

# CMPE2150 Notes 09

## Stepper Motors

Taylor, Moore, and Armstrong

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One very special type of motor is the Stepper Motor – a motor that rotates in very clearly defined “steps” in response to a specialized controller circuit.

If a stepper motor is working properly (i.e. not overloaded or underpowered), its change in position can be known precisely. However, its absolute location cannot be known precisely without additional position-locating circuitry. Consequently, many stepper motor driven devices have limit switches that are used at boot-up or during recalibration to provide a reference point, after which the changes in position can be relied upon to provide subsequent positioning information.

A stepper motor uses a magnetically active armature with clearly defined “teeth” to match similar teeth on the stator electromagnets. In its simplest form of motion, when a particular stator electromagnet is activated, the nearest set of armature teeth are forced to align with the stator electromagnet teeth, resulting in a small rotation of the armature. Activating a different stator electromagnet will cause the armature teeth to align with the teeth of that electromagnet. This process can be seen best in an animation, available at [this link](#).

Although the animation shows only one coil active at a time, typically that coil would be wound half on one side and half on the other side of the armature to keep the forces on the armature and its bearings balanced.

The half coil on the opposite sides would generate the opposite magnetic poles to align the magnetically-active armature.

Stepper motors typically have two sets of stator electromagnets to move the armature through its rotational steps.

### Bipolar Stepper Motors

Reasonably powerful stepper motors are often Bipolar Stepper motors. In Bipolar Stepper motors, the coils in the stator electromagnets are simple coils without a centre-tap. The entire coil is used when activated, unlike in the Unipolar Stepper motors we will investigate soon, which only use half of any given coil at a time.

Here's a simplified model of a Bipolar Stepper Motor:

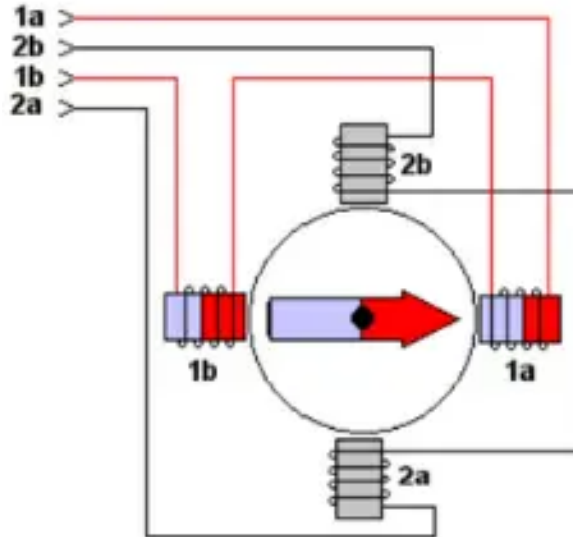


Figure 1: Bipolar Stepper Motor

In a Bipolar Stepper motor, the direction of the current is reversed in the coil to generate the opposite magnetic polarity, alternating through the sequence.

The simplest control cycle for a Bipolar Stepper motor might look like this:

- Coil 1: positive current
- Coil 2: positive current
- Coil 1: negative current
- Coil 2: negative current

In order to reverse the coil currents, the coils must be driven by two H-Bridges. That's why the L293D is a quad half-bridge: its two H-Bridges can be used to reversibly control the two coils in a Bipolar Stepper motor.

Bipolar Stepper motors are sometimes called Four-Wire Stepper motors, as the only the two connections to the two coils are needed.

### Unipolar Stepper Motors

Small stepper motors for low-power applications are typically Unipolar Steppers motors, so-called because they are designed for operation without reversing the direction of current flow. To achieve this, each coil is centre-tapped, with power provided at the centre tap. One side of the coil is activated by connecting it to common (or ground) for one "polarity", and the other side of the coil is similarly activated by connecting it to common when needed.

Here's a simplified model of a Unipolar Stepper motor:

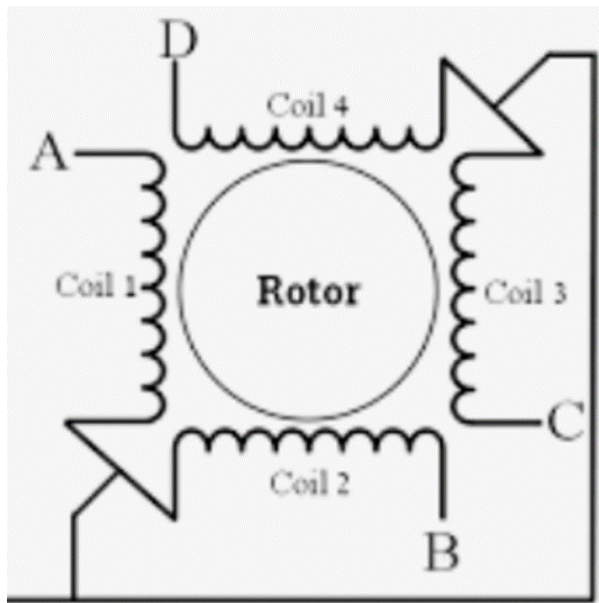


Figure 2: Unipolar Stepper Motor

This is usually rearranged to simplify it even further:

Unipolar Stepper motors will have five, six, or eight wires, depending upon how the centre taps are handled. For a five-wire motor, the two centre taps are connected internally; for a six-wire motor, the two centre taps are brought out separately; for an eight-wire motor, the ends of all four half-coils are brought out.

The simplest motion of a Unipolar Stepper motor would look like this, assuming the two centre taps are connected to a positive DC supply:

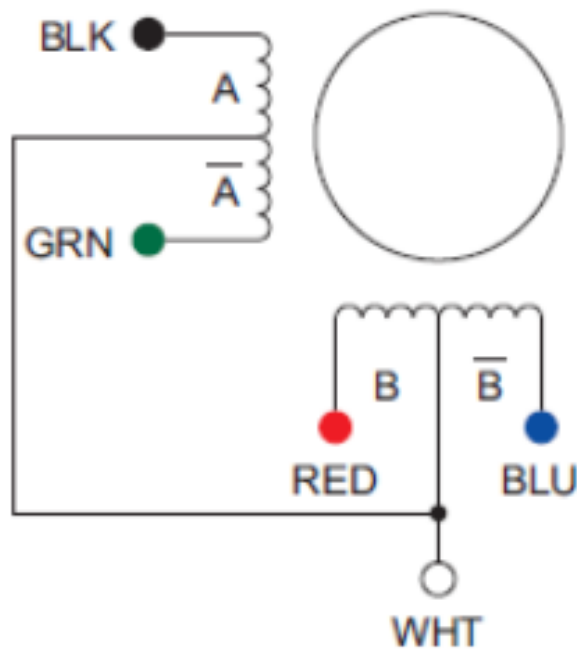


Figure 3: Unipolar Stepper (Rear-ranged for Clarity)

- Half-coil  $A$  grounded
- Half-coil  $\bar{B}$  grounded
- Half-coil  $B$  grounded
- Half-coil  $\bar{A}$  grounded

It's not hard to see why the Unipolar Stepper motor is typically less powerful than the Bipolar Stepper motor—only half of each coil is used at any given time.

The motor in your kit is a hobbyist Unipolar Stepper motor with the centre taps connected together. In addition, this motor comes with a controller board that has high-current motor drivers on it, so all we need to do is to supply logic levels to activate the motor drivers at the right times.

Here's the motor itself:



Figure 4: 28BYJ Unipolar Stepper

Note that there are five wires, as would be expected for a Unipolar Stepper motor. The simplified wiring diagram shows how these are connected internally.

Also note that the drive shaft isn't in the middle. that means that there's a conventional gear and pinion gearbox between the actual stepper motor and the output shaft. Here's a synopsis of the gearing ratios:

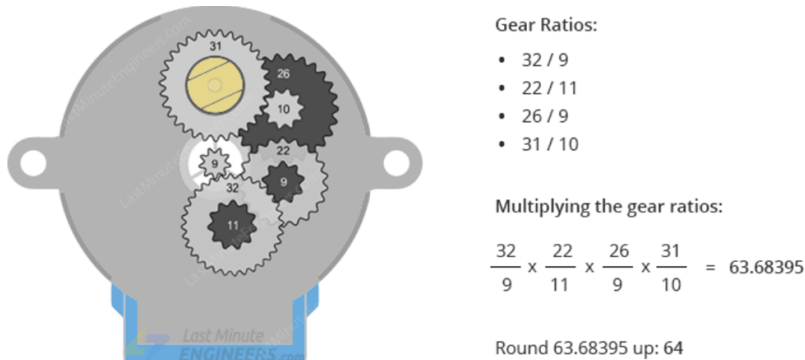


Figure 5: 28BYJ Stepper Gear Ratios

The data sheet states the rounded value of 64 : 1, which may be close enough for most applications, particularly those that move forward and reverse like the platen or print head of a 3D printer; however, if the motor was intended for continuous rotation in a particular direction, the error would accumulate.

The motor itself has 32 full steps (more on that later) per rotation.

For the motor in your kit (described previously), how many degrees are there in a full step of the basic motor? \_\_\_\_\_ °.

With the actual gearing ratio, how many degrees does one full step translate to at the output drive shaft? \_\_\_\_\_ °.

What percent error in motion would be introduced using the rounded value from the specification sheet? \_\_\_\_\_ %.

### Stepper Motor Driver

The driver board that comes with your Unipolar Stepper motor really just contains a single IC which is the inverting seven-driver ULN2003A, along with connectors and some LEDs because everyone loves flashing lights. (Only four of the seven drivers are actually used, one for each half-coil or “phase”.)

From a Logic perspective, the ULN2003A looks like the figure below.

In reality, it's really seven Darlington Pair BJTs, also included in a figure below.

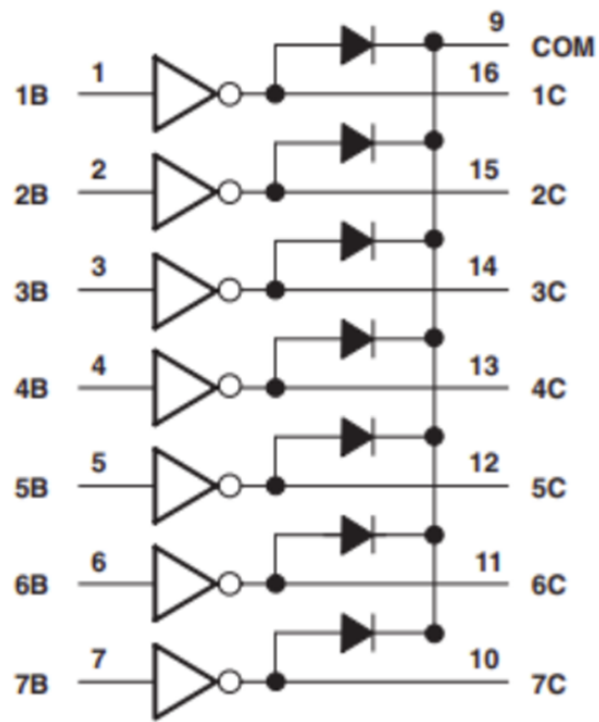


Figure 6: ULN2003A Driver Chip

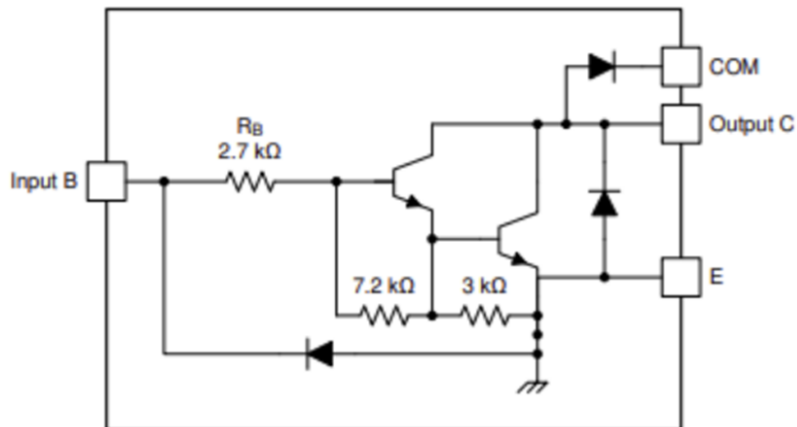


Figure 7: ULN2003A Darlington Pair Driver Channel

As with most transistor switches, it's an inverter from a Logic perspective, but it's a current switch from an electrical point of view. When the input goes HIGH, the transistor is saturated, pulling the collector nearly to zero volts, allowing current to flow through the transistor from the Collector to the Emitter. If we connect the Collector to one of the Stepper coils, and if the centre tap in the Stepper is connected to a positive DC supply, current will flow through the selected coil, activating it.

Long story short: we drive an input to this IC HIGH to activate the associated coil in the Stepper motor.

The diodes connected to the *COM* pin are flyback protection diodes, so if *COM* is connected to the motor power supply, we don't need any additional external protection. That's how the driver board for your Unipolar Stepper motor is set up.

### Unipolar Stepper Motor Drive Modes

It should, at this point, be fairly clear that, to drive a Stepper motor, a logical sequence of activating the various coils is required. It turns out that the process of generating these logical sequences is more involved than it might appear on the surface.

### Wave Stepping

What we've been alluding to in the introductory discussion is a mode in which the motor moves from coil to coil as each one is activated independently of other coils. Although the motor performs a full step in this mode, the term "Full Stepping" is reserved for a better mode of activation than Wave Stepping. However, Wave Stepping is the easiest to explain and visualize, so it's a good starting point from an educational perspective. The sequence is diagrammed below.

Note that the armature, indicated by the moving arrow in the picture, always points directly to one of the coils, as only one coil is activated at any given time. More on that in a moment. Note that the timing diagram looks like a single wave moving across the page, hence the term "Wave Stepping". Let's see if you can interpret this diagram correctly. In order to drive the motor forward in a Wave Stepping sequence starting with the lowest numeric value, the logic values sent would need to be:

1. \_\_\_\_\_
2. \_\_\_\_\_
3. \_\_\_\_\_
4. \_\_\_\_\_

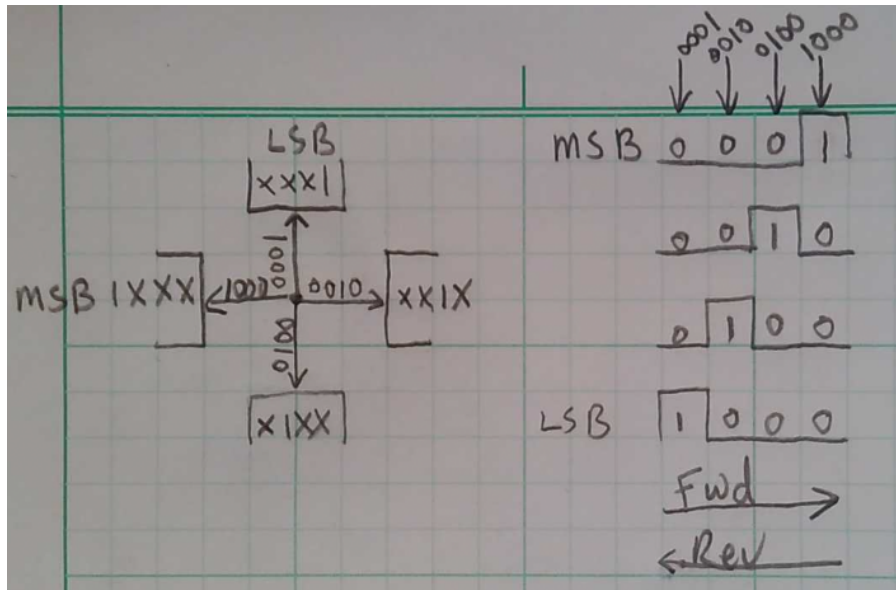


Figure 8: Wave Stepping Control Sequence

To drive the motor backward, starting with the highest numeric value, the logic values sent would need to be:

1. \_\_\_\_\_
2. \_\_\_\_\_
3. \_\_\_\_\_
4. \_\_\_\_\_

The Wave Stepping sequence generates the least torque of all the sequences, because only one coil is activated at a time.

## Full Stepping

Full-Stepping again moves the motor by a full step each time, although it has a slightly different starting position than Wave Stepping. The advantage of Full-Stepping over Wave Stepping is the torque: Full-Stepping activates two coils at the same time, with the armature positioned halfway between the two, so the torque is increased by a factor of  $\sqrt{2}$ , or approximately 1.41 times that of the Wave Stepping sequence.

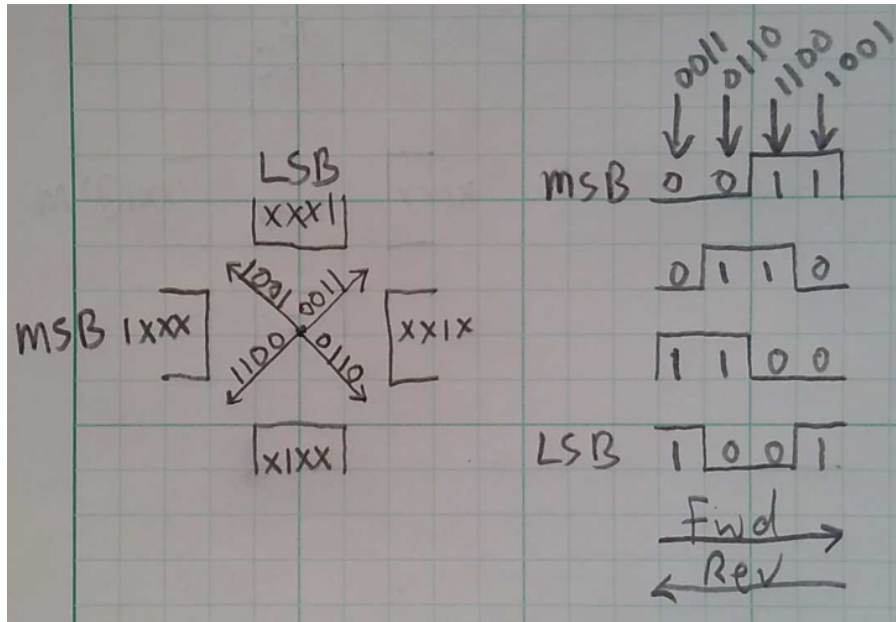


Figure 9: Full Stepping Control Sequence

Check to see if you can interpret this sequence correctly.

Starting with the “top” and “right” coils, write the sequence for driving the motor forward:

1. \_\_\_\_\_
2. \_\_\_\_\_
3. \_\_\_\_\_
4. \_\_\_\_\_

Starting with the “top” and “left” coils, write the sequence for driving the motor in reverse:

1. \_\_\_\_\_
2. \_\_\_\_\_
3. \_\_\_\_\_
4. \_\_\_\_\_

## Half Stepping

A third mode of operation combines the Wave Stepping and Full Stepping sequences to produce twice as many steps per rotation, and is therefore called Half Stepping. The resolution of Half Stepping is double the resolution of either of the previous two modes, and the torque is part way between that of Wave Stepping and Full Stepping.

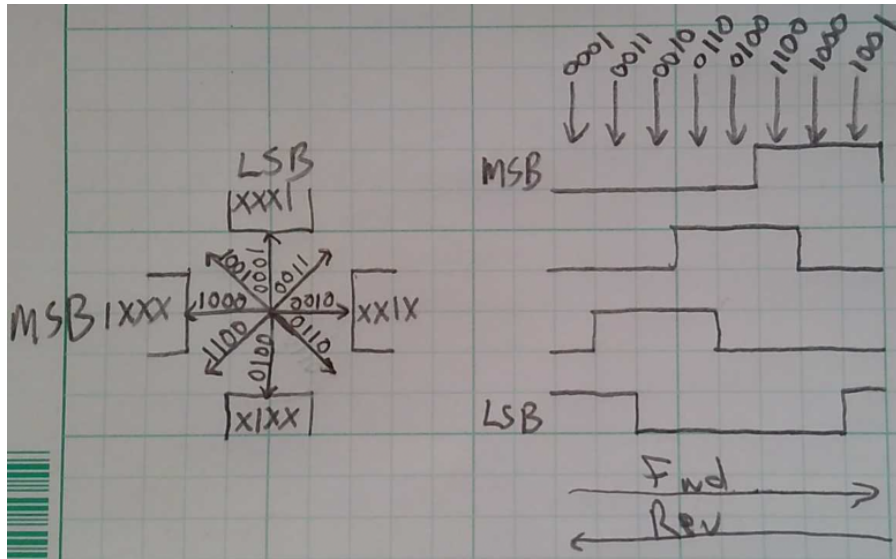


Figure 10: Half Stepping Control Sequence

For your Unipolar Stepper motor, what is the Half Stepping resolution at the motor itself, in degrees per step? \_\_\_\_\_  $^{\circ}/step$

What is the resolution at the output shaft, using the actual gearing ratios? \_\_\_\_\_  $^{\circ}/step$

Indicate the Half Stepping sequence for forward rotation, starting with just the “top” coil activated.

1. \_\_\_\_\_
2. \_\_\_\_\_
3. \_\_\_\_\_
4. \_\_\_\_\_
5. \_\_\_\_\_
6. \_\_\_\_\_
7. \_\_\_\_\_
8. \_\_\_\_\_

To drive the motor in reverse, you would simply reverse this sequence.

Which one of the following statements is correct?

- a. Half Stepping has higher resolution and higher torque than Full Stepping.
- b. Full Stepping has higher torque but lower resolution than Half Stepping.
- c. Wave Stepping has higher torque but lower resolution than Full Stepping.
- d. For greater speed of rotation, choose Half Stepping rather than Full Stepping.

### Micro Stepping

We've now discovered that we can locate the armature half-way between two coils by turning them both on fully. It should, therefore, be possible to locate the armature at other points between two coils by adjusting the power of the coils. This process is referred to as Micro Stepping.

The concept is to adjust the average current through two coils, typically so that the resultant force exerted on the armature is equivalent throughout the cycle. The best way to do this is to apply sinusoids to the two coils, one  $90^\circ$  out of phase with the other – as would be seen for a sine wave and a cosine wave.

Note that, at  $0^\circ$ ,  $90^\circ$ ,  $180^\circ$ , and  $270^\circ$ , the “logical” result is the same as Wave Stepping; however, in between, the position of the armature would vary smoothly through the positions in between the two activated coils.

It's not usually practical to try to control currents truly sinusoidally. It's much easier to create digitized approximations of sinusoids using Pulse Width Modulation. As the duty cycle increases, the average current increases, and as the duty cycle decreases, the average current decreases.

So, by varying the duty cycle from 0% to 100% using a sinusoidal approximation (maybe from a lookup table), it is possible to move the armature relatively smoothly between coils.

The “Micro Stepping” name comes from the tiny steps generated by the difference between different digitally-generated duty cycles, which depends upon the resolution of the Pulse Width Modulator (PWM).

How many micro steps could a 6-bit PWM generate as it changes the current from zero to maximum? \_\_\_\_\_.

What is the resolution, in degrees per step, that can be generated by a 4-bit PWM, for a Unipolar Stepper with 200 full steps per revolution? \_\_\_\_\_  $^\circ/\text{step}$ .

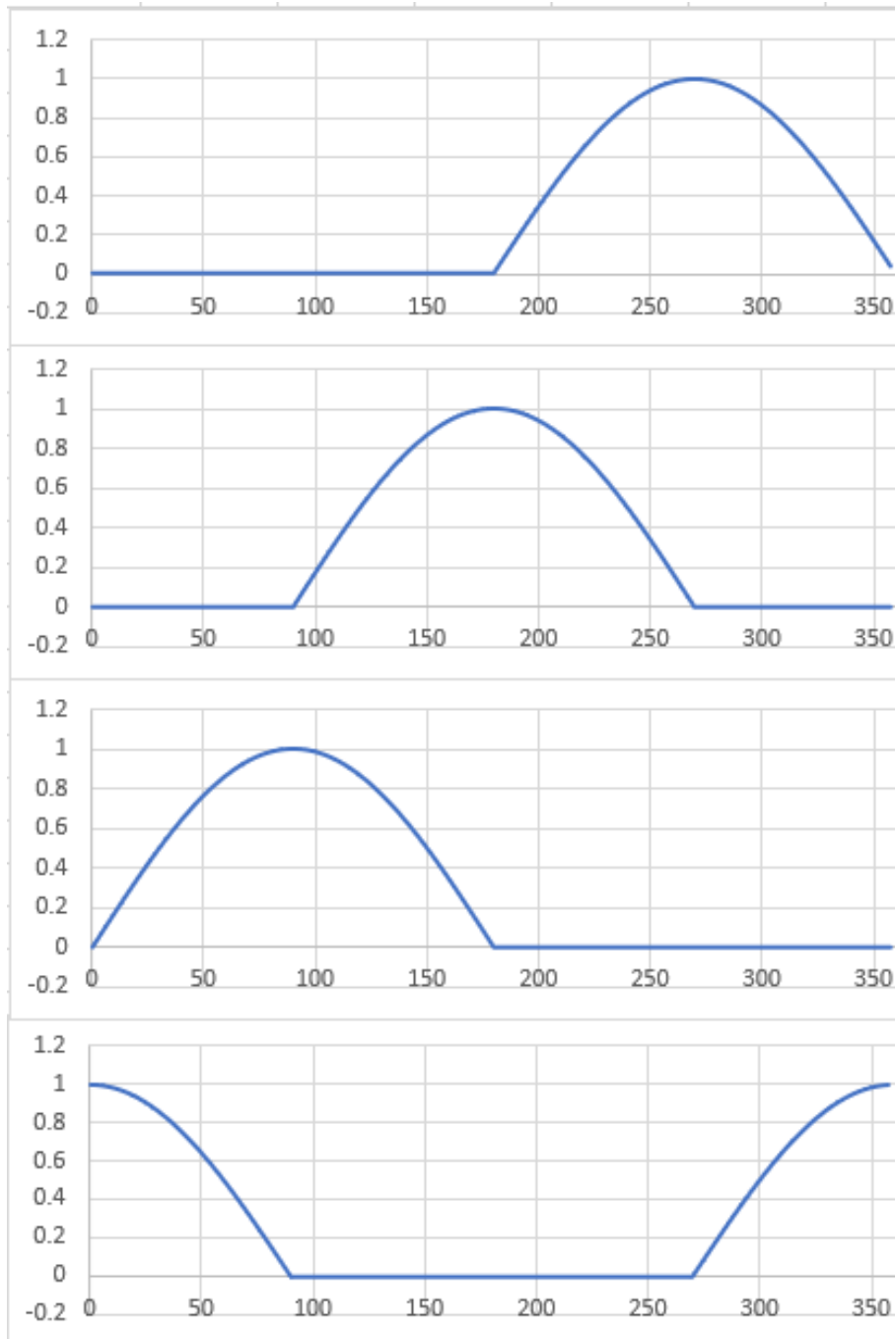


Figure 11: Microstepping Control Sequence

## Notes

Stepper motors have their limitations and quirks. Here are some of them.

- The speed at which a stepper can be operated is limited by the rate at which the magnetic fields in the motor can change. When a stepper motor is operating well within range, the motion isn't completely smooth, at the motor is attempting to stop at each new step or half-step. As the motor approaches its maximum speed, its operation becomes smoother, but the motor will begin to miss steps and get out of sync with the driver. At a high enough pulse rate, the motor will simply stop rotating. Consequently, it is important to determine what the maximum speed of rotation is and stay well below that for accurate motion control.
- When loaded too heavily, a stepper motor will occasionally miss steps and get out of sync with the driver. Again, it is important to stay below the specified loading torque for the motor.
- A stopped stepper draws just as much current as a rotating stepper, because the coils that stopped the armature will still be drawing current. This is both good and bad – good in that the motor will hold in the stopped position and will resist external forces on the shaft; bad, in that a stopped stepper is 0% efficient – drawing current but performing no useful work. This can also result in coil overheating and possible damage to the motor over time.
- It is possible to determine which leads on a stepper are connected to the same coil by shorting pairs of leads together and attempting to turn the shaft: if the pair you've chosen are the two ends of the coil, you will generate a current and the back EMF will try to prevent you from turning the shaft; if the pair you've chosen are isolated internally, the shaft will rotate much more freely. With a unipolar motor, you should even be able to tell the difference between the two ends of a coil and its centre tap, as half the coil will produce half the back EMF of the full coil.

**Answers**

- $11.25^\circ$
- $0.1767^\circ$
- $0.496\%$
- 0001, 0010, 0100, 1000
- 1000, 0100, 0010, 0001
- 0011, 0110, 1100, 1001
- 1001, 1100, 0110, 0011
- $5.625^\circ/step$
- $0.08833^\circ/step$
- 0001, 0011, 0010, 0110, 0100, 1100, 1000, 1001
- b. Full Stepping has higher torque but lower resolution than Half Stepping.
- 64
- $0.1125^\circ/step$