An introduction to stepper motors

Jim Tregellas VK5JST

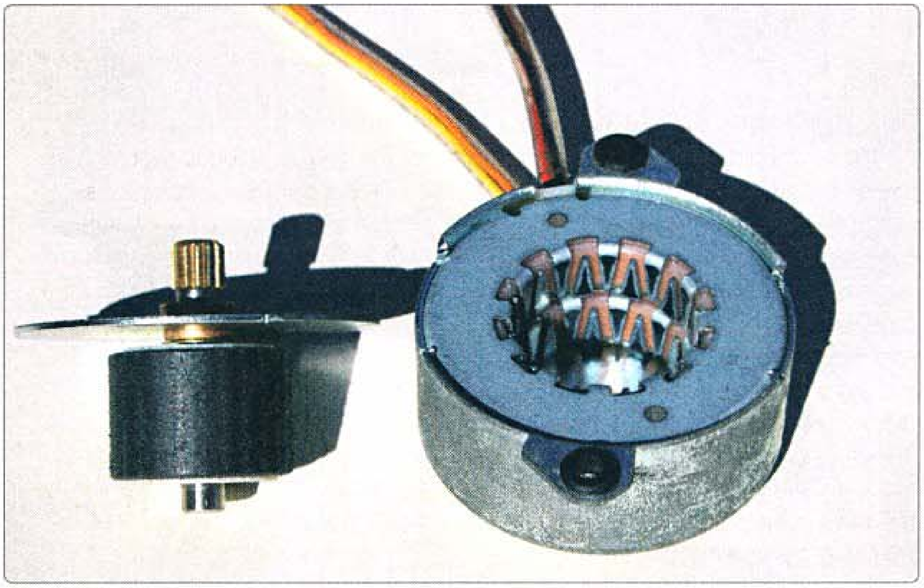


Photo 1: A disassembled 'tin can' stepper motor, showing field and rotor poles.

I have recently been involved in making a magnetic loop antenna for 80 metres and to tune this very narrow band system, once again found myself using a stepper motor. These motors are around our society in very large numbers but are not well understood. From an amateur radio point of view they are very useful for many things and examples include the remote operation of linears and antennas, automatic ATUs and antenna rotators. If you like to play around with robotics and CNC machine control then steppers are indispensable. And used in reverse as a generator, stepper motors make very good rotary position indicators.

General

Stepper motors come in many styles, but their operation basically involves only one of two things – an energised field coil which attracts a pole of a permanent magnet rotor – or an energised field coil which attracts the pole of a soft iron rotor. The first type of motor is known (obviously) as a permanent magnet motor, while the second type is called a variable reluctance motor. Permanent magnet motors are very common while variable reluctance units are quite rare.

The rotors of both of these motor types move round in small angular steps as the energy to adjacent field poles is switched on and off. Typical motors take between 24 and 200 steps (15 deg or 1.8 degree steps) to complete one revolution. The ability to rapidly start and stop with great angular precision is the most important advantage of these motors.

The permanent magnet motor retains its rotor position even when power is removed. The number of steps per revolution can be determined by turning the rotor by hand through one revolution and counting the number of 'bumps' which occur as the rotor regularly realigns itself with the field poles. This effect is called 'cogging'. Conversely when all power is removed from the field coils of a variable reluctance motor, the soft iron rotor turns quite freely. This may be an advantage or disadvantage depending on the application. This form of motor must have a field coil lightly energised before the number of steps per revolution can be counted.

Motors are made in various qualities. The cheapest are 'tin-can' motors which generally only offer 24 – 48 steps per revolution and will have sintered bronze self lubricating bearings. The rotor is a smooth cylinder of iron or ferrite with a pattern of alternating north and south poles imprinted parallel to its shaft on its surface. These rotor poles interact with two sets of pressed metal field poles which radiate from two field coils outside the rotor at its top and bottom. Motors constructed this way have relatively large air gaps between the rotor and stator due to manufacturing tolerances and generally do not deliver very high torques or speeds - but they are cheap. An example of this motor has been disassembled and is shown in Photo 1. The rotor has been lightly sprinkled with iron dust to show the pattern of magnetization and the two sets of offset field poles should be noted.

Better quality motors will almost always use ball bearings, and these, together with finely ground salient rotor and stator pole faces, allow much tighter tolerances and smaller air gaps. Such motors are capable of great torque and high stepping speeds. The diagram showing the 20 step/rev demonstration motor, refer Figure 1, shows the typical internal construction. All of the motors shown in Photo 2 are high quality units.

There are several ways of specifying motor size but the best is probably the NEMA system invented in the USA. A NEMA specification basically defines three things, motor outside diameter (in inches), mounting centre details, and shaft diameter. So a NEMA style 23 motor (commonly found in large dot matrix printers) has a diameter of 2.3 inches (57 mm), a shaft diameter of 0.25 inches (6.35 mm), and four well specified mounting points on a flat face.

Note that a NEMA specification does not specify the length of the motor frame and so a long frame NEMA style 23 motor (with its longer magnetic poles) will deliver more power and torque than a short frame NEMA style 23.

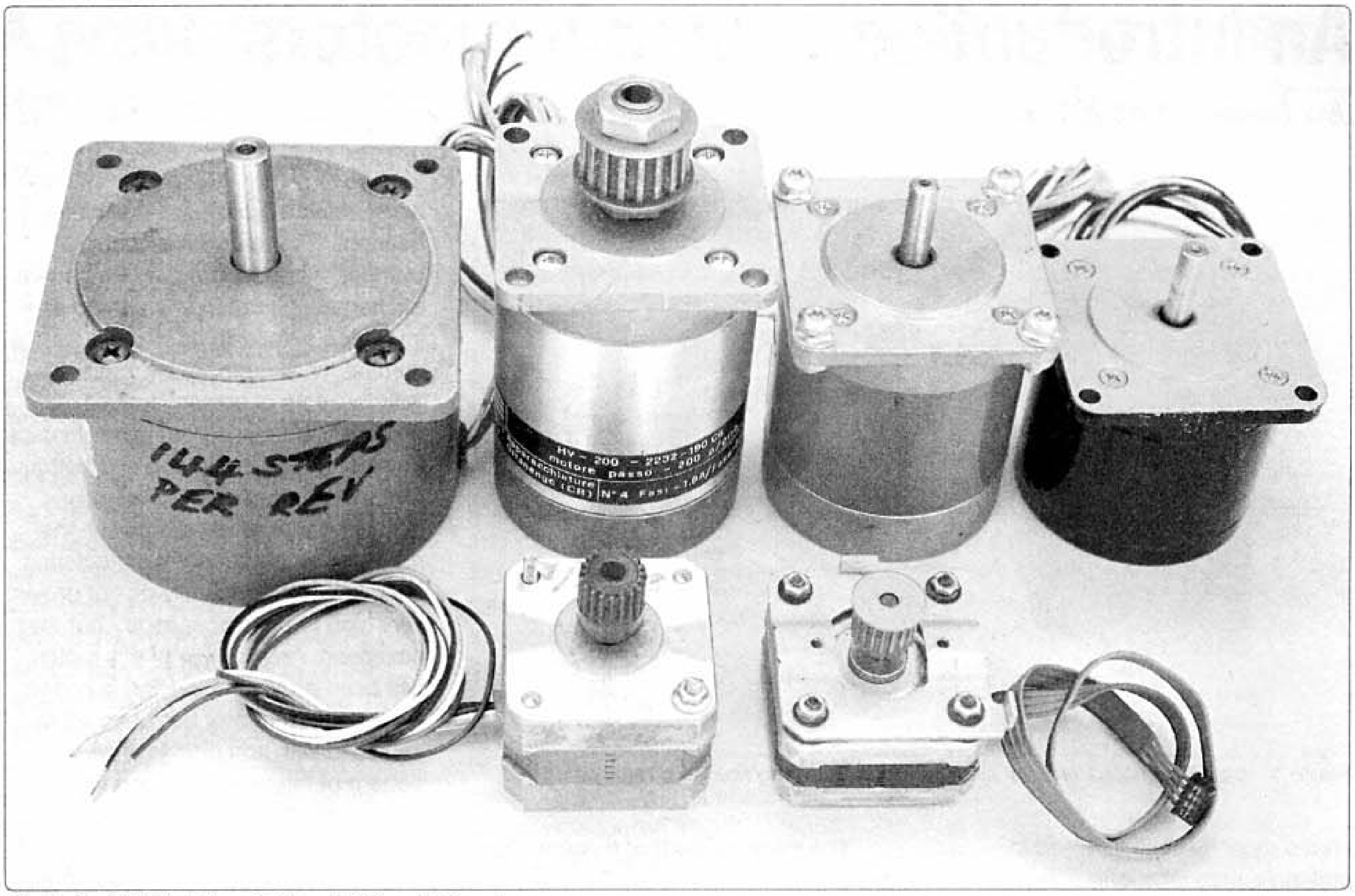


Photo 2: NEMA styles 17 (front), 21 and 34 motors.

But in general, commonly available motors usually have a diameter and length which is roughly the same.

Excellent amateur scroungers will probably accumulate a range of motors from the six common industry frame sizes. These are styles 11, 14, 17, 23, 34 and 42. Style 17 motors can be obtained from sources such as old 5.25 inch (133.35 mm) floppy disc drives and will deliver only small torque. At the other end of the scale, NEMA style 42 motors (4.2 inches or 106 mm diameter) from industrial machinery are real monsters with huge torque. Typically such motors will exhibit stepping speeds not exceeding 400 – 600 steps per second from a scratch start. Using a stepping speed beyond this limit will simply result in the rotor randomly vibrating back and forth around a central position as the magnetic forces are insufficient to bring the rotor up to speed within a single step. This limit can be exceeded by 'ramping up' the stepping speed from zero, which will cause the rotor to remain in lock with the rapidly increasing field rotation. Note however that this driving technique demands electronics with considerable intelligence (and cost). The simpler forms of drive described later in this article are limited to speeds of less than the cold start speed. But also note that if the magnetic forces are large enough to get the rotor up to speed in just one step, then it can also stop within one step. This in turn means that if the motor speed is ramped up to beyond the cold start speed, then it also must be ramped down in order to predict where it will stop, resulting in complex control software and hardware which must 'look ahead'.

All stepper motors lose torque rapidly as the speed of rotation increases. This is due to the fact that their field windings possess inductance as well as resistance. Current in a series LR circuit- and the magnetic field associated with it- takes time to build up and it is this which limits the maximum motor speed.

Windings

There are many ways of winding the field coils in a motor, but commonly available units use either two or four coils and this article will only deal with these types. Motors with five, six, eight and more field coils are obtainable and all that is necessary to get these working is to remember that the magnetic field must step around the field poles in a circular fashion. This is easy to do once the three methods of driving four pole motors are understood.

Figure 3 shows how connections can be made to motors with two or four field coils. As is shown in the demonstration motor diagrams, again refer to Figure 1, the user can elect to energise just one, or two adjacent field coils at any one time. Energising one coil at a time in a circular manner is called wave drive and this is little used. Energizing two adjacent coils in a circular fashion is called two phase drive and this latter technique doubles the magnetic force acting on the rotor and hence,

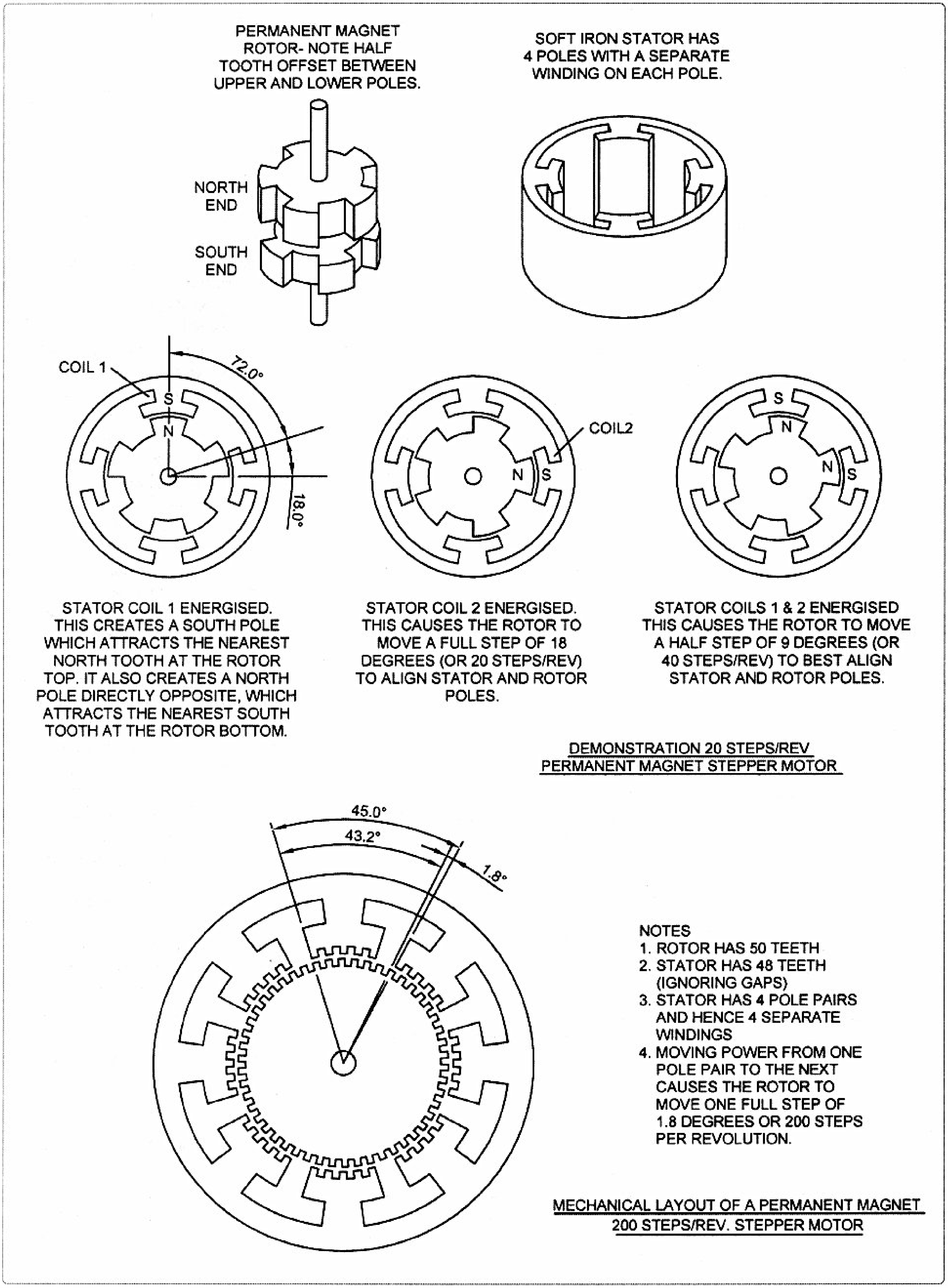


Figure 1: Demonstration 20 steps/rev permanent magnet stepper motor.

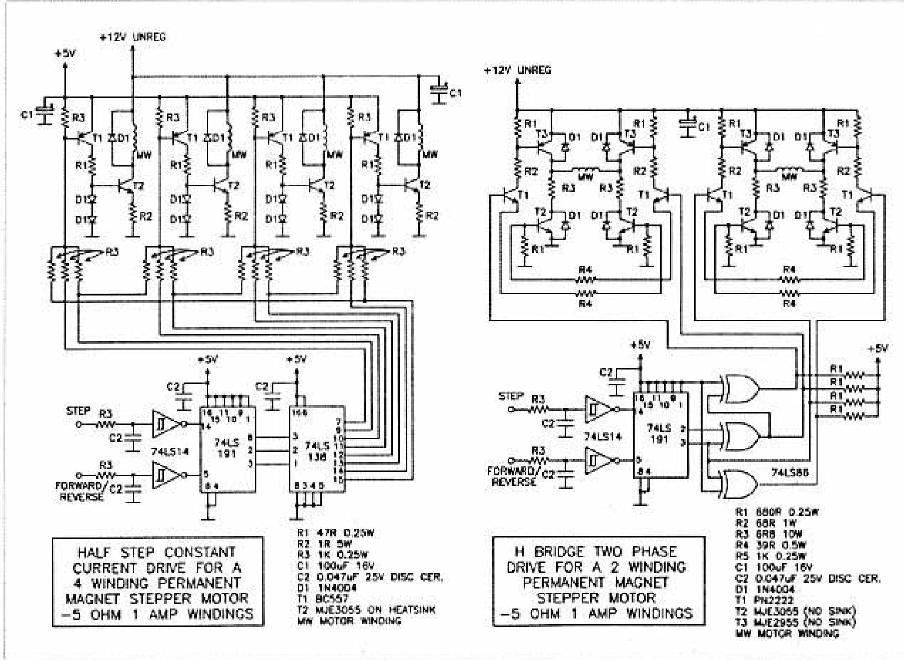
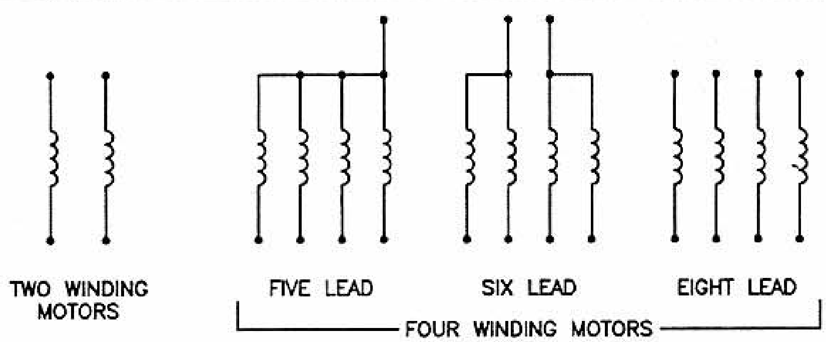


Figure 2: Common lead configurations for stepper motors.



COMMON LEAD CONFIGURATIONS FOR STEPPER MOTORS

WAVE DRIVE FOR FOUR WINDING STEPPER MOTORS

CLOCK PULSE	PHASE 1	PHASE 2	PHASE 3	PHASE 4
1	ON	OFF	OFF	OFF
2	OFF	ON	OFF	OFF
3	OFF	OFF	ON	OFF
4	OFF	OFF	OFF	ON

TWO PHASE DRIVE FOR FOUR WINDING STEPPER MOTORS

CLOCK PULSE	PHASE 1	PHASE 2	PHASE 3	PHASE 4
1	ON	ON	OFF	OFF
2	OFF	ON	ON	OFF
3	OFF	OFF	ON	ON
4	ON	OFF	OFF	ON

HALF STEP DRIVE FOR FOUR WINDING STEPPER MOTORS

CLOCK PULSE	PHASE 1	PHASE 2	PHASE 3	PHASE 4
1	ON	OFF	OFF	OFF
2	ON	ON	OFF	OFF
3	OFF	ON	OFF	OFF
4	OFF	ON	ON	OFF
5	OFF	OFF	ON	OFF
6	OFF	OFF	ON	ON
7	OFF	OFF	OFF	ON
8	ON	OFF	OFF	ON

Figure 3: Showing half step and H bridge motor drives.

relative to wave drive, doubles motor torque available. Half step drive, refer Figure 2, where first one coil is turned on and then two coils etc only allows the motor to produce the same torque as wave drive but doubles the number of steps per revolution.

There is also a drive technique called microstepping where the power to one field coil is steadily decreased in digital steps while the power to the next field coil is ramped up in digital steps. This results in a number of intermediate rotor positions in between two adjacent field coil poles. Microstepping gives smoother motor operation but considerably increases the complexity of the driver electronics. Reference should be made to the internet if the reader wishes to go down this path.

Drives

And now we get to the ugly nitty gritty. As mentioned earlier, all field coils have inductance and resistance, and it is the inductive component which gives us the headaches. This reactive component limits the rate at which current (and hence magnetic field) will build up when a particular DC voltage is applied across a field winding. It is the resistance of the winding which ultimately determines how much current will flow, and the mathematics tells us that to establish this final current five time constants of time (5L/R) must elapse. This idea defines the simplest drive possible where a series transistor is used to switch power to a field winding on and off. It is a relatively slow technique and the motor loses torque when there is insufficient time for the field current to build up to maximum. This technique and all of the other driving techniques are shown in Figure 4.

If we wish to speed the motor up, we must somehow reduce the time taken for the current to build up and the simplest way to do this is to increase the total resistance of the winding. If we add a series resistor of the same value as the winding resistance, then the time constant halves (L/2R) and we can then double the maximum motor speed.

Of course when we do this we will also have to double the supply voltage to the motor in order to attain the same final current, and so the price for this increase in operating speed is extra wasted power, in the form of heat in the series resistor. But this drive form still has the advantage of being very simple. With a five volt NEMA style 23 motor (serious torque) the driver transistor for each field winding will have to pass typically around one amp. So the collector dissipation for each driver transistor (which is either off or saturated) is about one amp times a collector emitter voltage of, say, 50 millivolts, or 50 milliwatts, and so no heatsinks are required. To put this in perspective a BC548 can safely dissipate 300 milliwatts, but will not pass currents of one amp.

If we wish to speed the motor up even further, then our final port of call is a constant current drive. Here we significantly increase the supply rail to the motor so that the current builds up very quickly along the exponential path to its final level, and then stop its growth at a safe level with a constant current source (say one amp in the example of the NEMA 23 just mentioned). There are standard driver chips around which will supply up to 36 volts to a five volt motor winding in order to get this rapid growth in current, and overdrive factors of three to five are very common. In fact overdrives of 50 are sometimes used (250 volt DC supply to a five volt motor!) in military applications to get the absolute best available speed from a motor. Of course once again the price for all this is waste heat and this time the waste heat will be generated in the driver transistors which cannot be operated in the saturated mode, but instead must operate under linear conditions. If we were to operate the five volt NEMA 23 motor above from, say, a 25 volt DC supply, then when the final winding current of one amp is reached, there will be a five volt DC drop across the field winding and about 20 volts of DC from collector to emitter of the driver transistor. With a winding current of one amp this means that the collector dissipation of each driver transistor is 20 watts, and so large heatsinks will be needed to dissipate the 40 watts of waste heat created in a two phase motor drive circuit.

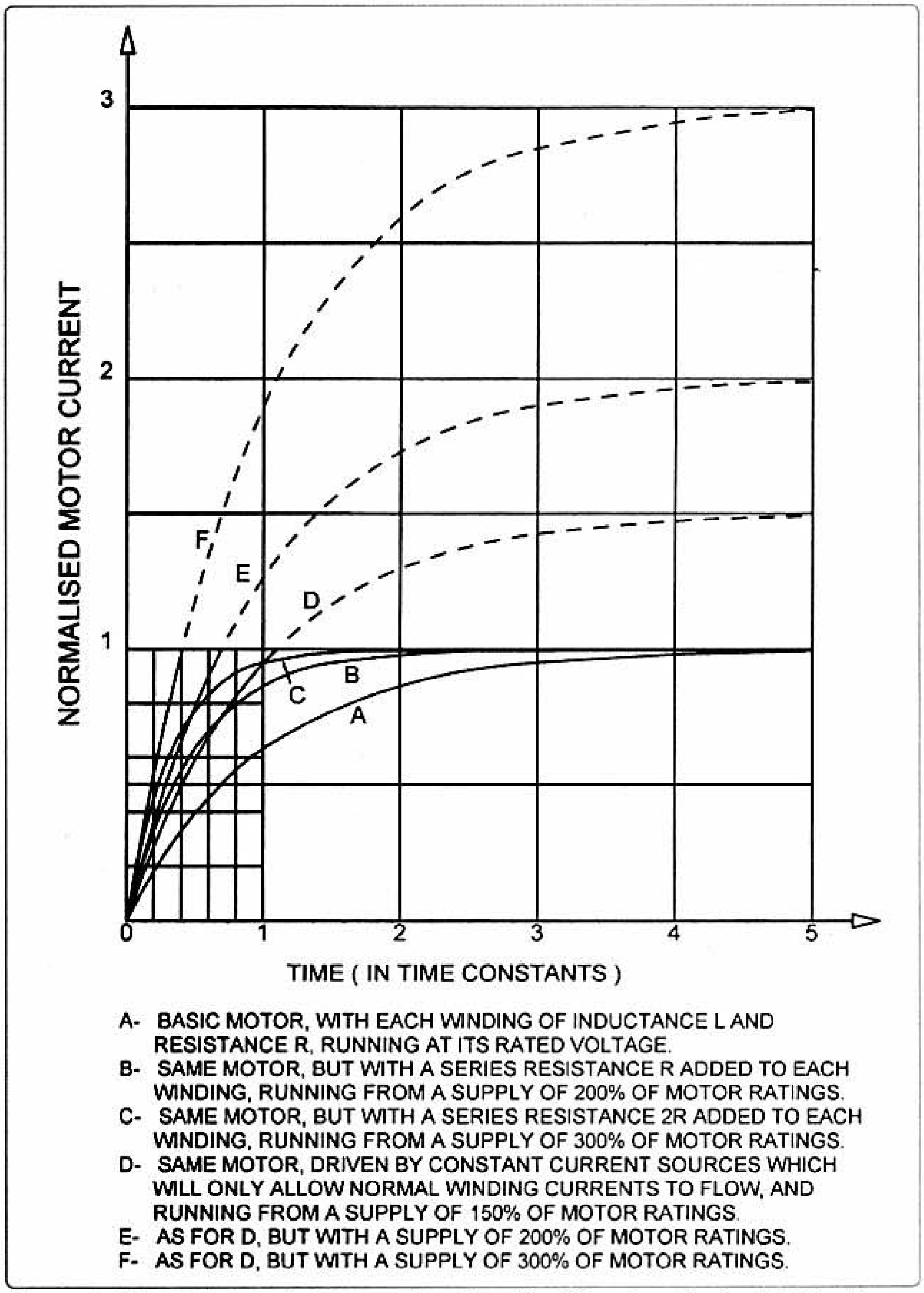


Figure 4: How motor maximum speed varies with different methods of driving the motor field coils.

As a final comment, there is a form of drive called a chopper drive. Chopper drives are very efficient at low motor speeds as they use a high supply voltage to allow fast current build up in the field windings. Once the maximum winding current has been reached and the rotor has been dragged into final position, the drive circuit goes into a switching mode to deliver very low average current to the winding. But, when the motor is flat out, this driving technique is no more efficient than the much simpler constant current drive and under these conditions has the same heat problems.

Other Comments

There is one other thing of which users of stepper motors should be aware, and this is that the rotor of every stepper ever made has its own natural frequency of resonance. This comes about because the rotor has mass and its position is determined by an elastic magnetic force. So when the rotor is abruptly moved

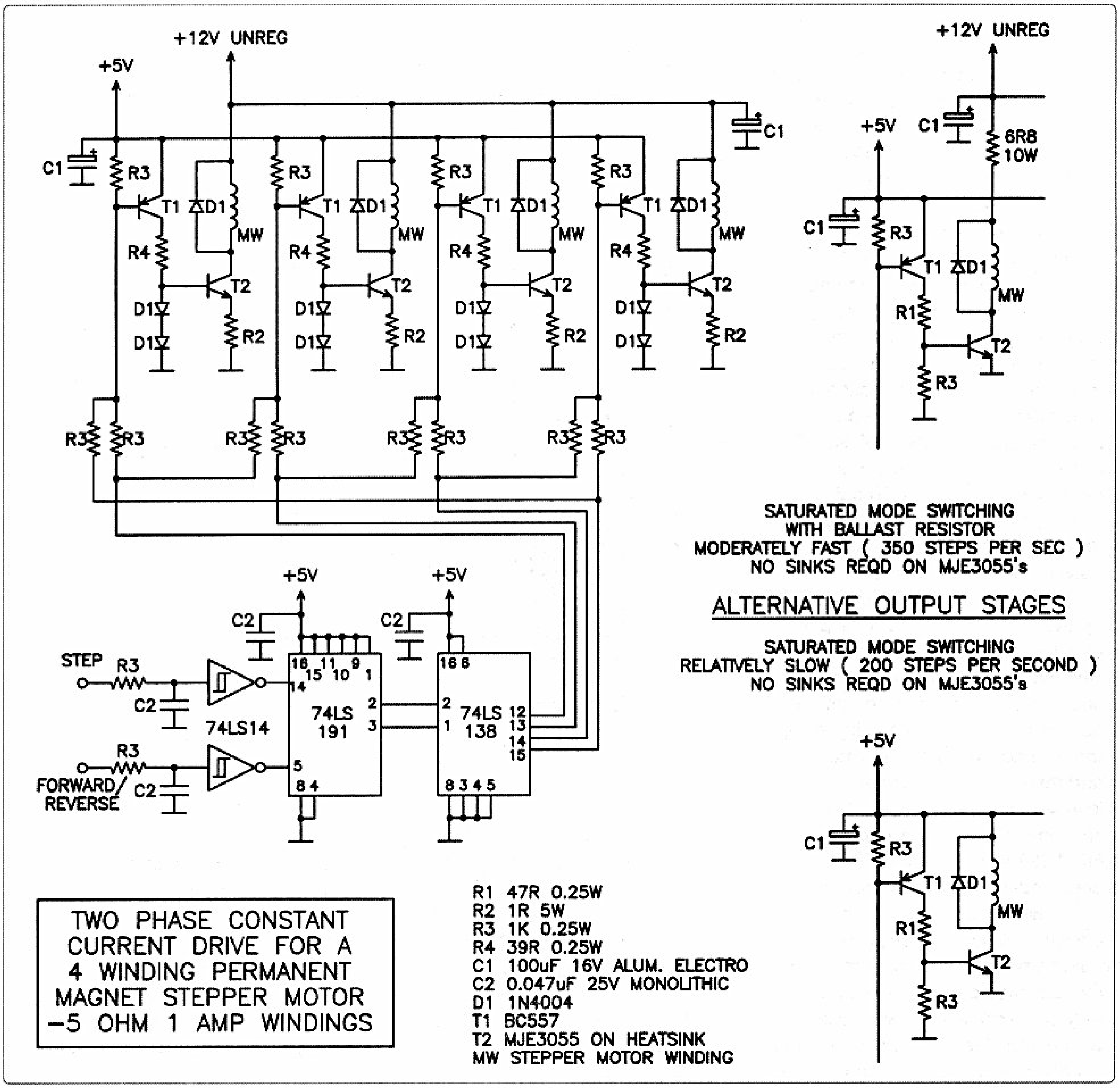


Figure 5: Three methods of driving motors with four field coils.

to a new position by switching field coils on and off, it will vibrate about its new position for a while until the kinetic energy of movement is dissipated in losses and the lines of magnetic force bring it to final position. If the frequency of pole changing happens to approximate this natural resonance then the rotor of the motor will cease stepping in an orderly fashion and take great uncontrollable positional leaps back and forth while emitting a lot of noise. From a user's viewpoint, there is little which can be done about this, apart from avoiding this frequency entirely and/or adding some losses to damp the resonance somewhat (a gear box full of thick grease?). One of the great advantages of ramping the motor speed up and down is that this region of resonance can be passed through quickly before rotor oscillations build up sufficiently to cause loss of position. Microstepping greatly reduces resonance problems because the rotor is gently moved using a large number of small steps rather than pulled into position in one great square wave leap.

Drive Circuits

A number of drive circuits are shown which can be directly connected to the parallel output port of a computer and which illustrate the various ways a motor can be driven. Long unshielded connections between computer and driver electronics can be used because all driver inputs feature a CR low pass filter to remove RFI and noise. The rounded off waveforms which result from this filtering are squared again up with a 74LS14 Schmitt trigger stage and applied to the direction and clock

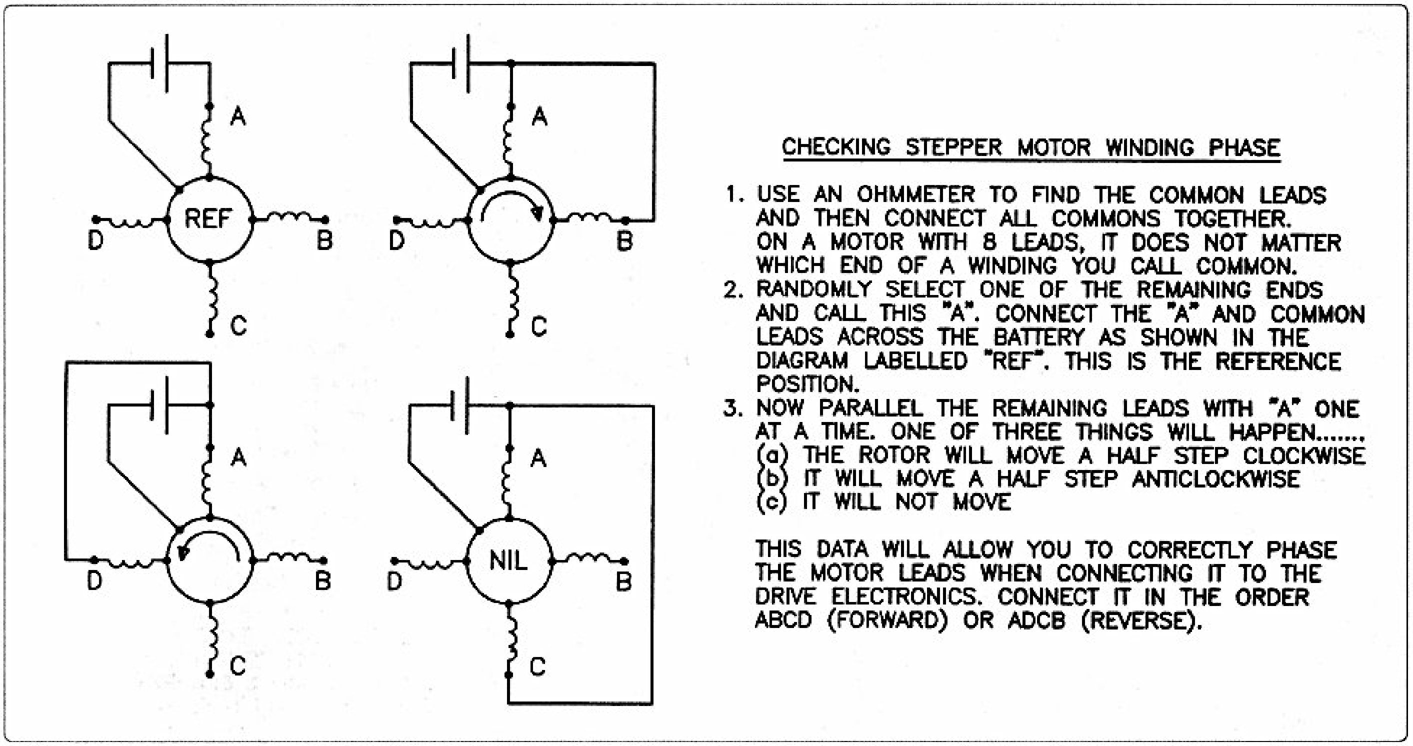


Figure 6: How to practically determine the field winding phasing of an unknown motor.

inputs of a 74LS191 reversible four stage binary counter. For motors with four field windings, the least significant two bits (or three bits for half stepping) of this counter are then decoded by a 74LS138 to give a one of four drive to the following motor winding driver stages (or one of eight for half step). Each winding driver circuit is OR connected to these 74LS138 output lines using 1K resistors so that either wave drive, two phase drive or half step drive can be obtained. Finally output stages are detailed for each of the three different ways of driving a motor winding. Refer Figure 5.

For two winding motors, an H bridge circuit is detailed. This uses the same input and counter structure as the other circuits but a 74LS86 (exclusive OR) is used to decode the two least significant bits of the counter and drive the output stages.

Scaling these circuits up or down for different motors is relatively simple once the basic operation is understood. For very large motors it is probably best to either go for the simple saturated driver type, or go directly to the expensive but high performance chopper drives. Chipsets such as the ST Microelectronics L297/298 and National Semiconductors LMD18245T are good examples of this drive type.

There is plenty of proprietary low cost software around on the 'net for NC machine control. Interfacing to this software may require the inclusion of another 74LS14 inverter in both the clock and/or direction lines of the 74LS191 counter. Using these motors is a lot of fun, and when you have finally developed a computer controlled system to push an aerial or a high powered woodworking router around, you really have achieved something that very few can do.

Figure 6 shows a method of determining the relationship of the windings of an unknown stepper motor so that it may be correctly driven.

Now go turn the world..............