Inexpensive Methods to Measure the Performance Characteristics of a Linear Motion Device

Rob Steves

This article describes a series of tests that can be performed by the average user, with little experience, and without sophisticated measuring instruments, to quickly determine the most important performance characteristics of linear motion systems. It is published here courtesy of Zaber Technologies Inc.

Introduction

Any object in space has six degrees of freedom: linear motion along *X*, *Y* and *Z* axes, and rotation about each of those axes. Consider a typical linear motion system—in this case a Zaber T-LSR75D linear slide. With reference to Figure 1, we define a coordinate system as follows:

X	Is the horizontal axis parallel to axis-of-travel
Y	Is the horizontal axis perpendicular to axis-of-travel
Z	Is the vertical axis perpendicular to *X* and *Y* axes
Roll	Is the rotation about *X* axis
Pitch	Is the rotation about *Y* axis
Yaw	Is the rotation about *Z* axis

The goal of a single-axis motion control device is to constrain five degrees of freedom while precisely controlling motion in the sixth. In the case of the pictured linear slide, all three rotational degrees of freedom are constrained, as well as two linear degrees of freedom. Motion in the *X* dimension is controlled.

Anyone who has purchased a linear motion product will recognize these most commonly quoted specifications:

- Range
- Speed
- Load capacity
- Position error (accuracy)
- Repeatability
- Backlash
- Resolution
- Assuming the reader is familiar with these, I will not define them here. But note that each of these specs describes behavior in the *X* dimension only. It may not be obvious, but it should be understood that a similar set of specs exists for each of the six degrees of freedom. It does not matter whether a degree-of-freedom is constrained; what can be measured in one degree of freedom can be measured in another.

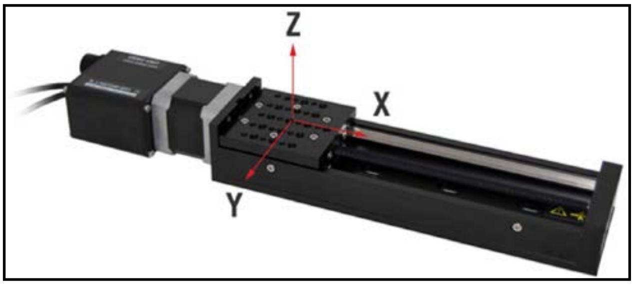

Figure 1 Defining a coordinate system. (all photos courtesy Zaber Technologies).

In some cases, the values of the corresponding specs are obvious. For example: the "range," "speed" and "resolution" in any constrained dimension should be 0. In other cases, the spec may be familiar by another name. For example: "horizontal run-out" and "vertical run-out" are familiar specs that simply represent the position error in the *Y* and *Z* dimensions, respectively. Other specs are obscure enough that no standard naming convention has been adopted. Consider: while it is not uncommon to see values quoted for the position error in pitch, yaw and roll dimensions, each manufacturer seems to call them something different; still other specs are rarely quoted at all. You are unlikely to see repeatability or backlash quoted for anything but the axis-of-travel, though these specs certainly do exist in the other degrees of freedom. While certain specs are rarely quoted, their values are often required by the user. Sometimes the only way to obtain these specs is DIY — do your own device testing. It is that process with which the remainder of this article is concerned.

Figure 2 Test subject and test equipment.

Test Equipment

The test subject and some typical test equipment are shown (Fig. 2). At the top-left is an optical bread board (an anodized aluminum plate with tapped holes at regular intervals). At top-right is a granite surface plate. Surprising accuracy in a surface plate can be had at very little expense these days; about $40 will buy you a 12" × 12" surface plate certified flat to within 0.0001". Note at the bottom of the figure two dial indicators with divisions of 0.0005" and some hardware for mounting them in various configurations; you will see other equipment used in the remaining figures, but it is all variation of the same theme.

Measuring speed. Typically the only axis of interest with regard to speed is the *X* axis (the axis of travel). There is invariably some motion in the other degrees of freedom, which we will measure shortly — but usually only the position error and not the speed is of concern. Along the axis of travel there are several speed-related specs the user may be interested in; these are minimum speed; speed resolution; speed error (accuracy); and maximum speed. Only specific, discrete speeds can be achieved by a digital control system. The minimum speed is typically the same as the speed resolution, and these are usually pre-defined by the control hardware and can be determined simply by referring to the "set speed" instruction or the equivalent that should exist for any motion system.

The speed error can be determined relatively easily with an ordinary stopwatch. Simply set the acceleration to 0, set the speed to a low value, and execute a move instruction calculated to take exactly 1,000 seconds to complete. Using a stopwatch — even accounting for human error — it's easy to achieve ± 1 second timing accuracy. So for a 1,000-second move you should be able to measure the speed to an accuracy of ± 0.1 percent.

If you require more accuracy you can try executing a move that takes 10,000 seconds to complete, thereby achieving ± 0.01 percent accuracy in measurement of the speed. If you have all day — literally — you can try 100,000 seconds to obtain ± 0.001 percent accuracy. This assumes you have a stopwatch that is accurate to better than one-second-per-day. If the motion device is computer-controlled, as our test subject happens to be, measuring the speed is much easier.

A test script can be written to execute a move, measure how much time it takes to complete, and calculate and display the actual speed and the speed error. Note, however, that operating systems are non-deterministic and may not be able to measure completion time any more accurately than a person with a stopwatch, depending upon which processes are running on the machine. The maximum speed can be determined by trial and error, but note that it will likely be load-dependent.

Measuring load capacity. The load applied to a linear motion device can be in the form of forces along *X*, *Y* and *Z* axes — or moments about those axes. For example, a centered weight mounted to the stage applies a force only in the *Z* dimension. If the weight is not centered, it applies both a force in the *Z* dimension and a moment about the *X* or *Y* axis — or both. These forces and moments will affect both the lifetime of the device as well as its ability to even move. There are two load specs commonly quoted: 1) the maximum load — above which the slide will stall; and 2) the recommended load — above which the lifetime of the slide may be reduced below the warranty period. Often, only the recommended load is quoted since manufacturers are not keen on encouraging users to push their devices to an early demise. However, users should be aware that the recommended load can often be exceeded by a significant margin if the corresponding reduction in lifetime is tolerable.

The maximum load is usually dependent on the speed. To measure it, a known force or moment — or a combination of a force and a moment since it is difficult to separate the two — can be applied by attaching fixed weights to the stage. Then the speed can be varied to determine the maximum achievable value. Testing a few different weights and interpolating will yield a reasonable plot of the maximum load as it varies with speed.

Determining the effect of load on lifetime is not nearly as easy as determining the effect of load on speed. It requires the cycle-testing of several devices until failure occurs at different loads — which is usually not practical for the end-user. For the manufacturer, however, it is often the case that individual components, such as bearings and rails, can simply be replaced for successive tests, thus reducing the cost of lifetime testing significantly.

Measuring position error. As mentioned, position error is generally the spec of greatest concern. Position errors can be measured in each of the six degrees of freedom. Often a single setup can be used to measure a position error in both a linear and a rotary dimension simultaneously.

Measuring* Y *error and yaw error. The setup for measuring the yaw error also serves to measure the *Y* error (Fig. 3). The granite surface plate is mounted parallel to the linear slide; the two dial indicators are mounted to the stage in such a way that their contact probes gently touch the vertical side of the granite surface plate. The surface plate is aligned parallel to the slide in such a way to minimize the change in dial gage readings over the range of travel of the slide.

In order to measure only yaw with no component of roll, it is important that the contact points of the probes with the surface plate lie in the same plane as the slide's bearings. Observing this setup, one can see that small motions in *Z* and *X* directions will have no effect on the dial readings; nor will small changes in pitch or roll angle. Thus it is clear that this is a good setup for measuring *Y* and yaw position errors.

At several locations throughout the travel of the slide, readings can be taken from both dial gages. At each location, the *Y* position can be calculated as the average of the two dial readings, while the yaw angle (in radians) is the difference between the two readings divided by the distance between the probes (5" in this case). The maximum variation in *Y* position and yaw angle over the full range of travel gives the *Y* error and yaw error, respectively. The *Y* error is more commonly referred to as the "horizontal run-out."

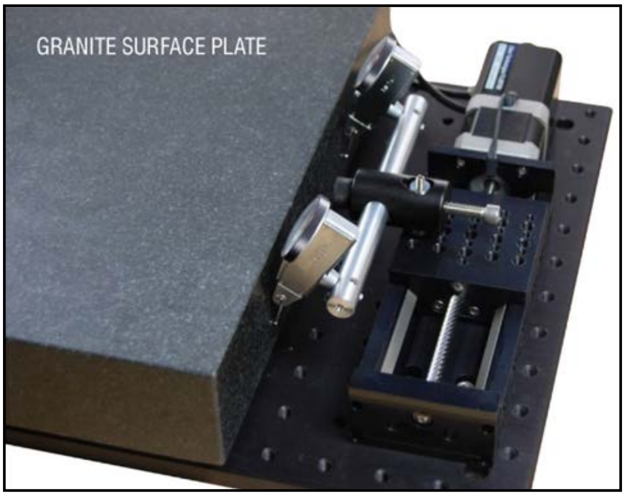

Figure 3 Setup for measuring Y error and yaw error.

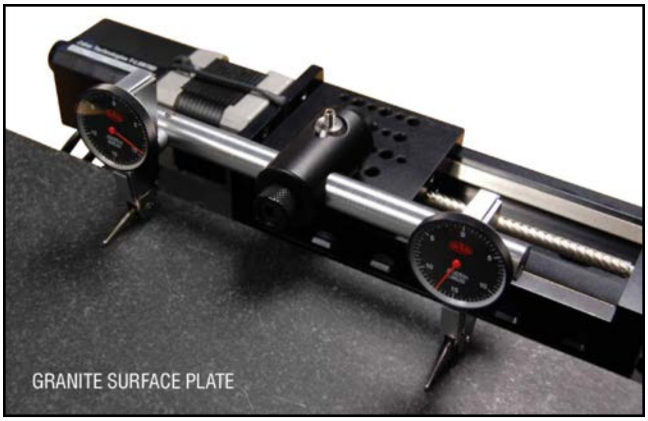

Figure 4 Setup for measuring pitch error.

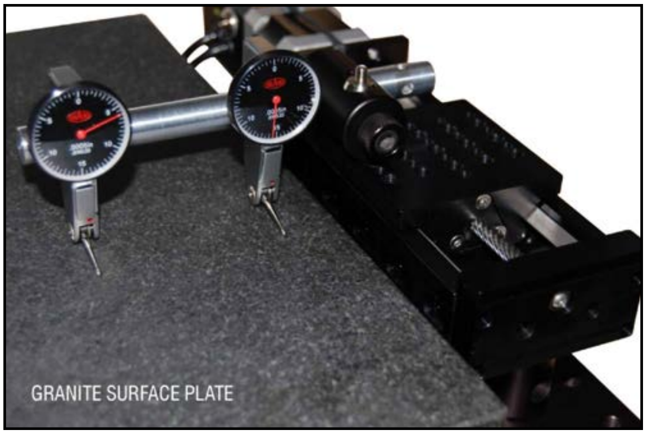

Figure 5 Setup for measuring Z error and roll error.

Measuring pitch error. Pitch error, in this context, should not be confused with lead screw pitch error. Lead screw pitch error manifests itself as a contribution to the *X* error, which will be measured later. The pitch error, in this context, refers to the variation in pitch angle of the slide platform as it travels over its full range of motion in the *X* dimension.

The setup for measuring the pitch error is shown (Fig. 4). It is similar to that for measuring the yaw error, but the probes of the dial gages are run against the horizontal edge of the granite surface plate, rather than the vertical edge. Again it is important that the points of contact with the surface plate lie in the same plane as the linear slide bearings. The slide has been raised off the optical breadboard on pillars to achieve this. One can see that small motions in *X* or *Y* have no effect on the dial readings; nor small changes in yaw angle. Changes in *Z* position and roll angle will affect the readings of the gages, but both gages will be affected equally. Since the pitch angle is related to the difference between the two readings, its measurement will not be adversely affected by the *Z* error or roll error.

The pitch angle (in radians) is given by the difference between the two readings divided by the distance between the probe contact points (5"). The variation in measured pitch angle over the full travel gives the pitch error. One might be tempted to use this setup to measure the *Z* error as well, but that would be a poor choice since it would be impossible to distinguish the *Z* error from the component of roll error that would also be measured.

Measuring Z error and roll error. The setup for measuring the roll error is shown (Fig. 5). The linear slide and granite surface plate are kept in the same positions as for pitch measurement, but the dial gage setup is turned so that the points of contact lie along the *Y* axis. One can see that small motions in *X* and *Y* will have no effect on the dial readings; nor will small changes in pitch or yaw angle. Therefore this is a good setup for measuring *Z* error and roll error, provided there is a way to distinguish between the two.

The dial gages are set up such that the points of contact are 2.5" apart and the contact point of the right-most probe is 2.5" from the center of the stage. It may not be immediately obvious, but a little geometry will show that the *Z* position is given by doubling the right-most reading and subtracting the left-most reading.

The roll angle is given by the difference between the two readings divided by the distance between the probes (2.5" in this case). The variation in *Z* position and roll angle over the full range-of-travel gives the *Z* error and roll error, respectively. *Z* error is more commonly referred to as "vertical run-out." There are simpler methods of measuring the *Z* error if that is your only interest, but if you are measuring position errors in all degrees of freedom, measuring *Z* error and roll error with the same setup is convenient.

Measuring X error. The position error along the *X* axis is often referred to as "accuracy," but that is a misnomer since a larger value indicates a less accurate device.

This spec is almost always quoted by the manufacturer, so it is usually not necessary for the user to test it — which is fortunate, since it is the most difficult spec to measure without expensive equipment.

Figure 6 shows a typical setup for measuring the *X* error. A linear encoder is mounted and precisely aligned parallel to the *X* axis. The resolution of the encoder must be smaller than that of the motion control device you wish to test. In this case a Heidenhain MT 1271-length is used. It has a resolution of 0.05 µm. The linear slide in question has a relatively coarse lead screw and therefore its resolution is only one µm. It is helpful if the range of motion of the gage is greater than that of the motion device being tested, but this isn't strictly necessary, as it is possible to get a good idea of the position error over a relatively short distance. The gage in the image has a travel of only 12 mm while the linear slide has a range of 75 mm.

Figure 6 Setup for measuring X error.

Keen observers will note that as set up in the photo, the gage will be measuring a small component of pitch and yaw error, in addition to the *X* error. However, given the short range over which the *X* error is being measured, it is unlikely that the pitch and yaw angles will change significantly. Especially in open-loop, stepper motor-controlled systems, most of the position error along the axis of travel can be traced back to the motor itself. If your device uses a microstepping controller, you should be sure to look at positioning errors under three different scenarios:

1. Moving in single microsteps over at least four full steps.
2. Moving in full steps over at least one full revolution of the motor.
3. Moving in full revolutions over the range of the device (or your gage).

In motion systems based on bipolar stepper motors, there will be cyclic errors that repeat with periods of one step, four steps, and one full revolution. In addition, there will be error associated with the lead screw. The total position error at any given location within the range of travel is the sum of all these error components. Usually only the total error is quoted, but it is useful to have an idea of the amount of error contributed by each source, since some errors can be eliminated, for example, by moving in full steps — or full revolutions — of the motor.

Understanding the contribution from each source of error allows one to reasonably estimate the degree to which moving in full steps, or full revolutions, may improve performance.

Measuring repeatability. Repeatability specs, if quoted at all, are usually quoted only for the axis of travel. But any degree of freedom that has a position error also has repeatability. By performing the abovementioned position error measurement tests multiple times for the same setup, the repeatability of the *X*, *Y*, *Z*, yaw, pitch, and roll errors can be determined. Depending on the application, it may not be important that a linear motion system be very accurate; sometimes it need only be very repeatable. Typically, the repeatability of linear motion systems (especially stepper motor-based ones) is significantly better than their accuracy.

Measuring backlash. Like repeatability, backlash is usually quoted only for the axis of travel, but any degree of freedom that has a position error can also have backlash. In other words, approaching a location from one direction may result in a different error measurement than approaching the same location from the other direction. The difference between the two error measurements is the backlash, which is usually relatively constant over the full range of travel. Backlash may also be referred to as bi-directional repeatability and can be measured as one might expect — simply by approaching locations from either direction and comparing the results.

Measuring parallelism. All of the specs mentioned thus far are dynamic specs. That is, they are related to the motion of the device rather than to its static geometry. A device must be moved in order to measure a dynamic spec. Parallelism is one of the few static specs a user may be interested in measuring. While the pitch, yaw and roll errors are measures of the change in angular position as the slide moves through its range of travel, parallelism is a measure of the baseline from which those changes occur. Figure 7 shows a typical setup for measuring parallelism. A height gage mounted to a granite surface plate is used to measure the height of the stage surface at various locations. The parallelism is simply the variation in height. If desired, one can be more specific and quote parallelism in the *X* dimension (the variation in height from front to back) and parallelism in the *Y* dimension (the variation in height from side to side) as separate entities. But, typically, only a single value is quoted. Parallelism can be converted to an angle in radians simply by dividing by the appropriate dimension (length or width) of the stage surface.

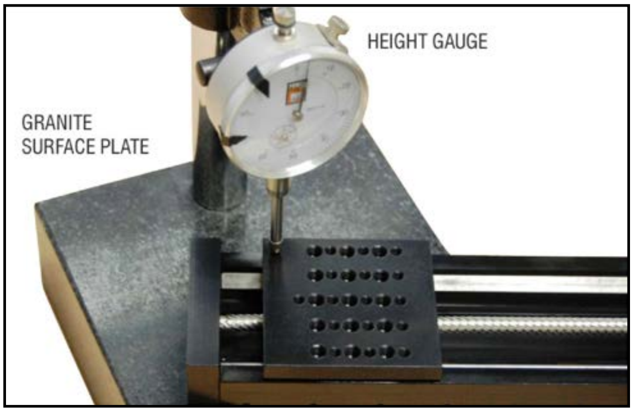

Figure 7 Setup for measuring parallelism.

Conclusion

Using relatively inexpensive equipment, it is possible to measure several important performance characteristics of a linear motion device. These measurement techniques are useful both for verifying specs quoted by the manufacturer and for determining specs that have not been quoted. **PTE**

For more information:

Zaber Technologies, Inc.
1777 West 75th Ave, 1st Floor
Vancouver, British Columbia
Canada, V6P 6P2
Phone: 1(888) 276-8033 (Toll Free Canada/USA)
1(604) 569-3780 (Direct)
Fax: 1(604) 648-8033
contact@zaber.com

Rob Steves, B.A.Sc., M.Eng. is an electro-mechanical design engineer and president of Zaber Technologies Inc., a manufacturer of stepper motor-based precision linear actuators, linear slides, and other motion control products used for optics, industrial automation, biomedical, and many other applications.