocity towards the next step. Similarly, when it reaches the peak of its overshoot it is at rest, but its distance to the next step is less than the step to step spacing.



If a new step is taken at or near the point of maximum velocity, it will overshoot its intended target by an even greater amount. Eventually the amount of overshoot will exceed the spacing between equilibrium states for the same excitation pattern and loss of synchronization will result.

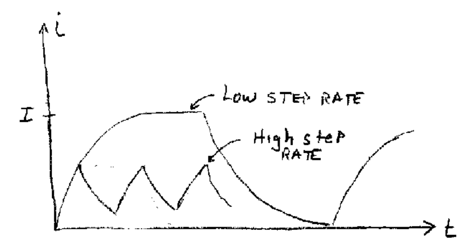


11.4.3 Continuous Rotation

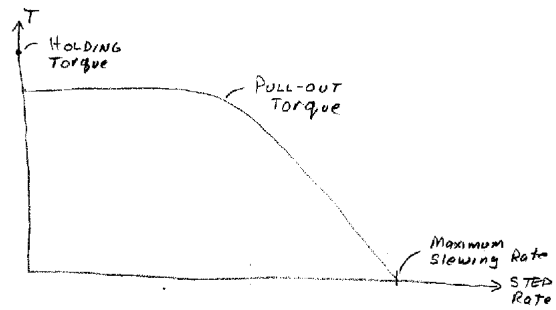
Because stepper motors are position controlling devices the notion of speed vs. torque is more complex than for conventional, velocity control motors. A single lost step will not change the speed of the rotor, but will cause a an error in phase, and hence an error in position. As a result, the speed/torque curve is a composite of several curves, with several distinct regions of behavior.

11.4.4 Running: Pull-out Torque

When running at a steady speed, the torque available to drive the load is the same as the single step torque. If the stator windings are driven by a current source, this torque will be independent of the step rate. But with voltage source drive, the stator inductance will prevent the current from reaching its maximum value.



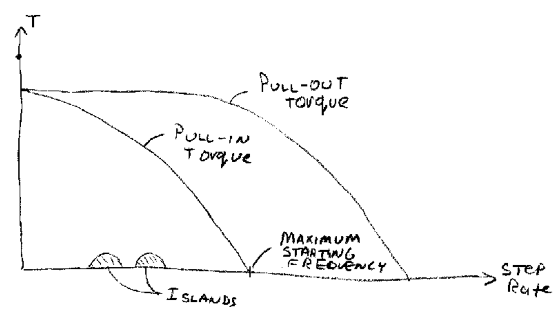
As a result, the torque will fall off as the stepping rate increases. Since this is the torque required to pull the rotor out of synch with the rotating field, it is called the *pull-out torque*. The step rate at which the pull-out torque goes to zero is called the maximum slewing rate and is roughly equivalent to the no-load speed in continuous rotation motors.



11.4.4.1 Starting: Pull-in Torque

Pull-out torque is the torque available to drive a load at constant speed. How do we get to that speed from a stop? If we try to accelerate a stepper motor to a constant speed by suddenly applying a stream of stepping pulses, we face the same problem as in trying to start a synchronous motor: the inertia of the load causes it to lag behind the rotating field and if the lag exceeds the period of the $T-\theta$ curve, instability or missed steps will occur.

The maximum stepping rate which, when abruptly applied to an unloaded motor at rest, will accelerate the rotor up to speed without loosing steps is called the *maximum starting frequency*. As the load torque increases, the torque available to accelerate the rotor decreases and hence the frequency at which the motor will start without loosing steps decreases. Since this is the torque available to pull the load into synchronization with the rotating field, it is called the *pull-in torque*. Because of resonance effects, there may be regions of frequency or "islands" where it will not be possible to start the motor if the frictional load is too light to provide adequate damping.



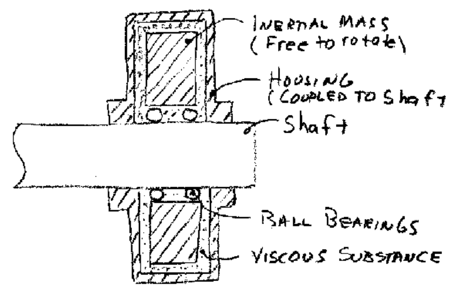
11.5 Controlling Dynamic Behavior

Although it is possible to use a stepper motor by connecting it directly to a system and stepping from one position to another at a fixed rate, the performance is likely to be disappointing. The potential for missing steps due to low starting torque or resonance effects restricts safe operation to relatively low stepping rates. To achieve maximum performance from a stepper motor requires paving over or navigating around the pitfalls in its dynamic behavior.

11.5.1 Damping

A straightforward way to control resonance is to deliberately add damping to the system. However, adding a significant amount of conventional viscous damping is undesirable as it reduces the torque available at high speeds.

It is possible to introduce damping which responds to *changes* in velocity by using a *viscous coupled inertia damper* (VCID). This consists of an inertial mass which is free to rotate on the shaft of the stepper motor, but is coupled to it via a viscous substance. At a steady speed, the shaft and mass will rotate at the same velocity, but if the motor changes speed, the inertia of the mass will introduce damping.

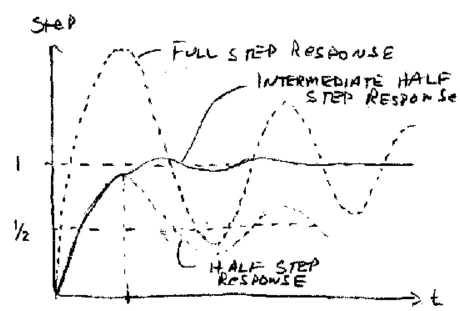


11.5.2 Pulse Timing

By adjusting the timing of the stepping pulses or adding additional intermediate states, it is possible to reduce or eliminate overshoot and ringing, producing an effect similar to damping, but without the accompanying sluggishness and loss of high speed torque.

One example of this is the *intermediate half step.* To take a single step, this technique leaves the current phase on for a short time after energizing the next. Two adjacent phases being on results in an equilibrium position halfway between the initial and final states, i.e. a half-step.

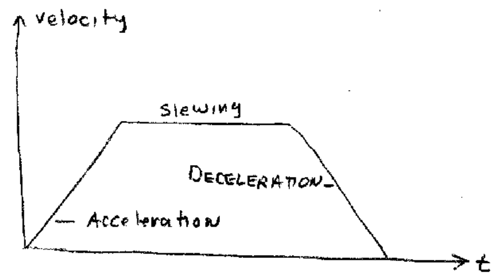
Inertia will cause the rotor to overshoot this position, continuing on toward the desired position. At the peak of the overshoot, the rotor will be close to the desired position and will have zero velocity. At this instant the original phase is turned off and the rotor will take a small step (with correspondingly small overshoot) to the final equilibrium position.



For this technique to be successful, the load dynamics must be known and consistent.

11.5.3 Velocity Ramping

Although the pull-out torque may be adequate to drive a load at a particular speed, the pull-in torque may be insufficient to reach that speed directly from a standing start. To achieve maximum performance for large excursions, it is necessary to gradually accelerate the load to maximum speed, and decelerate it to a stop to avoid overshooting the final position. This results in a ramped velocity profile. For simplicity, the acceleration and deceleration ramps are often linear, although optimum performance would result in an exponential profile.



11.5.4 Closed Loop Operation

The PM stepper motor has a physical structure and drive circuitry which are very similar to the brushless DC motor. Yet the brushless motor can accelerate smoothly to any desired velocity with none of the dynamic problems of the stepper. The reason for this is that the brushless motor is a closed loop feedback system: the decision on when to switch the current to the next stator winding is based on the measured current position of the rotor. This automatically compensates for the dynamics of the load and results in smooth, stable torque.

It is possible to utilize this closed loop approach in stepper motor systems. What is usually done is to sense the current rotor position with an optical encoder and use it to control the sequencing of the stator currents. For this to be effective, the encoder must have a resolution greater than the number of steps produced by the motor.