4 Definitions

actuator
part of a positioning system that provides the necessary forces for moving the carriage with respect to the base

angular deviation
reading of an angular measuring instrument in the direction around any of the three orthogonal directions in a reference coordinate system; angular deviations, which are measured at discrete intervals, constitute a limited representation of the actual angular error motion

axis
coordinate axis or the subset of a positioning system pertaining to a direction of motion, depending upon the context; a positioning system may be called an “axis” only within the context of the positioning system having motion along or about only one nominal line for linear or angular motion, respectively; see also coordinate axis and positioning system

coordinate axis
any fixed reference line of a coordinate system; a coordinate axis may be called an “axis” only within the context of the “axis” being within a coordinate system; see also axis

feed rate
commanded velocity of motion of the carriage

following error
magnitude of the steady-state value of the dynamic positioning deviation for a linear ramp input; see also dynamic positioning deviation and dynamic positioning error

7.2.2.6 Measurement Times

The measurement of in-position jitter is typically performed over a short time interval, because this test is not meant to measure long-term drift. The exact test length, or measurement time, is highly dependent on the final application or end-process and as a result, no default measurement times are provided. A process may last many minutes, hours, or days. Accordingly, the measurements may be sensitive to both short-term drift (in-position jitter) and long-term drift (thermal drift, etc.). However, guidance in selecting the measurement timing is given below:

Length of test: The measurement time (length of test) should be similar to the time required for the axis to sit stationary while processing occurs in the final application. If the end application/process is unknown or not specified, a suggested measurement time length is 250 ms or the move-and-settle time of the positioning axis (whichever is greater) and a minimum of 100 data points (to ensure an adequate statistical sample size).

7.3.4.3 Move-and-Settle Time

The move-and-settle time, \( t_{ms} \), is defined as a difference of two times, as the greatest time after which the absolute value of the given metric remains less than the position tolerance minus the beginning time of the move. In other words, the move-and-settle time is defined as the time the move takes for the metric magnitude to settle within a position tolerance. A different definition of the move-and-settle time may be used upon agreement between the user and the manufacturer/supplier, and in that case, the definition shall be reported in the test report. For example, a different definition may depend upon the velocity signal from the controller.
7.4.3.1 Prerequisites

For the incremental step test, the linear positioning system is commanded to perform a series of steps, whether unidirectionally or bidirectionally, as agreed upon between the user and the manufacturer/supplier. Figure 7.4.1 shows an example plot of displacement versus time for an incremental step test with a measured 2.5 nm commanded step size for bidirectional steps.

7.4.3.4 Criteria to Determine if Axis Performed the Commanded Incremental Step

The following criteria to determine if an axis performed the commanded incremental step should be utilized unless otherwise agreed upon between the user and the manufacturer/supplier. The criteria may be disregarded or modified within the agreement. For example, even if bidirectional data is collected, only the unidirectional incremental step criteria may be utilized to determine if the axis performed the commanded incremental step in a certain direction, if agreed upon between the user and the manufacturer/supplier.

7.4.5 Minimum Incremental Motion

The minimum incremental motion of a linear positioning axis is determined via iteratively performing an Incremental Step Test (see Section 7.4.3). Specifically, two minimum incremental motion values may be determined: the unidirectional minimum incremental motion and the bidirectional minimum incremental motion. Determination of either or both of those values shall be agreed upon between the user and the manufacturer/supplier.

The starting step size to determine the unidirectional minimum incremental motion may be any known step size that satisfies the unidirectional criteria (A1-A3 in Section 7.4.3.4) for the agreed-upon directions, while the starting step size to determine the bidirectional minimum incremental motion may be any known step size that satisfies the bidirectional criteria (B1-B3 in Section 7.4.3.4). For either determination, the step size is then decreased, e.g., in a divide-and-conquer manner, with the Incremental Step Test performed after each change. The Incremental Step Test may also be repeated for any step size but with a smaller move-and-settle time.

The unidirectional minimum incremental motion is the smallest step size in this process that satisfies the unidirectional criteria (A1-A3 in Section 7.4.3.4) for the agreed-upon directions, while the bidirectional minimum incremental motion is the smallest step size in this process that satisfies the bidirectional criteria (B1-B3 in Section 7.4.3.4). Either test is stopped upon reaching the desired refinement of the minimum incremental motion, as agreed upon between the user and the manufacturer/supplier.

7.5.1 Modes of Operation

The linear positioning system shall be programmed to move the axis under test and to position it at a series of target positions. At each target position, the system will remain at rest (dwell) long enough for the actual position reached to be measured and recorded. A measurement delay shall be used such that the axis under test is settled as determined by the Move and Settle Test described in Section 7.3. Additionally, a software trigger, generated by the controller and indicating that the target has been reached, can be used to commence each measurement.

7.5.2.3 Selecting the Target Position

(...)

Target positions are required over the full travel range. If the full travel range is to be sampled in equidistant steps such that \( Q = p \), the nominal interval is \( p = L/(m + 1) \). If \( Q \) is not defined explicitly, \( Q \) shall equal \( p \), provided that \( p \) is large enough that \( P_1 \) and \( P_m \) can be approached bidirectionally.

(...)

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The linear positioning system shall be programmed to move the axis under test and to position it at a series of target positions. At each target position, the system will remain at rest (dwell) long enough for the actual position reached to be measured and recorded. A measurement delay shall be used such that the axis under test is settled as determined by the Move and Settle Test described in Section 7.3. Additionally, a software trigger, generated by the controller and indicating that the target has been reached, can be used to commence each measurement.

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Target positions are required over the full travel range. If the full travel range is to be sampled in equidistant steps such that \( Q = p \), the nominal interval is \( p = L/(m + 1) \). If \( Q \) is not defined explicitly, \( Q \) shall equal \( p \), provided that \( p \) is large enough that \( P_1 \) and \( P_m \) can be approached bidirectionally.
Measurements shall be collected for at least 10 target positions at uniform or random intervals for the validation of the performance specifications of the system. The number of target positions should be chosen according to the application. The measuring intervals shall be no more than one-tenth of the axis length. If the measurement data are used for calibration purposes, then the number of target positions should be increased to capture the desired spatial frequency components. The number of target positions should be chosen in agreement between the user and the manufacturer/supplier and should be stated in the test report (see Section 7.5.11).

The target points shall not be the points used by the manufacturer/supplier to acquire data used for error compensation. In addition, periodic errors, such as errors caused by the lead of a ball screw or the period of an incremental position measuring system, should be considered when choosing sampling intervals. It may be desirable to either choose a nonuniform spacing of the target points or to select an interval that is not an integer fraction of the axis measurement system period (see Section 11). If an external measuring device is used that is known for having periodic errors, for example a displacement measuring interferometer (DMI), the position of the target points shall be chosen in a way that ensures that the measurement is not corrupted by these periodic errors. In that case, the sampling interval should be chosen in agreement between the user and the manufacturer/supplier.

The target positions will be initially calculated at the start of the test cycle and maintained for all test runs. The initial position, \(P_0\), lies at the start of the travel range, and the final position, \(P_{m+1}\), lies at the end of travel range. The measurement points are between and inclusive of \(P_1\) and \(P_m\).

The number of target positions, \(m\), defines the number of points that are measured bidirectionally within and bounding the measurement range. In addition to these \(m\) points, the two endpoints of the travel range will be approached and the positions will be measured. For example, if \(m = 10\) there will be 22 measurements, namely 20 bidirectional measurements spanning the measurement range and a unidirectional measurement at each end of the travel range.

### 7.5.4.5 Methods for Linear Normalization

In some situations, such as when it is desired to focus on periodic or other nonlinear deviations, it is desirable to normalize a set of measurement data by subtracting an overall linear trend. A typical reason for the need of such a linear trend correction is an angle in the basic orientation of the linear positioning system with respect to the measuring device (e.g., the beam of an interferometer) that results in a linear deviation of the measurement results. This linear trend correction is accomplished by calculating a linear fit, either the endpoint normalization line or the least-squares normalization line, based on the dataset and subtracting it from the measurement data. These normalization methods can be applied to any dataset.

### 7.5.8 Linearity and Hysteresis

The linearity \(^1\), \(L\), quantifies the maximum deviation of the system’s intermediate positions from a reference straight line defined by linear normalization. The linear normalization method, as described in Section 7.5.4, shall be agreed upon between the user and the manufacturer/supplier. Also, the corrected positioning deviations, \(x_{ij}^L\), used to evaluate the linearity are calculated separately for each repetition of each travel back and forth \(^2\) and may be corrected for drift, tilt, or both. The chosen linear normalization method and any other corrections shall be documented in the test report.

### 7.5.10.3 Drift Correction Method

(…)

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\(^1\) Linearity is distinct from linear normalization.

\(^2\) Although the correction is made for the intermediate points that are approached bidirectionally, the endpoints \(P_0\) and \(P_{m+1}\) are approached unidirectionally from the interior of the travel range.
If there were no thermal drift, the measured actual positions and therefore the deviations of position would be the same for each repetition, if not for the other sources of uncertainty. In practice, there can be a time-dependent thermal drift resulting in a positioning deviation of the measured actual positions. In the correction described here, it is assumed that the time rate of thermal drift is constant during one repetition. This is usually valid if the measurement time for one repetition is much smaller than the smallest significant thermal time constant of the linear positioning system. If this assumption is not agreed upon between the user and the manufacturer/supplier, then the following thermal drift correction method should not be applied.

7.6.6.2 Data Analysis for Three Phases of Motion

Velocity is defined as the rate of change of displacement, and acceleration is defined as the rate of change of velocity. Because the acceleration can be positive or negative, the metrics defined later in this section take this into account, so that the acceleration and deceleration phases can be compared.

If the velocity $v(t)$ is measured, then it can be used directly for analysis. However, if only the position $p(t)$ is measured at discrete times, then the velocity $v(t)$ shall be estimated by a finite difference approximation \cite{Press} as

\[ v(t) = \frac{p(t) - p(t-\Delta t)}{\Delta t} \]

9.6 Test Uncertainty Analysis

Uncertainties associated with the measurements for the Point Repeatability Test are related to uncertainties of the utilized measurement systems and uncertainties of the axis under test. These uncertainties should be considered when specifying measurement sampling rates and parameters, in order to avoid situations where neither conformance nor non-conformance to specifications can be demonstrated. Potential measurement uncertainty contributors include:

- Uncertainties of geometric error motions of the linear axis
- Measurement uncertainty of the test equipment
- Uncertainty due to misalignment of the measurement axis and the axis under test, $u_{MA}$
  - Cosine error is relatively small as motion is very small
- Uncertainty in the sensor calibration factor, $u_{CAL}$
- Uncertainty due to the sensor resolution/noise, $u_{SR}$
  - Evaluated via a sensor noise floor test
- Uncertainty due to setup repeatability, $u_{\Delta}$
  - Relatively small due to motion being very small
- Uncertainty due to fixturing vibrations, $u_{VIB}$

11.3 Linear Position

Position-sensing systems suitable for long-range applications include laser interferometers, linear encoders, LVDTs, eddy current transducers, and capacitive transducers. Many other position-sensing systems exist and may be used if it can be documented that they meet test requirements. A summary of typical capabilities of the relevant position-sensing systems, based in part on A.J. Fleming’s review manuscript \cite{Fleming} is summarized in Table 11.1. The values presented in the table are order-of-magnitude, so instruments with higher capabilities are available.