stepper motor control

part 1: stepper motor construction, function and control

Stepper motors have been with us since the early sixties and their significance has grown enormously over the past few years. They are used as driving mechanisms in clocks and other pointer-based instruments, in printers and plotters, various tools and, of course, in robots.

1

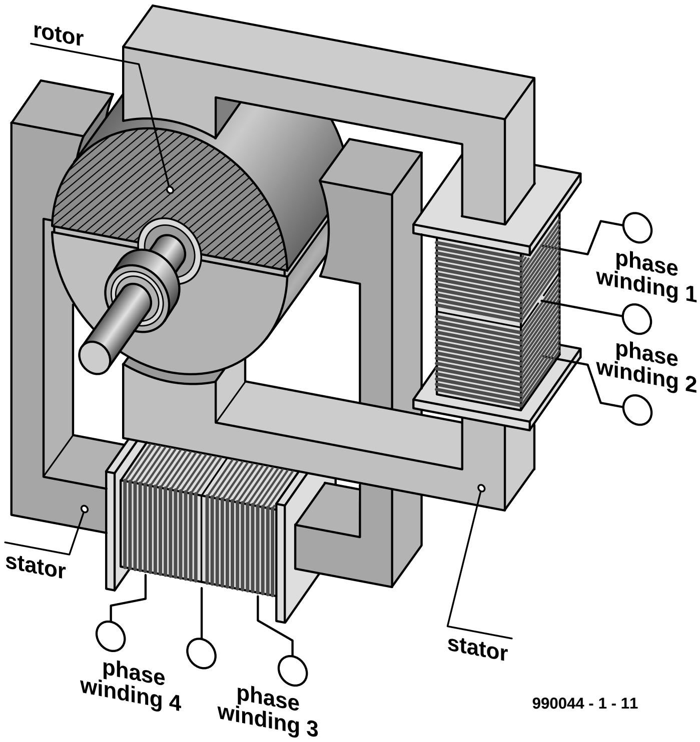

Figure 1. Model of an ideal stepper motor with a 2-pole rotor and two phase windings arranged at an angle of 90 degrees.

Just like almost any other electrically powered motor, a stepper motor consists of a fixed stator and a moving rotator. However, while the rotor (and sometimes the stator) is fitted with electromagnets in dc motors, the stepper motor has fixed electromagnets only. The rotor, consisting of non-magnetic soft iron or a permanent magnet, rotates as a result of the field reversals brought about by the stator magnets. So, before we know just how a stepper motor works, we've discovered an important advantage: there is no electricity supply to the rotor; consequently, the motor is brushless and therefore practically free of wear and tear.

The first (inexpensive) stepper motors were **reluctance** types with rotors consisting of cogged wheels made from soft iron. Disregarding the poor torque developed by these motors, reluctance motors lacked 'rest' positions of the shaft because the soft iron did not in itself act as a magnetic pole. This shortcoming was overcome with the introduction of stepper motors employing permanent magnets. Although the permanently magnetic rotor did allow rest positions, these occurred only at relatively large step angles. This shortcoming was caused by the limited number of **magnetic poles** that could be arranged on the radially-magnetised cylindrical rotor. None the less, this type of stepper motor provides a good starting point for our purpose.

Figure 1 shows a stepper motor in its most rudimentary form. The core is a single magnet (i.e., having just two

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poles), and there are two **phase windings** arranged at an angle of 90 degrees. When a current flows in one of the phase windings, a magnetic field is established. The rotor then turns its magnetic poles into a direction (or position) in which (1) the smallest air gap is established between the pole and the actuated phase winding, and (2) the largest magnetic flux density occurs (rule: opposite poles attract).

By reversing the current flow, the rotor can be made to turn to one of four different positions, with the rotational direction corresponding to the order in which the polarity changes occur. This so-called **wave drive mode** is shown schematically in **Figure 2**.

Another method of making the motor spindle turn is to energise the two phase windings in **normal mode**. This mode is marked by the presence of two pairs of two identical phase windings arranged next to each other. The resulting rotor action is easily explained using **Figure 2b**.

A **sequence** is one full 'electrical' revolution of 360° (electrical step angle), which is required to perform a complete mechanical step angle. With the two previously explained **full-step** modes, a sequence consists of four clock pulses. In the example, a mechanical step angle equals a complete spindle rotation of 360°.

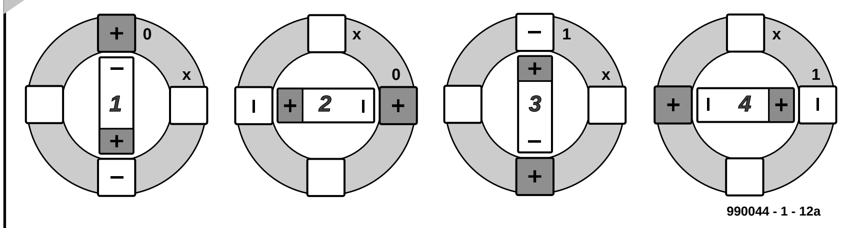
However, there can be no objection against combining the wave drive and normal modes **into half-step** control. This mode allows 'quasi' intermediate steps to be inserted, which is a free means of doubling the motor resolution (steps per revolution). In this mode, the supply is alternately connected to one or two phase windings, so that a sequence consists of eight clock pulses.

Depending on the actual construction of the phase winding coils, two more control techniques are used. **Unipolar** operation is achieved by adding just one switch (**Figure 3a**). This however requires the coils to have centre taps. Also, because of the reduced coil currents, both the torque of the motor and its spindle speed are relatively low. **Bipolar** operation as illustrated in **Figure 3b** was not possible until the arrival of integrated and inexpensive stepper motor drivers. In this mode of operation, both windings are reverse polarised end-to-end, which calls for two switches instead of one.

Stepper motors with a small number of phase windings will typically 'jerk' at low frequencies, even in half-step mode. Further improvements are, however, possible by gradually increasing and decreasing the coil current instead of simply switching it on and off. This so-called **microstep operation** guarantees smooth spindle movement. On the down side, both **torque** and **positioning accuracy** are reduced. These unwelcome side effects are particularly noticed with stepper motors having relatively few rotor positions.

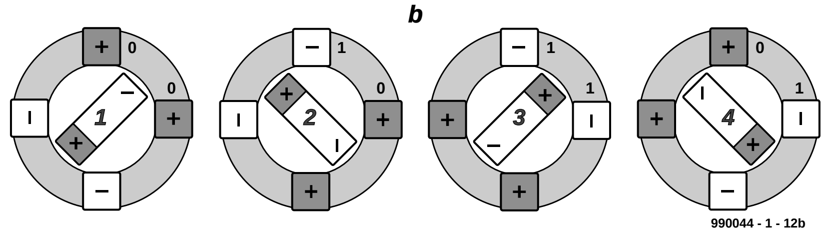
2

a



turn cw					turn ccw				
Clock	Phase 1		Phase 2		Clock	Phase 1			
	Polarity	Current	Polarity	Current		Polarity	Current	Polarity	Current
1	0	1	x	0	1	0	1	x	0
2	x	0	0	1	2	x	0	1	1
3	1	1	x	0	3	1	1	x	0
4	x	0	1	1	4	x	0	0	1

b



turn cw					turn ccw				
Clock	Phase 1		Phase 2		Clock	Phase 1		Phase 2	
	Polarity	Current	Polarity	Current		Polarity	Current	Polarity	Current
1	0	1	0	1	1	0	1	0	1
2	1	1	0	1	2	0	1	1	1
3	1	1	1	1	3	1	1	1	1
4	0	1	1	1	4	1	1	0	1

turn cw					turn ccw				
Clock	Phase 1		Phase 2		Clock	Phase 1		Phase 2	
	Polarity	Current	Polarity	Current		Polarity	Current	Polarity	Current
1	0	1	X	0	1	0	1	X	0
2	0	1	0	1	2	0	1	1	1
3	X	0	0	1	3	X	0	1	1
4	1	1	0	1	4	1	1	1	1
5	1	1	X	0	5	1	1	X	0
6	1	1	1	1	6	1	1	0	1
7	X	0	1	1	7	X	0	0	1
8	0	1	1	1	8	0	1	0	1

Figure 2. Coil current distribution in (a) wave drive, and (b) normal operation. Half-step operation is obtained by combining these two full-step modes.

IN PRACTICE

So far we've based our discussion on a stepper motor model that does not exist in practice. Modern **hybrid stepper motors** employ axially and permanently magnetised discs as a kind of core. These discs are fitted with cogwheels mutually offset by half a cog width, so that North and South poles alternate. The photograph in **Figure 4** shows the innards of a hybrid stepper motor. The toothed structure of the rotor is clearly recognisable.

The **step angle** or **resolution** of the motor not only depends on the number of pole pairs, that is, the North and South pole cogs on the rotor, but also on number of individually controllable phase windings. In practice, the number of poles is between two and five to keep wiring and circuit complexity within reason. If a specific application calls for high torque then two-pole

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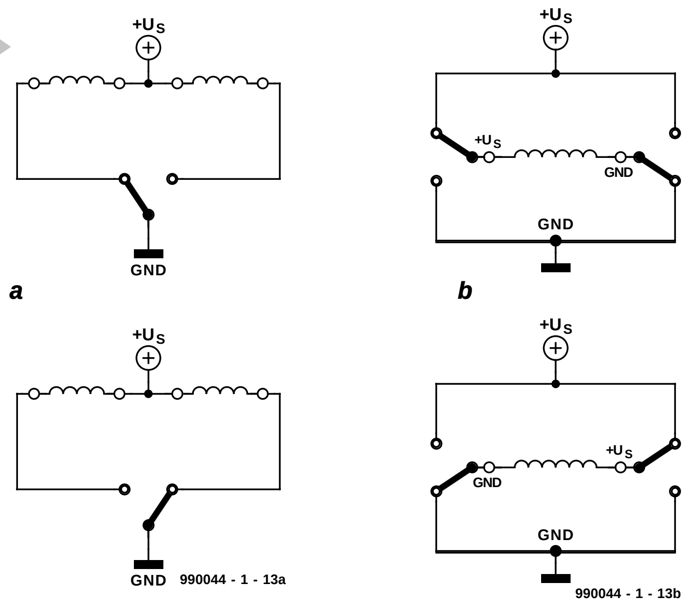

Figure 3. In unipolar mode (a) each motor coil should have a centre tap. Bipolar motors (b) require coil current drive using two switches per winding.

stepper motors will be preferred. If, on the other hand, smooth spindle action is the foremost requirement, a five-pole motor in microstep mode will be the best choice. For cases ‘in between’, a three-pole motor represents a good compromise.

Most of today’s stepper motors have a resolution of at least 24 steps (15°) or 48 steps (7.5°) per spindle revolution. To guarantee accurate positioning of the read/write head, most older hard-disk drives contain stepper motors with a resolution of 200 steps (1.8°) or even 400 steps (0.9°).

When a clock frequency of several kilohertz is applied the motor will typically not operate at all because the rotor’s inertia prevents it from keeping pace with the rapidly rotating stator field. The use of a **start/stop frequency** which, depending on the motor type, lies between 50 Hz and 2000 Hz, guarantees reliable starting of the motor. Once the motor runs, the clock frequency may be stepped up. Although there is no lower limit to motor acceleration, there will be a definite upper limit to observe. Exceeding the highest possible acceleration rate may cause the motor to stall, just as with any attempt to exceed the highest possible clock frequency.

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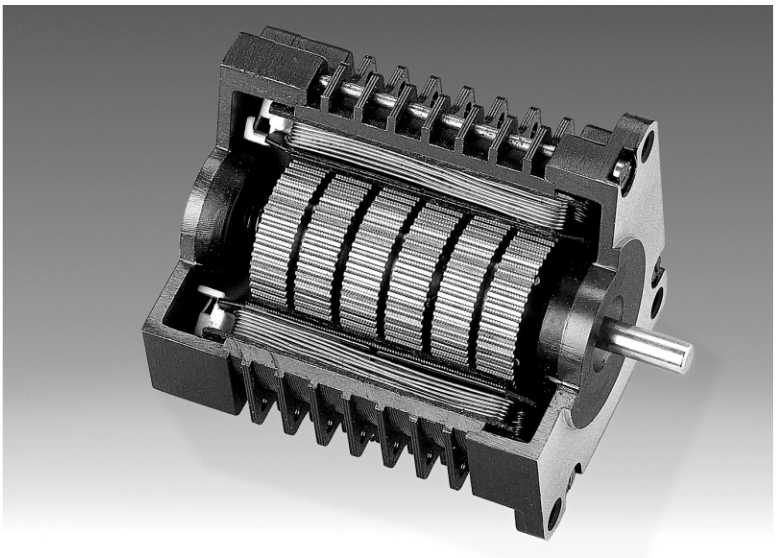

Figure 4. Photograph showing the cogs on the rotor.

The increase from the start/stop frequency, via the acceleration phase to the nominal speed is best described by a ramp-shaped curve like the one shown in **Figure 5**. Hence the term **acceleration ramp**. Likewise, the deceleration and the eventual switching off of the motor should also follow a ramp, this time a falling one. Abruptly switching off the coil currents would cause the rotor to keep turning because of inertia, and it would not be possible for the control system to tell the spindle position. Motor control without ramp-shaped coil currents and using clock frequencies low enough for reliable turning in both directions is only possible (and allowed) during zero calibration and slow operation.

Computer control is soon called for when it is required to make the motor turn in half-step or microstep mode while providing for the proper acceleration and deceleration slopes of the coil currents. These functions are admirably handled by the 80C166 microcontroller system described in next month’s instalment.

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Figure 5. Acceleration and deceleration (braking) is achieved by ramp-shaped control currents.

5