Introduction

Motion Control Coordinate System

Any positioning stage is considered to have six degrees of freedom: three linear, along the x, y, and z-axes and three rotational about those same axes (Figure 1).

All motions described here are with respect to a right-handed coordinate system. Thus, if the thumb of one's right hand points in the positive direction of an axis the fingers will wrap around the axis in the direction of positive rotation about that axis. All movements can be considered to be composed of translations along and/or rotations about the coordinate axes. We generally refer to the X and Y axes as being horizontal (the direction of travel of the first or bottom stage being aligned with the X axis) and the Z-axis as vertical.

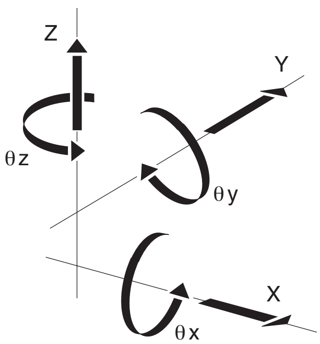

Figure 1—Right-handed coordinate system showing six degrees of freedom.

Important Specifications

The function of a stage is to constrain motion to a desired direction. For a linear stage, the desired motion is along an ideal straight line. Any motion in constrained directions will contribute to deviation from the ideal trajectory and/or position. Other contributors to deviations include load forces and everything associated with the formidable task of designing and constructing a perfect stage in a world where perfect machining and ideal materials do not exist. To put it mildly, high performance motion systems are complex, so overlooking a seemingly small issue, either in design or application, can produce undesirable results. Thus, the intended use of a product along with the various measures of performance must be thoroughly reviewed.

Unfortunately, many of the terms used by suppliers and users of motion systems mean different things to different people. In an effort to reduce confusion and misunderstanding, we use terms and definitions consistent with ASME B5.57 and ISO-230. Where terminologies in the referenced standards are not in harmony with or do not address an area, we have used those which are common to the motion industry. An understanding of each and a discussion of the application with a Newport Application Engineer will help in the selection of a system to accomplish the intended goal. The referenced standards served as a guide in the development of the Newport test procedure.

Please note: Unless otherwise stated, performance data in this catalog is on a per axis basis and are not intended to represent the performance of a stack of multiple stages. Always review stacked, multi-axis applications with a Newport applications engineer.

Minimum Incremental Motion

Minimum Incremental Motion is the smallest increment of motion a device is capable of consistently and reliably delivering. It should not be confused with resolution claims, which are typically based on the smallest controller display value or encoder increment and can be significantly smaller than the actual motion output. This is a key distinction, but unfortunately very rarely disclosed. All Newport motorized stages, unless otherwise specified, are designed with the capability of delivering minimum incremental motion equivalent the encoder resolution.

Resolution

Resolution, also referred to as display or encoder resolution, is the smallest increment that a motion system can be commanded to move and/or detect. It is not the same as the minimum incremental motion. A system may or may not be able to consistently make incremental moves equal to the resolution. Factors that can affect a move include friction, load, external forces, system dynamics, controller, vibrations, and inertia. (See the above discussion on minimal incremental motion.)

Reversal Value

Reversal Value is the difference between the positional values obtained for a given position when approached from the two opposite directions of travel. This value is a combination of backlash and hysteresis. In motion systems made up of several interacting components, it is extremely difficult to completely isolate backlash and hysteresis. It affects both bi-directional repeatability and accuracy.

Backlash

Backlash is a component of the reversal value. It is the result of relative movement between interacting mechanical parts of a drive system that do not produce output motion. Contributing factors include clearance between mechanical parts such as gear teeth and mechanical deformations. Bi-directional repeatability and accuracy are affected, however, backlash is usually quite repeatable and can thus be compensated for by capable controllers. Newport controllers are generally capable of compensating for backlash.

Hysteresis

Hysteresis is a component of the reversal value that is dependent on the recent history of the system. It is observed when the forces acting on a system reverse direction and is the result of elastic forces in the various components. It affects both bi-directional repeatability and accuracy.

Deviation

In general, deviation is the difference between an actual displacement value and the desired or commanded value. Used synonymously with error. Deviation is graphically illustrated in Figure 2.

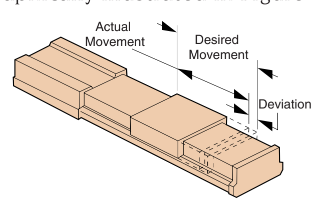

Figure 2—Position deviation in a linear translation stage.

Accuracy

Accuracy is a measure of the degree to which a given displacement, linear or rotary, conforms to an agreed upon standard. The accuracy of a motion system can be highly influenced by the test set up, environmental conditions, and the procedure used to measure displacement. In the micron and sub-micron world, thermal expansion can have a profound impact upon accuracy, particularly when temperatures are not constant or well controlled. Other common parameters that adversely affect accuracy include cosine error and Abbe error. Additionally, undesired motion in any of the six degrees of freedom will produce added uncertainty. For multi-axis systems, the influence of a combination of stages must be considered.

Accuracy is sometimes confused with incremental motion. For example, consider a screw-driven stage. If the drive screw has a pitch of 1 mm and is directly driven by a 200 step-per-revolution stepper motor, this does not necessarily mean the stage has an accuracy of 0.005 mm (proportional to one motor step). Variations in screw pitch and motor step angle must be included in accuracy analysis. Likewise, a stage utilizing a glass scale encoder has its own accuracy considerations that must be taken into account. The latter includes scale accuracy, alignment of the scale to the stage axis of motion (cosine error), alignment between read head and scale, and interpolation of the encoder signal.

Newport's accuracy and other performance measurements are conducted in a well-controlled environment (20 degrees Celsius with corrections made for atmospheric pressure and humidity). Tests are conducted in accordance with a written procedure that governs the set up, method, equipment and data analysis. Recognized national and international standards, including ISO-230 and ASME B5.57, guided the establishment of our procedure. All pertinent equipment is carefully maintained, regularly calibrated in accordance with accepted procedures and traceable to recognized national standards.

Absolute Accuracy

Absolute Accuracy is the actual output of a system versus the commanded or ideal input. It is more intuitively called inaccuracy. For example, when a motion system is commanded to move 10 mm and actually moves 9.99 mm, as measured by a perfect ruler and a test procedure that conforms to suitable standards, the deviation from the commanded position is 0.01 mm. Accuracy may be expressed per unit distance of travel or over the full travel of the stage. For example, a 200 mm travel stage may be specified as having an accuracy of 5 micro meters per 100 mm of travel or possibly 8 micro meters over its full travel. Newport specifications state how accuracy is to be interpreted for each product.

On-Axis Accuracy with Linear Error Compensation

On-Axis Accuracy with Linear Error Compensation is the deviation from absolute accuracy along the defined axis of travel after compensation of linear error sources have been accounted for. Linear or monotonically increasing errors include cosine error, inaccuracy of the lead screw pitch, angular deviation at the measuring point (Abbe error), and thermal expansion effects. Graphically, these errors can be approximated by the slope of a best fit, straight line on a plot of position versus deviation (Figure 3). Knowing the slope of this line (error/travel), we can approximate absolute accuracy as:

Absolute Accuracy = On-Axis Accuracy + (Slope x Travel)

With Newport motion controllers and stages, linear error compensation can be accomplished by entering the compensation factor into the controller. The controller User's Manual provides specific instructions.

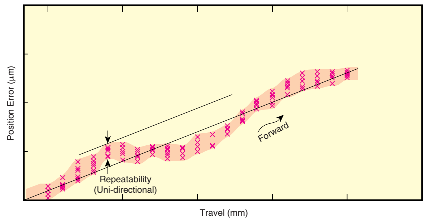

Figure 3—Slope of straight line fit for linear deviation compensation

Repeatability

There are two types of repeatability: uni-directional and bi-directional. They are not the same as accuracy. Thus, a system may be very repeatable yet lack in accuracy. Figure 4 graphically depicts the difference between accuracy and repeatability.

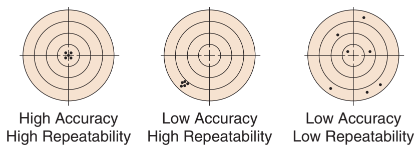

Figure 4—Accuracy vs. repeatability.

Uni-directional repeatability

Uni-directional repeatability is a measure of the ability of a system to achieve a commanded position over many attempts when approached from the same direction. Each position must be approached from a distance greater than the reversal value to achieve an accurate representation of repeatability. Figure 5 graphically represents uni-directional performance data. All positions are approached five times from the same direction. The dots represent the spread of the data at each position.
(Note: Overlapping dots may give the appearance of fewer than five values at some positions.)

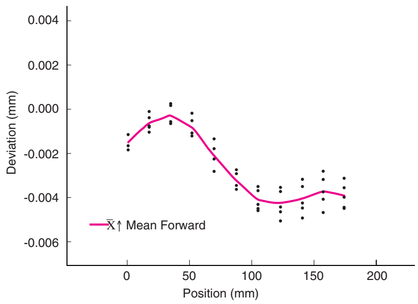

Figure 5—Uni-directional test data obtained from a linear stage showing the deviation at each position of measurement.

Bi-directional repeatability

Bi-directional repeatability is a measure of the ability of a system to achieve a commanded position over many attempts when approached from either direction. Each position must be approached from a distance greater than the reversal value to achieve an accurate representation of repeatability. Figure 6

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graphically represents bi-directional performance data. Vertical separation of the forward and reverse data is caused by the reversal value. Ten values are presented at each position: Five in the forward and 5 in the reverse directions. Like the uni-directional example, the dots represent the spread of the values at each position. All positions are approached from a distance that is greater than the reversal value. (Note: Overlapping dots give the appearance of fewer than five values at some positions.)

Figures 5 and 6 illustrate data that may be used to asses accuracy and repeatability of a stage.

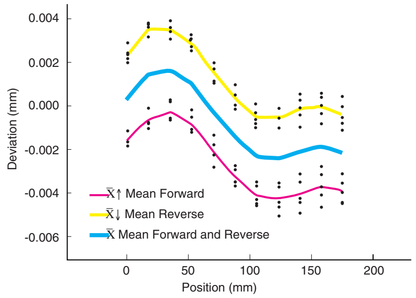

Figure 6—Bi-directional test data obtained from a linear stage showing the deviation at each position in the forward and reverse direction. The vertical offset between the forward and reverse directions is due to the reversal value.

Eccentricity of a Rotary Stage

Eccentricity is the radial (perpendicular to the axis of rotation) deviation of the center of rotation from its mean position as a stage rotates through one revolution (Figure 7). It is also referred to as radial runout. A perfectly centered stage with perfect bearings would have no eccentricity.

Wobble of a Rotary Stage

Wobble is mutation, through one revolution, of the axis of rotation relative to the ideal axis (Figure 7). It is most easily observed as a cyclic tilting of the rotating surface or table top of a stage and can produce Abbe error. Like eccentricity, it is generally the result of imperfect bearings.

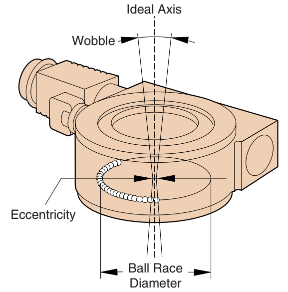

Figure 7—Off-axis deviations in a rotary stage.

Error

See Deviation

Runout of a Linear Stage

Runout of a Linear Stage is the linear (versus angular) portion of off-axis error. It is the departure from desired, ideal straight line motion and consists of two orthogonal components. In ISO-230 and ASME B5.57 standards, runout is referred to as straightness or the lack thereof. However, in the motion industry it is common to refer to flatness and straightness as defined below.

Flatness

In Figure 8, ideal straight line motion is depicted as being confined to the x-axis. Flatness deviation is displacement along the z-axis.

Straightness

In Figure 8, ideal straight line motion is depicted as being along the x-axis. Straightness deviation is displacement along the y-axis.

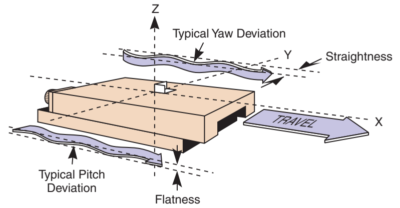

Figure 8—Off-axis deviations in a linear stage.

Tilt of a Linear Stage

Tilt of a Linear Stage is the angular deviation associated with ideal straight line motion and actual measured motion. Tilt has three orthogonal components commonly referred to as pitch, roll, and yaw (Figure 9). It can be a complex combination of the three components.

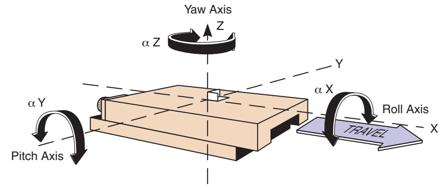

Figure 9—Roll, pitch and yaw are defined with respect to the direction of travel.

Cross-coupling

In multi-axis systems, cross-coupling refers to a change in one axis as a result of input to another axis.

Abbe Error

Abbe Error is the linear off-axis error introduced through amplification of tilt by an Abbe offset moment arm (Figure 10). This type of error becomes more of a problem when the point under measurement is at a relatively long distance from the axis of motion. This error will be approximately 0.02 micro-meters per 20 mm of offset per 1 micro-radian.

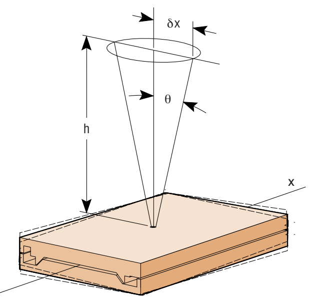

Figure 10—Abbe error due to measurement at an offset point. Note stage tilt.

Cosine Error

Misalignment between the measurement axis and the axis of motion produces cosine error. This error is a function of the angle between the measurement axis and the axis of motion (Figure 11). It is eliminated when the axis of motion and the measurement axis are parallel.

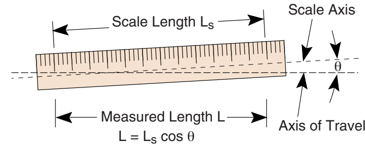

Figure 11—Cosine error due to misalignment of the measuring scale with the axis of motion.

Play

Play is the term for uncontrolled movement due to looseness of mechanical parts. Play is a contributor to backlash.

Friction

Friction is defined as the resistance to motion between surfaces in contact. Elements contributing to friction may be in the form of drag, sliding friction, depleted lubrication, system wear or lubricant viscosity.

Stiction

Stiction is the static friction that must be overcome to impart motion to a body at rest. Since static friction is generally greater than moving friction, the force which must be applied to impart motion is greater than the force required to keep the body in motion. As a result, when a force is initially applied, the body will begin to move with a "jump" that results in position and/or velocity overshoot. A stage design goal is to achieve static friction as close to the moving friction as possible in an effort to reduce the effect of stiction. One function of motion control electronics is to implement algorithms that reduce the impact of stiction by quickly making necessary corrections to a move profile.

Position Stability

Position Stability is the ability to maintain a position within a specified range over time. Deviation from a stable position may also be called drift. Contributors include worn parts, vibration, migration of lubricant, and thermal variations.

Load Capacity

Load Capacity is the maximum allowable force that can be applied to a stage, in a specified direction, while meeting stage specifications. This maximum force includes static (mass * gravity) and dynamic forces (mass * acceleration). Dynamic forces must include any external forces, such as vibrations, acting upon the stage. The amount of acceleration a stage can impart to a mass is limited to the accelerating force it can produce without exceeding a load capacity. For rotary stages, torque (the product of angular acceleration and rotational moment of inertia) is the analog of force. Rotational torques on linear stages can also be a significant factor when cantilevered loads are accelerated. Unless otherwise specified, catalog load capacities refer to a centered normal load (Figure 12).

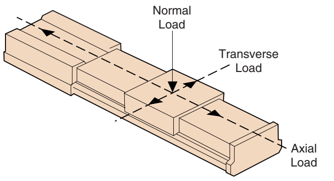

Figure 12—Capacity specifications refer to loads that are centered and perpendicular.

Centered Normal Load Capacity

For linear stages, this is the maximum load that can be applied to a stage, with the load center of mass at the center of the carriage, in a direction perpendicular to the axis of motion and the carriage surface (Figure 12). For rotary stages, it is the maximum load along the axis of rotation. In addition, the rotational moment of inertia must be with limits for rotary stages.

Transverse Load Capacity

Also called side load capacity, it is the maximum load that can be applied perpendicular to the axis of motion and along the carriage surface (Figure 12). This is typically smaller than the normal load capacity.

Axial Load Capacity

Axial Load Capacity is the maximum load along the direction of the drive train (Figure 12). For linear stages mounted vertically, the specified vertical load capacity is usually limited by the axial load capacity. However, cantilevered loading must also be considered when a stage is mounted vertically.

Off-Center Load Capacity Derating

Please note the equation and parameter values for individual stages in the specifications part of the catalog. In case of high loads, users should review their application with a Newport Applications Engineer.

Speed (Velocity)

Speed (Velocity) is the change in distance per unit time. Specifications for maximum speed are stated at the normal load capacity of the stage. Higher speeds may be possible with lower loads. Minimum stated speeds are highly dependent on a motion system's speed stability. In this catalog, velocity (a vector) and speed (a scalar) are used interchangeably.

Speed Stability

Speed Stability is a measure of the ability of a motion system to maintain, within specified limits, a constant speed. It is usually specified as a percent of the desired speed. Also specified as velocity regulation, this parameter depends upon the stage's mechanical design, its feedback mechanism, the motion controller, control algorithm, the magnitude of the speed, and the application.

Acceleration

Acceleration is the change in velocity per unit time.

Inertia

Inertia is the measure of a load's resistance to change in velocity. The larger the inertia, the greater the force required to accelerate or decelerate the load. Inertia is a function of a load's mass and shape. If there is a constraint on the amount of force available, then the allowable acceleration and deceleration must be adjusted to an acceptable value.

MTBF

MTBF, or Mean Time Between Failure, is a prediction of the reliability of a product. Tests and statistical analysis of parts and components are performed to predict the rate at which a product will fail. It is one of the most common forms of reliability prediction and is usually based on an established analysis model. Many analytical models exist, and choosing one over another must be based on a broad array of factors specific to a product and its application.

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