Mechanical hardware for accurate machine control

High-precision linear motion is key to achieving optimum machine control

Fast Forward

- Achieving high-precision motion requires a combination of advanced motion controllers and linear mechanical elements engineered for accuracy
- Factors such as component sizing, linear guide and bearing design, ball screw and nut options, and linear module housing material all impact motion precision and control
- Selecting the right size components to handle the load is essential to controlling precision

By Clint Hayes

Precise electronic motion controllers are certainly important in today's advanced manufacturing equipment. As a matter of fact, it is hard to imagine processes that require motion control of any kind without them. But just as the performance of a super athlete depends on a combination of brains and physical ability, so do high-precision linear motion systems. Without mechanical systems capable of taking full advantage of the instructions supplied by the motion controller, many of the processes we depend on today, from high-precision metal-cutting to advanced automated laboratory equipment, would not be possible. This article looks at how mechanical linear motion systems can affect precision motion and what machine designers and manufacturing engineers should know to get the most performance out of their machines.

The drive for increased precision is like the classic "chicken and the egg" question: Does the development of more precise technology drive machine innovation, or does the need for better and more precise machines lead to the development of more precise motion systems? Designers continue to dream up systems that were not even thinkable with previous generations of technology, with sometimes seemingly unrelated technologies driving progress in each other. For example, advances in linear motor technology now allow these high-speed linear guides to be used in hard disk manufacturing systems to transfer products without physically touching them. Wind turbine towers can now be welded faster, controlling the weld head to within 1/100th of an inch. Would the layperson using a computer, or seeing a row of windmills on a ridge, even consider that his or her need for more storage, or for more sustainable, less expensive electricity, might be driving the need for greater precision in linear motion technologies?

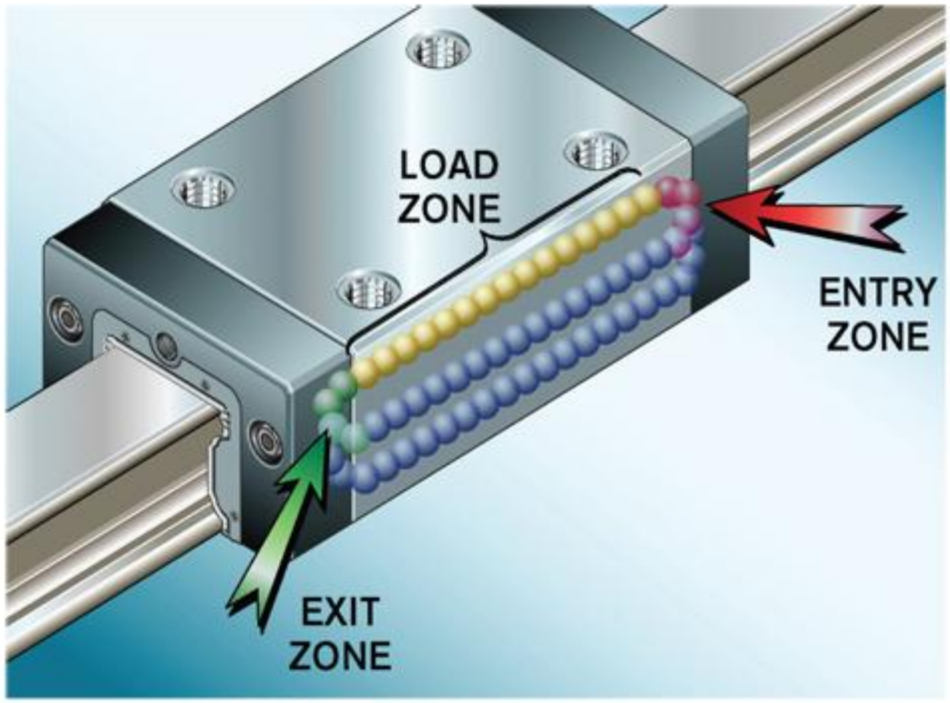
The same drive for precision leads to ongoing improvement in virtually every industry, from semiconductor and medical to automotive and woodworking. While there is a lot of focus on electronic controllers that can handle nano-level positioning or multi-axis synchronization, what do machine designers need to consider in mechanical linear motion components to keep the progress coming?

While there is a lot of focus on electronic controllers that can handle nano-level positioning or multi-axis synchronization, machine designers need to consider mechanical linear motion components to obtain the best accuracy possible.

Factors that affect precision motion

In many machines, motion is guided by runner blocks or carriages moving along one or more precision ground steel rails. The motion is commonly driven by a ball screw (or in cases where precision is not so critical, a toothed belt). A machine may have one, two, three, or more of these axes, depending on the job it is being designed to do. A very common configuration is an X-Y-Z system, with the machine's end-of-arm tool mounted to the Z axis.

If very precise operation is required, one of the most critical places to start is selecting the right size components to handle the load. Axial or torsional loading, for example, may require wider or heavier-duty components than simple radial loading. But even here it is critical to remember that one is building a system to do a job, not just buying the best linear motion components available. A poor machine frame design that is too light for the application will affect precision much more than the specified accuracy of the mechanical guide components. It is also important not to overpay for heavier-duty linear motion components simply as a result of compensating for other weaknesses in the system.



True high-precision performance with linear guides is only possible by limiting unwanted motion in the X, Y, and Z axes as the runner block travels along the rail; this can be done by optimizing ball recirculation inside the runner block.

In addition, it is important to consider other basic design criteria such as the environment in which the system is operating, the angle at which the load is mounted, the speed required, travel distance, and the required duty cycle. A good acronym for designers of linear motion systems to remember is LOSTPED, which stands for all of the key factors that should be considered in these applications (Load, Orientation, Speed, Travel distance, Precision, Environment, and Duty cycle.)

Linear guides and ball screws

Let us assume that all these fundamental machine design factors have been taken into account and look first at linear guides. Accuracy in linear guides depends on many factors: the trueness of the rail on which the runner block or bearing travels, the raceways inside the bearing through which the balls or rollers travel, as well as the flatness of the rail mounting surface, and a host of other factors. But among high-performance linear bearings, the most important area of refinement is the smoothness of ball recirculation inside the runner block as it travels along the rail.

Applications at the very high end of the accuracy spectrum, such as gaging, coordinate measuring machines, microelectronics—even super high-end metal cutting—can be adversely affected by even minute movement of the balls in the recirculation chamber, or by just a slight pivoting of the rail system about its axis. Any deflection or clearance at all reduces accuracy, and any roughness in the recirculation of the balls can cause inaccuracy in the machine output, even when coupled with highly sophisticated motion controllers. Non-recirculating linear systems, such as cross roller slides or air bearings, often allow only a limited stroke or require complex air supply systems and extremely heavy polished granite support systems. Considerable cost could be eliminated if highly accurate linear guides could be used instead.

To make linear guides that work in these applications, the solution is to alter the geometry of the recirculation pathways and eliminate roughness at key transition points. For example, optimizing the re-circulation can provide extremely smooth and consistent motion as the balls circulate in the bearing raceways, with accuracies ranging between four and six microns. As a result, this performance is highly repeatable, making it possible to compensate for minor deviations in the control of a precision machine, enabling achievement of near-perfect accuracy.

Ball screws are typically the technology of choice for driving motion in high-performance machines. Their combination of high rigidity, high precision, and respectable speed make them useful in a wide variety of situations. Specifically their ability to handle substantial axial loading often makes them a better choice than linear motors, particularly in metal, wood, and stone-cutting applications.

Ball screws are manufactured in a wide variety of accuracy classes that allows machine designers to select the product accuracy they need. In addition, rolling technology has now advanced to the point that rolled ball screws rival the performance of their ground screw counterparts in a given accuracy class. And since rolled screws are more cost effective than equivalent ground screws, many designers are taking a new look at them, especially if the application calls for a class 5 screw—about the highest precision current rolling technology allows.

As with runner block technology, ball recirculation inside the ball nut can also affect precision. As a result, ball nuts are available with a range of preload options to reduce the play as it rotates around the screw. Preload can be achieved by oversizing the balls inside the nut housing, using the so-called “double-nut” or “tensioned nut” method, or by using a manufactured offset in the raceway spiral to change the angle of ball engagement (the “lead shift” method). Each method has its advantages and disadvantages, but all serve to minimize backlash between the nut and screw.

In metal-cutting machines, tool travel is typically short, and higher speeds can be achieved by adding the proper end supports. However, in high-speed, long stroke applications, such as CNC wood routers, screw “whip” can become a problem, causing unwanted chatter and imprecise cutting. To overcome this, some ball screw manufacturers offer a driven nut option, in which the nut rotates along a stationary screw. When manufacturers couple these self-driven nut products with an integrated measuring system, driven nut technology can achieve precision ratings rivaling those of linear motors, even with long strokes. And the cost of ball screws is still considerably less than that of a linear motor.

Linear actuators and modules

Until now, these guidelines have focused on how mechanical linear motion components within the machine can affect precision. In some applications, such as Cartesian robotic systems, the “machine” consists primarily of linear motion components commanded by an electric controller. Cartesian robots are often used in so-called “pick-and-place” applications, assembly operations, material handling, or in light automation that does not require a substantial machine base. Laboratory and semiconductor applications are good examples of light automation because the parts handled are extremely delicate and lightweight, but they often require very high precision.

Cartesian robotic systems are frequently constructed from linear motion modules or actuators, which may be used in one axis, or combined in two or three axes with simple mounting plates. Each module consists essentially of a mechanism to *guide* motion and a mechanism to *drive* motion. In many cases, a module is composed of one or more linear guides plus a ball screw mounted in an aluminum extrusion or on a steel base. In cases where precision is not a critical factor, the drive mechanism is a toothed belt.

The same factors mentioned earlier, relative to linear guides and ball screws, apply with modules, too. If the module has high-performance components inside, it is likely to give you better precision overall. And since it is possible to combine such a wide range of components inside different housing designs, a module design can be found that suits virtually any application.

Besides the internal ball screws and guides, the housing design itself is crucial when it comes to accuracy and precision. The most widely-used housing material is extruded aluminum because it allows longer continuous lengths. With aluminum extrusion modules, the mounting surface or number of supports will have the most significant influence on the deflection of the system. The design of the extrusion and guide system will also affect system rigidity. Some linear modules integrate two ball rails into the aluminum extrusion to add stiffness while providing smooth motion. This combination has been shown to support lengths up to 10 meters, load capacities up to 15,000 pounds, and positioning accuracy of 52 microns for every 300 mm of travel.

Linear modules that are mounted on a steel base, or that have a steel housing, provide an additional level of travel accuracy that aluminum extrusion-based modules cannot achieve. Because steel can be machined much more precisely than aluminum, applications such as semiconductor inspection that require very high flatness or straightness of travel often lead designers to use modules that are built with a steel base or housing. These products are typically driven by a ball screw to achieve high positioning accuracy.

In summary, machine designers working on highly accurate systems must incorporate precise electronic systems. But equal billing should be given to the mechanical components as well. Factors such as component sizing, linear guide and bearing design, ball screw and nut options, and linear module housing material are just as critical in providing the best accuracy possible in your machine. Considering these items early in the design will help ensure your mechanical elements work as smoothly as possible with your motion controller to provide the precision your application demands.

ABOUT THE AUTHOR

Clint Hayes (Clint.Hayes@boschrexroth-us.com) is the Manager of Product Management for Bosch Rexroth Linear Technologies located in Charlotte, N.C. He has more than 14 years of experience in Applications Engineering and Product Management.

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