Dedicated to the Science of Motion

Linear Motors

Application Guide

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A little history

Let's take a trip through time, back to August 29, 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 fibers, end-to-end, at acceleration rates of ten meters per second, at resolutions measured consistently in nanometers?" We can only guess 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 we will 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 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 December 6, 1997 at age 76. It projected a shuttle across a weaving loom using a linear motor. Professor Laithwaite was 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, 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 discussion, we can assume most linear motors for motion control use brushless technology.

Back to basics

If you've never puzzled whether or not to put gravity (g) into an equation, 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 4,500 kg (nearly 10,000 lb)!

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!

Take 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 because the frictional resistance is normally very low, which can be a disadvantage 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 air-gap between the moving parts. In the same way, linear motors require linear guide rails that will maintain the position of the forcer in the magnetic field of the magnet track. Rotary servomotors 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, the position of the load is measured directly which 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 the load. However, this arrangement requires 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 is N (lb). Velocity is measured in rev/min for the rotary and m/s (ft/s) 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 5 m/s, with high accelerations of 5 g in practice. Theoretically, motors can reach over 20 g with 40 m/s 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 for linear motors. Finally, there is higher system bandwidth and stiffness, giving better positional repeatability and accuracy as well as higher speeds.

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

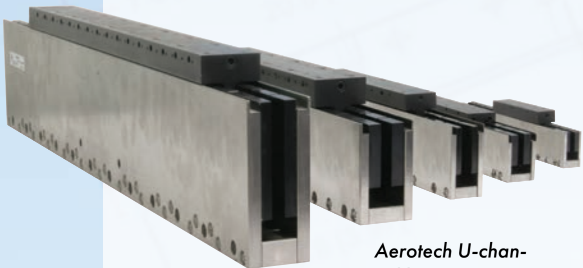
In these motors, the forcer is cylindrical in construction and moves up and down a cylindrical bar that houses the magnets. These motors were among the first to find commercial application, but do not exploit all of the space saving characteristics of their flat and U-channel counterparts.

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 the magnetic rod and an attracted surface. A major problem with the design of tubular motors is shown 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.

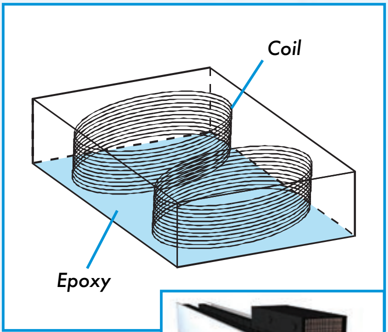
U Channel Linear motor

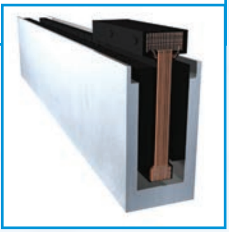
This type of linear motor has two parallel magnet tracks facing each other with the forcer between the plates. The forcer is supported in the magnet track by a bearing system.



Aerotech U-channel linear motors

The forcers are ironless, which means 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.

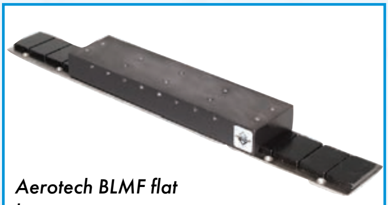




Typically the coil winding is three phase, with brushless commutation. Increased performance can be achieved by adding air cooling to the motor. This linear motor design is better suited to reduced magnetic flux leakage due to the magnets facing each other and being housed in a U-shaped channel. This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



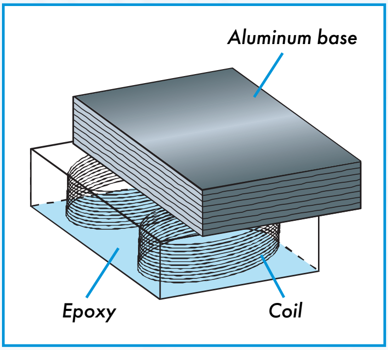
Aerotech BLMF flat linear motor

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

Slotless ironless flat motors

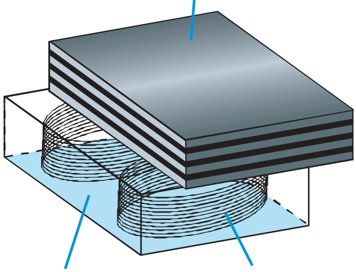
The slotless ironless flat motor is a series of coils mounted to an aluminum base. Due to the lack of iron in the forcer, the motor has no attractive force or cogging (the same as U-channel motors). This will help with bearing life in certain applications. Forcers can be mounted from the top or sides 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 care should be taken while handling these to prevent injury from magnets trapping you between them and other attracted materials.



Slotless iron flat motors

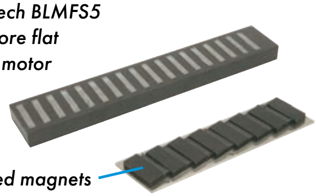
The slotless iron flat motor is similar in construction to the slotless ironless motor except the coils are mounted to iron laminations and then to the aluminum base. Iron laminations are used to direct the magnetic field and increase the force.



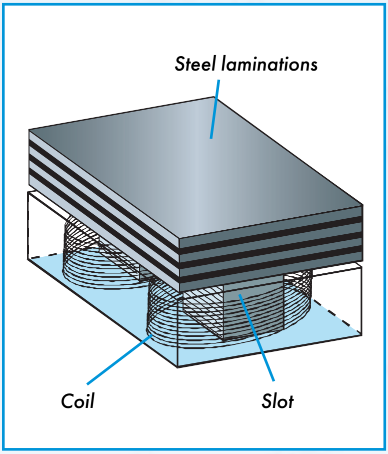
Due to the iron laminations in the forcer, an attractive force is now present between the forcer and the track and is proportional to the force produced by the motor. As a result of the laminations, a cogging force is now present on the motor. Care must also be taken when presenting the forcer to the magnet track as they will attract each other and may cause injury. This motor design 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 also 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, such as 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, including 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 lead screw, to a U-channel brushless linear motor.

The benefits of linear motors

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

However, positioning a load on a belt through a 5:1 gearbox to 6.3 μm 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 50 μm. 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 motor system can reach speeds of 10 m/s and position the load to within 0.1 μm 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 versus rack and pinion

The rack and pinion system is mechanically stiffer than a belt and pulley, but the same translational equations apply. So a 100 mm pinion gear through a 5:1 gearbox could produce a 3.14 m/s linear speed at 3000 rpm, 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.

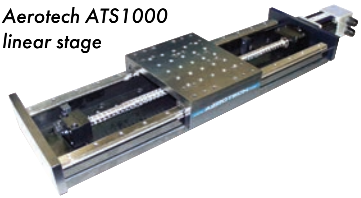
Linear motors do not encounter such system limitations and can push a machine to greater speeds. Even as the mechanics wear over time, the direct-coupled linear motor and encoder will always provide the most accurate positioning.

Linear motor versus screw systems

Probably the most common type of rotary-to-linear translational mechanics is the screw, which includes both lead screws and ball screws.

The lead screw system, though inexpensive, is an inefficient way of producing linear motion, which is typically less than 50% of the output. It is also not a good choice for high-duty-cycle applications because the nut that rides the screw suffers from wear due to the friction interface. Furthermore, positional accuracy and repeatability are a problem because

Aerotech ATS1000 linear stage



the screw is typically not precision-made and has inherent inaccuracies. The resulting high friction may minimize backlash but produces heat and wear, reducing accuracy and repeatability. The ball-screw system uses a ball nut on the screw and is therefore much more efficient at converting rotary motion to linear motion, at typically 90% of the output. This type of screw system outperforms the lead screw for high duty cycles. A precision-ground ball screw will improve accuracy, but is costly and, over time, will still wear and result in reduced accuracy and repeatability. Either way, whether lead screw or ball screw, the basic screw system cannot achieve high linear speeds without a compromise on system resolution. It is possible to increase the speeds of a ball screw by increasing the pitch (e.g., 25 mm/rev), but this directly affects 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 resolution.

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, reading actual load position.

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. Today 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 noncontact 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 led to the downfall of many supposedly more robust solutions. Again, the motor supplier should be familiar with all of the options and 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.

Applying linear motors as components

As previously discussed, brushless linear servomotors offer numerous advantages over lead screw, ball screw, or belt-driven transmission systems for linear positioning. With higher bandwidth and better smoothness in speed control from very low to very high speeds, higher acceleration, zero backlash, and incredibly long life with almost no maintenance, linear motors are being specified for more and more production, test, and research applications.

Aerotech manufactures a wide range of linear motors available as components, or already built into complete positioning systems for applications from medium accuracy pick-and-place machines to ultra-high precision systems used for semiconductor production and sub-micron laser processing. With all of the components necessary to support and position the load, provide position and speed feedback, advanced motion controls, and complete cabling and safety features, these systems are ready for integration into the application.

However, while linear motors can be readily purchased as components and built into customized assemblies, there is little information available to help the designer decide how best to integrate all of the components for optimum results. The following is just a brief overview of some of the considerations when purchasing and using linear motors as components. It suggests what other components might be required and how they can be utilized within the overall design of the positioning system.

What other components to consider

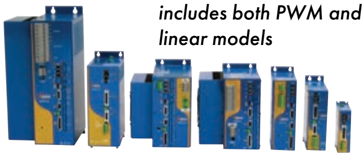
The basic additional elements required for brushless linear-motor-driven positioning systems are the servo drive or amplifier with its commutation system, the feedback system, and the linear bearings that support the load to be driven and to maintain the precision of travel. To complete the design, motor power and encoder cable management is essential. Additionally, mechanical protection devices such as hard stops may also be desirable as are over-travel limit switches and datum or home switches, although these functions are sometimes handled through the linear position feedback.

As linear motors are friction-free and the linear bearing system is normally a low friction device, braking may be required for power-loss or power-off conditions. For those vertical positioning applications where it is desirable to use a linear motor, designers will almost certainly need to consider a counterbalance and a braking system. As we covered in the previous section, in many cases it may be preferable to stay with traditional lead screw or ball-screw designs for vertical axes where their design reduces back-driving under power-off conditions.

Consideration should also be given to motor cooling, which may be required to increase performance or improve thermal stability for the application. Both air cooling and water-jacket cooling systems can be supplied.

Choice of motor and which drive technology to use

The choice of linear motor that best suits the application will clearly determine the design requirements for the rest of the system. As discussed in previous chapters, linear motors are generally divided into three groups: cylindrical moving magnet, U-channel, and flat. Within these three motor types there are significant variations in construction and performance, and the resulting specifications are available from each manufacturer.



Aerotech Ndrive series includes both PWM and linear models

A note of caution: When choosing the best linear motor for the job, care should be taken when comparing manufacturers' specifications to ensure a legitimate "apples-to-apples" comparison. Aerotech linear motor specifications are clearly defined in both the model specifications data as well as in our Engineering Reference that defines the metrology method as well as each specification term.

Essentially, U-channel and flat linear motors will require bearings to complete the design, whereas the cylindrical type can replace or complement the bearing because its construction often includes a ball-bushing-type bearing that can support a small load. However, caution should be observed when considering the cylindrical linear motor as the supporting bearing because the magnetic rod will increasingly sag or deflect in proportion to its length and, if unsupported, can make contact with the forcer with catastrophic results.

Aerotech's range of linear motors is divided between flat and U-channel types that include slotted and slotless, iron core, and ironless designs. Iron-core linear motors can provide more force, but a slight cogging effect is always present that may prove detrimental to very high position stability. In the ironless design, force is reduced but the exceptionally smooth cog-free performance is more suited to high-precision positioning. However, for many applications overall performance (acceleration, deceleration, and settling time) is determined by a combination of the limitations of the bearings, feedback device, and cable management system.

Servo drives or amplifiers can be divided into two main types: PWM (Pulse Width Modulation) or linear. Both require commutation to deliver current to the motor (commutation is covered in depth in a following chapter of this guide). The PWM amplifier uses high frequency switching to force current into the motor, whereas the linear amplifier uses a smoother but less dynamic analog voltage control.

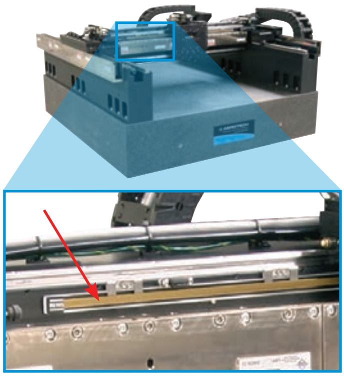
As a general guide to the performance for slotless linear motors with these amplifiers, PWM power stages deliver higher speeds and produce more load carrying motor force than linear amplifier stages, and are used for the majority of applications. While the PWM stage provides a high level of smoothness with excellent in-position stability for micron-level positioning, for those applications where ultra-high precision positioning is required, and position stability into the nanometer range is paramount, linear amplifiers should be considered. This type of amplifier also has a much reduced EMC noise footprint (almost negligible) and its high bandwidth and zero crossover distortion is also of significant benefit for ultra-high precision synchronized multi-axis positioning applications.

Feedback System

Linear encoder feedback and commutation systems are required for all closed-loop brushless servo linear motors, although there may be some brushless linear motor applications where position feedback could be provided by other devices such as linear potentiometers or magnet-based systems. However, the principal of designing-in these feedback devices is similar to the linear encoder.

Most linear motor stages use optical scale and reading-head-type encoders, although it is also possible to use magnetic encoder systems that are extremely robust and useful for hostile environment applications. For precision applications, linear optical encoders are capable of higher levels of accuracy than their magnetic counterparts due to their finer scale pitch. Whereas magnetic linear encoders can provide accuracies to around ±3 μm over a one meter length, the best linear optical scales exceed ±1 μm per meter. With the use of suitable amplified sinusoidal encoders, resolutions with multiplication for magnetic encoders can be as low as 0.05 μm, while the optical designs can provide 0.010 μm (10 nm) and beyond.

Aerotech AGS15000 linear motor gantry uses optical encoders



One of the major benefits of using a linear encoder system in a linear motor setup is that the reading head and scale can be placed very close to or at the bearing centerline, where it will measure the linear position at its most accurate point – i.e., free from Abbe errors that are caused by very small angular deviations in straightness and flatness being amplified by the distance between the bearing and the point of measurement.

Optical linear encoders can take the form of glass scales or tapes. Glass or other specialized low thermal coefficient materials used as scales are normally the more expensive choice and have superior temperature stability, but tapes are much easier to install and are more durable.

In most precision applications where optical or magnetic encoders are used, the actual scale pitch is presented as a sine wave and interpolated to yield much finer resolution, but this does not improve the overall linear accuracy. The accuracy of the full scale can be seen as a gradient with increasing error over distance. This dominant scale error is accompanied by a smaller cyclic or sub-divisional error caused by the interpolation method. And while this error is non-accumulating, it can have a significant effect on the servo control loop and can cause hunting, temperature rise, and generally reduce the dynamic system accuracy, so it will need to be considered.

It is possible to map an encoder-based single-axis (or dual-axis) setup with an interferometer and calibrate the accuracy with actual positional information at a point of reference. This information is then used within the motion controller as a look-up table to dynamically correct position during motion. This error correction method is increasingly specified for high precision systems such as high-accuracy laser machining where the resulting calibrated position information can be included to precisely trigger laser pulse delivery.

Bearing Technology

The bearing technology used in a linear motor application should be capable of supporting the load as well as maintaining the air gap between platen and moving forcer, which is typically less than 0.75 mm for the flat motor. As we are dealing with precision systems, only high-precision bearing systems are considered here and in this category the main choices are air bearings, crossed-roller bearings, and linear motion guide bearings. Aerotech's own range of medium to ultra-high precision positioning stages with direct-drive linear servomotors use all of these bearing styles to suit performance and cost requirements for the application.

Aerotech ABL1500 air-bearing stage

Air bearings are normally used for very high-precision applications where the friction-free characteristics of the bearing perfectly complement the noncontact linear motor and feedback device design, allowing the very best positioning performance. Air bearings typically rely upon a very small air gap of just a few microns with pressurized air forming a cushion between the moving and fixed parts.

Most linear motion guide, ball, and crossed-roller-based bearing designs include cages to separate the actual ball or roller, and a top to eliminate bearing-to-bearing contact during motion. This also helps to reduce skewing and noise, improve lubrication, and generally to optimize acceleration and high-speed performance while providing a much longer life potential. The choice of ball or roller bearings is dictated by the type of loading that the mechanical system is subjected to, and linear motion guides are also supplied in a choice of preload to suit load requirements. Roller-based bearings provide much higher load, shock, and impact load characteristics due to increased contact area between bearing surfaces and the bearing ways, but they increase friction and in some high-precision positioning applications, this factor may hinder in-position performance and low-speed stability. Lubrication is another critical factor for high-precision applications, where the wrong lubricant may introduce stick-slip (stiction) and render very short duration, micron-level moves erratic or otherwise difficult to achieve.

Aerotech ANT series nanopositioners use direct-drive linear motors and crossed-roller bearings

It is very important that the bearing system is fixed to a rigid and sound base to ensure that bearing straightness and flatness can be achieved and that the system harmonics are minimized so as not to interfere with dynamic positioning and motion performance. It should be noted that unsupported linear bearings are not inherently straight and must be fixed to a datum surface with the aid of calibrated alignment equipment such as an angle collimator or laser-based system to ensure the desired straightness and flatness and pitch, roll, and yaw accuracy.

Linear motion guide bearings may be specified for demanding applications such as cleanroom, vacuum, corrosion resistant, high speed, and low/high temperature. These bearings usually include sealing strips as standard and provision for special lubrication. Even fine movement applications can be addressed with modified standard products that include special lubrication.

During the design phase, all of the direct and offset loading requirements, the speeds and duty cycle, and life calculations of the complete positioning system must be carefully determined to ensure that the bearing system selection is suited to the application. When a complete positioning stage is selected, these calculations have already been made and all the specification details are available from the manufacturer. In the case of purchased components the choice of bearing system and its design must be determined and suitable cable management pre-selected before the linear motor and feedback system are sized and selected.

Linear brakes that fit the form of linear motion guide rails are available as a convenient solution for preventing stage movement under power-off conditions.

Cable management

As linear motors and feedback devices are essentially friction-free and linear bearings have a predictable life, the working life of a complete positioning system and the frequency of maintenance downtime is often dependent upon the cable management system.

E-chain can be used for motor power and encoder cables, as well as other electrical, fiber optic, pneumatic, or even hydraulic services required for a particular project. The first task is to define the total cable requirement and determine the diameter, weight, and bend radius for each. Most cable manufacturers specify cable bend radius but it is very important to use the dynamic rather than the static rating. The bend radius refers to the inside diameter of the cable and wherever possible "chain rated" cable should be specified. This cable is specifically designed to withstand the rigors of constant flexing and high accelerations to provide a much longer working life than standard cable. Consideration for the cable performance in the correct environment should also be given – i.e., temperature, humidity, cleanliness, vibration, etc. all have an effect on cable performance and life. The cable chain orientation – horizontal, side mounted, standing or hanging – is also of importance as is the space and clearance envelope, how the chain may need supported, and requirements for maintenance access.

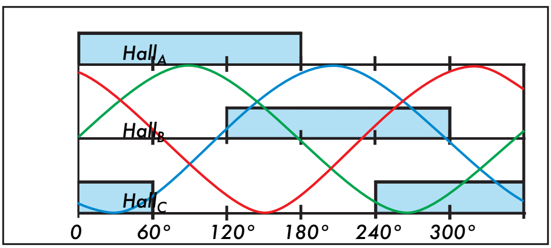
As with the choice of linear bearing, the weight and drag from the E-chain system will influence linear motor sizing and will be required to correctly select the motor type and power for the finished system design.

Commutation of linear motors

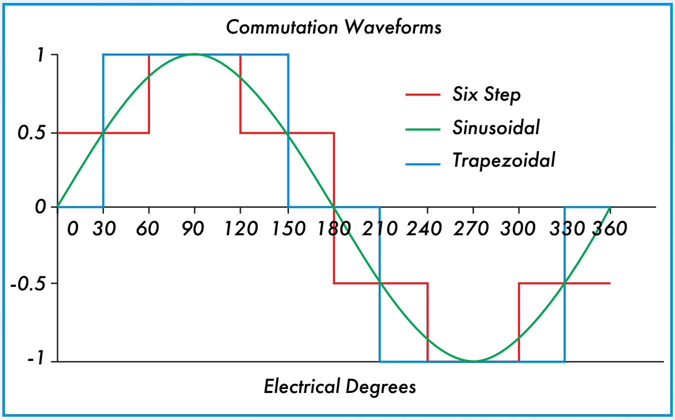
What is commutation and how does it affect the performance of the linear motors? Commutation is the process of switching current in the phases in order to generate motion. Most linear motor designs today use a three-phase brushless design. In brushed motors, commutation is easy to understand as brushes 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 are a little more complex.

The method of commutation depends on the application of the motor, 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 energized 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 energized. In brushless motors, because there is no fixed reference, the first thing a control or amplifier must determine is which phase needs to be energized. There are a number of ways that this can be achieved, but by far the most popular is by using Hall effect devices. 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 analyzing these fields, it is possible to determine which part of the magnet



Hall sequence for brushless motor and phase current

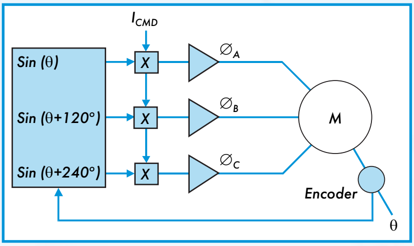


track the forcer is in and therefore energize the correct phase sequence.

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 30º 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 per the 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 two current levels. Both of these Hall-based methods will cause disturbance forces resulting in higher running temperature and motion that 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 can 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 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 linear motors

To start with, here is a list of useful formulae for sizing linear motors:

Force

$$f_a = ma$$
$$f_f = mg\mu$$
$$f_g = \sin(\theta)mg$$
$$f_p = f_a + f_f + f_g$$

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

$$s = ut + \tfrac{1}{2}at^2$$
$$s = \frac{(u-v)t}{2}$$
$$s = \frac{(v^2-u^2)}{2a}$$

Time

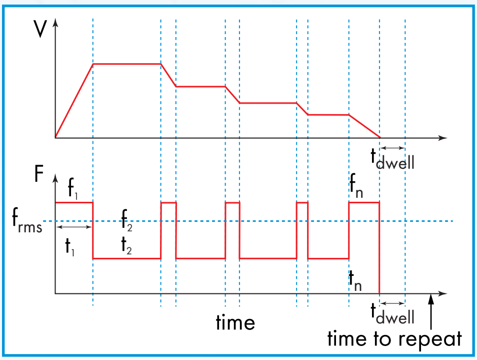
$$t = \frac{v-u}{a}$$
$$t = \frac{2s}{v-u}$$
$$t = \sqrt{\frac{2s}{a}}$$

Coil temperature

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

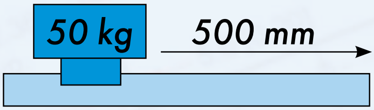
rms force

$$f_{rms} = \sqrt{\frac{t_1f_1^2 + t_2f_2^2 + t_3f_3^2 + \ \dots\ + t_nf_n^2}{t_1 + t_2 + t_3 + \ \dots\ + t_n + t_{dwell}}}$$



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/s^2)
- g gravity (9.81 m/s^2)
- μ coefficient of friction
- θ angle from horizontal in degrees (vertical = 90°)
- 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)

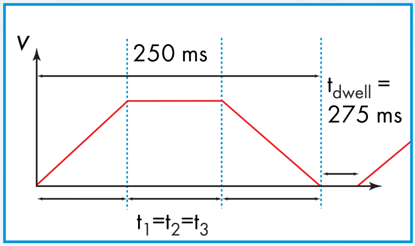


As an example, we will consider a 50 kg load (mass), that is required to move 500 mm in 250 ms, dwell for 275 ms, and then repeat. In this case we can calculate the required forces and therefore find the size of linear motor and amplifiers required.

The first thing to consider is the move characteristics: What is the peak speed? How fast do we need to accelerate? How long will the move take? 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 three parts. The first part is acceleration, the second constant velocity, and the third part is deceleration. This should give a balance between speed and acceleration to give the best motor combination. But please remember that if you size the motor this way, then you should program it this way.

Based on trapezoidal motion, time taken to accelerate is:

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



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:

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

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 on the previous page. The load cannot accelerate instantaneously from 0 to 3 m/s and as already shown it will take 0.0833 s to reach this speed. We now need to calculate the acceleration rate:

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

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

$s=ut+½at^2=½x36x0.0833^2=0.125$ m

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

f_a = ma = 50 kg x 36 m/s² = 1800 N

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 crossed-roller bearing used to carry the load has a coefficient of friction of about 0.0005 to 0.003. When the 50 kg rides on these bearings, the frictional force is:

f_f = mgμ = 50x9.81x0.003 = 1.47 N

Because friction always opposes motion, it adds to the driving force required. Another force that 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(θ)mg = sin(0)x50x9.81 = 0 N

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

$f_p=f_a+f_f+f_g=1800+1.47+0=1801.47$ N

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 a trapezoidal profile, the calculation will be:

rms force

$$f_{rms} = \sqrt{\frac{t_1f_1^2+t_2f_2^2+t_3f_3^2+\ \dots\ +t_nf_n^2}{t_1+t_2+t_3+\ \dots\ +t_n+t_{dwell}}}$$

$$= \sqrt{\frac{0.0833x1801.47^2+0.0833x1.47^2+0.0833x1801.47^2}{0.0833+0.0833+0.0833+0.275}}$$

$$= 1015 \text{ N}$$

The rms force of 1015 N 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 maximize stroke length.

For this application, the motor with specifications shown below suits our requirements.

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	1962 N
f_{rms}	1105 N
v	3 m/s

Parameter	Unit	Value
Continuous force @1.36 bar	N	1063
Continuous force no air	N	601
Peak Force	N	4252
BEMF line-line	V/m/s	54.79
Continuous current @1.36 bar	Amp Peak	22.30
Continuous current no air	Amp Peak	12.60
Force Constant, sin drive	N/Amp Peak	47.67
Motor Constant	N/√W	46.23
Thermal Resistance @1.36 bar	ºC/W	0.12
Thermal Resistance no air	ºC/W	0.39
Resistance 25ºC, line-line	Ohms	1.1
Resistance 125ºC, line-line	Ohms	1.8
Inductance, line-line	mH	1.0
Max Terminal Voltage	VDC	340
Magnetic pole pitch	mm	30.00
Coil Weight	kg	4.45
Coil Length	mm	502.0

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

$$T = R_T \left(\frac{f_{rms}}{Mc}\right)^2 = 0.12 \times \left(\frac{1105}{46.23}\right)^2 = 68.56°C$$

In this application final coil temperature rise will be 88.56ºC. 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. First, we need to check our current requirement. If we need to create 1962 N peak with the specified motor, then the following formula is used to calculate peak current:

$$\text{PeakCurrent } (I_p) = \frac{f_p}{\text{Force\_Constant}} =$$

$$\frac{1962}{47.67} = 41.16\ A_{peak}$$

Continuous current is calculated in the same way, so for 1105 N continuous:

$$\text{ContCurrent } (I_{rms}) = \frac{f_{rms}}{\text{Force\_Constant}} = \frac{1105}{47.67} = 23.18\ A_{cont}$$

We also must check for the 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 motor voltages being generated. To do this we calculate as follows:

Drive_Voltage_minimum =
(Ip x Coil_Resistance) + (v x BEMF) =
(41.16 x 1.8) + (3 x 54.79) = 238.46 V

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

Peak Current	41.16 A
Cont. Current	23.18 A
Min Bus Voltage	238.46 V

With this controller/drive, the maximum speed that could be reached would be:

$$v = \frac{\text{Max\_Bus\_Voltage\_Amp} - (I_P \times \text{Coil\_Resistance})}{\text{BEMF}} = \frac{340 - (41.16 \times 1.8)}{54.79} = 4.85\ m/s$$

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

There are many different types of move profile, including sinusoidal acceleration profiles. All of these will affect the sizing of the linear motor. Aerotech has sizing software that will help you to size linear motors with many of these combinations built in. The key issue to remember 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 has a wealth of experience in using linear motors and we are happy to work with you to optimize your application.

Get our Motor Sizer

Visit **www.aerotech.com/resources/motor-sizer.aspx** for a quick, easy, and automatic way to size your linear and rotary motors.

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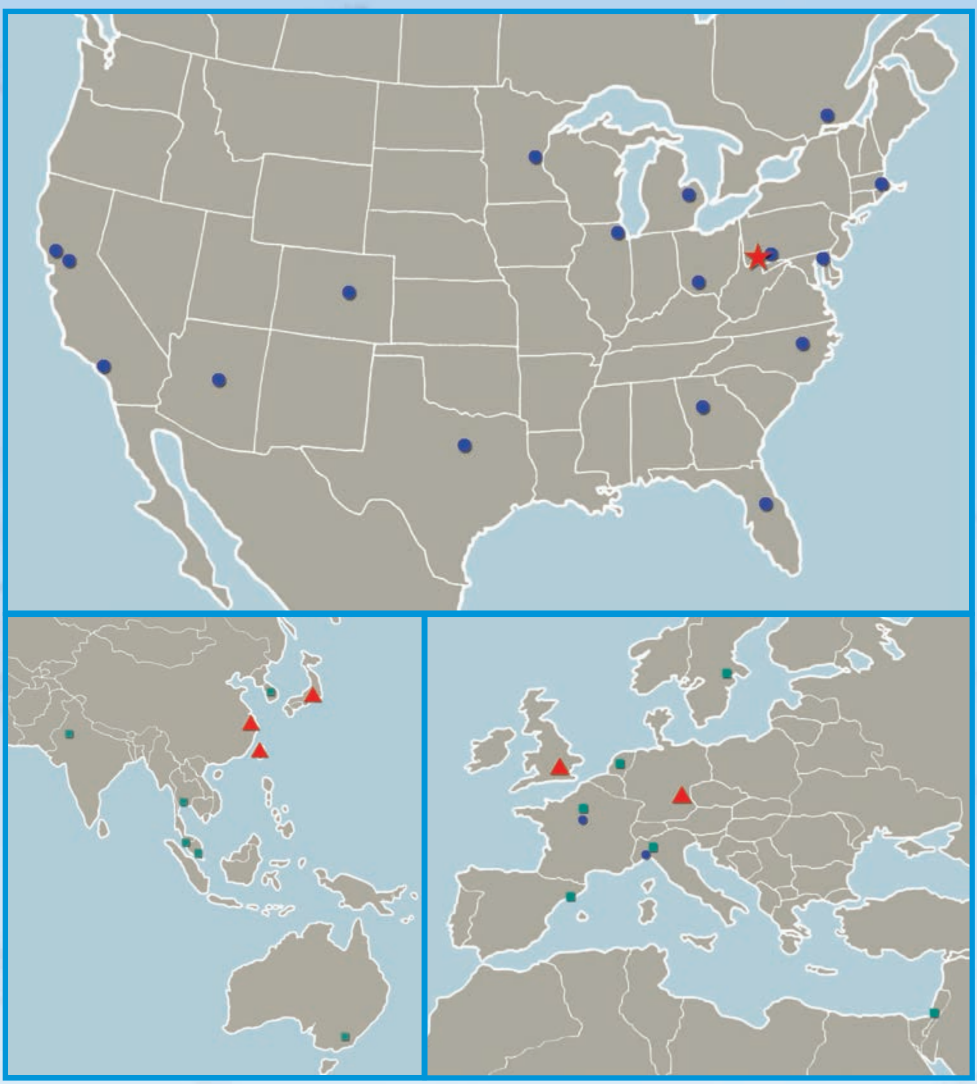

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