A Technical Guide To Stepper Motors

Written with engineers in mind this article deals with the technical aspects of stepper motors and their driving circuitry.

How Stepper Motors Work

As the name implies, stepper motors move in steps following a sequence of electro-magnetisation of stator/rotor pole alignments. Thus they are pure synchronous motors - unlike an induction motor there is no slip angle and unlike a DC brushed motor they do not exhibit speed variations with load changes. The mechanical output is said to be "in step" with the electrical input. If the load applied is greater than the torque that can be generated by the motor then it will de-synchronise and thereafter not generate any useful torque.

With all electrical machines the simplest way to understand the generation of torque is to visualise that the rotor will try to move relative to the stator into the "best alignment" position where the pole air gap is minimised for attracting poles and maximised for repelling poles; motion is then maintained by sequentially changing the electro magnetisation so that the "best alignment" position is always ahead of the actual rotor position. In a brushed DC motor this is achieved automatically by the commutator, in a brushless DC motor there is effectively an electronic commutator receiving some form of position feedback synchronisation from the rotor. Usually stepper motors are open loop with no position feedback to the driver whatsoever.

There are three basic forms of stepper motor:

A) Permanent Magnet (PM) - a rotor with an even number of opposing magnetised poles is caused to rotate into "best alignment" with soft iron stator poles by selective electro magnetisation of opposing stator pole pairs. PM motors generally have a large step angle between poles and care must be taken not to demagnetise the rotor. When not energised the torque required to rotate the rotor (detent torque) is high.

B) Variable Reluctance (VR) - a soft iron rotor with an odd number of poles is rotated into "best alignment" with an even number of soft iron stator poles by selective electro magnetisation of near opposing poles. VR motors generally have a large step angle between poles and relatively low torque. There is no significant detent torque.

C) Hybrid - a combination of both and not so easily explained !

Hybrids are the only choice for anything but very low power or very high speed applications because they combine relatively high torque with a narrow step angle. SmartDrive design equipment for Hybrid motors.

A hybrid has a permanent magnet mounted in the rotor between two soft iron toothed end caps as shown in Fig 1, the teeth on the front end cap are displaced relative to those on the rear cap so that they interleave. Motors may have several sets of magnets and caps, each set is called a "stack" so that generally motors are described as " 1, 2 or 3 stack". On smaller specialist motors the stack may be split but the operation is the same.

Fig. 1 A typical single stack rotor and stator

The stator consists of a number of opposing stator pairs running axially the full length of the body with axial teeth slots as shown in Fig 1. In a two phase motor there are 8 stator poles. The arrangement of two phase windings are shown in Fig 2. In practice the phase windings are usually bipolar wound so that each phase has two identical windings A-B and A'-B' - just imagine two wires being wound together rather than the one. This 4 winding

© 2001 SmartDrive Limited

arrangement allows the two windings for each phase to be wired in parallel or series or utilised separately - this will be discussed more later but for the mean time just consider each phase has one winding as shown.

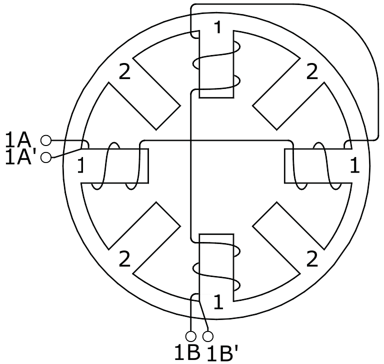

Fig. 2 Winding arrangement

Looking axially down the motor the tooth pitch on the stator poles is different to that of the rotor end caps so that when the teeth on the horizontal plane are fully aligned then those on the vertical plane are fully misaligned. Remembering that the teeth on the front rotor end cap are displaced so as to be interleaved with those on the rear cap then it follows that when the horizontal plane teeth are aligned on the front then those on the rear will be misaligned and vice versa.

The flux path for the permanent magnet is through the front rotor end cap across the air gap to the front of the stator, along the stator to the rear, through the rear air gap to the rear rotor cap as shown in Fig 3. The flux will always flow through the minimum air gap which will be where the rotor/stator teeth are best aligned.

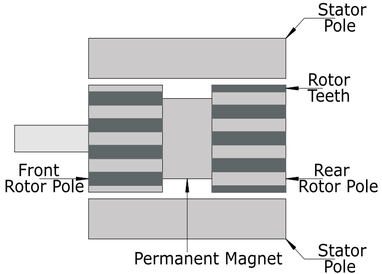

Fig. 3 Rotor Tooth Alignment

Just considering the front rotor cap being best aligned vertically (poles 1 and 5) as shown in Fig 4 then if the windings of poles 1 and 5 are energised in such a way as to strengthen the flux then the flux through those teeth will be concentrated strongly; if at the same time the field through 3 and 7 is weakened by the winding being wound opposing then those teeth will become repelling and this action together will then generating a restoring torque if the rotor is moved.

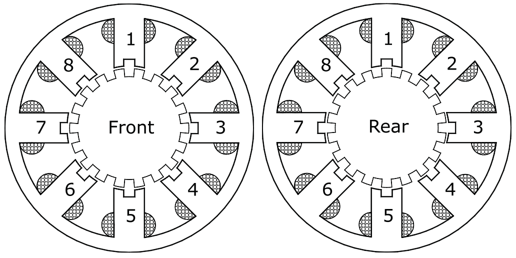

Fig. 4 Front and rear cross sections

At the rear cap the situation is fully reversed with poles 3 and 7 aligned and attracting and poles 1 and 5 misaligned and repelling, however because the flux direction from any given stator to rotor is in the opposite direction at the front from the back (refer back to Fig 3) then energising a stator winding whilst say strengthening the flux through the aligned poles 1 and 5 at the front will also be weakening the flux through the misaligned poles 1 and 5 at the rear; and the same applies to any pair front and back.

This situation is very stable, as the tooth alignment is displaced by forcing the rotor then the restoring torque will increase, but when the attracting teeth are fully misaligned there will be no restoring torque and the rotor is unstably balanced - any slight movement either way will allow the rotor to be attracted to the nearest pole alignment, thus forcing the rotor will produce a jump from one pole alignment to the next. In a typical hybrid motor there are 50 teeth on the rotor so that each stable position is at 7.2°.

If now the energisation of phase one is removed and phase two is energised then the best alignment position will be with poles 2 and 6 aligned and thus the restoring torque will move the rotor to this new position. If phase two is set off and phase one is energised again but with reversed polarity then the best alignment will be with poles 3 and 7. Now phase one off and phase two reversed then 4 and 8; and finally 1 and 3 again normal and the rotor has moved by one tooth interval or 7.2°. This movement was achieved in a 4 stage sequence or steps - so there are 4 steps per tooth and 50 teeth per revolution so that is 200 steps/revolution or 1.8°/step which is the normal way of specifying the motor's resolution.

This drive sequence is called “full step” because at each step the current in a winding is fully on or fully off. When this sequence is repeated then a rotary motion of the shaft is produced with the speed and total rotation being a direct numerical ratio of the frequency and total number of steps in the sequence. The motion in full step is quite noisy because the flux changes are abrupt so hence the torque and position changes are abrupt. By introducing an intermediate stage between each full step, where both phases are on but at a lower current, then the rotation is divided into twice as many steps and the transition from each to the next is smoother - this mode is called “half stepping”. That process can be extended further with more intermediate steps which is then called “micro stepping” which at the limit results in the two phases being driven by a sine and cosine current waveform with no discernible steps resulting in very smooth motion.

So now we have an open loop system where the motor can be driven at a precise speed and a precise number (and fraction) of revolutions by suitable electronic switching of the phases in sequence. At any point in the sequence whether static or in motion the rotor is pulled to the best alignment position by the restoring torque. Against a torque load then the actual rotor position will lag the electrical position by an amount proportional to the torque required. If the restoring torque is less than the applied torque then the motor will desynchronise as the tooth alignment is pulled past the highest restoring torque position, and will be drawn to the next alignment at which it will stop if the load has been removed, or else will continue.

It is most important to appreciate that with a DC motor an applied torque similarly causes the rotor to lag but the DC motor is self commutating and so can never desynchronise under load it just slows down - thus a DC motor should be considered to be a torque motor - the applied voltage determines the torque, the load determines the resulting speed. A stepper should be considered to be a position motor in that whilst the current determines the available torque the steps determines the position - if the motor cannot generate enough torque then it will not follow the demand position at all.

This becomes particularly relevant when working with inertial loads (and not forgetting the motor's rotor inertia). If the step rate is at a constant frequency then the motor will be rotating at the related constant speed. If the step rate is now abruptly increased then in order to similarly change the speed then a high torque must be generated to accelerate the inertia. If this exceeds the capability of the motor then the motor will simply desynchronise and all control is lost. In a similar situation a DC motor would accelerate as a function of it's developed torque and the inertia. Thus we have:

Stepper: required torque=inertia x acceleration+friction
DC: acceleration=developed torque-friction/inertia

It follows that to get the best from a stepper system the control of the step rate to maintain the required torque below that available is of prime importance.

Step rate generators that can only produce a fixed frequency or transit abruptly between a scale of frequencies ("staircasing") or that have instabilities ("jitter") will substantially degrade the system performance.

How to Drive Stepper Motors

Earlier we described how the windings are arranged in two phases and that each phase may have one or two windings. These are normally shown simplified diagrammatically as in Fig 5.

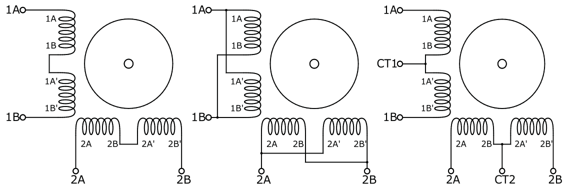

Fig. 5 Connection Modes - 8 Lead Series & Parallel, 6 Lead

The connection possibilities shown in Fig 5 are 8 lead series, 8 lead parallel and 6 lead. 5 lead is the same as the 6 lead, but with CT1 & CT2 joined. Sometimes motors are supplied pre-configured for one of the above, for instance a motor might be supplied with four leads and internally connected for either series or parallel. Generally an 8 lead motor is to be preferred as it can be connected externally to any configuration whereas internally connected motors can be limited in application.

Unipolar Driver

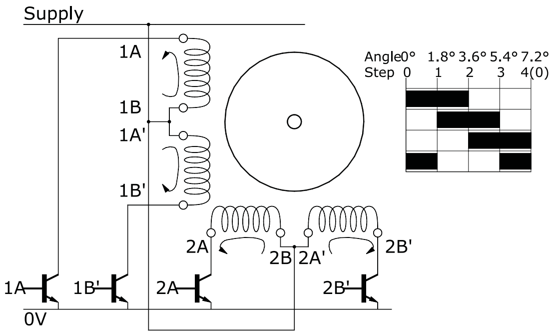

Fig. 6 Unipolar Driver

This is the simplest form of electronics where each of the 4 windings are switched by a transistor or MOSFET such that the current through the 1A/1B windings produces an opposite field to that through the 1A'/1B' windings - this leads to a 6 or 5 wire configuration for the motor.

In operation each switch is set on in the sequence as shown in the table so that at any instant both phases are energised with each full step transition being made by the reversal of current in one phase (by means of energising a different winding of the phase pair). This mode is called unipolar because current only flows in one direction in each winding - and are sometimes described as 4 phase because there are 4 switches although there are still in fact only 2 phases.

Unipolar drives are cheap because there is minimal electronics however performance is poor and motor heating is high because of inefficient copper usage (or torque is low for the same motor heating).

In a unipolar drive the current per winding is limited only by the product of supply voltage and winding resistance so that only low voltages can be used. The rate of change of current in a winding is a product of the winding inductance and the supply voltage and since the torque is a product of actual winding current the step rate must be slow to allow the current to build up after each step. The useful operating speed in unipolar is therefore low. The voltage can be increased, and therefore pro rata the useful operating speed, if a current limiting resistor ("forcing resistor") is fitted in series with each winding - however the heat loss in the resistors is very high so that such a drive design is very inefficient.

Bipolar driver

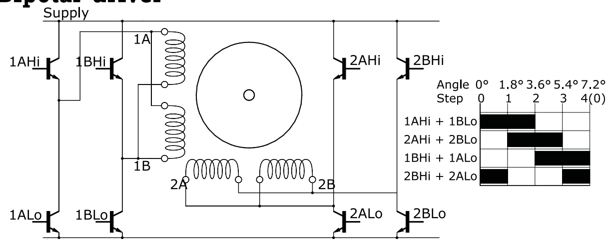

Fig 7. Bipolar Driver

By combining the windings in series or parallel maximum use is made of the copper to reduce motor heating however the current must now be switched so as to flow in two directions in each winding (hence bipolar) this requires 8 switches arranged in two full bridges which is therefore more expensive. Forcing resistors can also be used to extend the operating speed range with the same

© 2001 SmartDrive Limited

constraints as with unipolar.

Bipolar PWM driver

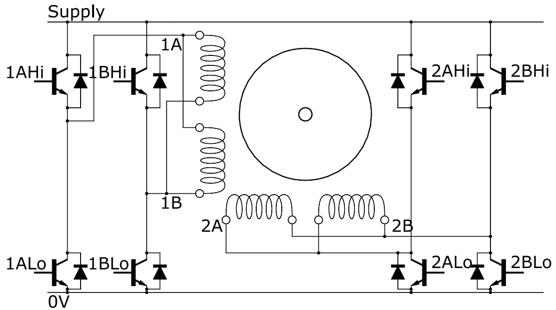

Fig. 8 Bipolar PWM Driver

By controlling the current with pulse width modulation (PWM) of the switching devices then the high speed performance advantage of high supply voltage can be obtained without resistor losses together with the motor efficiency of bipolar drive. During the switch ON time the full supply voltage is applied to the winding to give a rapid change in current, during the OFF time the back EMF drives the current through the flyback diode with virtually no change. By controlling the ON/OFF ratio then the average applied voltage is effectively variable but without losses. Incorporating an active feed back loop to link the current value to the PWM control then gives the ability to apply full voltage at the beginning of a step until the set current is reached whence the applied voltage is reduced via the PWM to that necessary to maintain the current.

With this control then the performance can be extended to much higher speeds and the overall efficiency remains relatively high.

The PWM control also allows the set current to be any value determined by an input reference voltage into the PWM controller. Thus with the use of a microprocessor and D/A convertor sophisticated current profiles can be generated to give half step and microstep operation where the rotor is positioned at intermediate positions between tooth alignment.

Good quality bipolar PWM drives will usually also incorporate extensive additional circuits to protect the drive power stage from short circuits, low motor inductance, over and under voltage and over heat conditions.

Note that with a PWM controlled driver it is important to match the current capability of the drive to the winding current rating of the motor. The rated winding voltage is of no interest whatsoever except as an indication of heat loss. The useful operating speed is proportional to supply voltage and inversely to inductance, but a low inductance motor can only have a low number of turns so therefore to obtain torque and speed the required current will be high.

Recent Developments

The design and manufacture of stepper motors had remained virtually static until the early/mid 90's when a number of improvements were introduced. The latest high performance motors incorporate many of these and can develop nearly twice the torque and shaft power from the same package size as conventional designs. The only significant down side is increased cost and rotor inertia however in many cases compared to a conventional motor the same performance can be achieved from a smaller package size and comes close to the cost.

The main improvements are:-

- stronger rotor magnets using rare earth compounds such as neodymium and samarium cobalt to give much higher flux density

- better laminate materials allowing higher flux density and reduced dimensions especially in the stator so that the rotor diameter can be increased (hence the inertia increase)

- improved mechanical design and manufacture allowing a much smaller air gap

- new stator winding techniques that allow the stator pole face to be larger so that each can have an additional tooth

- insertion of "flux focusing" magnetic material between the rotor teeth

How Motors are Rated

Stepper motors have been around since before WW2 and the early method of driving was unipolar - therefore ratings are usually expressed in unipolar terms which can be easily translated to bipolar use.

Current - **3A** - this means that used with a unipolar drive 3A can be run continuously through one winding of both phases (the other two with no current).

Resistance - **1ohm** - the resistance of each winding is 1ohm.

Voltage - **3V** - at rated 3A through 1ohm of one winding the voltage is 3V.

Inductance - **5mH** - measured at 1KHz on one winding with all others open circuit..

So your electrical maths will give you total unipolar copper loss dissipation of 2 x 3 x 3 x 1 = 18watts. This is a continuous rating under "normal conditions" which invariably includes some dissipation assistance e.g. being mounted on an aluminium panel.

If each phase winding pair is wired in parallel then the resistance of each phase is halved and the current can be increased by $\sqrt{2}$ and still give the same dissipation.

So a unipolar rated 3A motor can be run bipolar at 4.2A with parallel windings. Note that only an 8 leaded motor can be wired this way. A 4 lead motor is simply and 8 lead motor internally linked in parallel and would be rated as 4.2A.

Since the torque is a product of ampere turns and the current is now 41% up through the same number of turns then the torque will be similarly increased.

© 2001 SmartDrive Limited

The bipolar rating as above is a DC rating so that can also be considered to be an rms rating when using a microstep driver at lowish speeds and the peak rating will therefore be √2 up at 6A or 2 x the 3A unipolar rating. Additional heat is generated in the motor from hysteresis losses in the magnetic circuits which are proportional to current and speed and therefore the continuous run current must be reduced accordingly. Where the duty cycle is low and the drive has automatic current reduction when idle then the rating can be maintained or even increased - the final limit being not to exceed the maximum winding temperature.

Similarly if the windings are placed in series then the bipolar rating would be half the parallel rating i.e. 2.1A rms 3A peak (half the current through twice the turns). A 6 lead motor can be used this way as the series connection is already made internally.

Because the two windings of each phase are bifilar wound then they are magnetically coupled. The inductance in bipolar mode is therefore the same as the unipolar because the windings are together - but the series mode has 4X the inductance because the number of turns in the combined winding is doubled.

Holding torque - this is the maximum torque that can be applied without causing the rotor to jump and with both windings energise at rated current which can be unipolar or higher rating with bipolar.

Detent torque - the maximum applied torque without jumping when no windings are energised. Low detent motors generally have lower vibration and noise.

Useable torque - this is best given as a graph with operating conditions. Typically with a bipolar PWM drive the low speed torque is similar to the unipolar holding torque figure and reasonably constant up to a rollover point determined by supply voltage, inductance and specific motor design; thereafter the torque declines inversely with speed giving near constant power up to around twice the rollover speed. In practice a safety margin of +30 to +50% should be allowed.

Positioning Resolution and Accuracy

We are often asked to give data for "**positioning resolution**" or "**positioning accuracy**" with little intimation that the questioner appreciates the difference.

Positioning accuracy

In a stepper motor, as described in detail earlier, the positioning capability is achieved by the restoring torque pulling the teeth on the rotor and stator poles into alignment.

When a motor is energised in both windings at the rated current (lets call this phase 0) then if there is no load or friction on the rotor it will assume a position where no restoring torque is generated - phase 0 position. If the rotor is forced by a load to a new position one tooth pitch away then it will again assume a stable no torque phase 0 position and so on for the remaining positions in one revolution. For a 50 tooth rotor there are 50 phase 0 positions each 7.2° apart. If the current in one of the winding is reversed (phase 1) then the rotor will move 1.8° to the adjacent phase 1 position and again there are 50 phase 1 positions at 7.2° intervals. Similarly with phase 2 and phase 3 - so that there are 200 full step positions at 1.8° intervals.

That 1.8° is not however absolute because it is influenced by the accuracy of the machining (or stamping) of the teeth in the rotor and stator laminates and the concentricity of the rotor relative to the stator. Thus errors occur in the absolute positional accuracy of one step position relative to another composed principally of a cyclic error over 4 steps and a cyclic error per revolution.

Motors are typically specified as +/- 5%/step. This means that the accuracy any one step position relative to any other is limited to +/- 0.09°.

When the rotor is held at a step position (say step1) then a restoring force is generated when the rotor is displaced from the step position. The maximum value is the holding torque and occurs 1.8° from the step position, declines to 0 at 3.6° peaks in the opposite direction at 5.4° and drops to 0 at 7.2° when it is now at the next step1 position; this characteristic follows a sine profile. The useful operating range is about +/- 1° about the step position over which the torque varies roughly linearly by +/- 70% of the peak. This therefore gives a measure of the "torque stiffness" for the motor in Nm/°.

In a practical application there is always some load due to gravity, friction or stiction and this will result in the rotor assuming a static position displaced from the step position according to the torque stiffness. Stiction in particular is especially difficult as the induced error can appear to be somewhat random.

When a drive is operated in half step or microstep then it is tempting to assume that the "accuracy" has been improved to the same value as the microsteps ie a 200 step motor becomes 51,200 microsteps/revolution and that this gives a "positioning accuracy" of 360°/51200 ie to 0.007°. From the above considerations you can easily see that this is far from true even under no load.

Positioning resolution

Resolution is another aspect altogether and is a measure of the minimum interval unit that can be made between stopped positions. With a full step drive then the resolution is simply the number of steps per revolution ie 200 or 1.8°. With half stepping it is 400 per revolution or 0.9° because half stepping introduces an intermediate step between each full step. A microstep drive giving 51200 steps/revolution therefore has a theoretical resolution of 0.007°.

Stiction will set a limit on the minimum increment because to overcome the stiction there must be a torque and hence the torque stiffness comes into play, when the torque overcomes the stiction then the rotor will move to the zero torque position and the system inertia will then carry it beyond to a point where the increasing restoring torque stops it, it will then stay in that position

© 2001 SmartDrive Limited

because the restoring torque is not enough to overcome the stiction - or depending on the dynamics it may bounce back to some point between the two positions. Either way it is not possible to position the rotor to better than the product of stiction / torque stiffness. Stiction comes from bearings and slides in the motor and system .

The electronics in the control system of the drive has a certain limited capability to generate a precise voltage reference to feed to the current control hardware because some form of digital to analogue conversion is required and often this is from 8 bit D/As which cannot produce the accuracy of sine/cosine required for high resolution microstepping. Depending on the drive topology there may also be problems with controlling the very small currents needed at the sine/cosine zero crossing points resulting in degraded resolution at these points.

Stepper systems - myths and legends

“Steppers are so noisy and coarse at low speeds”

Full step systems are - a well designed microstep system can be virtually silent and very smooth especially at low speeds.

“I’ve got a 3A/phase stepper motor and drive so I will need 2 X 3A, that’s a 6A power supply”

This will be true for non-PWM drives, but not so for PWM drives. PWM drives operate as a power converter rather like a switch mode power supply. At stand-still say the 3A into 1ohm of each winding is a total of 18W so an 80V PSU will need to supply only 225mA - if the drive had no losses or own consumption so add another 125mA (10W). Note that if the supply volts are lower then the current will be higher so that the power is provided. As the motor speed is increased under no load up to say 500rpm then the hysteresis and other losses will build up but the total power will probably still be less than double say 40W or 0.5A + 125mA. When the shaft is loaded or accelerating inertia then additional power is drawn from the supply to compensate and this closely matches the shaft power. So our example motor producing 0.8Nm at 500rpm (ie about 40W) will draw about 0.5 + 0.125 + 0.5A or 1.125A from 80V or 90W and the system is 44% efficient. The graph in fig 9 give the no load and max load supply currents for a 2.8A motor.

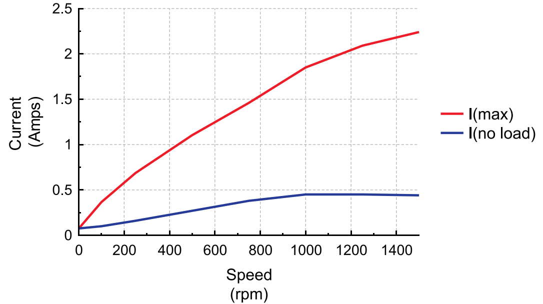

Fig. 9 Supply current for a 2.8A motor running at 92V

“Stepper systems are unreliable - always stalling”

Operational reliability is a direct function of the care taken to design the system. There are vast numbers of machines running faultlessly with open loop steppers from wrist watches through printers, copiers, faxes to industrial machining and automation systems. The usual failings in design are lack of attention to the torque requirements due to the effects of inertial acceleration or load variations through poor mechanical design considerations, and poor step pulse train stability.

“My system loses the odd step sometimes so it must be desynchronising”

If a motor de-synchronises then any error will be in multiples of 7.2° (assuming a standard 200steps/revolution motor). Any loss of position that is not a multiple of 7.2° must be from another cause, usually mechanical slippage in couplings etc or spurious/lost pulses between controller and drive.

“Resonance is a big problem with steppers”

Yes it can be in poorly designed systems. Resonance occurs when the torque pulse, caused by full and half stepping, excite the natural resonance of the rotor inertia and the developed torque. This usually occurs at a speed between 70 and 200 rpm, but may also occur at higher order harmonics. Good microstepping dramatically reduces resonance and removal of any mechanical slop in the system together with a small amount of compliance and an element of frictional load normally present anyway generally cures any problem.

“The motor is very hot.....there must be something wrong!”

There may be something wrong but steppers do run hot typically 80°C case temp - the limit usually being 120°C winding temp before irrecoverable degradation of winding insulation and magnetics.

“You mustn’t stall the motor - it will burn out “

No it wont - you can stall a stepper all day (at rated current) and it will not cook - in fact it will be cooler than if it were run continuously at high speed. The drive controls the winding currents by PWM so the motor cannot overheat. Continuous stalling with motion being attempted will however produce severe vibration as the torque builds up then drops back as the magnetic field rotates past tooth alignments - this can have damaging effects on couplings and other parts of the machine and in extreme case may eventually cause the motor stator or rotor to fail.

“I used a stepper in place of a servo and it just doesn’t perform”

The design considerations are very different especially load and inertia and speed - servos tend to run up to 3000rpm, steppers are best up to typically 700-800rpm but with higher torque and at lower overall cost.

“I need a to match the motor inertia to the load inertia”

That’s servo talk resulting from the inability of early servo control system algorithms to cope with a wide range of load inertia for a given drive/motor combination. With steppers, providing the load inertia is tightly coupled to the shaft, then the only inertia consideration is the total inertia (rotor + reflected from load) in respect of the torque needed to accelerate it at the required rate. Generally, if fast acceleration is not an issue, then a higher inertia will produce less vibration and smoother motion.