Achieving Your Accuracy Goals

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Tips for Avoiding Positioning System Speculation

Choosing the correct positioning technology for a motion application is often very frustrating because the underlying terminology can be vague and confusing. Incorrectly specifying positioning requirements can lead to an overly expensive motion system or disappointing results. The challenge of correctly applying motion technology is often compounded by misconceptions about the inherent abilities of the components that make up the positioning system. The goal of this article is to provide some practical tips for avoiding speculation when applying positioning technology.

Accuracy, Repeatability and Resolution

Accuracy, repeatability, and resolution are three of the most commonly misused and misunderstood positioning terms. First, it is important to understand that accuracy, repeatability and resolution provide meaningful application information only when they are used to describe the performance of a complete positioning system. This includes the controls, drives and motors as well as the entire mechanical system. It is dangerous and overly simplistic to only consider the performance characteristics of the motion system components.

Second, it is important to note that the positioning system performance measurements should be made under standardized, uniform conditions (temperature, warm up cycle, etc.) or under conditions that simulate the actual operating conditions. Eliminating a proper warm up cycle avoids frictional heating of the drive components, which exaggerates the accuracy of the system. Testing a positioning system under the most optimal conditions will provide outstanding performance results; however, these results will not be repeatable when the system is used in an actual application. A better understanding of repeatability and accuracy is addressed in IDC's July, 1998 Newsletter (Series A, Issue 2) that can be downloaded from http://www.idcmotion.com/engineers/index.html. For a complete, rigorous definition of repeatability, accuracy and how they both should be tested, please refer to the International Standard ISO 230-2:1997(E) and AMSE B5.54-1992.

Understanding Resolution Requirements

In addition to repeatability and accuracy, resolution is also frequently incorrectly specified or confused with accuracy and repeatability. First, it is important to note that there are two types of resolution for a motion system. The electrical resolution of the system is the resolution of the system encoder or encoders. This is the smallest incremental movement that the positioning system can detect. However, this is not the same as the system resolution, which is the smallest incremental the motion that the motion system can actually achieve. To determine the actual system resolution, it must be measured. For systems with high friction (stiction) or high inertia, the system resolution can be 5 to 10 times larger than the electrical resolution.

Finer resolutions are most commonly achieved with finer lead ballscrews or leadscrews, finer drive resolutions (step motors) and finer resolution encoders (rotary or linear for step motors and servomotors). Extremely fine resolutions (less than 1 micron) usually require piezo-ceramic drives. Again, specifying fine resolution components does not guarantee that the system will actually be able to move in such small increments. The actual system resolution still must be measured. Motion systems that must be positioned relative to an external gauge or sensor may only require high resolution without requiring high accuracy or high repeatability.

It is important to note that a finer lead, higher resolution leadscrew or ballscrew will not become more accurate because of its finer lead. For example, a JIS grade C3 ground ballscrew could have as much as 6 microns of lead error in one revolution regardless of ballscrew lead. For applications that require high accuracy and high resolution, the actual screw lead error should be mapped. Some controllers can use the error mapping information to compensate for the actual lead error.

Applications requiring high accuracy and high resolution should also measure the periodic error of the positioning system. This helps to gauge the errors caused by the mechanical periodic error (for example from a ballscrew or leadscrew) as well as the interpolation errors from an encoder and a controller. For details on periodic error and how it should be measured please consult ASME B5.54-1992.

Five Typical Positioning System Motion Requirements

There are five typical motion requirements that positioning systems are used to perform. The most common positioning applications require only repeatable, point to point motion with the destination point being approached only from one direction. For these applications, unidirectionally repeatable motion is required. These are relatively simple positioning applications. For example, typical high quality leadscrew or ballscrew driven positioning systems, without linear encoders, are unidirectionally repeatable to within 2-3 microns (as defined by ISO 230-2:1997(E)).

Motion applications that require unidirectional accuracy are somewhat more difficult. In these applications, the motion system has similar motion requirements to unidirectional repeatability, except that the positioning system must now also be used as a measurement device. Motion systems that exhibit excellent unidirectional repeatability can often be used in applications that require unidirectional accuracy because the inherent positional inaccuracy can be compensated for by offsetting the target positions. For a better understanding of error compensation, please refer to IDC's July, 1998 Newsletter (Series A, Issue 2). Typical high quality screw driven motion systems, without linear encoders, are unidirectionally accurate to within 6-7 microns (as defined by ISO 230-2:1997(E)).

Positioning applications that require repeatable point to point motion, with the destination approached from two directions require bi-directional repeatability. This is a common requirement for high throughput applications. Bi-directional repeatability is considerably more difficult to achieve than unidirectional repeatability because typical mechanical systems introduce two additional sources of error - backlash and hysteresis.

Backlash is observed when the commanded motion direction is reversed, but the positioning system does not move accordingly. In this situation, a rotary encoder mounted on the motor shaft would indicate that the system was moving in the opposite direction, but the actual motion of the system would lag behind the rotary encoder by several encoder counts. Some system components, such as gearheads, introduce backlash that is highly repeatable. Good motion controllers are designed to compensate for this type of backlash. Other sources of backlash, such as ballscrews or leadscrews, introduce backlash that is not as repeatable. Preloading the screw nut usually eliminates this type of backlash.

Hysteresis is observed when the same destination position has been commanded from opposite directions, but the actual position the motion system differ by an amount larger than the backlash. In this situation, a rotary encoder mounted on the motor shaft would indicate that exactly the same destination position had been reached when approached from opposite directions, but the actual destination positions would differ by an amount larger than the backlash alone. This additional positional error is the hysteresis, which is caused by unseen clearances and elastic deformations. A linear encoder can be used to compensate for backlash and hysteresis in point to point motion applications. Typical high quality screw driven positioning systems, without linear encoders, are bi-directionally repeatable to within 6-7 microns (as defined by ISO 230-2:1997(E)).

The relationship between bi-directional accuracy and bi-directional repeatability is similar to the relationship between unidirectional repeatability and unidirectional accuracy. Again, positioning systems with bi-directional accuracy requirements are being used as measuring devices. As in the unidirectional case, highly bi-directionally repeatable systems can have their inherent positional inaccuracies compensated for by offsetting the target positions. Linear encoders, when used with highly repeatable mechanical systems with small angular errors, can often achieve acceptable bi-directional accuracy results for single axis, point to point motion applications. Typical high quality ballscrew or leadscrew driven motion systems, without linear encoders, are bi-directionally accurate to within 10 microns (as defined by ISO 230-2:1997 (E)).

The most difficult motion applications are contouring applications. The positioning systems are required to be accurate while in motion. Typical high quality screw driven positioning systems performing contouring operations will typically exhibit accuracy errors 2-3 times larger than when they were used in point to point applications. Therefore it is important to use only the highest quality components when specifying a mechanically driven positioning system for a contouring application. Correct motor and drive tuning is also critical.

It is important to understand the limitations of a linear encoder in contouring applications. First, linear encoders and controllers both have bandwidth limitations that prohibit positional errors from being fully corrected while the system is in motion. Second, linear encoders measure the positional error at the encoder read head, not at the carriage surface (abbe error). They cannot compensate for any angular errors or structural irregularities experienced at the point of operations (usually the table surface) or cosine errors that occur due to a lack of parallelism of the encoder and the travel direction. Finally, most contouring applications involve some sort of material removal or marking. If the motion system makes positional errors while moving or stopping (overshoot), the linear encoder error corrections will occur after the error has been made and the material has been removed. The linear encoder cannot un-remove the lost material. For more detailed information regarding contouring performance evaluation, please refer to ASME B5.54-1992.

Based on the five different types of motion applications, it is clear that the proper components must be selected and their limitations must be understood.

Component Considerations - Drive Systems

The drive system is the most critical component of a positioning system. Currently, there are three main drive options. For relatively high speed, light load, low cost applications, belt drives are a popular choice. However, belt drives are not good choices for applications requiring high degrees of repeatability or accuracy.

Linear motors offer even higher speeds and repeatability (depending on the encoder) than belt drives. Because linear motors are directly driven, they do not have the backlash and wear problems that plague traditional mechanical drive systems. Almost all high throughput applications require a linear motor drive. Unfortunately, linear motors, except for asynchronous induction linear motors, are not really designed for high force applications. Linear motors are also significantly more expensive than traditional belt or screw driven systems. However, prices are expected to become more competitive as linear motors continue to gain acceptance. Most high accuracy, high throughput applications will be linear motor driven in the next few years.

It is important to note that a linear motor requires a linear encoder for positioning as well as motor commutation. Some of these encoders have very fine resolutions (sometimes as fine as 0.25 microns). However, a fine resolution encoder does not guarantee high system positional accuracy. As previously stated, the linear encoder only measures position at the point of the read head. It does not account for any of the angular errors or structural irregularities in the positioning system. Because the accuracy of a linear motor system is so dependent on the supporting mechanical components (support structure and bearings), linear motors can be used on everything from low accuracy, high throughput applications (linear motor actuators) to sub-micron positioning applications (air bearings on a granite surface with laser interferometer feedback).

Most current positioning systems utilize a ballscrew or leadscrew drive. These systems offer a good balance between load, speed, accuracy and cost. Leadscrews are typically lower cost, lower accuracy devices that offer smooth motion and low noise. However, there are also some very high precision, high cost leadscrews whose accuracy can be as high as 0.25 microns per revolution and 2.5 microns per 300mm. Both types of leadscrews can be used in positioning systems; however, most typical leadscrews are not appropriate for high accuracy applications (only the high precision leadscrews are really appropriate). The main limitations of leadscrews are duty cycle (typically 60%) and wear.

Ballscrews are typically higher cost, higher accuracy choices that offer high power transmission efficiency. Ballscrews can be preloaded to eliminate backlash and run at a 100% duty cycle. Their rolling contact eliminates the wear associated with leadscrews. There are 3 types of ballscrews. Commercial rolled ballscrews (lead accuracy worse than 200 microns per 300mm) are very low cost and primarily used in power transmission applications (actuators). They are not appropriate for positioning applications.

Ground ballscrews are significantly more expensive than rolled ballscrews; however, these types these ballscrews offer several advantages. First, ground ballscrew accuracy (between 50 microns per 300mm and 3.5 microns per 300mm) is classified according to one of two internationally recognized standards (JIS 1192 and DIN 69051). This clarifies and standardizes performance specifications. Second, ground ballscrews offer smooth, uniform motion throughout the entire range of travel. This is a key advantage for increasing system resolution (less stiction), achieving quicker settling times and contouring applications. Ground ballscrews are usually the best choice for positioning systems.

The third type of ballscrew is the high precision rolled ballscrew. Their accuracy range falls in between the commercial rolled and ground ballscrews (200 microns per 300mm to 25 microns per 300mm). Their other performance specifications also fill the gap between ground and commercial rolled ballscrews. High precision, rolled ballscrews are good choices for some lower accuracy positioning applications. However, ground ballscrews are usually more appropriate for accurate position applications.

All screw driven systems have some additional physical limitations. One limitation is critical speed. At the critical speed, a screw starts to resonate at its first natural frequency (whipping). The critical speed is proportional to the diameter of the screw and inversely proportional to distance between the screw supports squared. Critical speed is also strongly affected by how well the screw is supported. Except for very long, slender screw driven applications, most critical speeds are well above 2500 rpm. Column loading is not usually an important consideration because positioning systems are not usually used as thrust producing devices. Finally it important to restate that increasing screw resolution by decreasing the screw lead will not make the screw more accurate.

The fundamental accuracy of the positioning system is largely determined by the drive components. The additional system components (support structure, bearings, couplings, etc.) only add error (in the direction of travel and perpendicular to the direction of travel) to the fundamental errors (in the direction of travel) made by the drive components. As previously stated, linear encoders can only compensate for positional errors in the direction of travel at the encoder read head, not at the carriage surface (abbe error). Therefore, it is important to select the sufficiently accurate drive components.

Component Considerations - Support Structure and Bearings

In addition to the drive components, the support structure and bearings can also be an important source of errors. These errors are expressed as angular deviations (roll, pitch and yaw), planar deviations (straightness and flatness) or total deviation from a theoretically perfect straight line (straight-line accuracy). Please refer to IDC's July 1998 Newsletter (Series A, Issue 2) for further details. For a detailed description of how angular errors are defined and measured, please consult ASME B5.54-1992.

First it is important to consider the role of the structure. A positioning system cannot be accurate if its structure is not machined and assembled accurately. The fundamental straightness and flatness of each positioning system axis is determined by how well the base of each axis is manufactured. Ground surfaces are critical for systems with low angular error requirements. Poorly machined surfaces also contribute to cosine error (straightness and flatness errors between a linear encoder and the direction of travel), which limits the accuracy of linear encoders.

Aluminum is a popular material for positioning system structures because it is lightweight, corrosion resistant, easy to machine and inexpensive. For applications where aluminum is not rigid enough, steel is usually chosen because it is approximately three times stiffer than aluminum. However, steel is more expensive, more difficult to machine and not as corrosion resistant. Stainless steel is sometimes used instead of steel because it is corrosion resistant, but it is considerably more expensive and difficult to machine. Cast iron is usually used for systems where rigidity and vibration damping are important, such as machine tool applications. Granite is typically used with air bearings for systems with extremely low angular error and low stiction requirements.

Bearings are also an important consideration for positioning applications. Traditional slide bearings, such as dovetail slides, have high load capacities and are very stiff. However, stiction and the wear produced by the metal on metal contact are important limitations. Most typical mechanical bearings are either recirculating or non-recirculating. Recirculating bearings are best for higher load, longer travel or cantilevered load applications. They can be highly preloaded for high stiffness or vertical applications. Most are designed with wipers to keep out contaminants; however, these wipers significantly add to the system stiction, which reduces system resolution. Non-recirculating bearings are best for lighter load, smooth motion applications. They typically very economical and have no wiper stiction. Non-recirculating bearings are not designed to handle moment or impact loading.

Both types of bearings can utilize ball bearings or cross roller bearings. Cross roller bearings are stronger because of their increased surface area. Both types of bearings are rated to a B10 bearing life, which is the life (a linear distance, typically 50km), under a specified load, at which 90% of the contact elements will maintain geometric integrity. Both types of bearings can be used in positioning applications requiring straight-line accuracy up to 1 micron per 25mm. However, the ability to achieve these straight-line accuracies is dependent on the both the positioning system structure and the bearings. For example, typical precision grade bearings can achieve a cumulative running parallelism error of 10 microns over a 1 meter length, provided that the bearings are installed on a sufficiently straight and flat base. Poorly machined surfaces will cause errors far greater than the errors caused by the bearings. For applications with more demanding straight-line accuracy or low stiction requirements, air bearings are necessary.

Component Considerations - Couplings

One of the most common pitfalls when specifying components for screw or belt driven positioning systems is coupling selection. Couplings are often seen as a place to save money. Unfortunately this often causes very disappointing positioning results. Low cost couplings, such as aluminum beam couplings, can compromise the performance of a motion system in two main ways. First, most low cost couplings are very torsionally compliant. This causes windup errors. One consequence of windup is lost resolution. In this case, the motor shaft will turn slightly, but the position system will not move because the coupling will twist and absorb the motor shaft energy.

Other consequences of windup are positional overshoot and increased settling times. In these cases, the motor shaft stops, but the inertia of the load will carry the positioning system beyond the desired stopping point. As in the first windup example, the coupling will twist. The load will then oscillate around the desired stopping point, increasing settling time and reducing throughput. The torsionally compliant coupling acts like a spring storing energy. Linear encoders do not significantly improve these types of positioning errors.

The second way that torsionally compliant couplings can undermine positioning system performance is resonance. We have already seen how long travel, screw driven tables can have critical speed limitations due to resonance. However, couplings with poor torsional rigidity are actually a more common source of resonance problems. The natural frequency for a coupling is proportional to the square root of the product of the coupling frequency and the sum the inverses of the load inertia and the motor inertia. For typical screw driven positioning systems, critical frequencies are under 600 Hz.

Based on windup and resonance considerations, it is almost always worthwhile to spend a little more money on an oldham or bellows coupling because they are approximately 2-3 times torsionally stiffer than a typical aluminum beam coupling.

Component Considerations - Linear Encoders

Linear encoders have already been discussed in several other sections. This will serve as a brief summary. First, systems that use linear encoders will be more likely to be accurate (unidirectionally or bi-directionally) than systems without any encoders or with rotary encoders attached to the motor shaft. This is because linear encoders measure the actual position of a point on the carriage of one of the axes instead of only measuring at the shaft. However, it is important to recognize some of the limitations of linear encoders.

First, the straightness and flatness of the surface that the encoder is mounted to can severely limit linear encoder accuracy. Any surface errors that prevent the encoder from achieving parallelism with the direction will cause cosine errors. Second, linear encoders only measure accuracy in the direction of travel at the read head of the encoder. They cannot compensate for any angular errors experienced at the carriage surface. Also, because the read head and the surface of the table are at different locations, abbe error will also occur. Finally, linear encoders cannot compensate for orthogonality or stack up errors in multi-axis applications.

Linear encoders are best suited for eliminating backlash and hysteresis in point to point motion applications. They are not suited for contouring applications due to bandwidth limitations. To better understand bandwidth limitations, consider the following example. If a controller and a 1 micron resolution linear encoder are both limited to 2 MHz, the maximum speed that can be handled is 2 meters per second. For material removal and marking applications, permanent, uncorrectable errors will occur before the linear encoder can compensate for them.

Applications that require accuracy beyond what is available from a linear encoder should use a laser interferometer as a feedback device.

Multi-Axis Considerations

Most of the previous discussions have been concerned with the errors in single axis systems. Multi-axis systems have additional error considerations. The first consideration is orthogonality. Orthogonality errors arise from the lack of perpendicularity between axes. Another type of multi-axis error is the stack up error. These errors occur when one motion axis is supported by another motion axis. The angular errors (roll, pitch, yaw or straightness and flatness) of the supporting axis are transmitted to the supported axis. However, both of these errors are highly repeatable. Therefore, multi-axis systems that are highly repeatable can be used in applications requiring accuracy if the orthogonality and stack up errors can be compensated for. Linear encoders cannot compensate for orthogonality or stack up errors.

It is also important to consider the overall structural needs of a multi-axis system (statics and dynamics). Is the overall system stable and rigid? Are there critical forces or moments that are generated by the motion of the system? How much stiction does the overall system have? Are there any safety issues?

Coordinated movements also introduce additional errors. For example, a 2-axis system performing linear interpolation will have the linear errors of each axis combined according to the Pythagorean theorem, the orthogonality errors between the axes, and the stack up error between axes. In addition to these errors, both encoders (rotary or linear) and the controller must also synchronize the motion between the 2 axes. To effectively test the coordination between 2 axes, it is necessary to check a circularly interpolated contour. For further information on multi-axis performance measurement, please refer to ASME B5.54-1992.