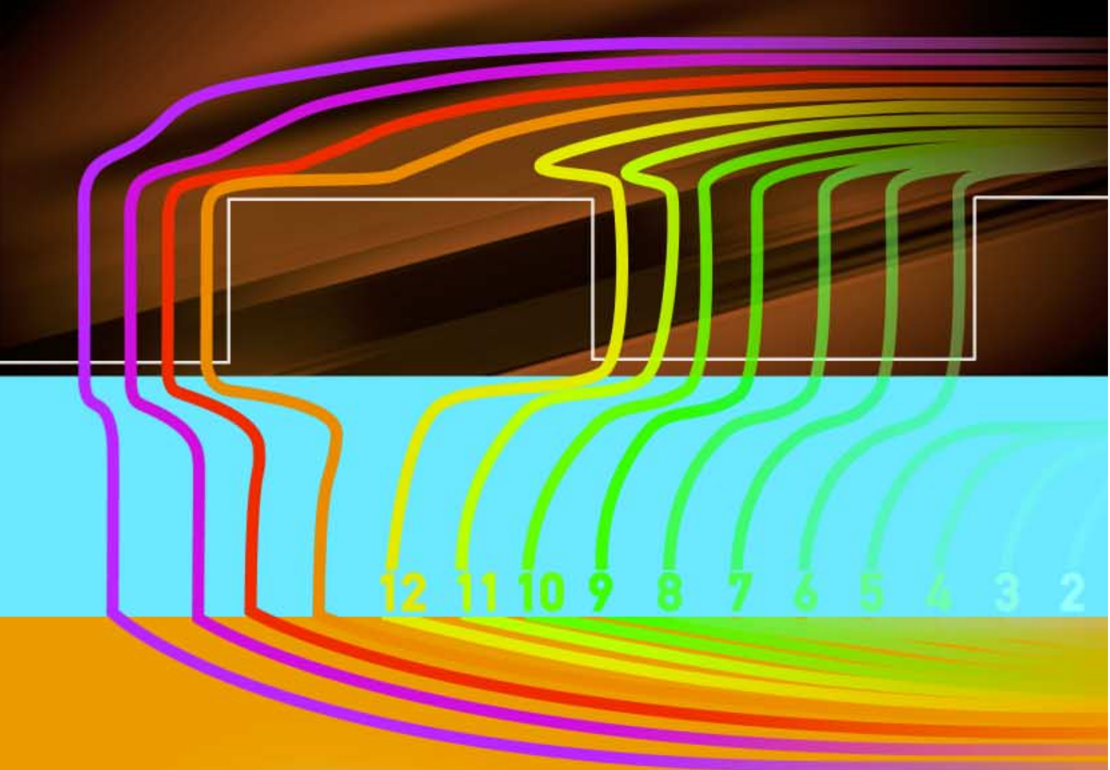


Linear Motors

Application Guide

Dedicated to the Science of Motion

AEROTECH®

Contents

A little history

Let's take a trip through time, back to 29 August 1831, arriving at Michael Faraday's workshop. The great scientist and father of electrical engineering has just discovered that a copper disk, spinning within a horseshoe magnet, generates electricity in a wire. This "induction" is fundamental to all electro-technology that will follow. Mr Faraday has created the first ever generator.

We approach Mr Faraday and ask the question: "Sir, do you think that one day your discovery will be capable of positioning nine micron thick optical fibres, end to end, at acceleration rates of ten metres per second, at resolutions measured consistently in nanometres?" We can only guess as to what his reply might have been.

However, the linear motors of today, which are capable of breathtaking speeds and accuracies, are founded on the same basic principles that Faraday discovered. It is by examining these principles, together with some practical hints and formulae that this book aims to remove any mystery about the construction and application of direct drive linear motors.

Those that know anything about linear motors can be forgiven for immediately thinking of maglev trains, superguns or even futuristic elevator systems. You might even recall Major Boothroyd using the linear motor of one of Q's toys to propel a tray at decapitating speed in the 1977 Bond movie "The Spy Who Loved Me". All have captured public attention and its imagination in recent years. The linear motor has really come of age in the past decade, through a dramatic increase in practical and beneficial industrial applications.

The linear motor was invented by Professor Eric Laithwaite, the British electrical engineer who died on 6 December 1997, aged 76. It projected a shuttle across a weaving loom using a linear motor. Professor Laithwaite had been fascinated with the weaving process ever since his boyhood spent in Lancashire, the UK's home of textile manufacture.

Professor Laithwaite described his invention as "no more than an ordinary electric motor, spread out". The principle created magnetic fields on which an object rested and travelled without being slowed by friction. This magnetic levitation had long been understood, but it was Laithwaite who pioneered the commercial development of the first practical applications, developing direct linear drives for both machinery and transport.

Linear motors have evolved in several guises but perhaps the most commonly encountered are tubular types, flat or "U" channel types, which are finding increasing use thanks to their low profiles and high output. For all intents and purposes, and for the purposes of this book, we can assume most linear motors, for motion control, use brushless technology.

Back to basics

If you've never puzzled whether to put gravity (g) into the equation or not, and have never struggled to state the difference between weight and mass, then you may skip this chapter.

For the rest of us mere mortals, here is a simple reminder of what we're dealing with when considering motor specification. All we, as engineers, really need to consider are the laws according to Faraday's predecessor, Sir Isaac Newton.

Let's start with mass and weight. Mass is the unchanging quality of a body (Fatty Arbuckle had a large mass) while weight is the force that mass exerts in a gravitational field (don't let Mr Arbuckle fall on you). However, the weight varies according to gravity. For instance, in outer space you could throw Mr Arbuckle a long way, whereas on the surface of the sun, apart from getting warm feet, Mr Arbuckle might weigh near 4,500kg (getting along for 10,000lb)!

There, we've already fallen into the trap. As far as SI units are concerned, it is mass that is measured in kilograms. The unit of weight is named after good old Sir Isaac and is of course the Newton. Weighing machines are scaled in kilograms for convenience, but really should be marked in Newtons. Take our Hollywood pal Mr Arbuckle to the moon and he weighs one sixth of what he does on Earth. His mass has not changed, but the force acting on it has. A trip to the moon is a great way to lose weight, but does nothing for the waistline!

Looking at Newton's first law of motion: a mass continues in a state of rest, or of motion at uniform velocity, unless a force acts upon it. OK, so let's go back to space and give Mr Arbuckle a gentle shove. He now weighs nothing and we watch him float across the spacecraft.

Now, if we give him a harder push, he flies across and bangs into the bulkhead, enabling us to witness Newton's second law, which states: the rate of change of velocity (acceleration) of a mass is proportional to the applied force and occurs in the direction of the applied force.

However, when we gave spaceman Arbuckle a hard shove, we also flew backwards at the same rate. This occurrence is described by Newton's third law: action and reaction are equal and opposite.

So, what has all this got to do with specifying and using linear motors? Well, we are all interested in motion and that means considering the mass and the acceleration. What we need to know is the dimension and direction of the force required to make a load move how and where we want it to. That force is calculated as the mass x acceleration (and that means any acceleration including gravity). This is very important when making linear motor assessments since because the frictional resistance is normally very low it can be disadvantageous when the motor is in the vertical position.

Newton's laws indicate that once a moving mass has been accelerated, it should remain at a constant velocity, without the need for further force. Yeah right! As any engineer knows there are a lot of forces preventing that scenario:- friction, bearing resistance, air resistance, even lubricants and gravity all conspire against us as engineers.

Sir Isaac Newton

Types of linear motors

We've already heard Professor Laithwaite's description of a linear motor as a rotary motor rolled out flat. The forcer (rotor) is made up of coils of wires encapsulated in epoxy and the track is constructed by placing magnets on steel. The forcer of the motor contains the windings, hall effect board, thermistor and the electrical connections. In rotary motors, the rotor and stator require rotary bearings, to support the rotor, and maintain the airgap between the moving parts. In the same way linear motors require linear guide rails which will maintain the position of the forcer in the magnetic field of the magnet track. At the same time rotary servo motors have encoders mounted to them, to give positional feedback of the shaft. Linear motors need positional feedback in the linear direction and there are many different linear encoders on the market today. By using a linear encoder, position is directly measured from the load and this again increases the accuracy of the position measurement.

The control for linear motors is identical to rotary motors. Like a brushless rotary motor, the forcer and track have no mechanical connection; i.e., no brushes. Unlike rotary motors, where the rotor spins and the stator is held fixed, a linear motor system can have either the forcer or the magnet track move.

Most applications for linear motors, at least in positioning systems, use a moving forcer and static track, but linear motors can also be used with a moving track and static forcer. With a moving forcer motor, the forcer weight is small compared to load. However, there is the need for a cable management system with high flex cable, since the cable has to follow the moving forcer. With a moving track arrangement, the motor must move the load plus the mass of the magnet track. However, there is the advantage that no cable management system is required.

Similar electromechanical principles apply whether the motor is rotary or linear. The same electromagnetic force that creates torque in a rotary motor also does so in the linear counterpart. Hence, the linear motor uses the same controls and programmable positioning as a rotary motor. In a rotary motor, torque is measured in Nm (lb-ft) and for the linear motors force in N (lb). Velocity is measured in rev/min for the rotary and m/sec (ft/sec) for linear motors. Duty cycles are measured in the same way for both types of motor.

Looking at the various motor types, we see that a linear motor directly converts electrical energy to linear mechanical force and is directly coupled to the load. There is no compliance or windup, and higher accuracy and unlimited travel are achieved. Today, linear motors typically reach speeds of 5m/sec, with high accelerations of 5g in practice. Theoretically motors can reach over 20g with 40m/sec velocity, however bearings and required motion parameters de-rate this performance somewhat. There is no wear, no lubrication and therefore minimal or no maintenance cost. Finally, there is higher system bandwidth and stiffness, giving better positional repeatability and accuracy as well as higher speed.

A linear motor can be flat, U-channel, or tubular in shape. The configuration that is most appropriate for a particular application depends on the specifications and operating environment.

Cylindrical moving magnet linear motors

In these motors, the forcer is cylindrical in construction and moves up and down a cylindrical bar which houses the magnets. These motors were among the first to find commercial applications, but do not exploit all of the space saving characteristics of their flat and U channel counterparts.

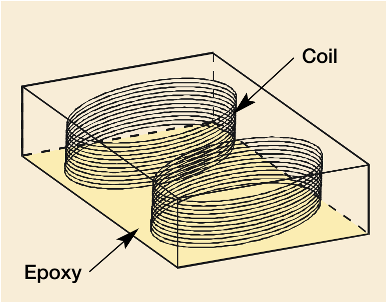
The magnetic circuit of the cylindrical moving magnet linear motor is similar to that of a moving magnet actuator. The difference is that the coils are replicated to increase the stroke. The coil winding typically consists of three phases, with brushless commutation using Hall effect devices.

The forcer is circular and moves up and down the magnetic rod. This rod is not suitable for applications sensitive to magnetic flux leakage and care must be taken to make sure that fingers do not get trapped between magnetic rod and a attracted surface. A major problem with the design of tubular motors is shown up when the length of travel increases. Due to the fact that the motor is completely circular and travels up and down the rod, the only point of support for this design is at the ends. This means that there will always be a limit to length before the deflection in the bar causes the magnets to contact the forcer.

U Channel Linear motor

This type of linear motor has two parallel magnet tracks facing each other with the forcer between the plates. The forcer is supported in the magnet track by a bearing system.

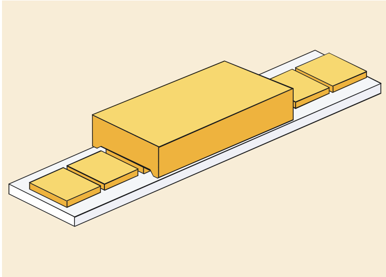
The forcers are ironless, which means that there is no attractive force and no disturbance forces generated between forcer and magnet track. The ironless coil assembly has low mass, allowing for very high acceleration.



Typically, the coil winding is three phase, with brushless commutation. Increased performance can be achieved by adding air cooling to the motor. This design of linear motor is better suited to reduced magnetic flux leakage, due to the magnets facing each other and been housed in a 'U' shaped channel. This also minimises the risks of being trapped by powerful magnets.

Due to the design of the magnet track, they can be added together to increase the length of travel, with the only limit to operating length being the length of cable management system, encoder length available and the ability to machine large flat structures.

Flat type linear motors

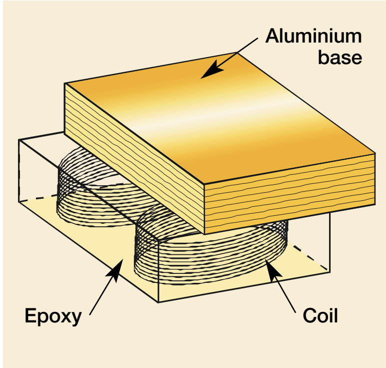


There are three design types of these motors: slotless ironless, slotless iron, and slotted iron. Again, all types are brushless. To choose between these types of motor requires an understanding of the application. The following is a list of the main characteristics of each type of motor.

Slotless Ironless flat motors:

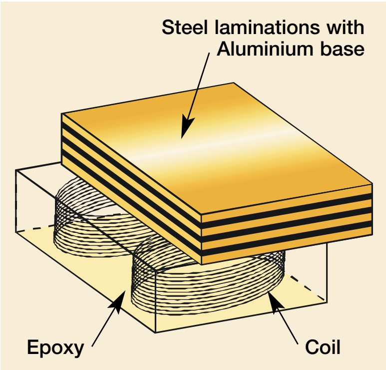
The slotless, ironless flat motor is a series of coils mounted to an aluminum base. Due to the lack of iron in the forcer, the motor has no attractive force or cogging (the same as U-channel motors). This will help with bearing life in certain applications. Forcers can be mounted from the top or sides to suit most applications.

Ideal for smooth velocity control, such as scanning applications, this type of design yields the lowest force output of flat track designs. Generally, flat magnet tracks have high magnetic flux leakage, and as such, care should be taken while handling these to prevent injury from magnets trapping you between them and other attracted materials.



Slotless Iron flat motors:

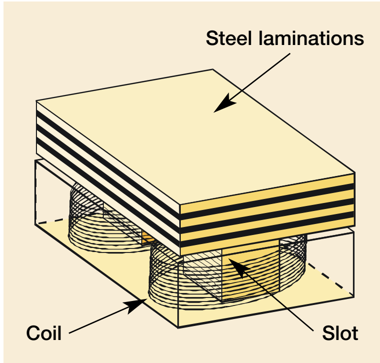
The slotless, iron flat motor is similar in construction to the slotless ironless motor except the coils are mounted to iron laminations and then to the aluminum base. Iron laminations are used to direct the magnet field and increase the force.



Due to the iron laminations in the forcer, an attractive force is now present between the forcer and the track and is proportional to force produced by the motor. As a result of the laminations, a cogging force is now present on the motor. Care must also be taken when presenting the forcer to the magnet track as they will attract each other and may cause injury. This design of motor produces more force than the ironless designs.

Slotted Iron flat motors:

In this type of linear motor, the coil windings are inserted into a steel structure to create the coil assembly. The iron core significantly increases the force output of the motor due to focusing the magnetic field created by the winding. There is a strong attractive force between the iron-core armature and the magnet track, which can be used advantageously as a preload for an air bearing system, however these forces can cause increased bearing wear at the same time. There will also be cogging forces, which can be reduced by skewing the magnets.



Before the advent of practical and affordable linear motors, all linear movement had to be created from rotary machines by using ball or roller screws or belts and pulleys. For many applications, for instance where high loads are encountered and where the driven axis is in the vertical plane, these methods remain the best solution. However, linear motors offer many distinct advantages over mechanical systems, such as very high and very low speeds, high acceleration, almost zero maintenance (there are no contacting parts) and high accuracy without backlash.

Achieving linear motion with a motor that needs no gears, couplings or pulleys makes sense for many applications, where unnecessary components, that diminish performance and reduce the life of a machine, can be removed.

In the following sections, we compare the performance and cost of various translational mechanics including belt and pulley, rack and pinion and leadscrew, to a U channel brushless linear motor.

The benefits of linear motors

Linear motor vs belt and pulley

A popular way to produce linear motion from a rotary motor, the belt and pulley system typically has its thrust force capability limited to the tensile strength of the belt. At the same time, accuracy and repeatability suffer from the inherent limitations of the belt travel system.

For example:
A belt and pulley system comprising a 100mm diameter pulley and a 5:1 gearbox could produce 3.14m/sec of linear motion, with the motor's input speed at 3000rev/min. The theoretical resolution of this system with a 10,000PPR (pulses per revolution) encoder through the gearbox would be 6.3µm.

However, positioning a load on a belt through a 5:1 gearbox to 6.3µm in any repeatable manner is practically impossible. Mechanical windup, backlash and belt stretching would all contribute to inaccuracies in the system. The fact that the measuring device (rotary encoder) is really measuring the motor shaft position, and not the actual load position, also contributes to inaccuracy. A second linear encoder could be used to measure the actual load position, but this would add more cost and require a special servo setup, so that position can be achieved quickly .

Settling time is also a problem with belt systems. Even the best reinforced belts have some compliance when positioning ±1 encoder counts. This compliance will cause a ringing, or settling delay, at the end of a very quick move, making it impossible to push the machine to a higher throughput. This problem worsens with longer belts.

The best that can be achieved in a belt and pulley system in terms of positioning repeatability is around 25 to 50µm. Since both speed and repeatability is the name of the game when it comes to servo mechanisms, the belt and pulley system is not a good choice for high speed, high accuracy machines.

On the other hand, a linear system can reach speeds of 10m/sec and position the load to within 0.1µm, or better. Only the resolution of the linear encoder used and the stability of mechanics limit the performance. Since there is no backlash or windup, a direct drive linear motor system will have repeatability to one encoder count over and over again.

Settling time is also unchallenged, since the load is directly connected to the moving forcer coil and there is no inherent backlash in the linear motor system. The encoder is also directly connected to the load to keep the positioning accuracy where it really matters. All this adds up to the shortest settling times achievable and high performance within an encoder count.

Even in long travel linear motor systems, performance and accuracy remain undiminished, since magnet tracks are stackable and the load remains directly connected to the forcer. At the same time, with thrust limited for the belt and pulley systems, loads have to be light. Conversely, a typical linear motor can produce several thousand Newtons of thrust force and still not compromise performance.

Linear motor vs rack and pinion

The rack and pinion system is mechanically stiffer than a belt and pulley but the same translational equations apply. So, a 100mm pinion gear through a 5:1 gearbox could produce a 3.14m/sec linear speed at 3000rpm, although rack and pinion provides more thrust capability.
Once again, the lack of accuracy and repeatability is the major drawback. The gearbox and pinion gear will have bi-directional inaccuracies and, over time, wear will increase the problem.

As with the belt and pulley system, backlash in the system prevents the encoder on the motor from detecting the actual load position. The backlash in the gears not only leads to inaccuracy but also causes instability in the servo system, forcing lower gains and slower overall performance.

Linear motors do not encounter such system limitations and can push a machine to greater speeds. Even as the mechanics wear over time, the direct-coupled linear motor and encoder will always provide the most accurate positioning.

Linear motors vs screw systems

Probably the most common type of rotary to linear translational mechanics is the screw, which includes both leadscrews and ballscrews.

The leadscrew system, though inexpensive, is an inefficient way of producing linear motion, typically less than 50 per cent of the output. It is also not a good choice for high duty cycle applications, as the nut which rides the screw suffers from wear due to the friction interface. Furthermore, positional accuracy and repeatability is a problem, as the screw is typically not precision made and has inherent inaccuracies. The resulting high friction may minimise backlash but produces heat and wears, reducing accuracy and repeatability. The ballscrew system uses a ball nut in the screw and is therefore much more efficient at converting rotary motion to linear motion, at typically 90 per cent of the output. This type of screw system outperforms the leadscrew for high duty cycles. A precision ground ballscrew will improve accuracy, but is costly, and, over time, will still wear and result in reduced accuracy and repeatability.

Either way, whether leadscrew or ballscrew, the basic screw system cannot achieve high linear speeds without a compromise on system resolution. It is possible to increase the speeds of a ballscrew by increasing the pitch (ie 25mm/rev), however this directly effects the positional resolution of the screw. Also too high a rotational speed can cause a screw to whip or hit a resonant frequency, causing wild instability and vibration. This problem is magnified as the length of the screw increases. This obviously limits the ability to increase a machine's throughput, or increase travel while maintaining positional resolutions.

When compared with a screw, the linear motor system does not introduce any backlash or positioning problems with the feedback device, as the linear slide bearing is its only friction point.

As with all the other translation systems discussed, the positioning of the load in a screw system is made with a rotary encoder mounted on the motor. The controller never really closes a loop at the load. In a linear motor system the encoder is at the load and is truly being positioned.

Consider the application

As with any technology, there are always limitations and caution must be used to employ the correct solution in any application. While cost was once a limitation in selecting linear motors, improved manufacturing methods and increasing volume have combined to make the expense of a linear motor solution comparable with a typical screw and motor alternative. Indeed, when cost of ownership is taken into account, a linear motor system will, over time, prove to be considerably less expensive than the traditional screw alternative. Nowadays, the superior performance of linear motors also helps meet the more exacting demands from OEMs for higher productivity.

A disadvantage with linear motors is they are not inherently suitable for use in a vertical axis. Due to its non-contact operation, if the motor is shut down, any load that has been held vertically would be allowed to fall. There are also no failsafe mechanical brakes for linear motors at present. The only solution that some manufacturers have achieved is the use of an air counterbalance.

Environmental conditions must also be considered. Although the motor itself is quite robust, it cannot be readily sealed to the same degree as a rotary motor. In addition, linear encoders are often employed as feedback devices and therefore care must be taken to ensure that the encoder is also suited to the environment. That said, linear motors have been successfully employed in ceramic cutting, an environment where highly abrasive ceramic dust has lead to the downfall of many supposedly more robust solutions. Again, the motor supplier should be familiar with all the options, and would be pleased to offer advice in each case.

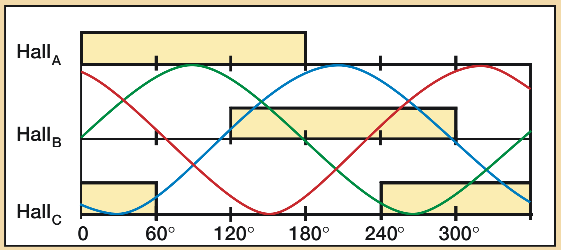
In conclusion, where loads are not excessive and the driven axis is horizontal, the linear motor has many advantages over traditional translational mechanical systems.

Commutation of linear motors

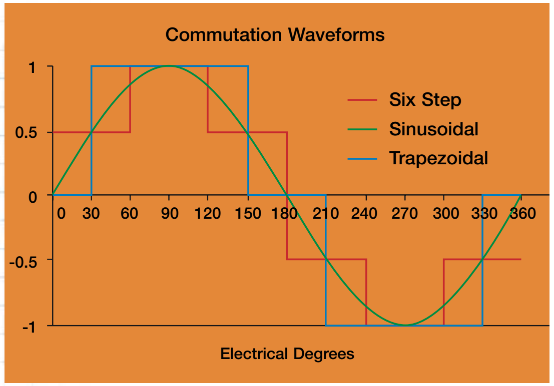
What is commutation and how does it effect the performance of the linear motors? Commutation is the process of switching current in the phases in an order to generate motion. Most linear motor designs today use a 3 phase brushless design. In brushed motors, commutation is easy to understand as brushes contact a commutator and switch the current as the motor moves. Brushless technology has no moving contacting parts and therefore is more reliable. However, the electronics required to control the current in the motor is a little more complex.

The method of commutation entirely depends on the application that the motor will be used for, but it is important to understand how the motor can be commutated and what disadvantages some methods have.

To start lets consider the brushed motor. When current is applied to the motor, the correct winding is energised by virtue of the brushes being in contact with the commutator at the point where the winding terminates. As the motor moves, the next coil in the sequence will be excited. In brushless motors because there is no fixed reference, the first thing a control or amplifier must determine is which phase needs to be energised. There are a number of ways that this can be achieved, but by far the most popular is by using Hall effect devices (Halls). There are three of these devices, one for each phase, and they give a signal that represents the magnetic fields generated by the magnet track. By analysing these fields, it is possible to determine which part of the magnet track the forcer is in and therefore energise the correct phase sequence.



Hall sequence for brushless motor and phase current

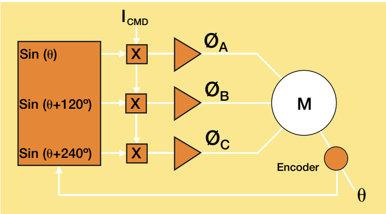


There are three different types of commutation currently available on the market: Trapezoidal, Modified six step and sinusoidal. Trapezoidal commutation is the simplest form of commutation and requires that digital Hall devices are aligned 30° electrically from the zero crossing point of the phase. At each point that a Hall signal transition takes place, the phase current sequence is changed, thus commutation of the motor occurs. This is the cheapest form of commutation and the motor phase current looks like the diagram shown above.

Modified six step commutation is very similar to trapezoidal commutation. The digital Hall devices are aligned with the zero crossing point of the phase as per diagram showing the Hall sequence of a brushless motor. Again at each point that the Hall signal translation is seen the phase current is switched. However, with this method two current sensors are used and it provides a commutation sequence that is closer to the ideal sinusoidal phase current. This method is slightly more costly than trapezoidal commutation due to sensing 2 current levels. Both of these Hall based methods will cause disturbance forces resulting in higher running temperature and motion which is not smooth.

The ideal means to drive any sinusoidally wound brushless motor is by sinusoidal commutation. There are two ways that this is commonly achieved. Analog hall effect devices, which generate a sinusoidal signal as the motor passes over the magnetic poles of the magnet track.

The signals, which are correct for motor commutation, are then combined with the demand signal to correctly commutate the motor.



This method is the lower cost of the two methods, but noise can easily be picked up on the hall devices affecting commutation.

Another more popular method of sinusoidal commutation is by using the encoder. When a change of state is detected in the digital Hall signal, the incremental encoder signals can then be used to digitally determine where in the commutation cycle the motor is. Commutation is done by generating a sin(θ) phase A command signal and a sin(θ +120) phase B command signal and multiplying this by the current command.

This method of commutation gives the best results, due to the same processor being used to control current, velocity and position and yields faster settling time and tighter servo loops. Also the noise on the digital Halls is much easier to filter out creating a more reliable system. When sinusoidal commutation is used with linear motors, the motion is smooth and the motor is driven more efficiently causing less heating.

Sizing up linear motors

So how do we take advantage of the linear motor's superior performance and what are the correct procedures when sizing and applying a linear motor?

To start with here is a list of useful formulae:

Force

$f_a = ma$

$f_f = mg\mu$

$f_g = \sin(\theta)mg$

$f_p = fa + f_f + f_g$

Velocity

$v = u + at$

$v^2 = u^2 + 2as$

$v = \frac{2S}{t^2} + u$

Acceleration

$a = \frac{v - u}{t}$

$a = \frac{v^2 - u^2}{2s}$

$a = \frac{s - ut}{2t^2}$

Distance

$s = ut + {}^1/_2 at^2$

$s = \frac{(u - v)t}{2}$

$s = \frac{(v^2 - u^2)}{2a}$

Time

$t = \frac{v - u}{a}$

$t = \frac{2s}{v - u}$

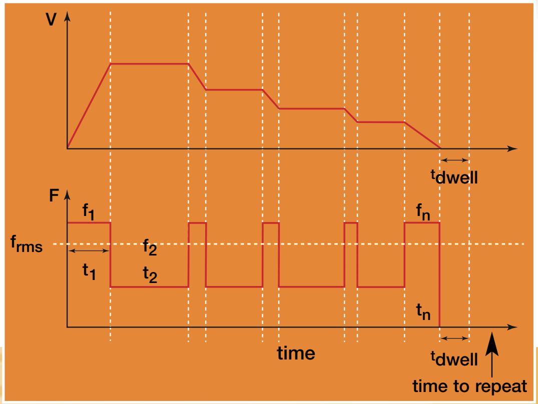
$t = \sqrt{\frac{2s}{a}}$

Coil temperature

$T = R_T \left(\frac{f_{rms}}{M_c} \right)^2$

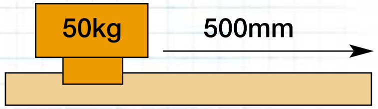
RMS force

$$f_{rms} = \sqrt{\frac{t_1 f_1^2 + t_2 f_2^2 + t_3 f_3^2 + \ldots + t_n f_n^2}{t_1 + t_2 + t_3 + \ldots + t_n + t_{dwell}}}$$



Where:

- f_a acceleration force (N)
- f_f friction force (N)
- f_g gravitational force(N)
- f_p Peak force (N)
- m mass (kg)
- a acceleration (m/sec²)
- g gravity (9.81 m/s²)
- μ coefficient of friction
- θ angle from horizontal in degrees (vertical = 90º)
- v final velocity (m/s)
- u initial velocity (m/s)
- t time (s)
- s distance (m)
- f_{rms} Average force
- T Temperature rise
- R_T Thermal resistance (°C/W)
- M_C Motor constant (N/√W)

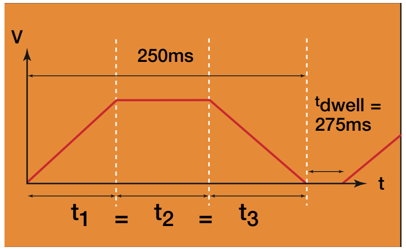


As an example, we will consider a 50kg load (mass), that is required to move 500mm in 250ms, dwell for 275ms, and then repeat. In this case we can calculate the required forces and therefore find the size of linear motor and amplifiers needed needed.

The first thing to consider is the move characteristics, what is the peak speed?, how fast do we need to accelerate to this?, how long will the move take? And what dwell do we have when the move finishes? In general when you are unsure of the move parameters and just want to move from point to point the basic profile is the trapezoidal move. With this move, the move time is divided equally into 3 parts. The first part is acceleration, the second constant velocity and the third part deceleration. This should give a balance between speed and acceleration to give the best motor combination, but please remember if you size the motor this way, then you should program it this way.

Based on trapezoidal motion, time taken to accelerate is:

$$\frac{0.25s}{3} = 0.0833s$$



We now determine the peak speed required to make the move, in this case because the move is symmetrical and divided into 3, the following formula is used.

$$v = \frac{3s}{2t} = \frac{3 \times 0.5m}{2 \times 0.25s} = 3m/s$$

Note that this formula only works with a trapezoidal move, if you have a desired acceleration rate, then you can work out the speed using one of the formulae above. The load cannot accelerate instantaneously from 0 to 3m/sec and as previously worked out it will take 0.0833s to reach this speed. We now need to calculate the acceleration rate:

$$a = \frac{v - u}{t} = \frac{3m - 0}{0.0833s} = 36m/s^2 \simeq 3.6g$$

If required, you can also calculate the distance taken to accelerate the load:

$$s = ut + \tfrac{1}{2}at^2 = \tfrac{1}{2} \times 36 \times 0.0833^2 = 0.125$$

Newton's equation finds the force required for the acceleration:

$$f_a = ma = 50kg \times 36m/s^2 = 1{,}800N$$

This is the peak rating needed from the prospective motor, derived only from the acceleration force. It does not account for friction, gravitational or other opposing forces. For example, a quality cross-roller bearing used to carry the load has a coefficient of friction of about 0.0005 to 0.003. When the 50kg rides on these bearings, the frictional force is:

$$f_f = mg\mu = 50 \times 9.81 \times 0.003 = 1.47N$$

Because friction always opposes motion, it adds to the driving force required. Another force which becomes relevant is the gravitational force. In this example the force is zero because the load is supported by the bearings, but should the load be at an angle, then the following formula is used:

$$f_g = \sin(\theta)mg = \sin(0) \times 50 \times 9.81 = 0N$$

Calculating the peak force is simply a case of adding these numbers together:

$$f_p = f_a + f_f + f_g = 1{,}800 + 1.47 + 0 = 1{,}807.47N$$

Care must be taken with this peak force. Any other external forces such as cable management systems should also be added to the peak force total. Next, with a known total of acceleration and friction forces, the next step is to calculate the continuous force requirement. The rms force is the average force from the motor and helps determine the final temperature that the coil will reach. Based on the above example using trapezoidal profile, the calculation will be:

RMS force

$$f_{rms} = \sqrt{\frac{t_1 f_1^2 + t_2 f_2^2 + t_3 f_3^2 + \ldots + t_n f_n^2}{t_1 + t_2 + t_3 + \ldots + t_n + t_{dwell}}}$$

$$= \sqrt{\frac{0.0833 \times 1801.47^2 + 0.0833 \times 1.47^2 + 0.0833 \times 1801.47^2}{0.0833 + 0.0833 + 0.0833 + 0.275}}$$

$$= 1014.77N$$

The rms force of 1015N together with the peak force requirement can then be used to choose a specific size and model of motor that can apply this force continuously. Adding air-cooling can significantly increase the rms output force of a particular motor, which allows a smaller forcer coil to maximise stroke length.

For this application an Aerotech motor that suits the above requirement is the BLMX-502-B motor with air cooling. The specification of this motor is as follows:

Once selected the previous formulae would be repeated with the weight of the forcer added onto the load.
For simplicity the new values are:

f_p 1963.63N

f_{rms} 1106.15N

v 3m/s

To determine the coil temperature rise in this configuration we need to

Parameter	Unit	Value
Continuous force @1.36 bar	N	1186
Continuous force no air	N	816
Peak Force	N	4744
BEMF line-line	V/m/s	**54.33**
Continuous current @1.36 bar	Amp Peak	25.03
Continuous current no air	Amp Peak	17.11
Force Constant, sin drive	N/Amp Peak	**47.38**
Motor Constant	N/√W	**41.20**
Thermal Resistance @1.36 bar	ºC/W	0.11
Thermal Resistance no air	ºC/W	0.24
Resistance 25ºC, line-line	Ohms	1.3
Resistance 125ºC, line-line	Ohms	**1.8**
Inductance, line-line	mH	1.0
Max Terminal Voltage	Vdc	320
Magnetic pole pitch	mm	30
Coil Weight	Kg	4.45
Coil Length	mm	502

calculate it, if we assume the ambient temperature is 20ºC, then this should be added to the coil to get the final coil temperature rise:

$$T = R_T\left(\frac{f_{rms}}{M_c}\right)^2 = 0.11x\left(\frac{1106.15}{41.20}\right)^2 = 79.29ºC$$

In this application final coil temperature rise will be 99.29ºC. Typically temperatures over 100ºC should be avoided. If you are designing a high accuracy system then the temperature that the coil reaches will be significant. As the temperature of the coils increase, so will surrounding areas, and expansion will occur changing the accuracy of the system.

Next we need to size an amplifier to drive this motor. As it is sinusoidally wound, a sinusoidal amplifier is recommended and we have worked out the characteristics for one. Firstly we need to check on current requirement.
If we need to create 1963.63N peak with the BLMX502-B, then the following formula is used to calculate peak current:

$$\text{PeakCurrent } (I_p) = \frac{f_p}{\text{Force\_Constant}} = \frac{1963.63}{47.38} = 41.44A_{peak}$$

Continuous current is calculated in the same way, so for 1106.15N continuous:

$$\text{ContCurrent } (I_{rms}) = \frac{f_{rms}}{\text{Force\_Constant}} = \frac{1106.15}{47.38} = 23.35A_{peak\ cont}$$

Also to select the amplifier we need to check for required bus voltage. To do this we need to make sure that we have enough voltage to drive the peak current across the coil resistance taking into account the motors voltages being generated. To do this we calculate as follows:

Drive_Voltage_minimum =
(I_p x Coil_Resistance) + (v x BEMF)
= (41.44 x **1.8**) + (3 x **54.33**) =
237.58V

The amplifier required to drive this motor for this application will have the following specification:

Peak Current	41.44A
Cont. Current	23.35A
Min Bus Voltage	237.58

A suitable amplifier from Aerotech would be the BAS50-320. With this amplifier, the maximum speed that could be reached would be:

$$v = \frac{\text{Max\_Bus\_Voltage\_Amp} - (I_p \times \text{Coil\_Resistance})}{\text{BEMF}} = \frac{320 - (41.44 \times 1.8)}{54.33} = 4.52\text{m/s}$$

Please note that in these calculations the resistance of the coil at 125°C was assumed as this was worst case.

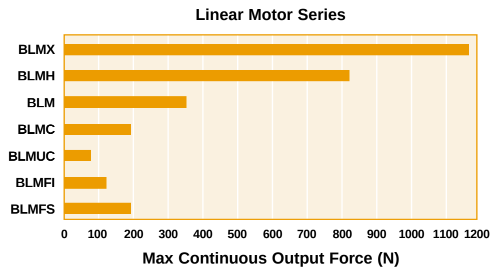
There are many different types of move profile, including sinusoidal acceleration profiles. All of which will effect the sizing of the linear motor. Aerotech have sizing software that will help you to size linear motors with many of these combinations built in. The key issue to remember however is to program the motor the same as the calculated parameters. In the above example if we altered the acceleration rate, the force would dramatically increase and could damage the motor coil.

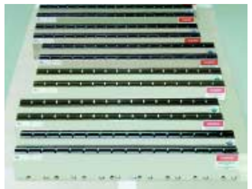
Aerotech have a wealth of experience in using linear motors and if there is any doubt about the application characteristics or any other parameters, it is always best to ask. We will be happy to work with you to solve these uncertainties.

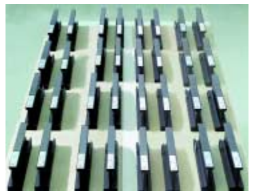
Linear Motor quick selection guide

Performance-matched to Aerotech's amplifiers and controllers for a complete motion solution

Series	Type	Continuous Force		Peak Force		Peak Speed (m/s)	Cross Section (mm x mm)
		N	lb	N	lb		
BLMUC	U-Channel	32 - 73	7 - 17	130 - 292	29 - 6	20	20.8 x 52.0
BLMC	U-Channel	82 - 193	19 - 43	330 - 770	74 - 173	15	31.8 x 57.2
BLM	U-Channel	168 - 352	38 - 79	673 - 1408	151 - 316	17	34.3 x 86.4
BLMH	U-Channel	260 - 822	57 - 185	1040 - 3288	234 - 740	10	50.8 x 114.1
BLMX	U-Channel	1030 - 1186	231 - 266	4120 - 4744	924 - 1064	6	50.8 x 152.0
BLMFI	Slot/Ironless	26 - 116	6 - 26	102 - 464	23 - 105	40	65.4 x 35.6
BLMFS	Slotless Iron	42 - 190	9 - 43	168 - 760	30 - 141	25	65.4 x 35.6







Speciality and custom motors

Aerotech's unique in-house motor design and manufacturing capabilities allow for easy changing of electrical and mechanical specifications.

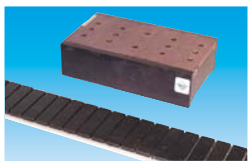
Linear motors - custom windings, magnet tracks, air and water cooling options and complete motor designs with minimal lead times.

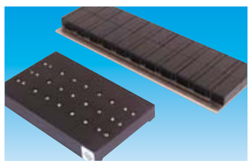
Motor Model	Units	BLMFS2-200	BLMFS3-160	BLMFS3-220
Performance Specifications				
Continuous Force, no air	N lb	286.0 64.3	387.0 87.0	525.0 118.0
Peak Force	N lb	1144 257	1550 347	3080 700
Attraction Force	N lb	1600 400	2780 626	3860 870
Electrical Specifications				
Winding Designation		–A	–A	–A
BEMF, line-line	V/m/s V/in/s	59.4 1.51	41.6 1.06	63.0 1.60
Continuous Current, no air	Amp_{pk} Amp_{rms}	5.5 3.9	13.8 9.8	10.4 7.4
Force Constant sine drive	N/Amp_{pk} lb/Amp_{pk}	51.6 11.6	36.5 8.2	50.8 11.4
	N/Amp_{rms} lb/Amp_{rms}	72.7 16.4	51.6 11.6	71.8 16.1
Motor Constant	N/-W lb/-W	20 4.51	29.8 6.6	36.8 8.3
Thermal Resistance	ÞC/W	0.49	0.45	0.36
Resistance, 25ÞC	ohms	6.2	1.52	2.3
Resistance, 125ÞC	ohms	8.7	2	3
Inductance	mH	5.2	16.5	25
Max Terminal Voltage	VDC	320	320	320
Mechanical Specifications				
Coil Weight	kg lb	2.4 5.2	5.4 11.9	7.5 16.5
Coil Length	mm in	200.0 7.87	160.0 6.3	220.0 8.67
Heat Sink Area Thickness 12.7mm (0.5 in)	mm in	300x300 12x12	250x250 10x10	250x250 10x10
Magnet Track Weight	kg/m lb/ft	4.8 3.2	6.8 4.6	6.8 4.6
Magnetic Pole Pitch	mm in	30.0 1.18	22.5 0.89	22.0 0.89

All Aerotech amplifiers are rated in Amp_{pk}; use force constant in Amp_{pk} when sizing.

All performance and electrical motor specifications ±10%.

Specifications at 125ÞC operating temperature unless otherwise specified.





Motion control and positioning

Motion Controllers

Aerotech motion controllers are used in our own positioning systems and in motion control and positioning systems throughout the world. We offer a complete line of controllers including the Automation 3200 software-based, 1- to 32-axis motion, vision, PLC, robotics, and I/O platform; the Soloist™ single-axis servo controller; the Ensemble™ multi-axis stand-alone controller; and our PC-card-based multi-axis controllers for both PCI and ISA buses.

Automation 3200

Soloist™

Ensemble™

Drives

Aerotech manufactures drives that power our own high-performance servomotors and complement Aerotech motion controllers in applications as diverse as laser machining, industrial robots, vision systems, assembly machines, machine tools, semiconductor manufacturing equipment, electronic manufacturing, and in a variety of other industrial control solutions. Aerotech drives, controllers, and linear and rotary servomotors are perfectly matched to provide the ideal solution to your motion control application. Aerotech drives are available in PWM and linear output, with from 10 to 100 amps peak current.

Motion control and positioning

Linear and Rotary Motors

Aerotech's "U-channel" and "flat" brushless linear servomotors are ideal for many industrial automation applications. The noncontact design of the forcer and magnet track results in a maintenance-free system. Aerotech's rotary motor family addresses the needs of both ultra-precision positioning and high-throughput industrial automation applications. Our motors have among the highest torque to inertia ratios available. Aerotech manufactures brushless, brush, and frameless motors.

Complete Motion Subsystems

Aerotech has over 35 years of experience manufacturing custom-engineered systems for use in semiconductor, medical, laboratory, photonics and fiberoptics, lasers, automotive, packaging, and other applications. We are well versed in vacuum and clean room techniques. We use over 35 years of motion control and positioning system experience to engineer systems tailor-made for our customers' operations, while employing the most accurate, highest performance motion control and positioning components available.

Dedicated to the Science of Motion

AEROTECH is a world leader in positioning and motion control, with offices and subsidiaries in the United States, Europe and Asia.

We are at the forefront of linear motor technology, with a wide range of linear motors and stages.

These form part of a comprehensive line-up of class-leading standard products including motion controllers, amplifiers and rotary motors.

We can also provide bespoke engineered systems for specific applications.

Our products and solutions are backed by a worldwide technical support and customer service network, dedicated to providing outstanding life-cycle support services.

Aerotech North America

Aerotech Ltd.

Aerotech GmbH

To select and configure your system, download CAD files and interface wiring diagrams, view product specifications, or order on-line, visit our interactive website www.aerotech.co.uk

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