1 INTRODUCTION

Stepper motors have been around for many years but due to the availability of cost effective, modern, high performance electronic drives and microprocessor based controllers that they are now used in many machine control systems. Motion control as it is known involves the accurate control of distance, position, velocity, acceleration or any combination of these by electric motors and electronic controls. A system consists of a motor, electronic drive and a controller. Examples are extremely varied, ranging from XYZ computer controlled engraving systems to machines that unpeel and stick adhesive labels on jars whilst moving on a conveyor. By using electronic motion control, engineers can design machines for special applications where off the shelf machines are too expensive or just not available for a particular application. Electronic motion control also offers flexibility not available in many mechanical systems. Speeds, accelerations, speed ratios and displacements can be reprogrammed in a few minutes rather than refitting of gears, levers and cams.

This text has been prepared as a guide to the specification and application of stepping motors and drives used in motion control systems. It is intended for use by electrical and mechanical engineers involved in the selection of motors and drives and machine design. It replaces the A5 booklet "Stepping Motor Applications Guide" published in 1996. The graphics have been sized for printing on A4 pages (portrait configuration) with margins of 20mm left, 10mm right, 10mm top and 10mm bottom.

It is a guide only and every effort has been made to ensure accuracy of the data. Due to a variety of operating conditions and applications the user through his own analysis and testing is solely responsible for making the final selection of products used in systems and assuring that all safety and warning requirements of the application are met. Automated Motion Systems Pty. Ltd. does not accept responsibility for system performance. Needless to say our engineers are always available to assist with motor, drive and gearing selection. Please note that it is the machine manufacturer’s responsibility to ensure a completed machine meets Australian EMC directive requirements and is sufficiently safeguarded to AS4024.

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2 MOTOR OPERATION

MOTOR CONSTRUCTION

The majority of stepping motors used in industry are hybrid motors being a combination of permanent magnet and variable reluctance types. Most hybrid motors are usually 2 phase although 5 phase versions do exist and require a different drive system. The operation of a two phase hybrid motor is seen by this very simple model of a 12 step/rev motor in Fig. 2.1.

The rotor of this motor consists of two pole pieces with three teeth on each. In between the pole pieces is a permanent magnet which is magnetised along the axis of the rotor, making one end a North pole and the other end a South pole. The teeth are offset at the North and South ends also as shown in Fig. 2.1.

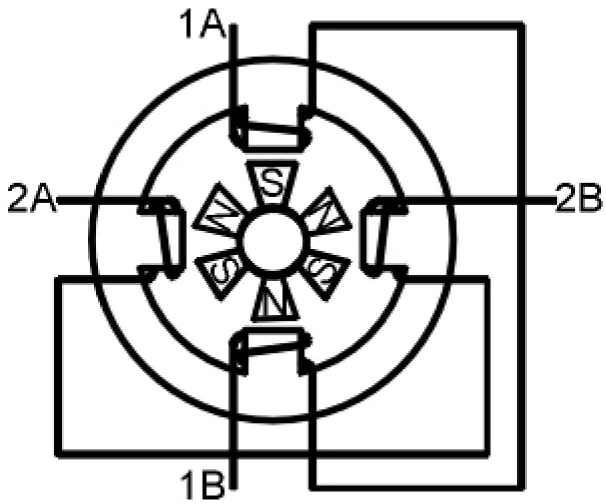


Fig. 2.1 Simple Hybrid Stepper Motor

The stator consists of a shell having four teeth which run the full length of the motor. Coils are wound on the stator teeth and connected together in pairs.

With no current flowing in any of the motor windings, the rotor will tend to take up one of the positions with one tooth on the stator aligned with a tooth on the rotor. This is because the permanent magnet in the rotor is trying to minimise the reluctance (magnetic resistance) of the flux path from one end to the other. The torque holding the rotor in one of these positions is usually small and is called detente torque. The motor will have twelve possible detente positions.

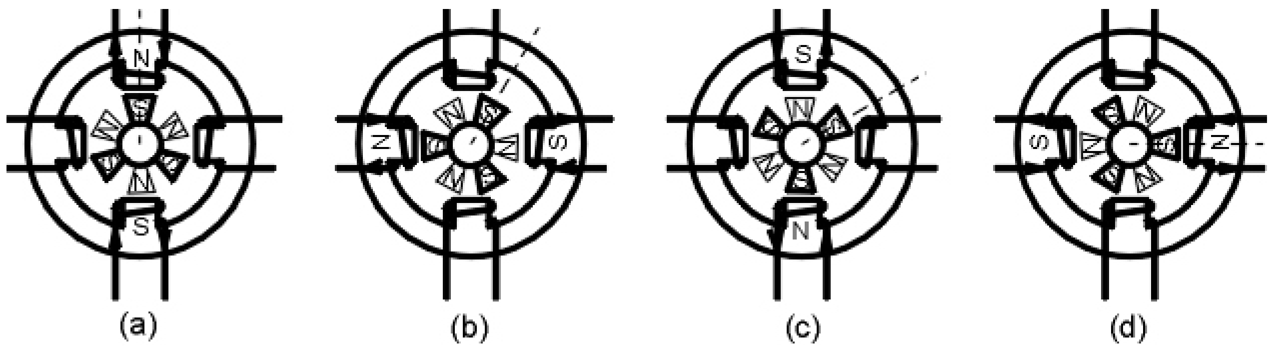


Fig. 2.2 Full Stepping, one phase on

If current is passed through one pair of windings as shown in Fig. 2.2a the resulting North and South stator poles will attract teeth of the opposite polarity on each end of the rotor. There are only three stable positions for the rotor, the same as the number of rotor teeth. The torque required to deflect the rotor now from its stable position is very much greater and is called holding torque.

By changing the current flow from the first to the second set of stator windings as in Fig 2.2b, the stator field rotates through 90 degrees and the rotor turns 30 degrees. This movement corresponds to one full step. Reverting to the next set of stator windings but energising them in the opposite direction, the stator field rotates another 90 degrees and the rotor rotates another 30 degrees or one step. Finally if the second set of stator windings is energised in the opposite direction, we go to the third step position. If we energise the first winding as in 2.2a we go back to the first step position. This simple motor requires 12 steps to make the rotor rotate one revolution.

If two coils are energised simultaneously as in Fig. 2.3a the rotor takes up an intermediate position since it is equally attracted to two stator poles. Greater torque is produced under these conditions, because all the stator poles are influencing the rotor. The motor can be made to rotate a full step simply by reversing the current in one set of windings. This is the normal way of driving a motor in full steps, by keeping two windings energised at all times and simply reversing current in each winding alternatively.

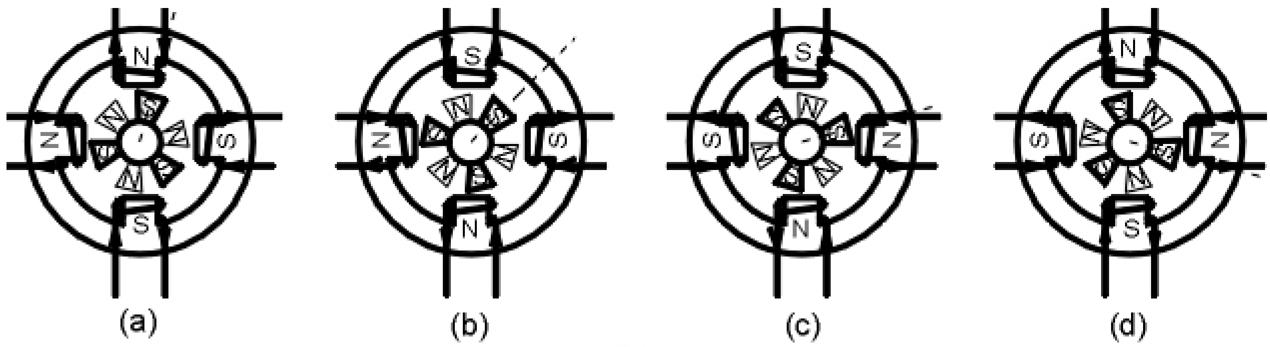


Fig. 2.3 Full Stepping, two phases on

By alternately energising one winding and then two as in Fig. 2.4, the rotor moves through only 15 degrees instead of 30degrees and the number of steps required to rotate one revolution will be doubled. This is called half stepping and this is the mode that most motors use. The advantage is much smoother running and greater resolution, although there is a slight reduction of torque.

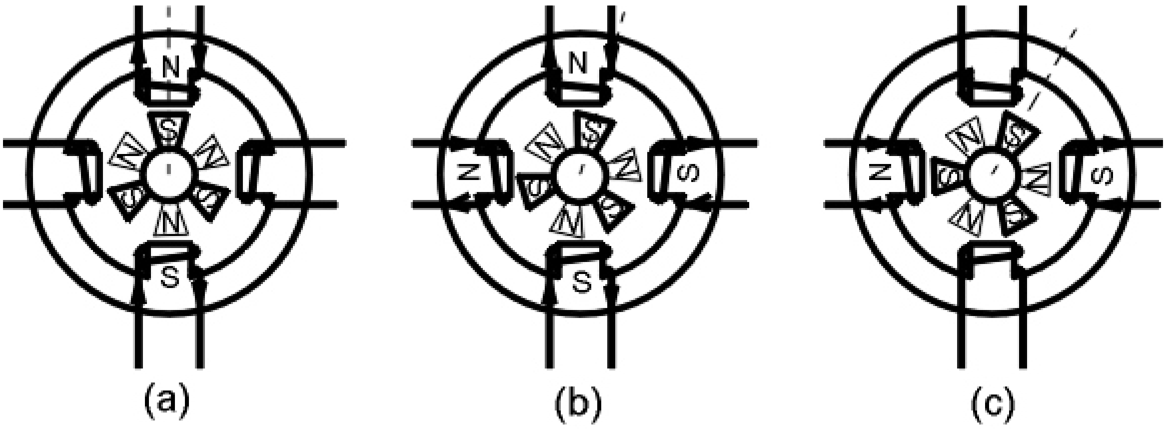


Fig. 2.4 Half Stepping

Due to advances in electronics it is possible to obtain even lower step angles and smoother running, although at a higher cost. Some drives have the ability to switch both windings on simultaneously but proportion the amount of current flowing in each winding. The rotor positions itself according to the ratio of currents in two stator fields. This is called ministepping and microstepping and typical motor resolutions for a standard 200 step/rev motor are as follows.

FULL STEPPING 200 step/rev
HALF STEPPING 400 step/rev
QUARTER STEPPING 800 step/rev
MINISTEPPING 2000 to 4000 step/rev
MICROSTEPPING 25000 to 50000 step/rev

STANDARD 200 STEP/REV MOTOR

The standard stepper motor operates in the same way as the model, but has a greater number of teeth on the rotor and stator giving smaller step size. The rotor is in two sections, each section having 50 teeth on each section. The stator has 8 poles each with 5 teeth, making a total of 40 teeth. The full step angle is 1.8 degrees.

BIFILAR WINDINGS

Most stepping motors are bifilar wound, meaning that there are two identical sets of windings on each pole as in Fig. 2.5, 8 lead version. Both sets have almost identical electrical and magnetic properties. The advantage of this type of winding method is greater flexibility when connecting to a drive. The basic styles are as follows and reasons will become clear later.

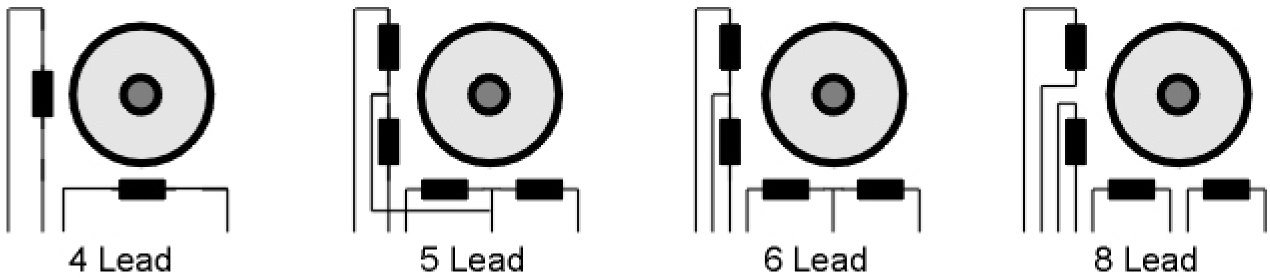


Fig. 2.5 Motor Leads

4 Leads

Some small motors are only supplied with 4 leads. These are not bifilar wound and are not very flexible in terms of connection. They can only be used with bipolar drives and there is no option of series or parallel connection.

5 Leads

This type has the centre taps of the phases commoned and brought out via a single wire. They are used only with unipolar drives and cannot be used with modern bipolar drives.

6 Leads

These motors have the centre taps of both phases brought out on two wires. Because the bifilar windings are connected in series it is not possible to connect them in parallel. It is possible to use only half a winding, but torque will be limited.

8 Leads

These motors are the best to use because they provide the greatest flexibility. The windings can be connected in series or parallel depending on required torque and speed. It is also possible to use only one set of windings or connect the motor to a unipolar drive as well as bipolar drives.

SERIES AND PARALLEL

When using 8 lead stepping motors, the motor can be connected in either parallel or series mode as in Fig. 2.6. Whichever method is chosen affects the torque/speed characteristic. This graph is called pull-out torque curve and is the torque applied to a motor shaft to desynchronise or "pull it out" of synchronisation whilst it is in motion. There are 4 terminals on a bipolar drive, two for each phase. However, if a motor has 8 leads, some of the leads must be commoned or ignored.

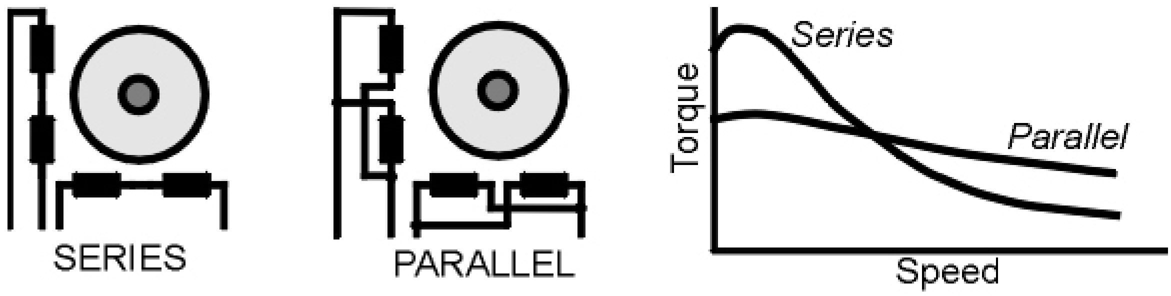


Fig. 2.6 Series and Parallel Connections

Compared to using one half winding only, connecting both halves in series results in the drive current flowing through twice as many turns. For the same current this doubles the Amp-turns, which should double the torque. In practice, the increase is not double due to non linearities in the magnetic material. Equally, the same torque will be produced at half the drive current when the windings are in series.

Therefore, having doubled the effective number of turns, we also increase the inductance by a factor of 4. This causes the torque to drop off more rapidly as speed increases because high inductance reduces the rate at which current can flow in the windings. Another problem is caused by putting two windings in series. This also doubles the resistance of the winding so, for a given drive current, (stepper drives behave like current sources) the resistance loss (usually called I^2R losses) is doubled leading to greater heat generation.

Now go back to the half winding only motor. Connecting the two half windings of an 8 lead motor in parallel allows the current to divide itself equally between the two coils. It does not change the number of Amp-turns and the inductance remains the same. The resistance is now halved. For this reason the torque characteristic of a parallel connected motor is the same as for one half winding.

The general rules are:

Parallel connection is usually the preferred connection method.
Parallel connection is for good torque over a wider speed range.
Series connection is for high torque at low speeds but reduces quickly.
Series connected motors may run hot due to high resistance and inductance.
Series connection is good for drives with limited current running large motors.

MOTOR CURRENT RATING

The current rating of a stepper motor is based primarily on the permissible temperature rise of the case. Operation at the rated current will produce the full rated torque of the motor at low speeds. Most motors on the market have greatly varying currents, resistances and inductances.

A motor with a low current rating probably has many turns of thin wire and therefore higher resistance and inductance. The high inductance prevents the motor from running at high speeds so is probably only suitable for low speed operation. A motor with a high current rating probably has less turns and lower inductance. This motor would be ideal for high speed operation. The rated current of a motor is usually printed on the manufacturer's label.

Referring back to our half winding only motor, when an 8 lead motor is connected in parallel this has the effect of halving the resistance.

It can be shown that for the same power dissipation in the motor the current can now be increased by 1.414 giving a significant increase in the available torque. Conversely, connecting windings in series will double the total resistance and the current rating is reduced by a factor of 1.414 (times 0.707) giving a much lower safe current.

As a general rule use a stepper motor drive with following rated currents.

PARALLEL: I_{motor} x 1.4

SERIES: I_{motor} / 1.4

Where I_{motor} = manufacturers unipolar rated current for the motor

STEPPER MOTORS SIZES

Stepping motors are often categorised by frame size and stack number. Frame sizes refer to the imperial diameter of the motor, while the stack number refers to the number of stacks.

A higher torque output can be produced from a motor by increasing its diameter, however, while increasing the torque by square of the diameter this also increases the inertia by the fourth power, making it much slower to accelerate. For this reason, manufacturers will stack extra rotors and stators into a stepper motor giving it more torque without greatly increasing inertia.

The power ratings for typical standard motor sizes on the market are as follows. The shaft power ratings are approximate and depend greatly on the type of electronic drive used. Some motors now available are high performance and use stronger magnetic materials and a larger diameter rotor. These motors will have higher shaft power output.

Frame Size	Number of Stacks	Diameter	Maximum Power
17	1	1.7"	12W
23	1	2.3"	50W
23	2	2.3"	70W
23	3	2.3"	80W
34	1	3.4"	100W
34	2	3.4"	300W
34	3	3.4"	600W
42	1	4.2"	800W
42	2	4.2"	1000W
42	3	4.2"	1400W

Note

Frame 17 motors are used rarely in industry due to their low torque outputs. There is a better price to power ratio with the 23 frame 1 stack motors. The 42 frame 1 stack and 23 frame 3 stack motors are also less common now as better price/power ratio can be achieved by other sizes and/or gearing.

START-STOP SPEEDS

Looking at the torque/speed curve in Fig. 2.7 there are two operating ranges, the start-stop (or pull in) range and the slew (pull out) range. Within the start-stop range the motor can be started or stopped instantly by switching pulses to the drive on and off. Within speeds of this range, the motor has sufficient torque to accelerate its own inertia up to synchronous speed without missing steps. Clearly if an inertia load is added this speed range is reduced.

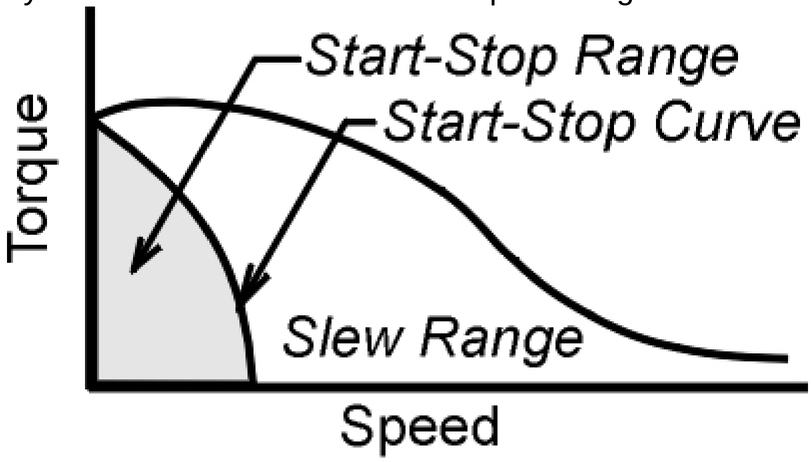


Fig 2.7 Slew Curve

This is why it is often necessary to ramp a stepper motor upto and down from a maximum speed by applying acceleration and deceleration in the motion, otherwise the motor may stall or miss steps. Ramping is a gradual controlled change in frequency of the steps to the drive, thereby keeping acceleration of the motor within an acceptable range. Using ramping allows much higher speeds than the start-stop speeds to be obtained. The maximum start-stop speed is inversely proportional to the square root of the total inertia.

STEPPER MOTOR ADVANTAGES

Low Cost

Due to simple construction and lack of commutation components, stepper motors are very economical to produce when compared to DC servomotors and brushless DC motors.

Maintenance Free

There are no brushes in a stepper motor to wear out. The only wearing surfaces are in the bearings, making them very reliable and ideal for applications where it is not convenient to gain access to the motor.

Speed Range

Stepper motors usually operate in the speed range of 0 to 3000 r.p.m., whereas conventional DC and AC motors have difficulty at very low speeds. This wide speed range often eliminates the need for a gearbox.

Thermal Path

A stepper motor has its windings on the stator (stationary outer section) of the motor. Heat generated in the windings can be easily dissipated through the motor casing. DC brushed motors on the other hand have windings in the rotor (rotating inner section), so there is a much greater resistance to heat transfer.

Torque
Stepper motors provide excellent torque at low speeds. This is often where it is required most, to accelerate loads from rest. A stepper motor will also provide a holding torque when at rest, locking all mechanical components and reducing the need for clamps and brakes. No damage to the motor will occur whilst being energised but not rotating.

Accuracy
Stepper motors are designed to move in increments of 1.8 degrees or precisely 200 steps per revolution. Step angle accuracy is usually 3%, but this error is not cumulative.

Digital Control
Because movement of a stepper motor is defined by number of steps fed into a drive, they are ideally suited to control from computers, PLCs and digital circuits. Motor drives have two inputs, one for step pulses and the other for a direction signal.

Standardisation
Nearly all hybrid stepper motors in the world conform to a NEMA standard of sizing. This means that an existing stepper motor on a machine can usually be replaced easily without redrilling holes or machining because shaft sizing, flange mounting holes length, and diameter will be the same regardless of manufacturer.

Vacuum
Stepper motors will operate in a complete vacuum, whereas brushed DC motors will not. This is useful in laboratory and aerospace applications.

Safety
Because stepper motors have no brushes and commutator, there is no arcing to ignite combustible materials.

STEPPER MOTOR LIMITATIONS
Stepper motors do have some limitations and these should be considered when selecting motors and drives for an application. If an application has one or more of the following problems then closed loop servomotors or brushless DC motors would be better suited.

Speed
Is the continuous running speed (over several hours) going to be greater than 2000 r.p.m? If so, the motor may become excessively hot causing demagnetisation of the motor.
Is speed going to exceed 3000 r.p.m? Stepper motors usually have an upper speed limit of 3000 r.p.m. beyond which the available torque is too low to be useful.

Noise
Is quiet operation necessary? Stepper motors are inherently noisy so applications like medical and laboratory equipment may require acoustic attenuation or microstepping drives.

Power
The largest econimically available stepper motors available are 4.2" frame size 3 stack. This motor can deliver about 2000 Watt shaft power and low speed torque of nearly 20Nm.

Load
Stepper motors are normally run in open loop mode (without position feedback). If the load torque is likely to change rapidly during operation or vary unpredictably then a stepper motor is not recommended. Normally a torque margin safety factor is designed into the system.

Feedback

Because of open loop operation, if position must be checked then a shaft encoder must be fitted to the motor.

Inertia

Stepper motors will operate well if the inertia ratio (load inertia as seen at the motor shaft divided by rotor inertia) is between 1 and 5. Inertia ratios outside this range may cause resonance or instability.

3 DRIVE OPERATION

DRIVE OPERATION

The drive delivers electrical power to the stepper motor in response to low level signals from the control system.

The motor is a torque producing device, the torque produced being roughly proportional to current and to the number of turns in the winding. This is often referred to as the Amp-turns product. Essentially, the drive acts as a current source. The applied voltage is only significant as a means of controlling the current.

Input signals to the stepper drive consist of clock pulses and a direction signal. One clock pulse is required for every step the motor is to rotate. This is true regardless of the stepping mode, so the drive may require anything between 200 and 50,000 pulses to produce one revolution of the shaft. The most commonly used stepping mode in industrial applications is the half step mode in which the motor performs 400 steps (0.9O per step) per revolution. At a shaft speed of 3000 rpm this corresponds to a clock pulse frequency of 20kHz.

The logic section of the stepper drive is often referred to as the translator, and its function is to translate the step and direction signals into control waveforms for the switch set (semiconductor switches). The basic translator functions are common to most types of drives, although the translator is necessarily more complex in the case of a microstepping drive. However, the design of the switch set is the prime factor in determining drive performance.

The types of step and direction signals vary from manufacturers although the most common types are as follows in Fig. 3.1. The signal must usually be present for at least 10m sec, but this again depends on the manufacturer.

NPN current sink *The signal is pulled up to 12V DC via a 4.7k resistor.*
To make the motor step you pull the input down to 0V.

Voltage source *To make the motor step you inject a DC voltage pulse.*
This type of input is often opto-isolated to prevent a faulty drive from damaging other equipment or faulty controllers damaging the drive.
Voltage level may be 5, 12 or 24 VDC, depending on the drive.

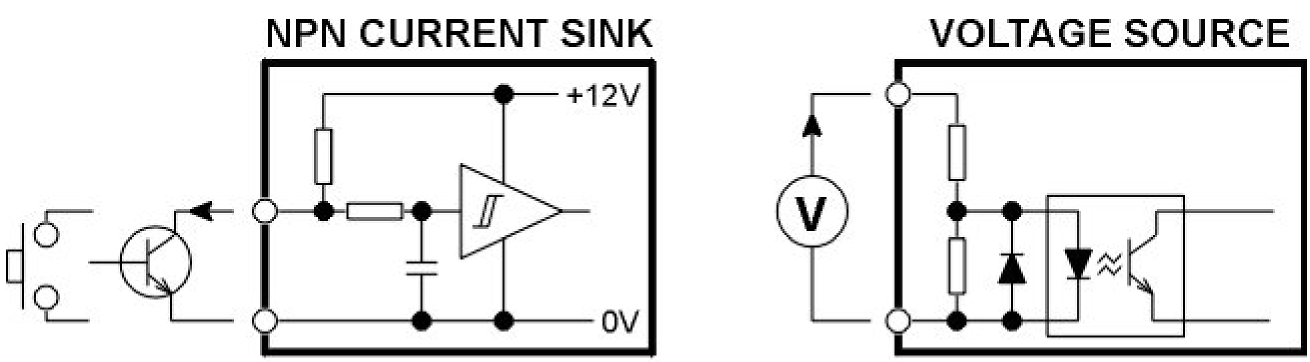


Fig. 3.1 Step & Direction Inputs

UNIPOLAR DRIVE

The simplest type of switch set is the unipolar arrangement in Fig. 3.2. It is referred to as a unipolar drive because current can only flow in one direction through any particular motor terminal. A bifilar-wound motor must be used since reversal of the stator field is achieved by transferring current to the second coil. In the case of this very simple drive, the current is determined only by the motor winding resistance and the applied voltage.

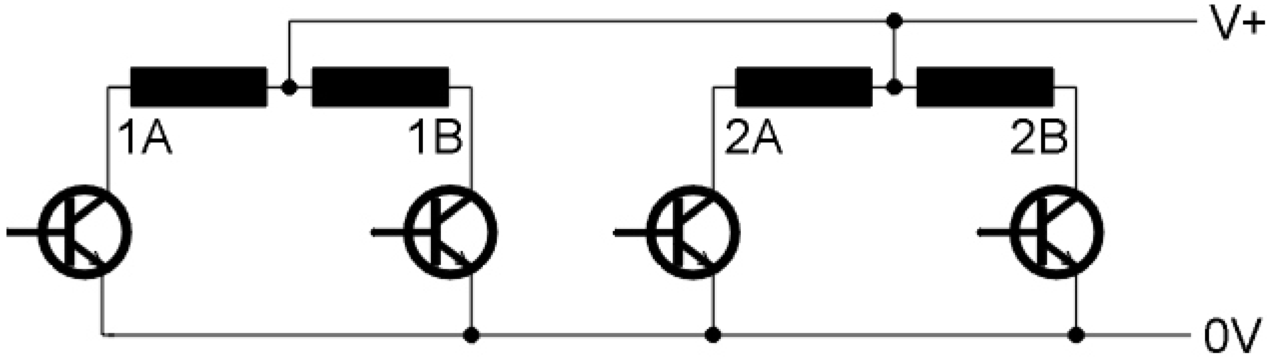


Fig. 3.2 Basic Unipolar Drive

Such a drive will function perfectly at low speeds but as the speed is increased the torque will fall off rapidly. This is because the applied voltage must be very low in order not to overheat the motor windings. This low voltage also means the current does not flow into the motor windings quickly due to inductance. When a voltage is placed across an inductor the current rises linearly with respect to time. The higher the applied voltage, the more rapid the rise of current. To solve this problem we could increase the supply voltage to the stepper motor windings, but this would also increase the steady state current, overheating the motor. One solution is to add resistors in series with the motor windings to keep the current the same as before as in Fig. 3.3. If an applied voltage of say 10 times the rated motor voltage is used, the current will reach its final value in one tenth the time. This is called a Resistance Limited (R-L) drive. It solves the speed problem but it comes at a price. There is much more power dissipated in the resistor than in the motor windings. This generates a lot of heat and makes the power supply unnecessarily large. Another drawback is that only one coil of the motor is on at a time. If both phases of the motor could be energised simultaneously there would be an increase in torque. R-L drives are good for small motors and low cost applications only.

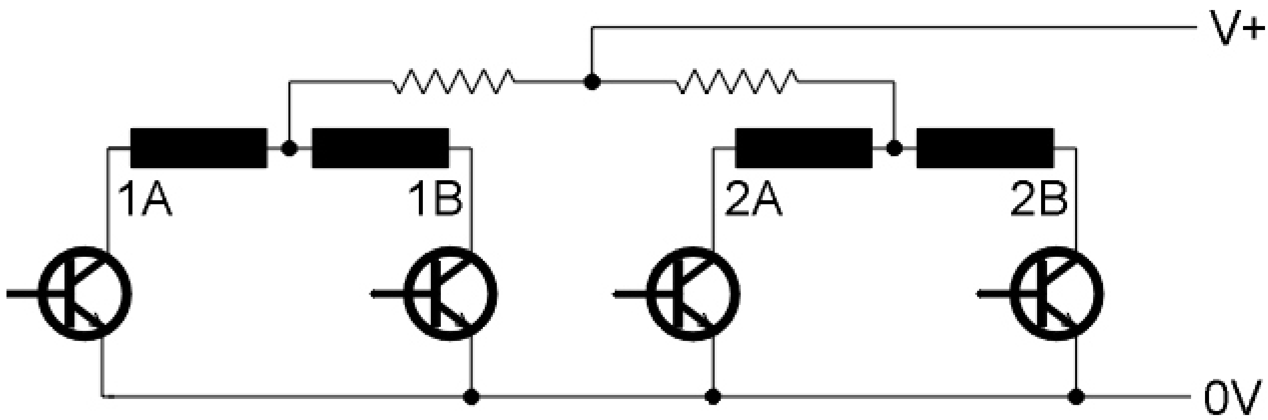


Fig. 3.3 R-L Drive

BIPOLAR DRIVE

A more efficient way of utilising the stepper motor is to use a bipolar drive in Fig. 3.4. One power supply is needed, but the current can be driven through the coils in either direction. If necessary, the voltage across the coil can be limited by using a resistor as with the unipolar drive. More motor torque is produced, but there is still a lot of power lost to heat in the resistor.

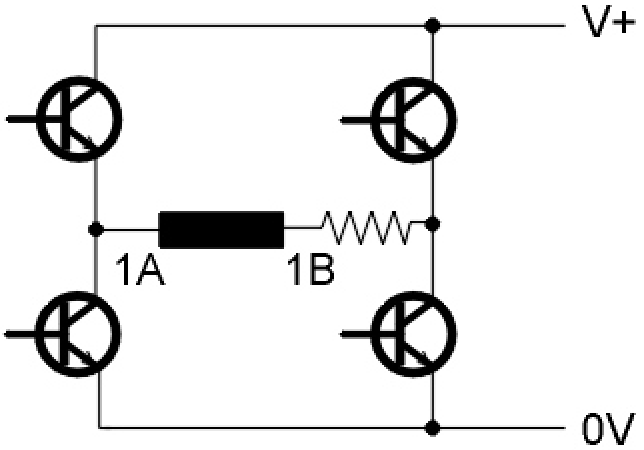


Fig. 3.4 Bipolar Drive (one winding shown only)

RECIRCULATING CHOPPER DRIVE

This is the method used in most modern stepper motor drives as shown in Fig 3.5. It is based on the four transistor bridge but also includes a recirculating diode and a current sense resistor. The sensing resistor is very low value (typically 0.1W) and provides a feedback voltage of the motor current.

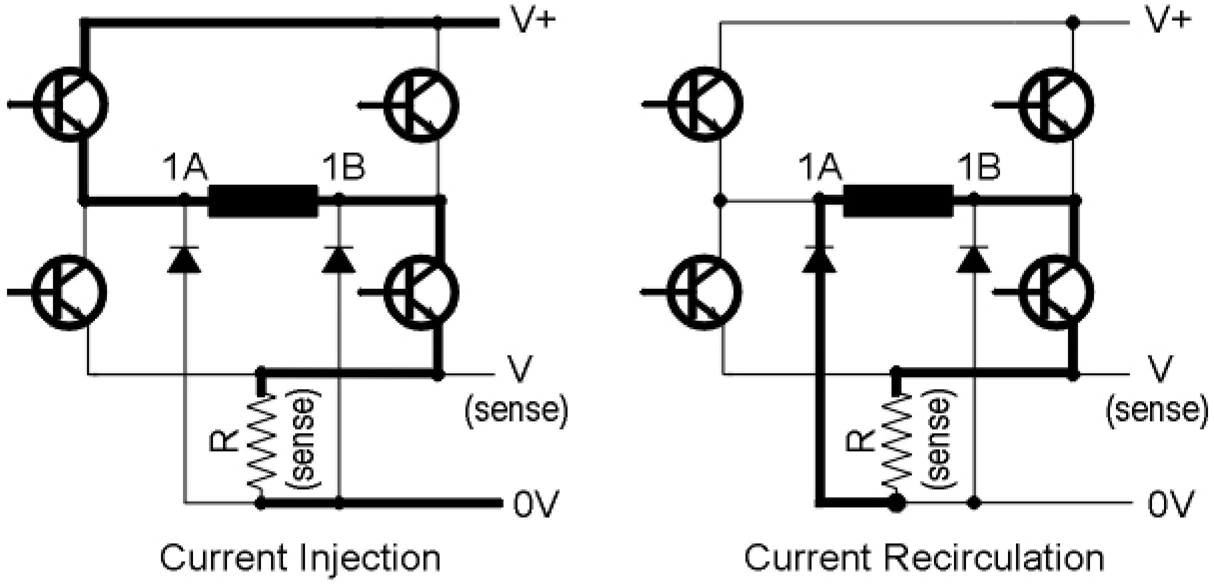


Fig. 3.5 Recirculating Chopper Drive (one winding shown only)

Current is injected into the winding by turning on one top and one bottom transistor switch. This applies full supply voltage across the coil so the current rises very rapidly. The rise is almost linear and this current can be monitored by checking the voltage across the sense resistor. When the preset required current level has been reached the top switch is turned off and the stored energy in the coil keeps the current flowing via the bottom switch and the diode. Losses in the system cause the current to slowly decay, and when a preset lower current level is reached the top switch is turned back on and the cycle repeats. The current is maintained at an average value by switching or chopping the supply to the motor at an ultrasonic frequency. Very little power is dissipated in the switching transistors other than during the switching state.

REGENERATION AND POWER DUMPING

A stepper motor like any other rotating machine with permanent magnets will act as a generator when the shaft is driven by an external force. This means that a motor can produce some high voltages when decelerating, particularly when there is a large inertia in the system. This will lead to an increase in motor current which could damage the transistor switches. This problem is solved by sensing the current and switching off the transistors when this occurs. There is now a path for the regenerated current back to the supply capacitor. Also a power dump circuit is switched across the supply to dissipate the generated power as in Fig. 3.6 . Without this the voltage produced may become high enough to damage the switching transistors.

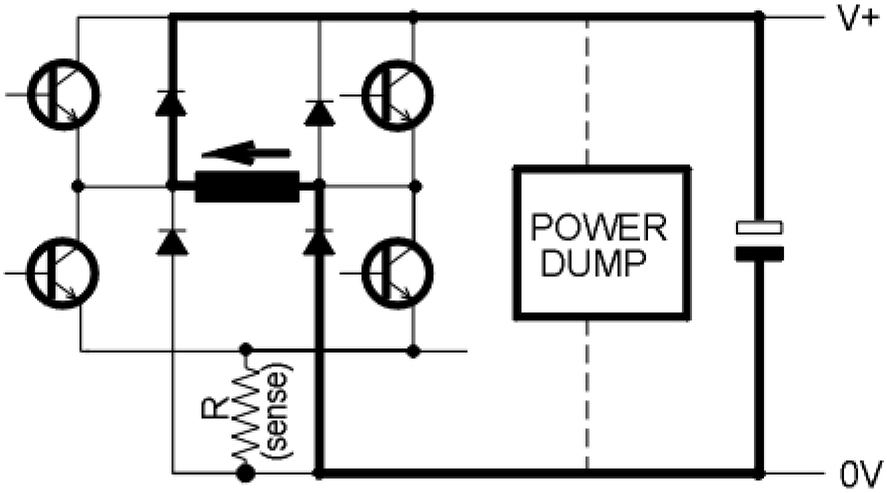


Fig. 3.6 Current Flow During Regeneration (one winding shown only)

TORQUE/SPEED CURVE

The motor inductance is the factor which opposes rapid changes of current and therefore makes it more difficult to drive a stepper at high speeds. Looking at the torque speed curve in Fig. 3.7 we can see what happens.

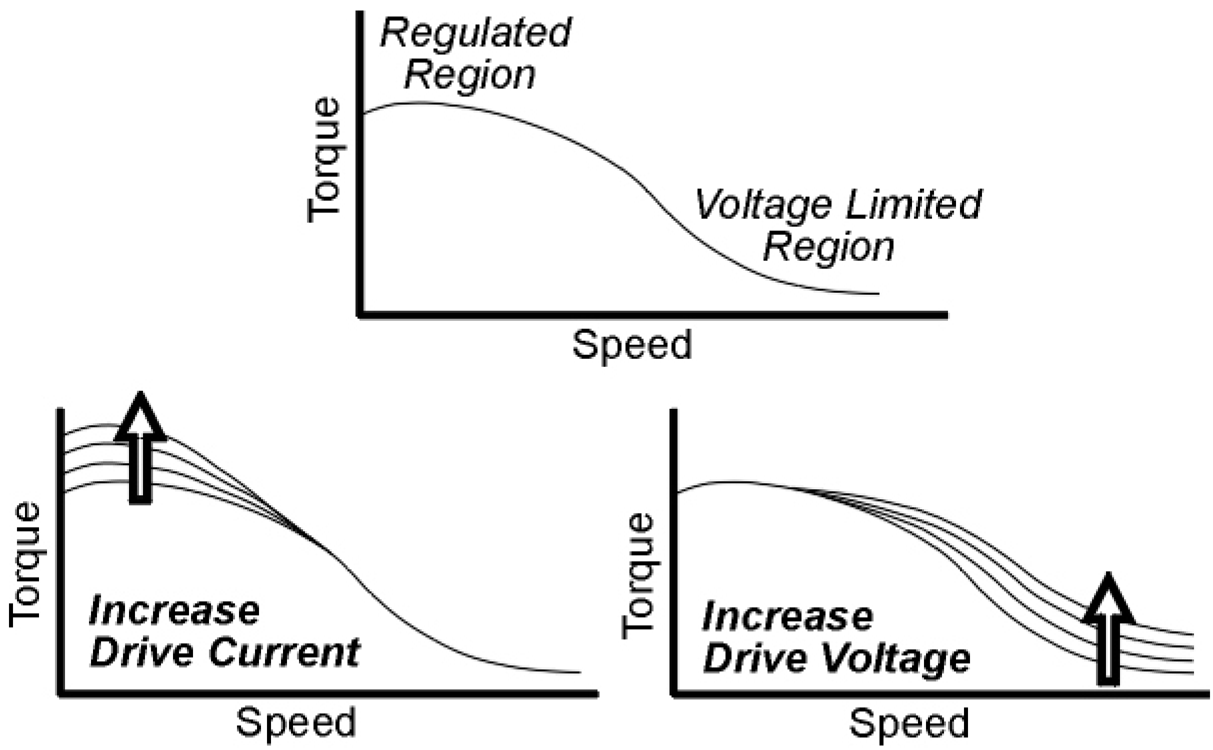


Fig 3.6 Effect of Current and Voltage on Performance

At low speeds the current has plenty of time to reach the required level and so the average current in the motor is very close to the regulated value from the drive. Changing the current setting on the drive, or changing to a drive with a different current rating, will change the available torque accordingly. This region of the curve is called the current regulated region. As speed is increased, the time taken for the current to rise becomes a significant proportion of the interval between step pulses. This has the effect of reducing the average current level, so the torque starts to fall off. As speed is increased further, the interval between step pulses does not allow the current time to reach a level where the chopping action can begin. Under these conditions the final value of current depends only on the supply voltage; if the voltage is increased, the current will increase more rapidly and hence, will achieve a higher value in the available time. So this region of the curve is described as voltage limited, and a change in the drive current setting would have no effect. We can therefore summarise by saying that at low speeds the torque depends on the drive current setting, whereas at high speeds it depends on the drive supply voltage.

STANDBY INPUT

When a stepper motor is at rest, the drive will still send currrent through the motor windings to keep the shaft locked in position. However, in the stationary mode, the current required is much less than when rotating. Most drives have a standby circuit built in to automatically reduce the motor current when not rotating. This reduces motor heating, keeps the drive cooler and conserves power.

ENERGISE INPUT

If it is necessary to rotate the motor manually, for example to change the position of a machine tool, most drives have an energise input. Switching this input will turn off the current through the windings allowing you to manually rotate the shaft. Care must be taken not to rotate the shaft too fast otherwise the motor will generate a voltage that could damage the drive.

NOISE

Recirculating chopper drives are very efficient in converting electrical power into mechanical shaft power. Because high currents are switched at high frequency, electrical noise can be emitted from the motor, cables and drive. Harmonics well into the MHz region can be produced. This is not normally a problem in industrial applications, but in situations where sensitive electrical measurements are made (eg. nucleonic sensors, strain guages, thermocouples and ultrasonic testing) electrical noise should be considered.

DRIVE CONNECTIONS

Contact Automated Motion Systems for unusual or non standard stepping motors. Stepping motors are sometimes manufactured with encoders, resolvers and electric brakes fitted to the rear shaft and these may have different wiring. Smaller motors are usually supplied with flying leads while larger motors of size 42 and greater usually have terminal boxes. Manufacturers occasionally change wire colors and windings so check with manufacturer if in doubt.

If the motor does not rotate in the required direction, this can be remedied by interchanging the connections on one phase. (eg. to change direction of a stepper motor on an RTA drive, reverse the A and A\ connections. If you reverse both the A & A\ and B & B\ connections, the direction of rotation will remain unchanged.

When linking cables for series connection, ensure join is soldered securely and insulated from other cables and earth. On some motors there may be surplass cables and these must also be insulated.

4 MOTOR INSTALLATION

MOTOR INSTALLATION

Mounting

Many people think that the pilot register (circular flange) in Fig 4.1 on the front of the flange of a motor is a nuisance because you need to put washers between the motor flange and the plate to stop the flange from bending.

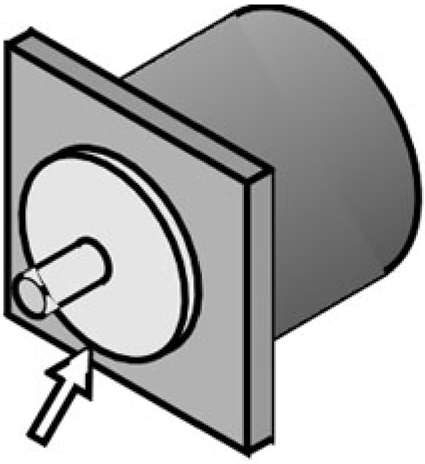


Fig 4.1 Motor Pilot Register

The pilot register has been provided by the manufacturer to locate the motor concentrically with the shaft. This is very important when the motor is attached to a gearbox or XY table. The register is intended to fit a mating recess on the mounting plate. This pilot register is machined to a tight tolerance, usually +/-0.05mm. When you specify a mating recess make the lower tolerance of the recess the same as the upper tolerance of the pilot register. This gives the best location whilst guaranteeing the motor will always fit. The depth of the recess must always be greater than the thickness of the pilot register so the register does not bottom in the recess. If you must mount the motor to a flat plate and concentricity is not important, the best way is to use a machined spacer that accommodates the pilot. In this case the tolerance of the recess is not important.

Shaft Loading

The bearings in a stepper must be precision bearings to enable closest possible tolerance between rotor and stator for maximum magnetic flux. It is bearing loads that usually determine motor life and these bearings will have very short life if high radial and axial loads are applied. A stepper motor is fitted with small spring washers which apply some axial load at all times to take up clearance between balls and races to prevent rattling which would cause wear. Motor manufacturers vary, but typical continuous maximum shaft loading values are as follows. These loadings are based on bearing life, although fatigue of the motor shaft must also be taken into consideration.

Frame Size	Axial Load	Radial Load
23	50N	90N
34	130N	200N
42	140N	300N
65	480N	640N

Note: Check with manufacturer's data as motors bearing capacities can vary.

Couplings

When coupling a motor to a load such as a screw or gearbox, care must be taken to ensure there is no parallel or angular misalignment between the two shafts. If any misalignment does exist it will cause high radial bearing load, limiting the life of the motor. No matter how hard you try there is always likely to be some misalignment as in Fig 4.2 and a flexible coupling is recommended.

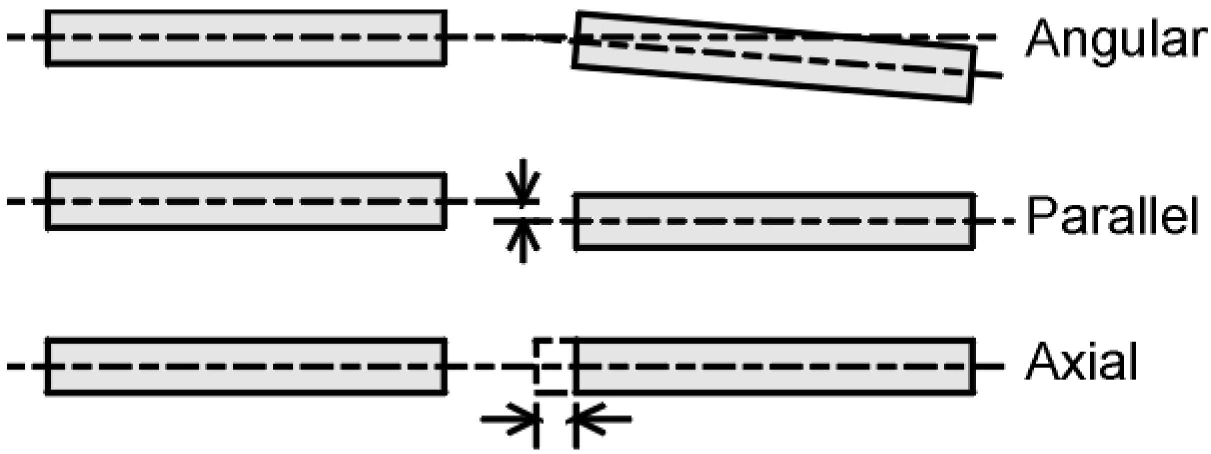


Fig 4.2 Alignment Errors

When choosing a coupling it is important to check the torque capacity and torsional stiffness. Ensure it can compensate for all types of misalignment without causing any backlash (lost motion when changing direction of rotation). A coupling such as the PANAMECH range is zero backlash and can compensate for all types of misalignment while matching different shaft diameters.

Most couplings are attached to a shaft by a setscrew or clamp type fixing as in Fig. 4.3. Setscrew fitting is usually limited to low torque and higher torques will require clamp type fixing. Motors of 42 frame size and higher will require keyways which are already machined into the motor shaft.

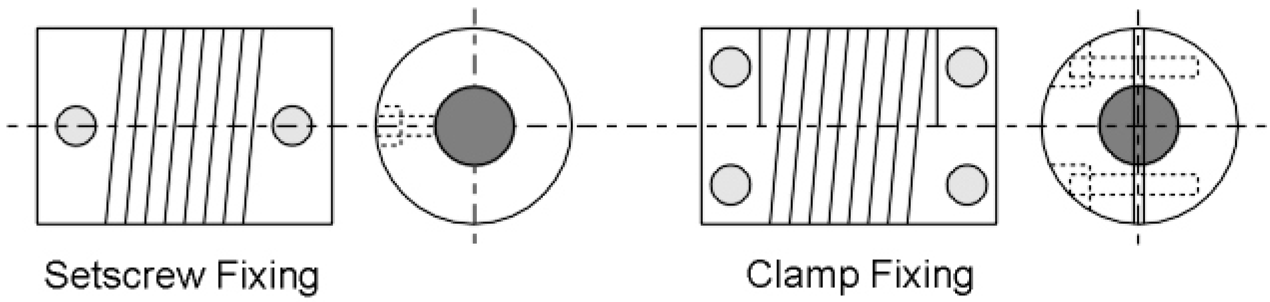


Fig 4.3 Coupling Fixing

Timing Belts

Timing belts or toothed belts are an economical way of reducing speed and increasing torque from a stepper motor. They also have some elasticity which is good for reducing vibration and audible noise.

Belts should be tight to avoid backlash or belt slipping however, applying too much tension will load the motor bearings and reduce the life of the motor as in Fig 4.4. To estimate correct belt tension use the following method.

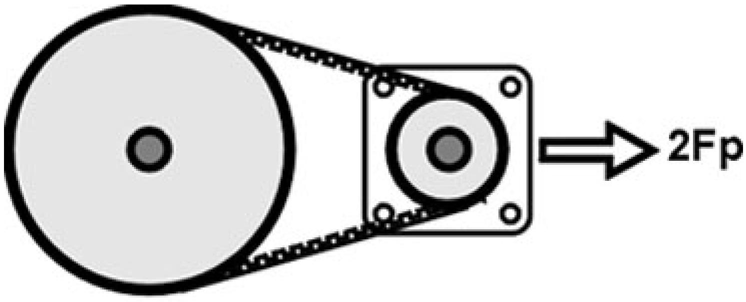


Fig 4.4 Belt Tensioning

Calculate the radial force on the driving pulley when maximum torque occurs.
This can be derived by dividing torque by the pulley radius. (force = Fp)

A static belt tension of between 30% and 50% of this force is used for short and stiff belts, whereas higher belt tensions of 50% to 65% are used for long elastic belts.

Check that belt tension does not cause excessive radial bearing loads.
(Radial bearing load = 2 X Fp)

Shaft tolerances

When fitting couplings and pulleys to motor shafts, ideally the upper tolerance of the shaft will equal the lower tolerance of the pulley bore so there will always be some small clearance between the two. If you are unlucky enough to have a fit that is too tight, do not force on the coupling with hammer blows. This will generate axial (and possibly radial) forces that are likely to damage the bearings of the motor. It will also make it very difficult to remove the pulley or coupling at a later date, requiring even greater forces.

If you have a tight fit you can either rebore the pulley or if the fit is very close, run the motor while holding some carborundum paper around the shaft. Push a ring of cardboard around the shaft first to prevent particles from falling into the bearing. Keep checking the shaft for size to make sure you don't take too much off.

Environmental Rating

In some cases care must be taken to prevent the stepper motor from damage from water or dust particles. Because the rotor and stator are constructed from iron, water ingress will cause internal rusting and the motor will fail very quickly. This is common in the food industry where washdowns are frequent. Similarly, small abrasive particles (eg. from a grinding operation) will get between the close tolerances between rotor and stator and cause wear. Most stepper motors are rated IP22 however, the environmental rating of your motor must be checked. Motors are available with upto IP65 rating, but the cost is considerably higher.

1st No.	Protection against solids	2nd No.	Prorection against liquids
0	No protection	0	No protection
1	Objects over 50mm *(eg. accidental touch by hand)*	1	Vertically falling water drops or condensation
2	Objects over 12mm *(eg. fingers)*	2	Direct sprays of water upto 15 degrees from vertical
3	Objects over 2.5mm *(eg. tools & wires)*	3	Direct sprays of water upto 60 degrees from vertical
4	Objects over 1mm *(eg. small wires & tools)*	4	Water sprayed from all directions *(limited ingress permitted)*
5	Dust *(limited ingress permitted)*	5	Low pressure water jets from all directions *(limited ingress permitted)*
6	Total protection against dust	6	Strong jets of water *(limited ingress permitted)*
		7	Immersion between 15cm & 1m
		8	Long periods of immersion under pressure

Fig. 4.5 IP Protection Table

General Handling

The shaft of a stepper motor is usually soft stainless steel because it has to be non magnetic to avoid a magnetic short circuit down the centre of the permanent magnet rotor. The shaft is not difficult to bend so dropping the motor on its shaft will bend the shaft. NEVER DROP A MOTOR OR HAMMER THE SHAFT!

Stepper motors are magnetised after assembly and dismantling the motor at a later date results in the permanent magnet being confronted with a high reluctance flux path, reducing the strength of the magnetic field. Once dismantled and reassembled, torque is reduced at least 50%. Also, there are very close mechanical tolerances between the rotor and stator and damage may occur on disassembly. NEVER DISASSEMBLE A STEPPER MOTOR!

Short shaft

Sometimes it is necessary to shorten the length of a stepper motor shaft, although good design should not let this happen. If amputation is unavoidable, it is essential that the shaft is secured in such a way that the motor experiences no shock or bearing loads.

There must be no coolant or swarf allowed to enter the motor bearing and the shaft must not get too hot (over 85°C) or permanent demagnetisation may occur. Adhesive tape or Blu-tak are good ways of sealing the shaft. The motor must be held by the shaft while the body of the motor must be allowed to float on a rubber block as in Fig. 4.6. The same would apply if you needed to machine a flat on a shaft.

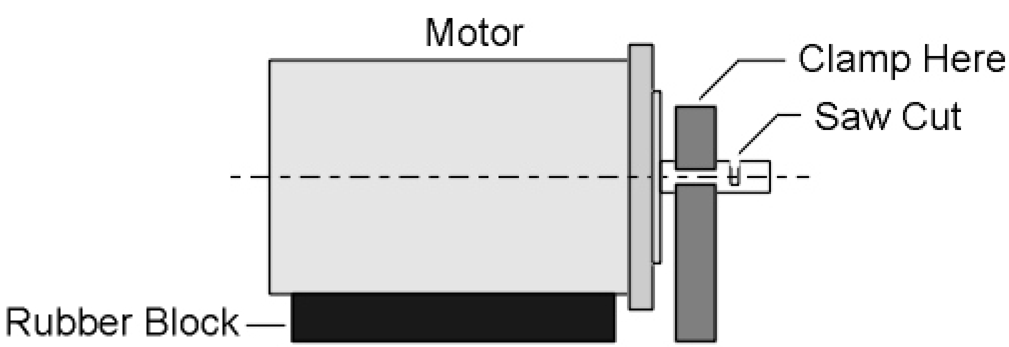


Fig 4.6 Shortening Motor Shaft

Heat

Motors should always be mounted by the flange to evenly distribute the torque around the casing. Another reason, is to allow heat generated by the motor to flow through the flange to a large mass acting as a heatsink. Stepper motors will get hot, particularly when operating at high speeds and duty cycle. Case temperatures of upto $85^{O}C$ are not uncommon. In applications where motor heating is likely to occur, allow air to circulate around it and discourage operators from touching the motor.

STEPPER DRIVE INSTALLATION

Earthing

The following recommendations apply particularly to rack mounting systems, however the same general principles apply when using self contained drive units. A motor and drive will operate without these precautions, however insufficient earthing may cause problems with other equipment in the system.

It is advisable to use a central earth stud mounted on the rack end plate or close to it. Mains earth, the transformer screen and rack 0V bus and the enclosure metalwork should all be connected to this stud. In particular, the connection to the rack 0V bus should use $1mm^2$ cable and should be kept as short as possible.

Input and output signal connections longer than about 500mm should use wires that are individually or collectively screened. Step and direction signal cables should also be screened as they convey signals of around 5 or 12 V and induced spikes could be interpreted by the drive as steps.

It is better to route signal conductors separately from power and motor connections. If the motor leads run in the same trunking as signal leads, then either the motor leads or the signal leads should be screened. Connect the screen to the earth stud at one end and insulate it at the remote end.

Avoid using the same cable trunking for signal or motor leads and power switching lines, particularly those driving unsuppressed inductive loads. Motor leads should be screened if they run close to such lines.

Many stepper motors are supplied with short flying leads or a terminal box. If the distance between motor and drive is within 3 metres then the only concern is that the cable can carry the current without overheating and screening is not necessary. However, when the distance is greater than 3 metres, it is better to use screened cable. Connect the cable screen to earth at the drive end or as close to the drive as possible such as on a 0V busbar. If the motor has short flying leads connect the leads to the screened cable using a terminal box.

The motor should be mounted onto a machine which is also earthed. If the motor is mounted onto a non metallic surface the motor body should be earthed by a separate cable. This is not only for safety, but also to prevent high frequency current flowing through the motor windings to the body by capacitance.

Motor Cable Sizes

The main consideration in sizing cables for power and motor is the current carrying capacity. For short motor leads, (less than 30 metres) use the following cable sizes. Use a cable of equal or greater rating than the drive current. Note that the current ratings shown relate to single cables in free air. If your cables are going to be in a loom, divide the current rating figures by 2.

Metric Area mm^2	Resistance Ω/metre	Nearest A.W.G.	Current Rating Amps
0.2	0.0850	24	3
0.5	0.0340	20	7
0.75	0.0220	18	9
1.0	0.0170	16	12
1.5	0.0110	16	16
2.5	0.0068	14	25
4.0	0.0044	12	40

Long Motor Cables

Stepper motors with bipolar chopper drives can accommodate cable lengths of up to 30 metres without a problem. Often it is necessary to use longer length cables and the manufacturer's manual may provide some recommendations. Cable size is not important for RL drives (as long as it can withstand the current), but for long cables on chopper drives this can be significant when the cable inductance and resistance approaches the motor inductance and resistance. It is suggested that the manufacturer of the drive is consulted, as the effects of cable inductance and resistance depend on the drive circuit.

Cooling

Many drives designed for larger motors have heatsinks to dissipate heat from the switching transistors. When installing the drive the cooling requirements must be checked with the drive manual. Often in a factory application it is necessary to supply a clean filtered airflow to the drive. The air volume will depend on the drive current, drive voltage and duty cycle of the motor. A stepping motor spending much of its time on standby (not rotating but energised) will draw half the set drive current and not have as much cooling
requirement as a motor running continuously.

5 MECHANICAL DESIGN

DRIVE METHODS

When designing the mechanical aspects of the machine the main problem is to decide how the motor is to drive the load. In an XY system for example the X and Y stepper motors convert the rotary motion into linear motion to control position on a cartesian co-ordinate system. In a cut to length application the motor would normally drive a set of rollers. Nearly all applications use one or a combination of these three types of drive.

Leadscrew

This method converts rotary motion of the motor into linear motion with motion being in the same axis to the motor shaft. Efficiency, load capability and resolution are high. Screws can use conventional thread or recirculating ball bearings, preloaded to eliminate backlash. See Fig. 5.1 and Reduction Section for more information.

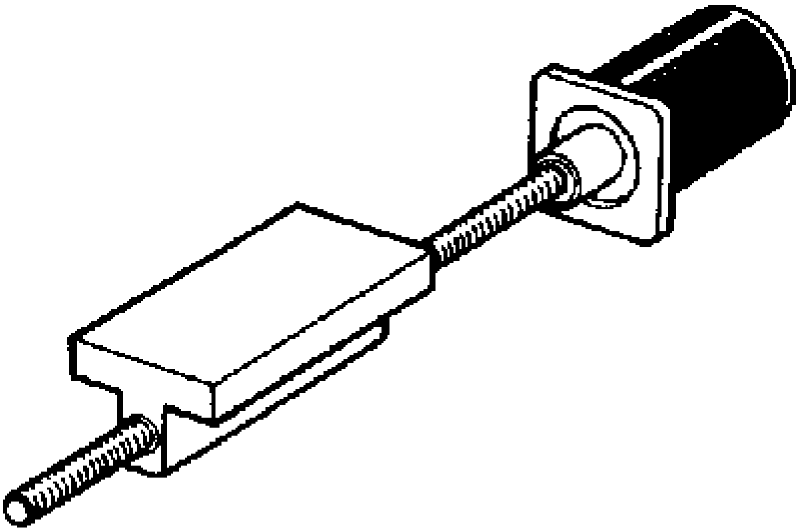


Fig. 5.1 Leadscrew Drive

Tangential Drive

This method is used to convert rotary motion into linear motion by belts, chains or rollers with the motion being perpendicular to the motor axis. This is the drive most commonly used with XY tables and roller feeds. Because there is a p (Pi) factor when using this method, the scaling factor (steps/mm) may be an irrational number and this must be taken into consideration when choosing a controller .

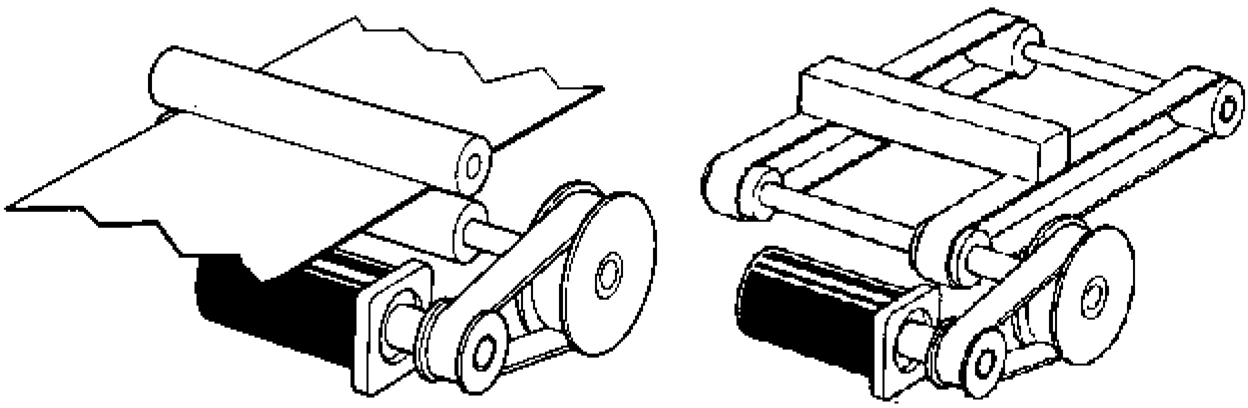


Fig 5.2 Tangential Drives

Direct Drive (sometimes called Gear Drive)

This method is used where rotary motion is the objective rather than linear motion as in Fig. 5.3. Reduction is achieved by one or more stages of gears, whether worm gears or spur gears. Direct drive methods are only used for rotary motion. If inertia and forces are low it may be possible to mount the load directly onto the motor, but normally it is necessary to use some gearing.

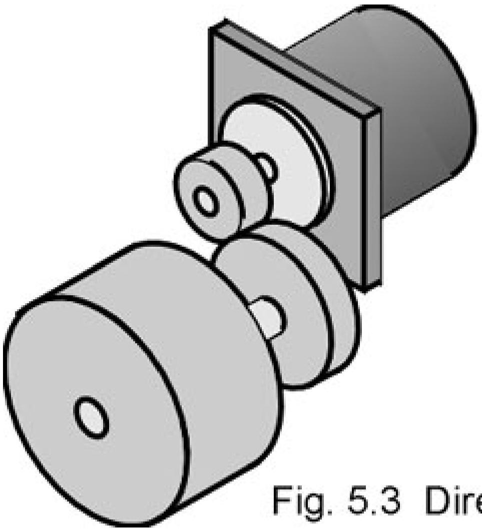


Fig. 5.3 Direct Drive

REDUCTION METHODS

A motor will rarely have sufficient torque to perform the required motion so various methods of reduction must be used. The main purposes of the reduction are as follows.

It reduces the inertia of the load for a better inertia match between the motor and load. The reflected inertia is reduced by the square of the reduction ratio.

It allows the motor to operate at a higher speed, where motion is smoother.

It amplifies the motor torque so a smaller motor can be used. Torque gain is directly proportional to the reduction ratio.

It allows the main operating speeds to be well clear of the resonance region on the torque/speed curve, so performance at low speeds is smoother.

It makes the effective resolution (mm/step) of the system smaller.
It can convert rotary motion of the motor into linear motion.

It can generate a meaningful system scaling factor (eg. 1step = 0.001mm)

Rack & Pinion (Fig. 5.4)

The rack and pinion method converts rotary into linear motion and can be useful where long travels are involved. As there is no elasticity or slippage, it is ideal for high loads. Usually the motor and pinion are carried on a moving carriage although it is also possible to keep the motor and pinion stationary and drive the rack. It avoids the problem of a long unsupported leadscrew which can bend with gravity or long belts which can stretch. The main problems with the rack and pinion drive is the low effective gear ratio which may mean that it is necessary to use an extra gearbox to obtain a reasonable resolution. If the rack is stationary and the pinion moves, then the motor also moves dragging electrical cables with it and this may cause problems.

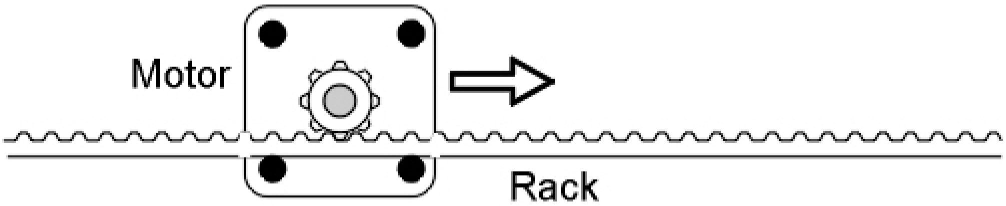


Fig. 5.4 Rack & Pinion

Toothed Belts (Fig 5.5)

Toothed belts and timing pulleys are probably the most economical method of speed reduction and rotary to linear motion conversion. Many belts are available 'by the metre' and good accuracies can be obtained over long distances, however, wide moving platforms may require driving from two pulleys on a common shaft to avoid counterlevering. In very long linear systems, belts may suffer from elasticity causing position errors, although many belts are now reinforced with steel cables. Tension adjustment mechanisms must be incorporated to ensure the tension is not too slack to cause backlash and not too high to cause stretching of the belts or damage to motor bearings. Reduction ratios of around 6:1 can be achieved in a single stage and for larger ratios it may be necessary to have multiple stages. High reduction ratios can take up a lot of space due to the large diameter of the driven pulley. Toothed belts also have the bonus of providing some elasticity which helps reduce shock and resonance.

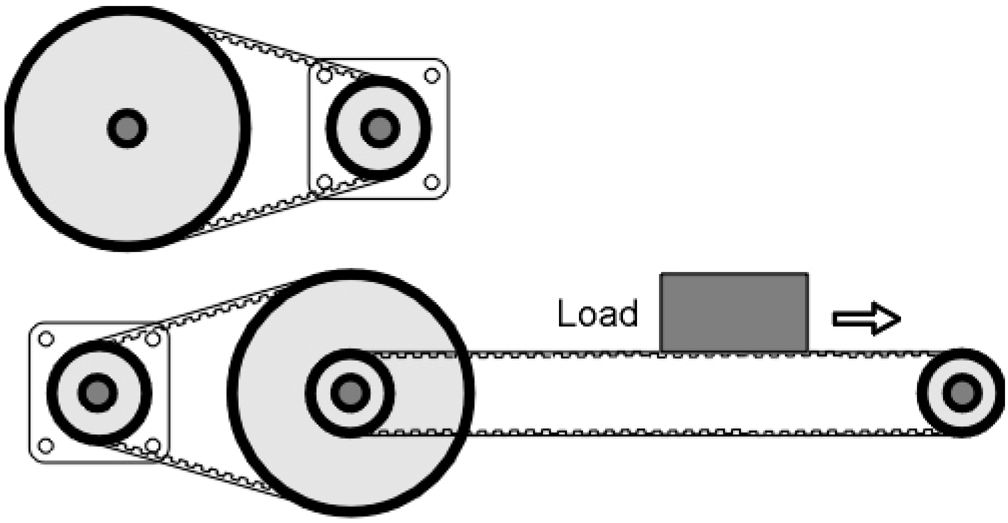


Fig 5.5 Toothed Belts

Chain & Sprocket

Chain and sprocket reduction works the same way as toothed belts although transmitted torque can be higher. Backlash is usually higher in chain systems and because the chain is rigid there is no resiliance to dampen vibration.

Leadscrews (Fig 5.6)

High accuracy linear motion applications always use screw drives. The mechanical advantage is much higher than gear drives and resolution and accuracy is usually greater. Typical screw types are the 'V' thread for smaller sizes and square thread for large loads. Efficiency is low for these and speed is not as high as with toothed belts and rack and pinion drives. The ultimate in screw drives is the recirculating ballscrew which is available in a number of pitches, however the price can be high. Efficiency can be as high as 95%, accuracy is very high and backlash can be eliminated by pretightening the ballnuts. Because efficiency is so high, unlike conventional screws, there is a risk of the load backdriving the screw. This is a problem where a vertical axis is working against gravity.

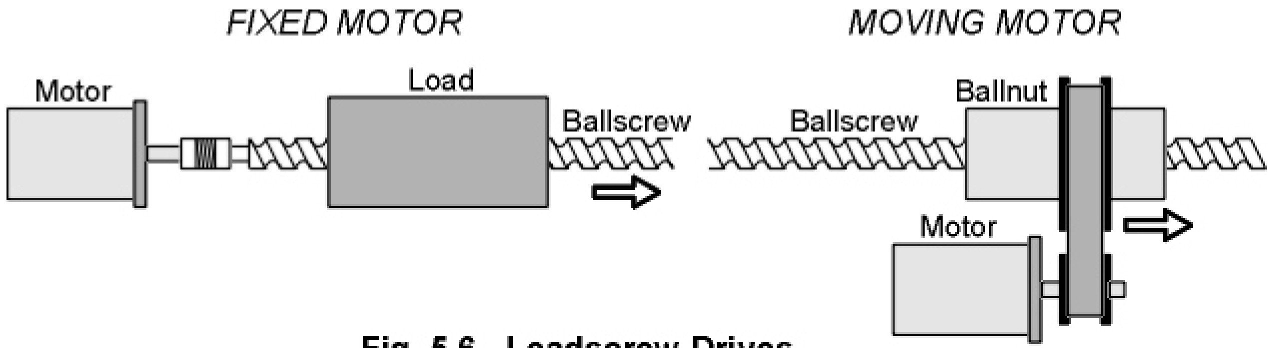


Fig. 5.6 Leadscrew Drives

There are two configurations for leadscrews. The most common is to rotate the screw and the nut drives the load backwards and forwards. Problems can occur when the screw is very long creating a very high inertia for the motor. Also, if the very long shaft is rotated at high speeds it may whip. The second method eliminates these problems by keeping the screw fixed at each end and rotating the nut with a motor.

Cable

On low cost machines a taught steel multistrand cable can be used in place of toothed belts. This cuts down the price of pulleys and belts, particularly on long runs. Care must be taken to ensure slippage does not occur as there are no synchronising teeth and the high tension forces may put large forces on bearings.

Gears & Gearboxes

Gearboxes and geartrains can provide excellent reduction ratios and generate very high torques. One problem to look for is high backlash that can occur with general purpose industrial gearboxes. Some gearboxes will mount directly onto the stepper motor flange and have low backlash down to 30 arcminutes, however the cost is significantly higher.

Worm Drive

This is a variation of a screw drive and is often used to drive rotating tables. It offers high reduction ratio but the efficiency can be very low at about 35%.

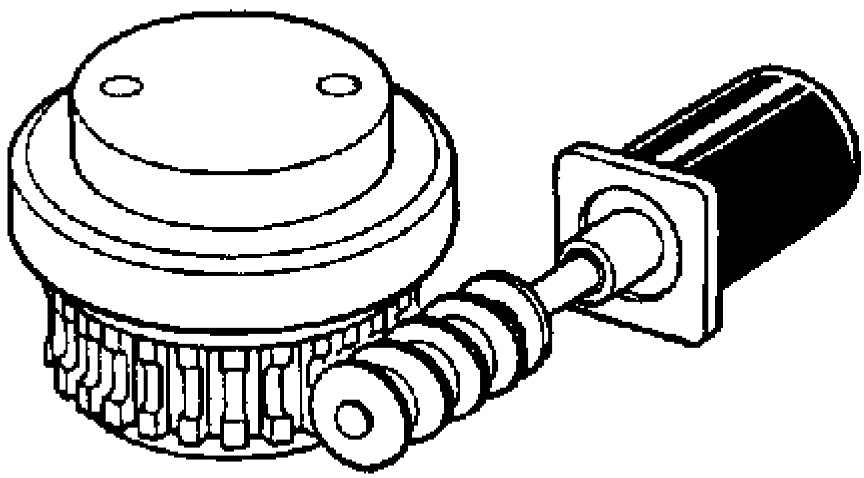


Fig. 5.7 Worm Drive

RESONANCE IN STEPPER MOTORS

When the shaft of a stepper motor is stationary, the rotor is held in position by the interaction of two magnetic fields. The two fields are produced by the permanent magnet in the rotor and the current flowing in the stator windings. When the rotor is deflected from its static position, the restoring force increases with deflection in the same way as in a mechanical spring. The rotor may therefore be thought of as a mass located by a "magnetic spring". When the rotor is stepped to a new position, this magnetic spring will act on the mass of the rotor to relocate it in its new position. As in any spring located system, there will be an oscillation about the new position before the rotor finally comes to rest. The amplitude, frequency and decay rate of the oscillation all depend on the motor torque, the inertia of the load and on the degree of damping in the system.

Resonance may occur when the stepping rate is at or close to the natural frequency of the motor and load. This results in an exaggerated response to each step, and if the overshoot increases to approximately two full steps there is a risk that the motor will desynchronise. Should this happen, the motor may miss steps or generally behave in an unpredictable way. The natural frequency of an unloaded motor is typically in the 70-100 full step/second range, although larger motors have lower resonant frequencies than smaller ones.

MINIMISING RESONANCE

If desynchronisaton occurs, it usually implies that the motor is producing more torque than the load requires and this is resulting in excessive overshoot. So the cure for resonance amounts to reducing the amplitude of the overshoot, and there are various methods of tackling this.

Use smaller steps

Overshoot is primarily a function of step size, so half stepping or quarter stepping will produce less overshoot than full stepping. The half step or quarter step modes are therefore preferable to full step in almost all situations. Similarly, ministepping and microstepping will improve the situation further, but in view of the additional cost and the problem of producing a high frequency pulse train, this should only be regarded as a last resort.

Use less torque

Reducing the current from the drive is frequently an effective cure for resonance. Most drives have current selectable by dip switches. Obviously it cannot be reduced too far or there will be insufficient torque at low speeds, but bear in mind that high speed torque is unaffected by the drive current setting. Reducing the current simply "flattens out" the torque curve.

Use parallel connection rather than series

This produces a similar effect to reducing the current, in other words it results in a flatter torque curve. The series mode should only be used where the load requires high torque at low speeds, and in this situation there is unlikely to be a resonance problem.

Add some damping

Perhaps the most obvious method of adding damping is to introduce some friction into the system, but in practice this is not very satisfactory. Unless the friction can be maintained reasonably constant it may fail to be effective, and of course it will reduce the torque throughout the whole speed range. Proprietary inertial friction dampers are available and these can be useful on small motors.

Most modern drives have built in electronic damping. Enabling this option slightly reduces torque but can make a big difference to resonance.

Reduce the drive supply voltage

This may be worth trying if the motor is not required to run at high speeds. The overshoot amplitude is related to the rate of rise of motor current, which in turn depends on the supply voltage. A lower voltage will give a "softer" characteristic.

Don't run at the resonant speed

This may seem an unreasonable suggestion, but it may be possible to avoid running the motor at the resonant speed by introducing a mechanical ratio into the system (e.g. toothed belt). Similarly, resonance in a point-to-point positioning system can result from starting and stopping at too low a speed.

When the motor is driving a large inertia, one effect on this is to reduce the start-stop speed range. However, the inertia must be very large before this range falls below the fundamental resonance. Introducing a ratio may also be a solution in this case. If the motor has to be started at a very low speed, it should be accelerated through the resonance region as quickly as possible.

Check your mechanics

It is also worth mentioning that resonance can also be a result of lost motion in the mechanics. Backlash in spur gears or sloppy couplings must be avoided, together with flexible couplings having excessive compliance.

Check your inertia

Resonance is more likely when the load inertia/motor inertia is too high. Ideally, inertia ratios of more than about 5 will cause problems. By adding some reduction the inertia is reduced by square of the reduction ratio. If inertia ratio in your system is very low (less than 1:1), adding some inertia may help reduce resonance.

FRICTION

Friction is a common problem in all stepper motor systems. Since stepper motors are usually used in open loop, (no position feedback) the machine must be designed for low or predictable friction.

Where possible, use bronze or ball bearings for shafts and linear slides where linear motion is required. Ballscrews are an excellent low friction drive, but can be expensive and will clog with dirt unless protected. Unless precautions are taken, friction forces can be surprisingly high. Friction is usually underestimated, so do not assume it is negligible or even constant as it may change with wear, temperature and lubrication.

In linear motion systems it is important to use linear bearings to ensure as much motor power as possible is converted into motion. Many types of linear bearings are available and most use recirculating ball bearings or rollers on precision hardened steel rods. Some common types are shown in Fig. 5.8

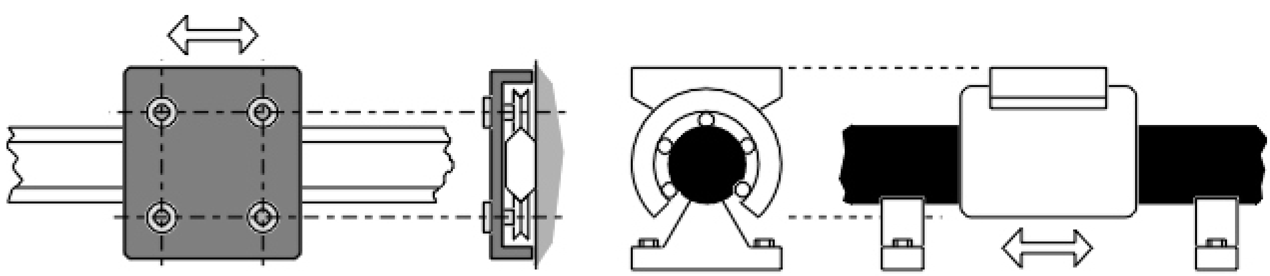


Fig. 5.8 Linear Bearings

START STOP SPEED

The maximum start-stop speed depends on the total inertia of the motor and load and is inversely proportional to the square root of the total inertia. This means that the unloaded start-stop speed is halved when the external load is three times the rotor inertia. Ensure that the speeds you intend to start and stop fall within the motor manufacturer's specifications.

MOTION PROFILE

We have seen that it is efficient to ramp stepper motors by applying some acceleration and deceleration. The acceleration rates and velocity depend on the motor, load, inertia and displacement. In nearly all cases there is a tradeoff between torque and velocity. Motor torque drops off with velocity and more gearing produces more torque but the motor is required to run faster. Common motion profiles are shown in Fig. 5.9

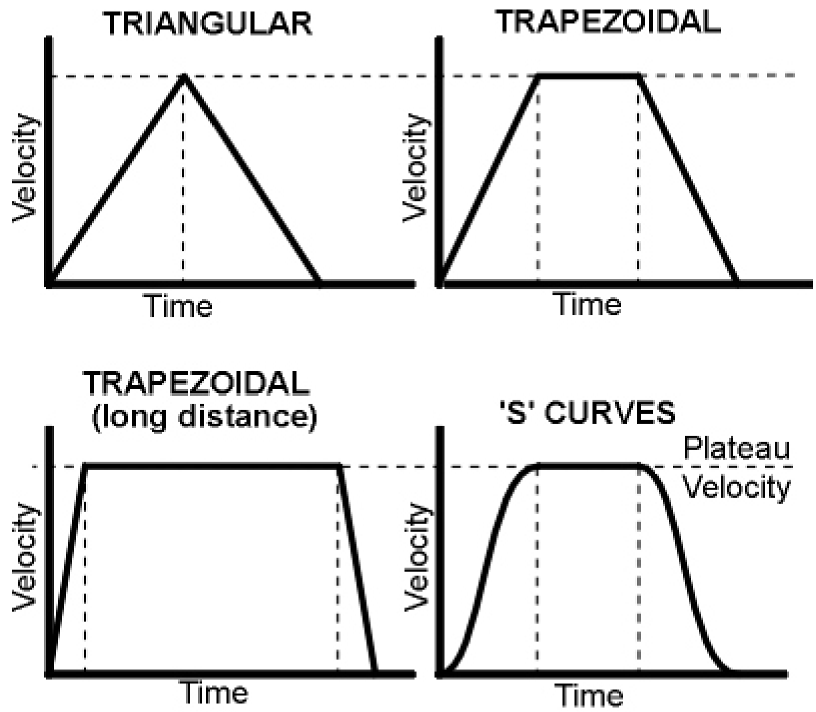


Fig 5.9 Motion Profiles

Triangular

This is used for short moves where the distance is insufficient to allow the motor to reach high velocity. For a given motor torque this profile gives the minimum move time.

Trapezoid

This profile is better for long distances where the velocity obtained in a triangular profile would be too high for the motor. It is usual for each section to occupy one third of the total move time. For the same overall distance and time it can be shown that the torque is 12.5% greater but the velocity is 25% lower than in the triangular profile. The peak shaft power requirement is reduced by 16% so it makes better use of the available torque from the motor.

Long Distance Trapezoid

In very long moves it is sometimes better to use a more powerful motor and get up to high speed as quickly as possible to increase production. This variation of the trapezoid also is useful in profiling machines such as flame cutters and lasers where the motor must run at required speed with a minimum of ramping without slowing down and burning holes in the workpiece.

'S' Curve

This variation can be applied to triangular and trapezoidal profiles. A parabolic or exponential non linear acceleration is used to limit the jerk (rate of change of acceleration) to avoid shock and damage to delicate machinery. Because the stepper motor controller must be more complex to achieve this profile, it is more commonly used with computer based controllers.

LIMIT & DATUM SWITCHES

When using linear drive systems, it is nearly always necessary to use limit and datum switches which are connected to the motion controller. Limit switches are placed at the ends of the axis and prevent overtravel that may cause mechanical damage or injury. A limit- switch prevents overtravel in the negative direction and a limit+ switch prevents overtravel in the other direction. These switches are usually normally closed for failsafe operation. When the load hits a limit switch, the motor will stop immediately and motion will then only be permitted in the opposite direction. There are numerous switches on the market that will suit many applications. When using a rotary axis which allows 360 degree motion, limit switches are normally unnecessary.

A datum switch is normally placed near the limit- switch but between the two limit switches. This switch is used to define the datum or zero position. Most motion controllers have a datum function on startup that runs a motor in the negative direction until the load hits the datum switch. The motor will then decelerate to rest, overshooting the datum switch as sbhoen in Fig. 5.10. The motor can then creep back in the reverse direction at slow speed until the switch is hit again, accurately reaching the exact position where the switch changes state.

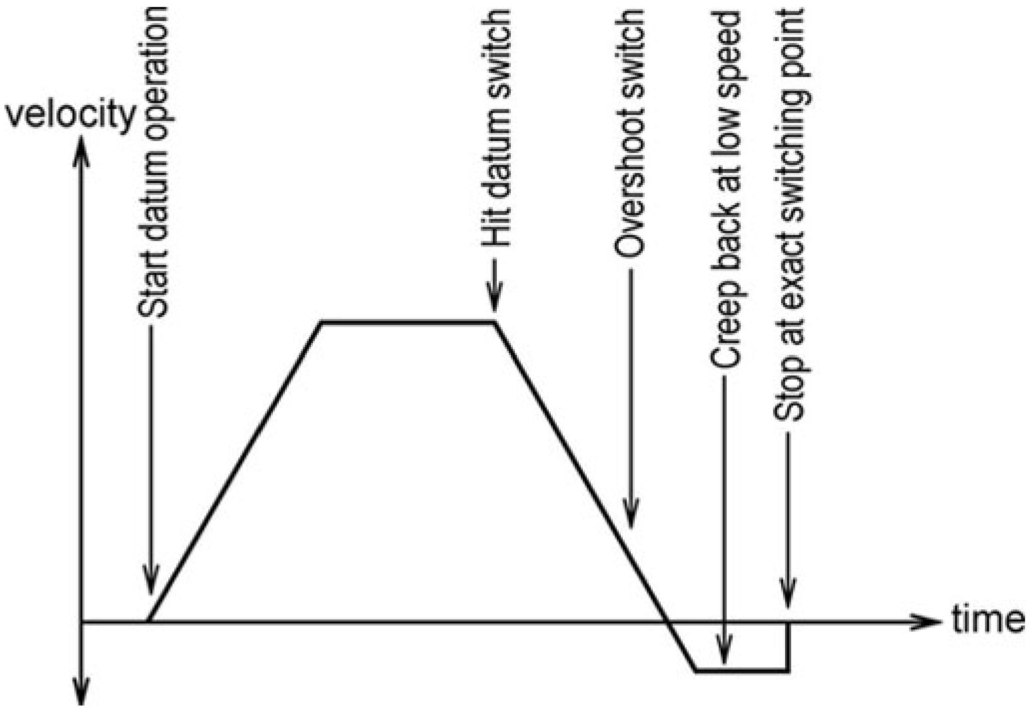


Fig. 5.10 Datum Procedure

When fitting switches to a machine, it is suggested to allow overshoot and position the datum switch a safe distance from the limit- switch to prevent a limit switch from being hit during a datuming procedure . This is usually achieved using a mechanical ramp.

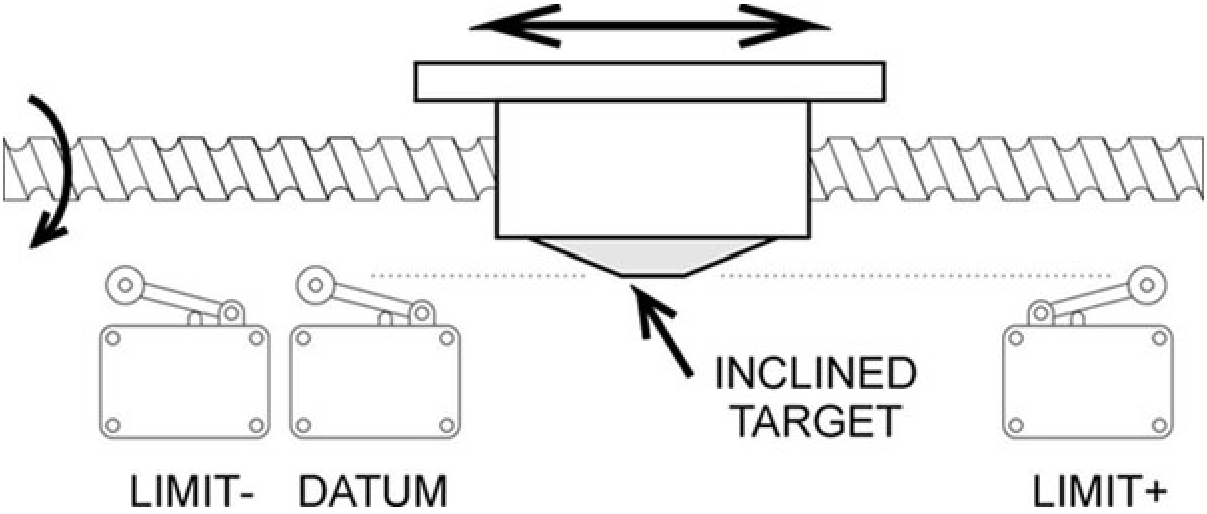


Fig. 5.11 Limit Swithch Ramps

6 GLOSSARY

Absolute Positioning
Refers to a motion control system that uses position feedback devices to check and maintain position.

Acceleration
The change in velocity with respect to time. When velocity is increasing the load is accelerating and when velocity is decreasing the load is decelerating.

Bipolar Drive
A drive in which the current passes through the motor windings in both directions.

Chopper drive
A constant current type drive in which the form of excitation is an initial high voltage applied to the phase winding until the current in that winding reaches a predetermined value and then the supply is switched off. When the current has decayed to a second predetermined value, the voltage is then reapplied.

Clock card
A clock circuit produces pulses at a set frequency when a switch is closed. These pulses can be fed into a stepper motor drive to make a motor run under manual control for positioning or variable speed control. Two types are commonly used, being the ramped clock and the buffered clock.

Ramped clocks start generating pulses when a switch is closed and have built in ramping circuitry to gradually increase the frequency of pulses, thereby allowing for high inertia loads.

Buffered clocks accept a burst of pulses at constant frequency from a controller and applies ramping at the beginning and end of the pulse train to allow the motor to accelerate and decelerate without stalling.

Closed Loop
Closed loop positioning systems have feedback devices to measure the actual position of a system , compare it to the desired position set by the input signal input and then adjust the output accordingly to achieve the correct position. Even if the system position is changed by external forces it will have the ability to correct itself.

Constant current drive
A drive circuit that attempts to maintain a constant current in the windings irrespective of motor speed.

Contouring
Running two or more motors simultaneously at mathematically controlled velocity and displacement with respect to time to produce curves. (eg. drawing curves on a XY plotter)

Damping
Mathematically damping is indicated by the rate of decay of a signal to its steady state value. Damping can be built into a motion control system by adding a small amount of viscous friction.

Detent torque
The torque that is applied to the shaft of a non-energized motor to cause motion. Detent torque is caused by bearing friction and residual magnetic attraction between poles on the rotor and stator.

Direction Bit
Signal fed into a drive to reverse direction of a motor.

Drive circuit
A combination of a logic translator and a power amplifier which switches the phases of a stepping motor in a pre-established mode.

Duty Cycle
For a repetitive cycle duty cycle is the ratio of on time to total cycle time. If a motor is running continuously then the duty cycle is 100%.

Encoder
A device that can be fitted to a motor or machine to measure angular rotation, direction and velocity.

ESTOP (Emergency Stop)
A large red mushroom switch conveniently placed on a machine for the operator to stop all motion in the event of an emergency, thereby avoiding machine damage or injury to operators.

Friction
Resistance to motion. Friction forces act opposite to the direction of motion, tending to slow down a component. Friction can be viscous, proportional to speed or static, being proportional to perpendicular load. Incremental Positioning Refers to a motion control system that does not use position sensors to check position. In a stepper motor system the position produced is determined only by the number of pulses fed into the drive. If external forces change the position the drive will not know the position is incorrect.

Indexer
Electronic circuit (usually computer controlled) that produces step pulses to control motor shaft displacement, direction, velocity and acceleration for one or more axes. Indexers are sometimes also called controllers. Some indexers can run two axes at once to follow a contour (eg. in an XY system).

Inertia
A measure of a body's resistance to a change in velocity. Inertia is a function of the body's mass and shape. In linear motion systems inertia is basically the mass but in rotary motion the mathematics is more complicated.

Inertia Ratio
Ratio of the load inertia of a system (as seen at the motor shaft) to the motor inertia.

Holding torque
The maximum steady torque at a specified current that can be applied to the stationary shaft of an energized motor without causing rotation.

Home (Datum)
A reference position in a motion control system derived from a mechanical datum switch. Also called the zero or origin position.

Limits
A sensor (switch or optical) used to alert a motion controller that the physical end of travel is about to be reached and motion must stop. Without a limit switch the machine would ram against the end stop causing damage.

Maximum reversing rate
The maximum pulse rate at which the unloaded stepping motor is able to stop and reverse instantly while remaining in synchronism under specified drive conditions.

Maximum slew rate
The maximum frequency at which a motor without load can remain in synchronism under specified drive conditions.

Mechanical damper
A device for damping angular oscillations.

Ministepping & Microstepping
The subdivision of the motor's basic step angle by partial energization of circuit.

Multi level drive
A multi level drive allows sequential application of two or more levels of voltage to the windings.

Open Collector
A signal output that is performed with a transistor. An open collector acts like a switch closure passing DC current.

Open Loop
Control that uses no sensors to check position. The current position is inferred by pulses already sent to the stepper drive.

Overshoot or transient overshoot
The amount the shaft of the stepping rotates beyond the final commanded step position.

Permanent magnet (PM) stepping motor
A stepping motor utilizing a rotor that has permanently magnetized poles.

Phase
The phase consists of one or more windings in a motor, which polarize a given magnetic circuit when energized with current.

P.L.C.
Programmable Logic Controller, a machine that accepts digital input signals, activates relays and digital (and sometimes also analog) outputs according to a logical program stored in its memory. These are very useful in controlling simple devices in machines and some PLCs even have optional step and direction outputs for controlling stepper motors.

Pull in rate
The (constant) maximum pulse rate at which the energized stepping motor will start driving a specified load without missing steps, under specified drive conditions.

Pull in torque
The maximum torque at which an energized stepping motor will start, driving a specified load, and run in synchronisation without losing steps, on application of a fixed pulse rate.

Pull out rate
The (constant) maximum pulse rate at which the energized stepping motor can run, driving a specified load under specified drive conditions, without missing steps.

Pull out torque
The maximum torque that can be applied to the rotating shaft of a stepping motor driven at a given pulse rate under specified drive conditions, without missing steps.

Pulse Rate
Frequency of step pulses fed into a drive. For convenience it is sometimes expressed as full steps/second to make allowances for comparing full/half step, microstepping and ministepping drives.

Pulse Width
The time duration of a single step pulse. It is usually about 10msec for full/half step drives but ministepping and microstepping drives require smaller pulse widths.

R/L drive
A drive in which series resistors are placed in series with the motor windings to enable a higher voltage to be used, improving the torque at high speeds.

Ramping
Acceleration and deceleration that must be applied to a motor when rotating at high speeds to prevent it from desynchronising.

Resolution
Smallest possible increment of motor shaft movement that can be achieved.

Resonance
Condition resulting from running the motor at close to one of its natural frequencies. The motion will become unstable and motor may miss steps.

Resonance rates
A stepping rate at which the stepping motor will miss steps when operating below the pull out torque curve, under specified load and drive conditions.

Response range
This is the frequency range in which the motor can start, stop, reverse rotation without losing steps under specified load and drive conditions.

Settling time
This is the total time between the beginning of the start impulse and the rest of the motor shaft.

Slew range
The range of frequencies in which the motor can continue to rotate without losing steps, under specified load and drive conditions, but in which it cannot stop, restart, or reverse.

Start stop range
The range of frequencies in which the motor can start, stop and restart without losing steps.

Static Torque
The maximum torque available from a stepper at zero speed.

Step
The movement of the rotor from one energized position to the next in sequence.

Step angle (basic)
The angle through which the shaft of an unloaded stepping motor can be made to turn when two adjacent phases are energized, singly in sequence.

Step angle error
The step angle error is the maximum deviation of the motor shaft position from the theoretical position.

Stepping Motor
A reversible brushless DC motor, the rotor of which rotates in discrete angular increments when its stator windings are energized in a programmed order. The rotor has no electrical windings, so there are no brushes or commutator to wear out.

Switching drive
Similar to the chopper drive described above from which it differs slightly, as it has a fixed and much higher frequency of operation.

Torque
Mathematically torque is force times perpendicular distance from a centre point. Torque is best described as a force that produces rotary motion.

Trigger
Inputs on a controller that initiate the next step in a program.

T.T.L
Transistor-Transistor Logic. A common type of electrical signal used on stepper motor drives. In TTL devices there are two defined states. A zero input or logic zero or low is less than 0.8V DC and a logic one or high is 2.5 to 5V DC.

Unipolar drive
A drive in which the current passes through the motor windings in only one direction.

Variable reluctance (VR) stepping motor
A stepping motor utilizing a rotor magnet to polarize salient pole pieces of low residual magnetic material on the rotor.

7 MECHANICAL DATA

STANDARD UNITS

Automated Motion Systems uses m, k, s, and A (metres, kg, seconds & Amps) standard units and their derivative units in the quotation and specification for motion control applications. Other units can be converted using the following factors. The example calculations give guidelines for motor and drive selection only. This is only one aspect of machine design and other factors such as deflection, bearing life, stresses in machine components and vibration should also be checked.

CONVERSION FACTORS

UNIT TYPE	UNIT	CONVERSION
Length	1 m	39.37 inch
Mass	1 kg	0.068522 slug ....2.20462 lb force
Force	1 N	0.22481 lb force
Power	1 kW	1.340 horsepower
Inertia	1 kg.m^2	5.467 x 10^4 oz.in^2 .... 3.417 x 10^3 lb.in^2
Torque	1 N.m	1.416 oz.in .... 0.73756 ft.lb .... 8.8507 in.lb

DENSITIES (kg/m^3)

MATERIAL	DENSITY
Steel	7.75 x 10^3 kg.m^3
Aluminium	2.66 x 10^3 kg.m^3
Brass	8.3 x 10^3 kg.m^3
Bronze	8.17 x 10^3 kg.m^3
Plastic (acrylic)	1.11 x 10^3 kg.m^3
Hard wood	0.80 x 10^3 kg.m^3 (varies with type)
Soft wood	0.5 x 10^3 kg.m^3 (varies with type)

COEFFICIENTS OF FRICTION

Steel / Steel (unlubricated)	0.6
Steel / Steel (lubricated *)	0.15
Teflon / Steel	0.05
Aluminium / Steel	0.45
Brass / Steel	0.20
Copper / Steel	0.25
Self lube bronze / Steel	0.10
	(varies greatly with temperature, surface condition and lubricant)

LEADSCREW EFFICIENCIES

Acme thread with metal nut	35 - 55%
Acme thread with teflon nut	50 - 80%
Recirculating ballscrew	85 - 95%

TYPICAL BALLSCREW SIZES

METRIC (mm)		IMPERIAL (inches)	
DIAMETERS	**PITCHES**	**DIAMETERS**	**PITCHES**
10	4, 5	0.375	0.125
16	4, 5, 6	0.50	0.2, 0.25, 0.5
20	4, 5, 6, 8	0.75	0.2, 0.25, 0.5
25	4, 5, 6, 8, 10	1.0	0.2, 0.25, 0.5
32	4, 5, 6, 8, 10, 12	1.5	0.25, 0.5, 1.0
40	5, 6, 8, 10, 12, 16	2.0	0.5, 1.0
50	5, 6, 8, 10, 12, 16, 20	2.5	0.5, 1.0

Different manufacturers have different variations of sizes and pitches.
For some manufacturers imperial screws are significantly lower in cost and have faster delivery times.
Non integer scaling factors (steps/mm factor) caused by metric/imperial conversion factors can often be programmed out when using microprocessor based controllers.

NOMENCLATURE

SYMBOL	DESCRIPTION	UNITS
F	Force	N
T	Torque	N.m
m	Mass	kg
J	Angular Inertia	$kg.m^2$
a	Linear acceleration	m/sec^2
α	Angular acceleration	rad/sec^2
v	Linear velocity	m/sec
ω	Angular velocity	rad/sec
x	Linear displacement	m
θ	Angular displacement	rad
p	Screw pitch	m
r	Radius arm	m
n	No. gear teeth	
μ	Friction coefficient	
η	Efficiency	
ρ	Density	kg/m^3

MOTOR DATA

Motor manufacturers vary the electrical specificatations, weight, length and rotor inertia, however, this data will be sufficiently accurate for most motor sizing calculations. 42 frame, 1 stack and 23 frame 3 stack motors are not available from some manufacturers due to economic reasons (often a better solution can be found by using next sized motor). High performance motors with larger rotor diameters and improved materials have higher torot inertias than standard motors.

FRAME SIZE	No. STACKS	ROTOR INERTIA *($kg.m^2 \times 10^{-6}$)*	LENGTH *(mm)*	WEIGHT *(kg)*
17	1	4.3	37	0.25
23	1	11	50	0.5
23	2	21	82	0.9
23	3	33	100	1.1
34	1	60	62	1.5
34	2	120	92	2.4
34	3	155	130	3.6
42	1	365	136	4.8
42	2	800	190	8.0
42	3	1150	250	11.0

FORMULA SUMMARY

SCREW DRIVES (eg. ballscrew, leadscrew)

Displacement $x = p\,\theta / (2\,\pi)$

Torque $T = F\,p / (2\,\pi\,\eta)$......(screwing)

$T = F\,p\,\eta / (2\,\pi)$ .....(backdriving)

Inertia $J = m\,(p / 2\,\pi)^2$

TANGENTIAL DRIVES (eg. belt, conveyor, cable)

Displacement $x = 2\,\pi\,r\,\theta$

Torque $T = F\,r$

Inertia $J = m\,r^2$

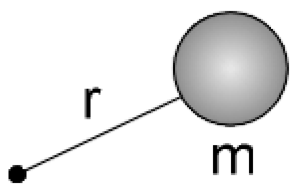
GEAR DRIVES (eg. gearboxes, belts & pulleys)

Displacement $\theta_2 = \theta_1\,(n_1/n_2)$

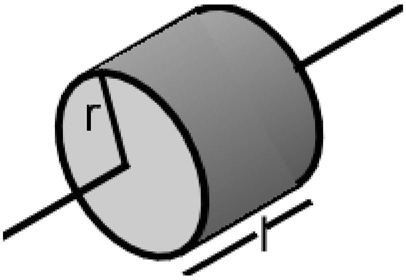
Torque $T_2 = T_1\,(n_1/n_2)\,\eta$

Inertia $J_2 = J_1\,(n_1/n_2)^2$

EFFECTIVE INERTIA



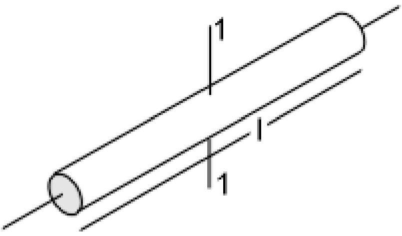
POINT MASS $J = m\,r^2$



CYLINDER

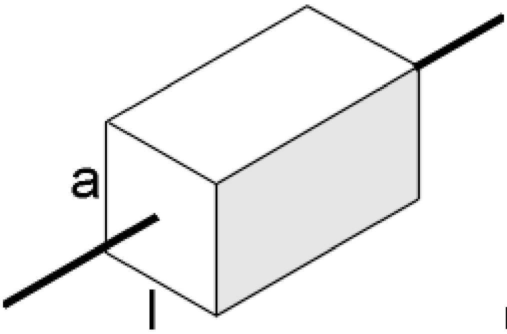
$J = 1/2\ m\ r^2$
$= 1/2\ \pi\ r^4\ l\ \rho$ .... (solid)

$J = 1/2\ m\ (r_2^2 - r_1^2)$
$= 1/2\ \pi\ (r_2^4 - r_1^4)\ l\ \rho$ .... (hollow)



SLENDER ROD

$J = 1/12\ m\ l^2$ .... (major axis)
$J_1 = 1/3\ m\ l^2$ .... (minor axis)



BLOCK

$J = 1/12\ m\ (a^2 + l^2)$

RECTILINEAR MOTION

Angular

$\omega = \alpha\ t$

$\omega_2^2 = \omega_1^2 + 2\ \alpha\ \theta$

$\theta = \omega_1\ t + 1/2\ \alpha\ t^2$

Linear

$v = a\ t$

$v_2^2 = V_1^2 + 2\ a\ x$

$x = v_1\ t + 1/2\ a\ t^2$

MOTION PROFILES

	Max. Acceleration	Max. Velocity
Triangular	$a = 4\ x / t^2$	$v = 2\ x / t$
Trapezoidal	$a = 9 / 2\ x / t^2$	$v = 3 / 2\ x / t$
Long Trapezoidal	$a = x / (t_1^2 + t_1\ t_2)$	$v = x / (t_1 + t_2)$

(t = total time, x = total displacement, v = maximum velocity)

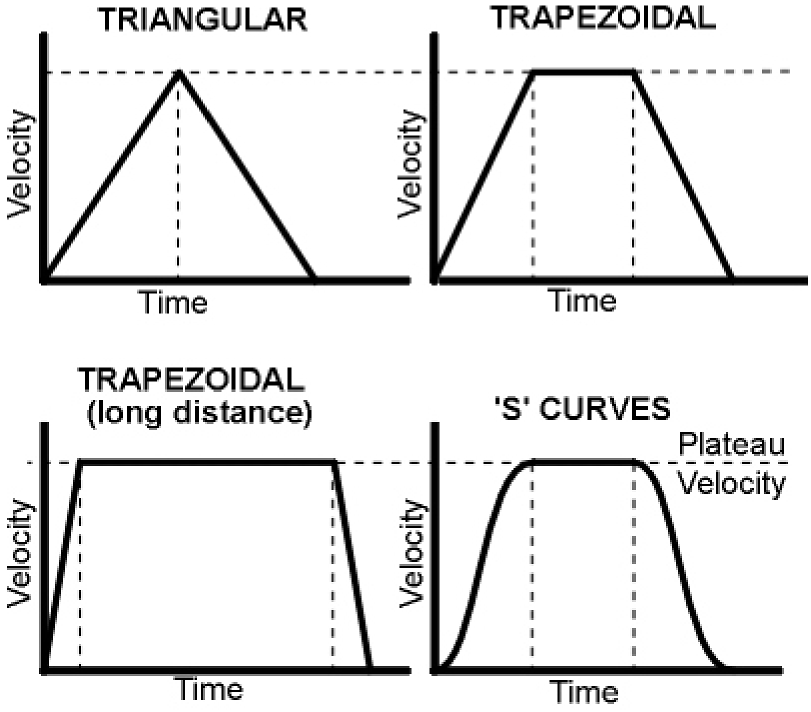


Fig 5.9 Motion Profiles