ASME B5.64-2022

Methods for the Performance Evaluation of Single-Axis Linear Positioning Systems

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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FOREWORD

Linear positioning systems are used in wide-ranging manufacturing applications from machine tools to high-precision applications such as semiconductors and photovoltaics. Many new high-precision single-axis linear positioning systems are emerging with exceptionally long ranges of motion and positioning resolutions as low as several nanometers. The ability to meet high-precision manufacturing tolerances requires accurate knowledge of the positioning performance of these systems, yet a dedicated standard for evaluating the performance of single-axis linear positioning systems did not exist. In contrast, performance standards have been used for decades to measure the performance of single-axis linear positioning systems within machine tools. However, use of these standards to measure high-precision systems with off-the-shelf instrumentation and test methods can be difficult because the performance of the high-precision class of positioning systems can approach the measurement uncertainty. Due to increasing demands on performance and new applications, many manufacturers and users have developed their own methods for characterizing these systems, but performance specifications based on these different methods and terminology has led to certain customer confusion. Hence, a new standard was needed with specific measurement methods for single-axis linear positioning systems.

Toward this end, this Standard was created by members from industry, academia, and government in coordination with the B5 Standards Committee of The American Society of Mechanical Engineers (ASME) to provide methods for the performance evaluation of single-axis linear positioning systems. The intended use of the tests described in this Standard are acceptance testing of new or reconditioned systems and verification of the performance of systems already in operation.

ASME B5.64-2022 was approved by the American National Standards Institute on December 5, 2022.

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Machine Tools — Components, Elements, Performance, and Equipment

(The following is the roster of the committee at the time of approval of this Standard.)

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Section 1
Scope

1-1 SCOPE

(a) This Standard establishes a methodology for specifying and testing the performance of single-axis linear positioning systems. It covers linear positioning systems with travels ranging from micrometers to meters.

(b) This Standard describes equivalent test methods and instrumentation described in existing machine tool standards (ASME B5.54, ASME B5.57, and ISO 230 series) and additional methods and instrumentation used for the characterization of positioning systems having a relatively high positioning performance when compared to standard machine tool performance.

(c) This Standard seeks to highlight the importance of understanding measurement uncertainty and the test uncertainty ratio (TUR) by providing methods for estimating the test uncertainty and the uncertainty of positioning performance results.

(d) In addition to clarifying the positioning performance evaluation, this Standard facilitates performance comparisons between systems by unifying terminology and the treatments of environmental effects and measurement uncertainty.

(e) This Standard provides a series of tests that should be used to perform acceptance testing of new and reconditioned positioning systems and could be used to verify the continued capability of systems, already in operation, through periodic testing. The set of acceptance tests and the specification limits for system conformance shall be the subject of contractual agreement between the user and the manufacturer/supplier.

Section 2
References

2-1 NORMATIVE REFERENCES

The following documents are referred to in the text in such a way that some or all their content constitutes requirements of this Standard. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies:

ASME B5.54-2005 (R2020). Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers. The American Society of Mechanical Engineers.
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2-2 INFORMATIVE REFERENCES

The following documents are referenced in this Standard and are indispensable for the application of this Standard. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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Section 3 Nomenclature

3-1 NOMENCLATURE

This Section defines variables, units of measure, and acronyms used in this Standard.

3-1.1 General

1D = one-dimensional
2D = two-dimensional
3D = three-dimensional
A = bidirectional positioning accuracy or rotation about the X-axis, depending upon the context
a_E = conversion factor
a_q = estimated acceleration at the qth time value t_q
$\tilde{a}$ = filtered acceleration
$\tilde{a}_q$ = filtered acceleration at the qth time value t_q
$\tilde{a}_{\mathrm{mean}}$ = mean filtered acceleration
$\tilde{a}_{\mathrm{max}}$ = maximum filtered acceleration amplitude
A^L = standardized bidirectional positioning accuracy
B = system reversal error or rotation about the Y-axis, depending upon the context
$\overline{B}$ = average reversal error
B_i = reversal deviation at a position
C = rotation about the Z-axis or system model for the feedback control algorithm in a servo loop, depending upon the context
c = control configuration number
csF = fixed coordinate system associated with the support frame of the positioning system
d = measured relative position
d_1 = disturbance at the input of a plant in a servo loop
d_2 = disturbance at the output of a plant in a servo loop
d_i = measured relative position at sampled time t_i
$d_{\mathrm{pk-pk}}$ = range, or peak-to-peak value, of all measured relative positions
dx_i = measured relative position in the X-axis direction
dy_i = measured relative position in the Y-axis direction
dz_i = measured relative position in the Z-axis direction
$\bar{d}x_i$ = mean measured relative position in the X-axis direction
$\bar{d}y_i$ = mean measured relative position in the Y-axis direction
$\bar{d}z_i$ = mean measured relative position in the Z-axis direction
csM = moving coordinate system, associated with the carriage
E = bidirectional systematic positioning error
E_{AX} = angular error motion about the X-axis as a function of the commanded position
$E_{AX,E}$ = bidirectional angular error about the X-axis
$E_{AX,E\uparrow}$ = unidirectional angular error about the X-axis, positive direction
$E_{AX,E\downarrow}$ = unidirectional angular error about the X-axis, negative direction
E_{BX} = angular error motion about the Y-axis as a function of the commanded position
$E_{BX,E}$ = bidirectional angular error about the Y-axis
$E_{BX,E\uparrow}$ = unidirectional angular error about the Y-axis, positive direction
$E_{BX,E\downarrow}$ = unidirectional angular error about the Y-axis, negative direction
E_{CX} = angular error motion about the Z-axis as a function of the commanded position
$E_{CX,E}$ = bidirectional angular error about the Z-axis

$E_{CX,E\uparrow}$ = unidirectional angular error about the Z-axis, positive direction
$E_{CX,E\downarrow}$ = unidirectional angular error about the Z-axis, negative direction
E_{FP} = representation of the translational error of the functional point in csF having coordinates $E_{XX\mathrm{FP}}$, $E_{YX\mathrm{FP}}$, $E_{ZX\mathrm{FP}}$
E_{MP} = representation of the translational error of a measurement point in csF having coordinates $E_{XX\mathrm{MP}}$, $E_{YX\mathrm{MP}}$, $E_{ZX\mathrm{MP}}$
E_{pose} = 3 × 3 matrix containing only the pose errors E_{AX}, E_{BX}, E_{CX} equivalent to $^{F R}M$ minus the identity matrix for a linear positioning system
E_X = straightness error motion in the X-axis direction
E_{XX} = linear positioning error motion in the X-axis direction as a function of the commanded position
E_Y = straightness error motion in the Y-axis direction
E_{YX} = straightness error motion in the Y-axis direction as a function of the commanded position
$E_{YX,E}$ = bidirectional straightness error in the Y-axis direction
$E_{YX,E\uparrow}$ = unidirectional straightness error in the Y-axis direction, positive direction
$E_{YX,E\downarrow}$ = unidirectional straightness error in the Y-axis direction, negative direction
E_Z = straightness error motion in the Z-axis direction
E_{ZX} = straightness error motion in the Z-axis direction as a function of the commanded position
$E_{ZX,E}$ = bidirectional straightness error in the Z-axis direction
$E_{YX,E\uparrow}$ = unidirectional straightness error in the Z-axis direction, positive direction
$E_{ZX,E\downarrow}$ = unidirectional straightness error in the Z-axis direction, negative direction
E_{TV} = environmental temperature variation error
E^L = standardized bidirectional systematic positioning error
$E'_{xi,j}$ = position error in the X-axis direction
$E'_{yi,j}$ = position error in the Y-axis direction
$E'_{zi,j}$ = position error in the Z-axis direction
f = temporal frequency in hertz (Hz)
F = system model for a feedforward control algorithm in a servo loop
$^{F H}M$ = 4 × 4 matrix containing direction cosines and origin offset components, which transforms the representation of the position vector of a point in csM into the representation of that point's position vector in csF
FP = functional point
$^{F R}M$ = 3 × 3 matrix containing direction cosines that transforms the representation of a vector in csM into that same vector's representation in csF
G = system model for the closed-loop response in a servo loop
H = hysteresis
HDA = hysteresis, corrected for drift and Abbe error
H_i = hysteresis at the ith position
i = index of target position
j = index for set of measurements
k = coverage factor
l_α = Abbe distance for angle α
l_β = Abbe distance for angle β
L = length, system model for the loop transmission in a servo loop, or bidirectional maximum linearity, depending upon the context
L_m = measurement range
L_t = travel range
$L_{t,\min}$ = minimum travel position
$L_{t,\max}$ = maximum travel position
$L\uparrow$ = forward linearity
$L\downarrow$ = reverse linearity
L^{DA} = linearity, corrected for drift and Abbe error
L^{DR} = laser display reading
m = number of target positions
M = mean bidirectional positioning error
M^L = standardized value of the mean bidirectional positioning error
$\overrightarrow{\mathrm{MP}_M}$ = vector from the origin of csM to a specific measuring point
MP_M = representation of $\overrightarrow{\mathrm{MP}_M}$ in csM having coordinates MP_{xM}, MP_{ym}, MP_{zM}

N = total number of sampled data points for a time-sampled function
n = number of measurements of a set of target positions
oF = origin of csF
oM = origin of csM
p = nominal interval based on uniform distribution of the target points
p_q = actual position at the qth time value
$p_{rn,i}$ = pseudo-random number for the ith target position
P = periodic linear motion error or system model for the plant in a servo loop, depending upon the context
P_{actual} = actual position as a function of time t
$P_{\text{actual},c}$ = actual position for the cth control configuration as a function of time t
$\overline{P}_0$ = average value of the measured starting point
$\overline{P}_{m+1}$ = average value of the measured endpoint
$P0$ = initial position
P_{m+1} = final position
P_i = ith target position
P_{ij} = actual position of the functional point on the jth approach to the ith target position
PiE = commanded position, open loop
$\overrightarrow{P_F}$ = vector from oF to a point P in space having representation P_F with components P_{XF} , P_{YF} , and P_{ZF}
$\overrightarrow{P_M}$ = vector from oM to a point P in space having representation P_M with components P_{XM}, P_{YM}, and P_{ZM}
P_{target} = target position as a function of time t
PRx = multi-directional point repeatability, X-axis component or direction
PRx_i = multi-directional point repeatability for the ith test configuration, X-axis component or direction
PRy = multi-directional point repeatability, Y-axis component or direction
PRy_i = multi-directional point repeatability for the ith test configuration, Y-axis component or direction
PRz = multi-directional point repeatability, Z-axis component or direction
PRz_i = multi-directional point repeatability for the ith test configuration, Z-axis component or direction
q = index of discrete sensor measurements collected at a defined sampling rate
Q = length of travel greater than zero at each end of the travel range that ensures that all points within the travel range can be approached bidirectionally
R = bidirectional positioning repeatability
r = number of discrete measurements collected in one measurement cycle
$R\uparrow$ = unidirectional positioning repeatability, positive direction
$R\downarrow$ = unidirectional positioning repeatability, negative direction
Rm = maximum of the unidirectional positioning repeatability
$\overline{R}$ = average value of the average unidirectional positioning repeatability
$\overline{R}\uparrow$ = average unidirectional positioning repeatability, positive direction
$\overline{R}\downarrow$ = average unidirectional positioning repeatability, negative direction
R_i = bidirectional positioning repeatability at ith position
$R_i\uparrow$ = extended unidirectional positioning repeatability at ith position, positive direction
$R_i\downarrow$ = extended unidirectional positioning repeatability at ith position, negative direction
S = stroke or system model for the output sensitivity in a servo loop, depending upon the context
s = standard deviation
S_d = power spectral density of measured signal, $d(t)$, as function of frequency, f
S_P = process sensitivity for a servo loop
$s_i\uparrow$ = estimator for unidirectional axis positioning repeatability at ith position, positive direction
$s_i\downarrow$ = estimator for unidirectional axis positioning repeatability at ith position, negative direction
s_{inc} = sample standard deviation for incremental motion
sx_i = standard deviation of measurement cycle data set, X-axis direction
sy_i = standard deviation of measurement cycle data set, Y-axis direction
sz_i = standard deviation of measurement cycle data set, Z-axis direction
T = temperature, or system model for the complementary sensitivity in a servo loop, depending upon the context
$\overrightarrow{T}$ = translation vector, generally from the origin of one coordinate system to the origin of another coordinate system, specifically from oF to oM
T_F = representation of $\overrightarrow{T}$ in csF, generally having coordinates T_X, T_Y, and T_Z

t = time
t_{ave} = average time
t_{ms} = move-and-settle time
t_q = time at the qth time value
t_{CV1} = time at which a commanded constant-velocity phase begins
t_{CV2} = time at which a commanded constant-velocity phase ends
t_{VS} = time at which vibration is settled
t_{W1} = minimum window time
t_{W2} = maximum window time
u = standard uncertainty
u_{Δ} = standard uncertainty due to setup repeatability
u_C = combined standard uncertainty
u_{AR} = standard uncertainty due to linear axis position repeatability
u_{CAL} = standard uncertainty due to sensor calibration
u_{DAQ} = standard uncertainty due to data acquisition system noise
u_{DDS} = standard uncertainty due to distance between displacement sensors
u_{EVE} = standard uncertainty due to environmental variations
u_{MA} = standard uncertainty due to sensor misalignment
u_r = sum of strongly positive correlated contributors
u_{RES} = standard uncertainty due to resolution
u_{SCE} = standard uncertainty due to sensor correction error
u_{SR} = standard uncertainty due to sensor resolution
u_{SRE} = standard uncertainty due to straightness reference error
u_{SYNC} = standard uncertainty due to temporal synchronization of position and error motion data
u_{TD} = standard uncertainty due to thermal drift of the measurement setup
u_{TR} = standard uncertainty due to triggering
u_{VIB} = standard uncertainty due to fixturing vibrations of the measurement points
u_{uc} = standard uncertainty of uncorrelated contributor
uPRx = unidirectional point repeatability, X-axis component or direction
uPRx_i = unidirectional point repeatability for the ith test configuration, X-axis component or direction
uPRy = unidirectional point repeatability, Y-axis component or direction
uPRy_i = unidirectional point repeatability for the ith test configuration, Y-axis component or direction
uPRz = unidirectional point repeatability, Z-axis component or direction
uPRz_i = unidirectional point repeatability for the ith test configuration, Z-axis component or direction
U = measurement uncertainty, the expanded uncertainty
$U(A)$ = measurement uncertainty of bidirectional accuracy of positioning
$U(A\uparrow)$ = measurement uncertainty of unidirectional accuracy of positioning, positive direction
$U(A\downarrow)$ = measurement uncertainty of unidirectional accuracy of positioning, negative direction
$U(B)$ = measurement uncertainty of reversal value
$U(E)$ = measurement uncertainty of bidirectional systematic deviations
$U(E\uparrow)$ = measurement uncertainty of unidirectional systematic deviations, positive direction
$U(E\downarrow)$ = measurement uncertainty of unidirectional systematic deviations, negative direction
$U(M)$ = measurement uncertainty of the mean positioning deviation
$U(R)$ = measurement uncertainty of bidirectional repeatability
$U(R\uparrow)$ = measurement uncertainty of unidirectional repeatability, positive direction
$U(R\downarrow)$ = measurement uncertainty of unidirectional repeatability, negative direction
$u(A)$ = standard uncertainty of bidirectional accuracy of positioning
$u(A\uparrow)$ = standard uncertainty of unidirectional accuracy of positioning, positive direction
$u(A\downarrow)$ = standard uncertainty of unidirectional accuracy of positioning, negative direction
$u(B)$ = standard uncertainty of reversal value
$u(E)$ = standard uncertainty of bidirectional systematic deviations
$u(E\uparrow)$ = standard uncertainty of unidirectional systematic deviations, positive direction
$u(E\downarrow)$ = standard uncertainty of unidirectional systematic deviations, negative direction
$u(M)$ = standard uncertainty of mean positioning deviation
$u(R)$ = standard uncertainty of bidirectional repeatability
$u(R\uparrow)$ = standard uncertainty of unidirectional repeatability, positive direction

$u(R\downarrow)$ = standard uncertainty of unidirectional repeatability, negative direction
$v(E_{\mathrm{FP}})$ = variance of the determined error vector of the functional point
$v(E_{\mathrm{MP}})$ = variance of the determined error vector of a measurement point
v_{pose} = variance of the pose error matrix E_{pose}
v_q = estimated velocity at the qth time value t_q
$\tilde{v}$ = filtered velocity
$\tilde{v}_{\mathrm{CV}}$ = mean filtered velocity during the constant-velocity phase
$\tilde{v}_H$ = Hilbert metric of the filtered velocity $\tilde{v}$
$\tilde{v}_{\mathrm{mean}}$ = mean filtered velocity
$\tilde{v}_q$ = filtered velocity at the qth time value t_q
$\tilde{v}_{\mathrm{sd}}$ = standard deviation of the filtered velocity $\tilde{v}$
W = windowing function
W_q = windowing function at sampled time t_q
x = dynamic positioning deviation between the actual position and the target position as a function of time t
x_c = dynamic positioning deviation between the actual position and the target position for the cth control configuration as a function of time t
xF = x-axis of csF
xM = x-axis of csM
$\bar{x}$ = mean bidirectional deviation of axis positioning
$\bar{x}_i$ = mean bidirectional deviation of axis positioning at ith position
$\bar{x}_i\uparrow$ = mean unidirectional positioning deviation at ith position, positive direction
$\bar{x}_i\downarrow$ = mean unidirectional positioning deviation at ith position, negative direction
x_{ij} = positioning deviation for jth measurement at ith position
$x_{ij}\uparrow$ = positioning deviation for jth measurement at ith position, positive direction
$x_{ij}\downarrow$ = positioning deviation for jth measurement at ith position, negative direction
$x^D{}_{ij}$ = positioning deviation for jth measurement at ith position with applied drift correction
$x^A{}_{ij}$ = positioning deviation for jth measurement at ith position with applied Abbe correction
$x^L{}_{ij}$ = positioning deviation for jth measurement at ith position with applied linear correction
$x^{DA}{}_{ij}$ = positioning deviation for jth measurement at ith position $\bar{x}$ with applied drift and Abbe correction
$x^{DAL}{}_{ij}$ = positioning deviation for jth measurement at ith position with applied drift, Abbe and linear correction
$\bar{x}_i^l\uparrow$ = mean unidirectional linearly corrected positioning deviation, positive direction
$\bar{x}_i^l\downarrow$ = mean unidirectional linearly corrected positioning deviation, negative direction
$\bar{x}_i^l$ = mean bidirectional positioning deviation at a linearly corrected position
X_{CS} = commanded step size for incremental motion
$\bar{x}_{\mathrm{inc}}$ = sample mean for incremental motion
yF = y-axis of csF
yM = y-axis of csM
zF = z-axis of csF
zM = z-axis of csM
Z_i = commanded value at ith position
α = axis direction or coefficient of thermal expansion, depending upon the context
β = straightness error direction or angular error direction, depending upon the context
α_{ij} = angles resulting from an angular measurement
κ = thermal conductivity of a material
τ = time constant of a physical quantity
β_{ij} = angles resulting from an angular measurement

3-1.2 Symbols and Units of Measure

$\uparrow$ = positive/forward direction
$\downarrow$ = negative/reverse direction
N = newton, unit of force
μm = micrometer (one millionth of a meter), unit of length
μrad = microradian (one millionth of a radian), unit of angle
rpm = revolutions per minute

3-1.3 Acronyms

BCF = broadband correction factor
CLR = corrected laser reading
CMR = corrected machine reading
CNC = computer numerical control
CPC = controller position corrected for thermal expansion of the internal scales, which is attributable to the external environment
CTE = coefficient of thermal expansion
DPE = dynamic positioning error
DMI = displacement measuring interferometer
ETVE = Environmental temperature variation error
FP = functional point
LVDT = linear variable differential transformer
LUT = look-up table
MAE = moving average error
MM = moving mean
MP = measurement point
MPE = moving peak error
MSD = moving standard deviation
NE = nominal expansion
PSD = position sensing detector
PSD = power spectral density
RH = relative humidity
RMS = root-mean-square
SD = standard deviation
SDR = system display reading
TUR = test uncertainty ratio

Section 4
Definitions

4-1 INTRODUCTION

This Section defines technical terms used in this Standard. Definitions quoted or adapted from other sources include a parenthetical citation of the source. Definitions that do not include a parenthetical citation are specific to this Standard.

4-2 TERMS AND DEFINITONS

Abbe error: measurement error resulting from angular motion of a movable component and an Abbe offset. [ASME B5.54-2005 (R2020)]

Abbe offset: perpendicular distance between the desired point of measurement and the reference line of the measuring system.

Abbe principle: path of the measurement point of a displacement-measuring system should be colinear with the functional point whose displacement is to be measured.

accuracy: quantitative measure of the degree of conformance to recognized national or international physical standards and methods of measurement. [ASME B5.54-2005 (R2020)]

actual position, P_{ij}: measured position reached by the functional point on the *j*th approach to the *i*th target position. (ISO 230-2:2014)

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

ambient temperature: temperature of the ambient air surrounding a machine [ASME B5.54-2005 (R2020)]; see also *mean ambient temperature*.

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.

angular displacement sensor: sensor used to measure angular displacements between two objects such as an autocollimator that converts an angular displacement to a numerical or analog value.

angular error (of a linear axis): value of the largest positive angular deviation added to the absolute value of the largest negative angular deviation measured during a complete traverse of the moving component, evaluated for any one of the three orthogonal directions. (ISO 230-1:2012)

angular error motion (of a linear axis): unwanted rotational movement of a moving component commanded to move along a (nominal) straight-line trajectory. (ISO 230-1:2012)

artifact: see *reference artifact*.

autocollimator: optical instrument that allows measurement of the angle between its optical axis and a mirror whose calibration is independent of the distance between the instrument and the mirror

average: see *mean*.

average reversal value of an axis, $\overline{B}$: arithmetic average of the reversal errors, B_i, at *m* target positions.

$$\overline{B} = \frac{1}{m}\sum_{j=1}^{m} B_i \tag{4-2-1}$$

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.*

axis acceleration/deceleration: rate of change of velocity of the carriage.

axis position: instantaneous position of the carriage of the positioning system.

axis travel: maximum travel over which the carriage can move under numerical control.

backlash: error associated with mechanical looseness, e.g., clearance between a screw and a nut; this error will induce a position change dependent on the direction of travel toward the specified control position.

bandpass filter: filter that significantly attenuates signal components with frequencies outside of a specified range (band) between two cutoff frequencies.

bandwidth: range of frequencies (usually expressed in hertz) where the amplitude or the amplification of a signal exceeds a particular threshold level or limits within which the power spectrum is considered (ISO/TR 230-8:2010); see also measurement bandwidth and servo bandwidth.

base: portion of a positioning system that provides structural support for the actuator and carriage guideway of a positioning system.

base coordinate system: reference coordinate system that is attached in space to the base of a positioning system.

base frame: see *base.*

bidirectional: a parameter derived from a series of measurements in which the approach to a target position is made in either direction along or around an axis [ASME B5.54-2005 (R2020)]; the symbol "↑↓" signifies a parameter derived from a test performed with approaches in the forward direction and the reverse direction (e.g., $R\uparrow\downarrow$).

bidirectional positioning accuracy of an axis, A: range derived from the combination of the mean bidirectional systematic positioning errors and the estimator for axis repeatability of bidirectional positioning using a coverage factor of $k = 2$. (ISO 230-2:2014)

$$A = \max[(\bar{x}_i\uparrow + 2s_i\uparrow;\ \bar{x}_i\downarrow + 2s_i\downarrow]) - \min([\bar{x}_i\uparrow - 2s_i\uparrow;\ \bar{x}_i\downarrow - 2s_i\downarrow)] \tag{4-2-2}$$

bidirectional positioning repeatability at a position, R_i: range representing the expanded uncertainty of positioning at any position P_i.

$$R_i = \max[(2s_i\uparrow + 2s_i\downarrow + |B_i|;\ R_i\uparrow;\ R_i\downarrow)] \tag{4-2-3}$$

bidirectional positioning repeatability of an axis, R: maximum value of the repeatability of positioning at any position P_i. (ISO 230-2:2014)

$$R = \max(R_i) \tag{4-2-4}$$

bidirectional systematic positioning error of an axis, E: difference between the algebraic maximum and minimum of the mean unidirectional positioning deviations for both approach directions $\bar{x}_i\uparrow$ and $\bar{x}_i\downarrow$ at any position P_i. (ISO 230-2:2014)

$$E = \max[(\bar{x}_i\uparrow;\ \bar{x}_i\downarrow]) - \min([\bar{x}_i\uparrow;\ \bar{x}_i\downarrow)] \tag{4-2-5}$$

Bode plot: graph of the frequency response of a dynamic system that shows both the magnitude gain and the phase shift that the system applies to a signal as a function of frequency.

Bryan principle: if applying the Abbe principle is not possible, either the slideways that transfer the displacement must be free of angular motion or angular-motion data must be used to calculate the consequences of the offset.

calibration: operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication. (OIML V1:2013)

cap test: see *isolated sensor check*.

capacitance gauge: displacement sensor of relatively short range and high resolution that functions by measuring the electrical capacitance between the probe tip and the surface being displaced. [ASME B5.54-2005 (R2020)]

capacitance probe: see *capacitance gauge*.

capacitive displacement sensor: see *capacitance gauge*.

carriage: moving component of a positioning system used for transporting a functional point, a tool, probe, workpiece, or a second positioning system to a commanded location; a linear carriage has a nominal direction of motion referred to often as an (X, Y, or Z, etc.) axis.

carriage average line: see *reference straight line*.

carriage coordinate system: reference coordinate system that is spatially fixed relative to the moving carriage of a positioning system, identified, e.g., csM.

carriage travel: see *axis travel*.

coefficient of thermal expansion (CTE): true coefficient of expansion, α, at a temperature, T, of a body is the rate of change of length of the body, L, with respect to temperature at the given temperature divided by the measured length at the given temperature, L_T. [ASME B5.54-2005 (R2020)]

$$\alpha = \frac{1}{L_T}\left(\frac{dL}{dT}\right)_T \tag{4-2-6}$$

combined standard uncertainty, u_C: standard uncertainty of the result of a measurement when that result is obtained from the values of several other quantities, equal to the positive square root of a sum of terms, the terms being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities. (JCGM 100:2008)

command: operative order to initiate a movement or a function. [ASME B5.54-2005(R2020)]

compensation: practice of using prerecorded error tables and in-process sensing of variables such as temperature for correcting the axis position of a linear positioning system using a controller.

compliance: translational (or rotational) displacement per unit static force (or moment) between two objects, specified with respect to the structural loop, the location and direction of the applied forces (or moments), and the location and direction of the displacement of interest.

computer numerical control (CNC): numerical control system in which the data-handling sequence, control functions, and response to data input are determined primarily by a control program executed by a digital data-processing system. [ASME B5.54-2005 (R2020)]

controller: see *control system*.

control system: part of a positioning system that uses alphanumeric data input to define the controlled motion and position of the carriage with respect to the base; see also numerical control system.

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

coordinate system: theoretical mathematical construct for providing kinematic analysis of position, orientation, and motion, which is typically a right-hand rectangular system (i.e., Cartesian system) composed of three orthogonal coordinate axes; see also *reference coordinate system*.

cosine error: measurement error in the motion direction caused by angular misalignment between a linear displacement measuring system and the displacement being measured. [ASME B5.54-2005 (R2020)]

coverage factor, k: numerical factor used as a multiplier of the combined standard uncertainty to obtain an expanded uncertainty. (JCGM 100:2008)

cumulative amplitude spectrum: the square root of the cumulative power spectrum.

cumulative power spectrum: function of frequency that integrates the power spectral density over a given frequency range.

cumulative root-mean-square: see *cumulative amplitude spectrum*.

cutoff frequency: frequency above (or below) which a filter significantly reduces frequency components of a signal, typically defined as the frequency at which the gain of the filter decreases to $1\sqrt{2}\,(\approx 0.7071)$ of the nominal gain or the gain at a defined frequency.

deviation: difference between an actual value and the desired value, or commanded value, of a quantity [ASME B5.54-2005 (R2020)]; see also *positioning deviation*.

deviation of position: see *positioning deviation*.

displacement sensor: sensor used to measure displacements, whether linear or angular, which converts the displacement to a numerical or analog value; see also *angular displacement sensor* and *linear displacement sensor*.

drift: time-dependent variation of indications of the measurand that is observed while holding controllable parameters constant; this includes effects from the measurand, the measuring instrument, and the environmental effects on the experimental setup such as the mounting structure or sensor-carriage interface; ambient parameters such as temperature are often simultaneously recorded for compensation purposes.

drift compensation: mathematical method to compensate the drift occurring during a measurement sequence; see also *compensation* and *drift*.

dynamic positioning: procedure where the positioning system is not settled and may be moving at a target position during measurements or usage; in contrast, see *static positioning*.

dynamic positioning deviation, x: signed difference between the actual position, P_{actual}, and the target position, P_{target}, as a function of time, t; see also *dynamic positioning*.

$$x(t) = P_{\text{actual}}(t) - P_{\text{target}}(t) \tag{4-2-7}$$

dynamic positioning error (DPE): maximum absolute difference of the actual position and the target position for the entire motion.

eddy current sensor: sensor using oscillatory magnetic field excitation and a probe head to detect (sense) changes in its surroundings, e.g., the presence of a target near the probe head; within the framework of this Standard, eddy current sensors can be used as distance-measuring devices.

eddy current position sensor: see *eddy current sensor.*

endpoint linear normalization: method that results in a dataset corrected by an endpoint reference straight line; see also *linear normalization*.

endpoint reference straight line: straight line connecting the first and the last point of the measured straightness deviations. (ISO 230-1:2012)

environmental temperature variation error, ETVE: estimate of the maximum possible position uncertainty induced solely by deviation of the environment temperature from average conditions. [ASME B5.54-2005 (R2020)]

error: value representing a property of a set of deviations related to the response of a machine to a command issued according to the accepted protocol; for example, see *angular error*, *reversal error*, and *straightness error*.

error motion: unwanted linear or angular motion of a component commanded to move along a (nominal) straight line trajectory. (ISO 230-1:2012)

expanded uncertainty, U: quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand (JCGM 100:2008), obtained by multiplying the combined standard uncertainty by a coverage factor.

estimator for the unidirectional axis positioning repeatability at a position, $s_i\uparrow$ and $s_i\downarrow$: estimator of the standard uncertainty of the positioning deviations obtained by a series of n unidirectional approaches at a position P_i (ISO 230-2:2014)

$$s_{i\uparrow} = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(x_{ij\uparrow} - \bar{x}_{i\uparrow}\right)^2} \tag{4-2-8}$$

$$s_{i\downarrow} = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(x_{ij\downarrow} - \bar{x}_{i\downarrow}\right)^2} \tag{4-2-9}$$

feed hold: see *system hold*.

feed rate: commanded velocity of motion of the carriage.

filter: device or process that significantly attenuates unwanted frequency components of a signal; there are three basic types of filters available for signal conditioning and analysis: low-pass filters, high-pass filters, and bandpass filters (ISO 13373-2:2016); filters may be electronic, mechanical, optical, or algorithmic in nature, and frequencies may be temporal or spatial; see also *bandpass filter*, *low-pass filter*, and *high-pass filter*.

filter cutoff frequency: see *cutoff frequency*.

filter characteristics: properties of a filter that characterize the relationship of the filter output to the filter input; for example, simple filters, analogue as well as digital, will have gradual as opposed to sharp cut-off characteristics, because the filter slope outside of the transmission band is relatively shallow. (ISO 13373-2:2016)

fixture: device that securely locates and orients an object to another object.

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.*

Fourier spectrum: result of a Fourier transform (ISO 13373-2:2016), which is the complex amplitude of a signal as a function of frequency.

Fourier transform: mathematical technique that identifies the sinusoidal frequency components of a signal.

functional point: point where a process and/or measurement occurs; the point may move or be fixed with respect to the base of a positioning system.

gain crossover frequency: frequency where the open-loop magnitude of the system frequency response equals one; see also *phase margin*.

gain margin: amount of change in open-loop gain needed to make a closed-loop system marginally stable, which equals the gain change required to make the open-loop gain equal 1 at the frequency where the open-loop phase equals −180 deg (i.e., at the phase crossover frequency); see also *phase margin*.

high-pass filter: filter that significantly attenuates signal components with frequencies below a cutoff frequency.

home position: see *positioning system datum*.

hysteresis: linear (or angular) displacement between two objects resulting from the sequential application and removal of equal forces (or moments) in opposite directions (ISO 230-1:2012); it is a component of bidirectional repeatability that is caused by mechanisms such as drive train clearance, guideway clearance, mechanical deformations, friction, and loose joints [ASME B5.54-2005 (R2020)]. For piezo electric actuators, hysteresis is an intrinsic characteristic and can be measured; see also *open loop hysteresis*, *positioning system hysteresis*, and *setup hysteresis*.

incremental step test: test in which the linear positioning system is commanded to move in a series of either unidirectional or bidirectional steps.

indication: quantity value provided by a measuring instrument or a measuring system. (OIML V1:2013)

indicator: see *linear displacement sensor*.

initial position: fixed point along an axis referenced with respect to a machine datum. [ASME B5.54-2005 (R2020)]

initialization: sequence of operations establishing the starting point of a machine. [ASME B5.54-2005 (R2020)]

isolated sensor check: test for drift and electrical noise of a measuring instrument, most commonly applied to displacement sensors, and typically performed by fixing the main sensor measurand, such as by placing a stable “cap” on a displacement sensor and monitoring the sensor’s output over time; aside from inhibiting or blocking the main sensor measurand, the sensor should be connected and monitored as it would be otherwise.

laser interferometer: fringe-counting interferometer for displacement measurement that uses a laser as a light source and is based on the principals of optical interference. [ASME B5.54-2005 (R2020)]

latency: measure of the time delay between a cause and its effect in a system.

least-squares method: mathematical method to approximate the solution of an overdetermined system of equations by minimizing the sum of the squares of the residuals; see also residual.

least squares reference straight line: straight line, where the sum of the squares of the measured straightness deviations is minimum. (ISO 230-1:2012)

least-squares linear normalization: method that results in dataset corrected by a least squares reference straight line; see also *linear normalization*.

linear axis: see *linear positioning system*.

linear displacement sensor: device such as a linear variable differential transformer, capacitance gauge, or other sensor that converts a linear displacement to a numerical or analog value that is used to measure displacements between a surface and a reference point.

linear normalization: method to normalize a set of measurement data by subtracting an overall linear trend; see also *endpoint linear normalization*, *least-squares linear normalization*, and *minimum zone linear normalization*.

linear positioning error motion: unwanted motion along the direction of motion that results in the actual local position reached by the moving component at the functional point differing from the local commanded position along the direction of motion. (ISO 230-1:2012)

linear positioning system: positioning system that is designed to constrain, move, and position the carriage relative to the base along a commanded (nominal) straight-line trajectory.

linearity: maximum absolute straightness deviation with respect to the endpoint reference straight line.

linear variable differential transformer (LVDT): electromagnetic device used for displacement measurement [ASME B5.54-2005 (R2020)]; normally an LVDT has the capability to convert a displacement into a proportional electrical signal. [ASME B5.54-2005 (R2020)]

look-up table (LUT): method for mapping a numerical input to an output involving interpolation or locating the closest entry in the input column of the table and outputting the corresponding value from a precalculated output column.

loop transfer function: see *loop transmission*.

loop transmission: combined response of all systems in a path around the feedback loop, which captures the response of each system in the chain from an actuator command through the overall system response, the state measurement, feedback control algorithm, and finally back to a new actuator command.

lower tolerance: minimum permissible value of a parameter.

low-pass filter: filter that significantly attenuates signal components with frequencies above a cutoff frequency.

machine: see *positioning system.*

machine coordinate system: see *positioning system coordinate system.*

machine datum: see *positioning system datum.*

machine hysteresis: see *positioning system hysteresis.*

manufacturer: party that manufactured the positioning system under test.

mean: average value of a set of physical values, calculated by dividing the sum of all values by the number of values; the mean value is denoted with a bar over the symbol.

mean ambient temperature: mean temperature of the ambient environment surrounding a positioning system as computed from at least two readings taken as close as possible to the functional point during the interval required for the test; see also *ambient temperature*.

mean bidirectional positioning deviation at a position, $\bar{x}_i$: arithmetic mean of the mean unidirectional positioning deviations $\bar{x}_i\uparrow$ and $\bar{x}_i\downarrow$, obtained from the two directions of approach at a position P_i. (ISO 230-2:2014)

$$\bar{x}_i = \frac{\bar{x}_i\uparrow + \bar{x}_i\downarrow}{2} \tag{4-2-10}$$

mean bidirectional positioning error of an axis, M: difference between the algebraic maximum and minimum of the mean bidirectional positioning deviations $\bar{x}_i$ at any position P_i. (ISO 230-2:2014)

$$M = \max(\bar{x}_i) - \min(\bar{x}_i) \tag{4-2-11}$$

mean minimum zone reference straight line: arithmetic mean of two parallel straight lines in the straightness plane enclosing the measured straightness deviations and having the least separation. (ISO 230-1:2012)

mean scale temperature: mean temperature of a positioning system's measuring scale as computed from at least two temperature readings taken on that scale during the interval spanning the time required for a test.

mean temperature: average temperature computed from a stated number of temperature measurements at equally spaced time intervals at a specified location. [ASME B5.54-2005 (R2020)]

mean reversal error of an axis, $\bar{B}$: arithmetic mean of the reversal errors B_i at all target positions. (ISO 230-2:2014)

$$\bar{B} = \frac{1}{m}\sum_{i=1}^{m} B_i \tag{4-2-12}$$

mean unidirectional positioning deviation at a position, $\bar{x}_i\uparrow$ and $\bar{x}_i\downarrow$: arithmetic mean of the positioning deviations obtained by a series of n unidirectional approaches to a position P_i. (ISO 230-2:2014)

$$\bar{x}_i\uparrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij}\uparrow \tag{4-2-13}$$

$$\bar{x}_i\downarrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij}\downarrow \tag{4-2-14}$$

measurement: see *indication*.

measurement bandwidth: bandwidth for the measurement, calculated as the frequencies common to all bandwidths used for the measurement, including those of the sensor and data acquisition equipment.

measurement frequency range: see *measurement bandwidth*.

measurement home: position of the carriage after an initialization followed by an initial preselected displacement by the controller or user, or both; this position sets the initial alignment of the carriage (moving) coordinate system to the base (fixed) coordinate system; this position is both physical and has an associated controller-determined numerical value that may differ from zero.

measurement point: point at which measurements are taken.

measurement range: total range of travel over which measurements are taken; in contrast, see *measuring range*.

measurement resolution: smallest change of the measurement magnitude that can be detected and displayed by a measuring system; see also *resolution*.

measurement time: time range over which measurements are taken.

measurement travel: part of the axis travel that is used for data capture, selected so that the first and last target positions may be approached bidirectionally. [ASME B5.54-2005 (R2020)]

measuring device: see *measuring instrument*.

measuring instrument: device used for making measurements, alone or in conjunction with one or more supplementary devices; a measuring instrument that can be used alone is a measuring system. (OIML V1:2013)

measuring range: total range that a device can measure in accordance with its specified conditions; in contrast, see *measurement range.*

measuring system: set of one or more measuring instruments and often other devices, including any reagent and supply, assembled, and adapted to give information used to generate measured quantity values within specified intervals for quantities of specified kinds. (OIML V1:2013)

measuring transducer: device, used in measurement, that provides an output quantity having a specified relation to the input quantity. (OIML V1:2013)

median: middle value of an odd-numbered ordered set, or the mean of the two middle values of an even-numbered ordered set.

minimum incremental motion: size of the smallest reliably detectable step that the positioning system can execute.

minimum zone linear normalization: method that results in the mean minimum zone reference straight line; see also *linear normalization* and *mean minimum zone reference straight line*.

movable component: major structural component that is movable relative to the base of the positioning system during measurement

move-and-settle time: time the move takes for a given metric magnitude to settle within a given position tolerance.

multidirectional: a parameter derived from, or a test composed of, a series of measurements in which the approach to a target position is made from multiple directions and/or orientations in three-dimensional space. Single-axis positioning systems have only two directions of approach; multiaxis positioning systems have an infinite number of possible directions of approach.

nominal coefficient of thermal expansion, α: estimate of the coefficient of thermal expansion of a body; for the purposes of this Standard and in reference to the nominal coefficient of expansion of machine scales, it shall mean the effective coefficient of the scale and its mounting to the machine as measured in line with the scale for typical machines of the given design. [ASME B5.54-2005 (R2020)] *nominal differential expansion (NDE):* difference between the nominal expansion (NE) of the object to be calibrated and the standard (NE_s); when measuring at temperatures other than 20°C, corrections for the NDE must always be made. [ASME B5.54-2005 (R2020)]

$$NDE = NE - NE_s \tag{4-2-15}$$

nominal expansion (NE): estimate of the expansion of an object from 20°C to its time-mean temperature [ASME B5.54-2005 (R2020)]; NE shall be determined with the object length L from the following relationship:

$$NE = \alpha L(T - 20°C) \tag{4-2-16}$$

numerical control system: special purpose digital data processing unit that processes primarily numeric data to control the movements and functions of a positioning system to which it is connected.

open-loop hysteresis: hysteresis in situations where there is no active feedback control such as in piezoelectric actuators whose positioning is derived directly from an applied voltage.

overshoot: maximum amount by which a response exceeds its steady-state value.

peak-to-peak value, d_{pk-pk}: difference between the signal maximum and the signal minimum during the measurement time.

performance test: test procedure used to measure machine performance. [ASME B5.54-2005 (R2020)]

periodic error of positioning: component of the positioning deviation that is periodic over an interval that normally coincides with the natural periodicity of the machine scales or their equivalent; for example, in a lead-screw-driven machine with rotary encoders, the periodicity is usually synchronous with the pitch of the lead or ball screw. [ASME B5.54-2005 (R2020)]

phase crossover frequency: frequency where the open-loop phase equals −180 deg; see also *gain margin*.

phase margin: amount of change in open-loop phase needed to make a closed-loop system marginally stable, which equals the angle, in degrees or radians, between the phase of the open-loop system response and −180 deg measured at the frequency where the magnitude equals 1 (i.e., at the gain crossover frequency); see also *gain margin*.

point repeatability: multidirectional repeatability of the three-dimensional position of a functional point using a coverage factor of k = 2.

position sensing detector (PSD): photodetector, used for measuring displacements in 2D, composed of one photodiode that provides numerical or analog outputs directly proportional to the position of a light spot on the detector active area.

position tolerance: tolerance for a position; see also *tolerance*.

positioning deviation, x_{ij}: signed difference between the actual position reached by the functional point and the target position. (ISO 230-2:2014)

$$x_{ij} = P_{ij} - P_i \tag{4-2-17}$$

positioning system: device consisting of a carriage, a base, a constraining guideway/bearing, an actuator for placing or moving in a prescribed fashion the carriage relative to the base, an associated feedback system to determine the (linear or angular) position, and a control system to drive the actuator according to position commands and the feedback. The carriage, base, and guideway may be a monolithic structure or separate components; see also *axis*.

positioning system coordinate system: reference coordinate system that corresponds to the axes of the machine [ASME B5.54-2005 (R2020)], which is a right-hand rectangular system with the three principal axes labelled X, Y, and Z, with rotary axes about each of these axes labelled A, B, and C, respectively. (ISO 230-1:2012)

positioning system datum: built-in zero position of the machine elements used to establish the origin of the coordinate system. [ASME B5.54-2005 (R2020)]

positioning system home: condition in a machine coordinate system where all elements are at the home position (i.e., at the machine datum). [ASME B5.54-2005 (R2020)]

positioning system hysteresis: hysteresis of the machine structure when subjected to specific loads. [ASME B5.54-2005 (R2020), ISO 230-1:2012]

positioning system load hysteresis: see *positioning system hysteresis*.

positioning system zero: see *positioning system home*.

power spectral density (PSD): distribution of power density components that compose a signal as a function of frequency, usually expressed in units of mean-squared "power density" ($nm_{rms}{}^2$/Hz) for linear displacement time-series measurements.

power spectrum: distribution of power components that compose a signal as a function of frequency, usually expressed in units of mean-squared "power" ($nm_{rms}{}^2$) for linear displacement time-series measurements.

pseudo-random position sequences: sequence of target positions based on the calculation methods of pseudo-random numbers, e.g., the Sobol algorithm.

quadrant photodiode: photodetector, used for measuring displacements in 2D, composed of four separate photo detectors arranged in a form that resembles the quadrants of a circle. [ASME B5.54-2005 (R2020)]

quasi-static: without dynamic influences and servo (control) limitations. (ISO 230-1:2012)

radian: natural unit of angle. For small angles, the radian is often represented by "rise over run"; radians can be converted to decimal degrees by multiplying by 57.29 or to arc seconds by multiplying by 206,265; the microradian (μrad) is a millionth of a radian. [ASME B5.54-2005 (R2020)]

range: difference between the maximum and minimum values of a set of measurements of nominally the same quantity. [ASME B5.54-2005 (R2020)]

reference artifact: stable, physical object used as a master in machine testing, such as a ball, a set of balls, or a mandrel.

reference coordinate axes: see *reference coordinate system*.

reference coordinate frame: see *reference coordinate system*.

reference coordinate system: mutually perpendicular *X*-, *Y*-, and *Z*-axes fixed with respect to an object [ASME B5.54-2005 (R2020)]; it has a well-defined origin, axes directions, and a unit spatial metric (scale) linked to the definition of the meter (millimeters, inches, etc.); see also *base coordinate system*, *carriage coordinate system*, and *positioning system coordinate system*.

reference position: see *positioning system datum.*

reference straight line: associated straight line fitting the measured trajectory of a functional point in accordance with specified conventions, to which the straightness deviations and the straightness error are referred (ISO 230-1:2012). The line is estimated analytically by using straightness deviations resulting from least-squares linear normalization, endpoint linear normalization, or minimum zone linear normalization.

repeatability: measure of the ability of a positioning system to repeatedly position a functional point.

residual: difference between a measured value and the fitted value provided by a model.

resolution: least significant bit for a digital instrument [ASME B5.54-2005 (R2020)]; see also *measurement resolution*.

retroreflector: optical element with the property that an input light beam is reflected to return along the same angle as it was incident. [ASME B5.54-2005 (R2020)]

reversal: change in direction of motion of the positioning system.

reversal error at a position, B_i: difference between the mean unidirectional positioning deviations obtained from the two directions of approach at a position P_i. (ISO 230-2:2014)

$$B_i = \bar{x}_i\uparrow - \bar{x}_i\downarrow \tag{4-2-18}$$

reversal error of an axis, B: maximum of the absolute reversal errors $|B_i|$ at all target positions along or around the axis. (ISO 230-2:2014)

$$B = \max(|B_i|) \tag{4-2-19}$$

root-mean-square (RMS): square root of the mean of the squares of a set of values. For a set of n measurements $\{q_1, q_2, \ldots, q_n\}$ of a quantity, q, the RMS is defined as q_{RMS}.

$$q_{\mathrm{RMS}} = \sqrt{\frac{1}{n}(q_1^2 + q_2^2 + \ldots + q_n^2)} \tag{4-2-20}$$

sampling rate: number of samples per time unit measured from a continuous signal to yield a discrete signal.

sensor: see *measuring instrument*; in this Standard, the term sensor is normally used to mean a displacement sensor; whenever a different kind of sensor (e.g., a temperature sensor) is meant, this is stated explicitly.

sensor nest: group of more than one sensor assembled in a stable fixture to allow displacement measurements in more than one direction. [ASME B5.54-2005 (R2020)]

servo bandwidth: bandwidth for the servomechanism, representing the capability of the servo control to follow rapid changes in the commanded input.

settled: condition of a positioning system after a move-and-settle time when a given metric magnitude is within the position tolerance.

setup hysteresis: hysteresis of the various components in a test setup, normally due to loose mechanical connections. (ISO 230-1:2012)

SI system: International System of Units.

signal: mathematical encoding of information about the behavior or nature of some phenomenon; typically, a continuous signal is measured with a sampling rate to yield a discrete signal; in this Standard, a signal means a discrete signal unless stated otherwise.

stage: see *carriage*.

standard deviation: positive square root of the variance of a set of indications.

standard uncertainty (of a quantity, q), u_q or $u(q)$: uncertainty of the result of a measurement expressed as a standard deviation (JCGM 100:2008). For a set of n measurements $\{q_1, q_2, \ldots, q_n\}$ of a quantity, q, the standard uncertainty is defined as u_q or $u(q)$.

$$u_q = u(q) = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(q_j - \bar{q}\right)^2} \qquad (4\text{-}2\text{-}21)$$

static positioning: procedure where the positioning system is settled at a target position during measurements or usage; in contrast, see *dynamic positioning*.

stiffness: reciprocal of compliance.

straightedge: physical artifact with a surface that provides a reference straight line for measurement comparison; the physical sensing for the measurement may be achieved mechanically, optically, or electromagnetically.

straightness: property of a straight line. (ISO 230-1:2012)

straightness deviation: distance of the functional point from the reference straight line fitting its trajectory, measured in one of the two directions orthogonal to the direction of a commanded (nominal) straight-line trajectory (ISO 230-1:2012). Straightness deviations, which are measured at discrete intervals, constitute a limited representation of the actual straightness error motion.

straightness error: value of the largest positive straightness deviation added to the absolute value of the largest negative straightness deviation with respect to any previously defined reference straight line. (ISO 230- 1:2012)

straightness error motion: unwanted motion in one of the two directions orthogonal to the direction of a linear axis commanded to move along a (nominal) straight-line trajectory. (ISO 230-1:2012)

stroke of an axis, S: difference between the algebraic maximum and minimum of the average actual positions for the endpoints of the axis travel; the stroke is a measure of the travel range based on test data.

structural loop: assembly of mechanical components that maintain relative position between specified objects [ASME B5.54-2005 (R2020)]; a typical pair of specified objects is the displacement sensor and target artifact. The structural loop would include the positioning system structural components, the target, and sensor fixtures.

supplier: party who contracts, or indicates readiness to contract, to supply a positioning system to a user.

system: combination of components that work together to perform a useful function.

system hold: action of the controller to temporarily suspend all axis motion and program execution, in response to some condition or command that is not part of the main program.

systematic error: mean of the values that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus a true value of the measurand. The systematic error is equal to error minus the random error; like the true value, the systematic error and its causes cannot be completely known (JCGM 100:2008). For a measurement instrument, the systematic error is often called bias. [ASME B5.54-2005 (R2020)] *target:* reference artifact from which a measurement is taken with a displacement sensor; for example, a target may be a precision-ground sphere or a straightedge.

target position, P_i: position to which the moving component is programmed to move. The subscript i identifies the particular position among other selected target positions. (ISO 230-2:2014)

test uncertainty: expanded uncertainty of the resulting parameter of a test; see also coverage factor, *k*.

test uncertainty ratio (TUR): ratio of the resulting parameter of a test and its test uncertainty.

tolerance: permissible limit of variation of a parameter; see also *lower tolerance*, *tolerance zone*, and *upper tolerance*.

tolerance zone: range of permissible values of a parameter between the lower tolerance and upper tolerance.

transducer: see *measuring transducer*.

travel: potential axis positions; see also *axis travel*.

travel range: difference between the algebraic maximum and minimum of the axis travel.

uncertainty (of measurement): parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand. (JCGM 100:2008)

unidirectional: refers to a series of measurements in which the approach to a target position is always made in the same direction [ASME B5.54-2005 (R2020)]. The symbol ↑ signifies a parameter derived from a test performed with an approach in the forward direction (e.g., $x_{ij}\uparrow$), and the symbol ↓ signifies one in the reverse direction (e.g., $x_{ij}\downarrow$).

unidirectional point repeatability: unidirectional repeatability of the three-dimensional position of a functional point using a coverage factor of k = 2.

unidirectional positioning repeatability at a position, $R_i\uparrow$ or $R_i\downarrow$: range derived from the estimator for the unidirectional axis positioning repeatability at a position P_i using a coverage factor of k = 2. (ISO 230-2:2014)

$$R_i\uparrow = 4s_i\uparrow \tag{4-2-22}$$

$$R_i\downarrow = 4s_i\downarrow \tag{4-2-23}$$

unidirectional positioning repeatability of an axis, $R\uparrow$ or $R\downarrow$: maximum value of the positioning repeatability at any position P_i. (ISO 230-2:2014)

$$R\uparrow = \max(R_i\uparrow) \tag{4-2-24}$$

$$R\downarrow = \max(R_i\downarrow) \tag{4-2-25}$$

unidirectional systematic positioning error of an axis, $E\uparrow$ or $E\downarrow$: difference between the algebraic maximum and minimum of the mean unidirectional positioning deviations for one approach direction $\bar{x}_i\uparrow$ or $\bar{x}_i\downarrow$ at any position P_i along or around the axis. (ISO 230-2:2014)

$$E\uparrow = \max(\bar{x}_i\uparrow) - \min(\bar{x}_i\uparrow) \tag{4-2-26}$$

$$E\downarrow = \max(\bar{x}_i\downarrow) - \min(\bar{x}_i\downarrow) \tag{4-2-27}$$

user: party who contracts to accept a positioning system from the supplier.

upper tolerance: maximum permissible value of a parameter.

validation: verification, where the specified requirements are adequate for an intended use. (ISO/IEC 17025:2017)

variance (of a quantity, q), s_q^2 or $s^2(q)$: measure of the dispersion of a set of indications, which is the sum of the squared deviations of the indications from the set average divided by one less than the number of indications; for a set of n measurements $\{q_1, q_2, \ldots, q_n\}$ of a quantity, q, the variance is defined as s_q^2or $s^2(q)$.

$$s_q^2 = s^2(q) = \frac{1}{n-1}\sum_{j=1}^{n}\left(q_j - \bar{q}\right)^2 \tag{4-2-28}$$

velocity profile: velocity of a measurement point as a function of time for a linear positioning system that is commanded to accelerate from rest, then move at a constant velocity for a defined distance, and then decelerate to stop.

vendor: see *supplier*.

verification: provision of objective evidence that a given item fulfils specified requirements. (ISO/IEC 17025:2017)

Section 5
Measurement Points, Coordinate Systems, and System Positioning Errors

5-1 INTRODUCTION

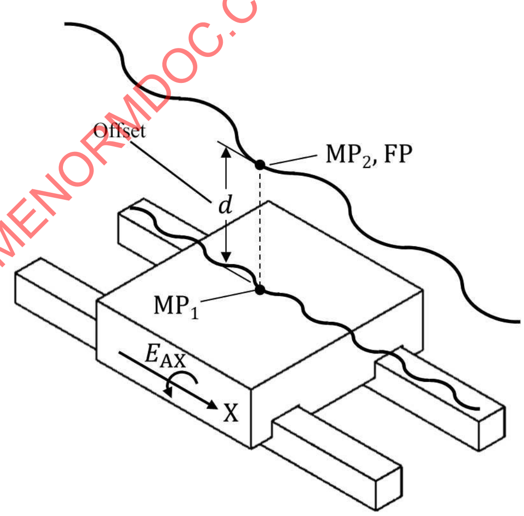
This Section provides methods for defining, describing, and relating functional and measurement points of interest fixed to the carriage or base of a single-axis linear positioning system via associated coordinate systems.

5-2 MEASUREMENT POINT

A positioning system can be directly characterized using the various methods and techniques described in this performance standard. The error motions of positioning systems are normally characterized by measuring the motions of a single point which is fixed with respect to the carriage as it traverses through specified target positions or follows commanded motions. The measurement point (MP), as indicated in Figure 5-2-1, may vary for different measurements but should be well defined for each particular measurement.

The linear positioning errors (see subsection 7-5) and the lateral motions of MP (straightness errors) (see subsection 8-1) are affected by the angular error motions of the positioning system's carriage and, thus, can vary significantly for different measurement points. The differences are related to the offset distance vector, *d*, between the desired measurement point and the actual measurement line (Abbe offset) and the angular error motions of the carriage. These effects are understood and minimized through the Abbe principle (Abbe, 1890) and the Bryan principle (Bryan, 1979). Additionally, these translational error motions may also be affected by the non-rigid body behavior of the carriage and/or base of the positioning system.

Figure 5-2-1
Measurement Point (MP)



GENERAL NOTE: This illustration compares the motion of two distinct measurement points (MP_1 and MP_2) from a myriad of possibilities fixed with respect to the carriage of a linear positioning system. The functional point (FP) is where a particular manufacturing process would occur. Other symbols are described in the text.

5-3 CARRIAGE AND BASE COORDINATE SYSTEMS

Two coordinate systems are necessary and sufficient for fully characterizing the performance of a single-axis linear positioning system. In right-handed fashion, each coordinate system has three orthogonal principal axes typically denoted as *X*, *Y*, and *Z*, and rotations about each of these axes that are typically denoted as *A*, *B*, and *C*, respectively (per Figure 5-3-1).

Figure 5-3-2 shows the moving coordinate system, csM, having origin oM, which is spatially fixed with respect to the carriage as the carriage is moved to a target position, and the fixed coordinate system, csF, having origin oF, which is spatially fixed with respect to the base of the positioning system. The coordinate systems, csM and csF, shall be considered to have coincident origins and aligned axes at the home position.

One principal axis of csF (chosen as the *X*-axis for evaluations in this Standard) shall be aligned with respect to the nominal motion direction of the carriage as the positioning range of the system is traversed. For an MP error transformation, this axis shall be well-defined via the oM least-squares average line, two specified positions, minimum zone average line, etc. A second principal axis, orthogonal to the first, shall be aligned nominally parallel or normal to an accessible physical reference datum of the positioning system or associated measurement fixturing, e.g., the carriage mounting (table) surface. The third principal axis shall be orthogonal to the first two, completing a right-handed coordinate system. The nominal position(s) of the measurement point, origins, and the nominal axis directions of the carriage and base coordinate systems for which their system specifications are valid shall be specified by the manufacturer.

Figure 5-3-1
Right-Handed Coordinate System Showing Directionality of Motion

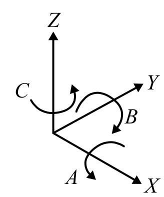
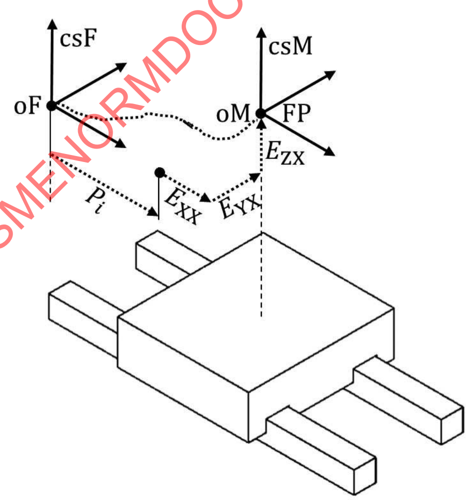
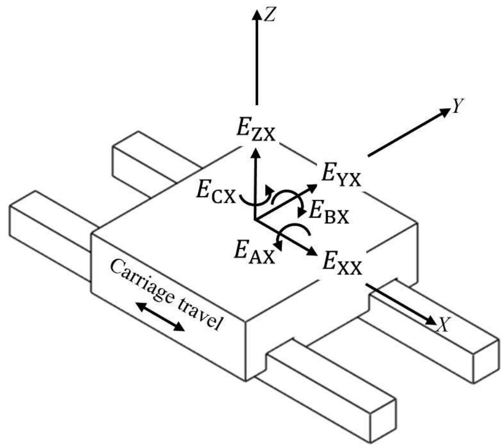


Figure 5-3-2
Motion of the Functional Point (FP) With Respect to the Frame Coordinate System (csF)



GENERAL NOTE: The origin (oM) of the moving coordinate system (csM) is coincident with the functional point in this illustration. Other symbols are described in the text.

Figure 5-5-1
Error Motions of a Single-Axis Linear Positioning System Designed to Traverse Along the *X*-Axis



5-4 CARRIAGE ORIGIN POINT

Although multiple MPs associated with varied points of interest are possible, oM shall be defined with respect to the physical features of the carriage. Other points of interest [e.g., a functional point (FP)] can ultimately be represented with respect to the related carriage or base coordinate system described previously. It is recommended that all translational error motions be characterized using a common MP that coincides with the FP of the application in which the positioning system is intended to be used. If possible, this common point should be oM. Spatial constraints due to instrumentation and fixturing, however, may limit measurement of the FP. In this instance, it is recommended that oM be as close as possible to the FP and the locations of oM and FP with respect to the base or carriage be documented. When the positioning system is to be characterized as a general-purpose system or an FP is not defined or known, then the positions of all MPs shall be documented and presented with the results. The point oM can be described relative to the center of the table (surface), mounting surface, or edges of the carriage, fiducials, holes, etc. As a real example, oM could be defined as the point 25 mm above the center of the rectangular mounting surface of the carriage.

5-5 SYSTEM POSITIONING ERROR MOTION NOMENCLATURE

System measurements shall include the static or quasi-static translational error motions of the carriage (via oM) and the static or quasi-static angular error motions of the carriage (via csM) with respect to the base (via csF). These motions are nominally constrained to 1 degree of freedom in the positioning direction but, in practice, variations in all six degrees of freedom are inherent and must be determined. These error motions vary as the target position changes. These measurements are detailed in later sections.

System static or quasi-static errors shall be described using a common nomenclature consisting of three letters, as shown in Figure 5-5-1. The first letter, *E*, represents error, the first subscript represents the direction/orientation of the error, and the second subscript represents the nominal motion of the axis. Examples of the error motions for a single-axis linear positioning system having nominal travel in the *X*-axis direction are as follows:

E_{AX} = roll error motion (A rotation): angular error motion of the *YZ* axes of csM around the *X*-axis of csF as the target position is varied

E_{BX} = pitch error motion (B rotation): angular error motion of the *ZX* axes of csM around the *Y*-axis of csF as the target position is varied

E_{CX} = yaw error motion (C rotation): angular error motion of the *XY* axes of csM around the *Z*-axis of csF as the target position is varied

E_{XX} = positioning error motion: deviation from the commanded positions of oM in the *X*-axis direction of csF as the target position is varied

E_{YX} = lateral *Y*-straightness error motion: deviation from a reference straight line of oM in the *Y*-axis direction of csF as the target position is varied

E_{ZX} = lateral Z-straightness error motion: deviation from a reference straight line of oM in the Z-axis direction of csF as the target position is varied

NOTE: This error motion is not "flatness," but "flatness" is used by some practitioners for this term in certain contexts.

5-6 MEASUREMENT POINT TRANSFORMATIONS

Using the translational and angular error motions for any MP on the carriage, transformations can be performed to represent the error motions of the FP following the method outlined in Mandatory Appendix I. Measured errors may also be transformed to calculate the errors for any chosen point of interest in the base or carriage coordinate system. If the FP is to be fixed with respect to the base, then measurements can be determined directly by measuring with respect to the carriage (csM) or calculated analytically. For all instances, measurement data, transformed data, and their locations shall be provided as agreed upon between the user and the manufacturer/supplier.

Section 6 Environmental Specifications

6-1 GENERAL

It shall be the responsibility of the user or manufacturer/supplier to provide an acceptable environment for performance testing of the single-axis linear positioning system at their respective site. A performance specification that is to be verified according to the tests of this Standard shall include a statement of the rated conditions under which the specified performance is to be achieved. The rated conditions include acceptable limits on the environment related to temperature, humidity, barometric pressure, and base vibration. The rated conditions also include any applicable limits on utilities needed to operate the system elements during testing such as condition of electrical power and compressed air. The manufacturer/supplier shall also state whether testing may occur outside of the rated conditions using prescribed correction methods.

Recommended parameters for rated conditions are given in the forms of Mandatory Appendix III. The environment shall be considered acceptable if the requirements of Mandatory Appendix III and this Section are met. The user shall be responsible for conducting all environmental tests at the installation site. The manufacturer/supplier shall have a right to witness all tests. The manufacturer/supplier shall, on request, supply test equipment as specified in Section 11 and support for equipment and tests, at a price to be negotiated between the user and the manufacturer/supplier.

6-2 TEMPERATURE

6-2.1 General

Temperature has a significant influence on the accuracy of machine elements and measuring instruments, and its effects are often misunderstood. The provisions of ASME B89.6.2 form a part of this Standard, but interpretation is needed for application to single-axis linear positioning systems. ASME B89.6.2 defines two alternative conditions under which a test environment is thermally acceptable. The first, that all pertinent components of the measuring system be at exactly 20°C (68°F), is generally unobtainable. This Standard is primarily concerned with the second: that the expanded thermal uncertainty be a reasonable percentage of the specification zone. Acceptability of a thermal environment is specified in terms of its effects on the system under test.

6-2.2 Thermal Environment Guidelines

The manufacturer/supplier shall offer guidelines regarding the acceptable thermal environment for the positioning system. Such general guidelines could contain, for example, a specification on mean room temperature, maximum amplitude, and frequency range of deviations from this mean temperature, environmental thermal gradients, air flow rate, and air speed surrounding the system, as listed in Mandatory Appendix III. The user shall be informed that the conformance to such guidelines does not guarantee an acceptable thermal environment but does constitute due care on the user's part and thus shifts responsibility for performance degradation due to environmental sensitivity from the user to the manufacturer/supplier. When environmental and other conditions are provided for testing within the stated rated conditions, then there is no significant uncertainty in the test results related to these factors. However, if testing occurs outside rated conditions and corrections are made to test results according to the manufacturer's prescribed method, then the uncertainty of the correction becomes part of the test uncertainty.

6-2.3 Time Variations

Particular attention should be given to time variations of temperature, although this Standard does not offer specific guidelines in this area. Positioning systems are composed of numerous elements, each with different thermal behavior. Components may be of different material, thus different thermal diffusivity. They may also have different thermal time constants. For example, a ball in a roller pack may react relatively quickly while the table is more massive and reacts more slowly to changing temperature. Therefore, when the system is in an environment with time variations of temperature, the resulting motion of the functional point can be quite complex. Efforts should be made to quantify the effects and reduce them to acceptable levels.

6-2.4 Thermal Radiant Energy

The positioning system under test shall not be exposed to direct sunlight or other powerful radiant energy sources. Other direct radiant energy sources (e.g., fluorescent lighting, radiant heaters, high-intensity lamps) shall be as far from the positioning system as possible to reduce their effects on the system. Where this distance requirement is impractical, indirect lighting designed for diffuse reflection and increased path length shall be used.

6-3 AIR HUMIDITY

6-3.1 General

Humidity of the air environment for the given experimental setup may affect certain positioning systems, especially those using laser interferometers. For example, accurate temperature, humidity, and barometric pressure values are required to correct the air index of refraction when using a laser interferometer to measure position.

6-3.2 Responsibilities

For all positioning systems that require operation within an environment of a certain humidity, it shall be the responsibility of the user to control humidity according to the requirements specified by the manufacturer/supplier.

6-3.3 Specifications

For air humidity, the manufacturer/supplier shall provide specifications required for the proper operation and maintenance of the positioning system, whenever air humidity requires a specification. These specifications should include a minimum and maximum acceptable air humidity, when applicable. These parameters are listed in the environmental specification section of Mandatory Appendix III.

6-4 BAROMETRIC PRESSURE

6-4.1 General

Barometric pressure of the air environment for the given experimental setup may affect certain positioning systems, especially those using laser interferometers. Barometric pressure changes with altitude and weather and both effects can be important.

6-4.2 Responsibilities

For all positioning systems that require operation within an environment of a certain barometric pressure, it shall be the responsibility of the user to monitor it according to the requirements specified by the manufacturer/supplier. While an end user is unlikely to be able to control atmospheric pressure, if necessary, it should be measured and used to correct test results according to the manufacturer/supplier's specifications.

6-4.3 Specifications

For barometric pressure, the manufacturer/supplier shall provide specifications required for the proper operation and maintenance of the positioning system, whenever barometric pressure requires a specification. These specifications should include a minimum and maximum acceptable pressure (or altitude), when applicable. These parameters are listed in the environmental specification section of Mandatory Appendix III.

6-5 BASE VIBRATION

6-5.1 General

The support surface (floor, foundation, isolation pad, etc.) upon which the positioning system will be mounted can have motion induced because of external forces in the surrounding area (due to other machines, lift trucks, compressors, etc.). This motion can be continuous vibration, interrupted shock, or both. Such motion, if transmitted to the positioning system, has a degrading effect on its accuracy and repeatability.

6-5.2 Responsibilities

The user shall be responsible for site selection, environmental shock and vibration analysis, and additional special isolators required to ensure conformance with the maximum permissible vibration levels specified by the manufacturer/supplier. All questions of conformance with the specifications shall be determined at the interface between the support system provided by the user and the system provided by the manufacturer/supplier.

6-5.3 Base Vibrational Parameters

The specifications provided by the manufacturer/supplier shall include a statement of the acceptable vibration spectra as part of the rated environmental conditions. An environment within the rated vibration specifications shall be provided for all testing, or isolation shall be used to achieve the specified vibration level.

It is preferred that the vibration environment be characterized each time a positioning system is to be evaluated. However, if laboratory conditions are deemed identical from system to system and test to test, a single vibration assessment may suffice, but the possibility that the vibration isolation system or support structural stiffness has degraded over time should be considered.

Vibration limits are suitably characterized by Vibration Criterion curves (VC curves VC-A through VC-M), which typically are presented in terms of RMS velocity versus frequency (Gordon, 1999). It is therefore recommended that the vibration amplitude of the environment supporting the measurement setup be limited by the appropriate VC curve. In practice, the VC curve is typically a horizontal line representing constant RMS velocity from 1 Hz to 100 Hz (Gordon, 1999; IEST-RP-CC024.1). For example, the VC-D curve limits the RMS velocity to 6.25 μm/s and the VC-E curve limits it to 3.12 μm/s.

6-6 ELECTRICAL

6-6.1 General

The electrical power supplied to motors and sensors can influence the positioner's ability to perform accurate and repeatable operations. Electronic and electrical components such as sensors can be sensitive to voltage variations. For this reason, it is necessary to know the operating range in which the positioning system was designed to operate and ensure a proper environment for testing.

6-6.2 Responsibilities

The manufacturer/supplier shall be responsible for providing an electrical power specification for which the system will operate properly. It shall be the responsibility of the user to provide electrical power satisfying the specification. Preferably, power requirements should be specified by current publicly available consensus standards, such as those that specify limits of harmonic components of the input current that can be produced by test equipment. (IEC 61000-3-2:2018)

6-6.3 Electrical Parameters

The manufacturer/supplier shall provide, as part of the machine specification, a statement of the steady-state requirements including voltage(s), frequency, and amperage for the positioning system, allowable short- and long-term RMS voltage variations, and allowable transient voltages expressed in percent of nominal voltage. For example, a tolerance of 5% means that the voltage must be in a tolerance band between 95% and 105% of the nominal voltage. These electrical parameters are listed in Mandatory Appendix III.

6-7 UTILITY AIR

6-7.1 General

Air supplies can affect accuracy and useful working life of components. Temperature variations in the utility air can generate thermal gradients in the positioning system, while particulates, oils, and water in the utility air can degrade bearing performance, increase friction, and accelerate wear.

6-7.2 Responsibilities

For all positioning systems that require utility air, it shall be the responsibility of the user to supply utility air satisfying the requirements specified by the manufacturer/supplier.

6-7.3 Specifications

For utility air, the manufacturer/supplier shall provide specifications for all air parameters required for the proper operation and maintenance of the positioning system. For air bearing positioning systems, these specifications should include mean temperature, permissible temperature variation, air pressure, and air pressure variations. Humidity and the particulate content shall also be specified as applicable. These parameters are listed in the environmental specification section of Mandatory Appendix III. Control of air quality parameters, such as particulate, oil, and water content, is the responsibility of the user.

Section 7
Positioning Performance

7-1 GENERAL

The positioning performance of a single-axis linear positioning system is composed of various errors related to the ability of the axis to be positioned at, and to maintain, a command position or to move with commanded dynamics along a commanded path. This Section describes the test procedure, data analysis, and reporting of results required to perform command position tests (in-position jitter, move and settle, incremental step, and static positioning) and command path tests (constant velocity and acceleration, and dynamic positioning) to evaluate the positioning errors of a linear axis. The positioning performance of a linear axis directly influences the geometric accuracy of processes performed using the axis or the uncertainty in the measurement of component geometric features performed using the axis. All positioning errors described in this Section are determined by measuring the relative motion of a functional point (or another agreed-upon location between the user and manufacturer/supplier) while the axis is commanded to perform various positioning tasks. Many test parameters, such as location of the measurement point, axis motion direction, servo state, measurement bandwidth, measurement time, and pretest conditions affect the measurement results. These parameters need to be considered when designing these tests and reported as part of the results.

7-2 IN-POSITION JITTER TEST

7-2.1 General

This subsection describes the test setup and procedures required to evaluate the in-position jitter of a single-axis linear positioning system. In-position jitter is determined by measuring the motion at a point (the functional point or other agreed-upon location between the user and the manufacturer/supplier) when no motion is commanded to the axis under test. Many variables, such as location of the measurement point, measurement direction, servo state, environment, measurement bandwidth, measurement time, type of instrumentation, fixturing and mounting of instrumentation and other pretest conditions affect the measurement results. These factors need to be considered when designing this test and reported as part of the results of the in-position jitter test.

7-2.2 General Measurement Setup

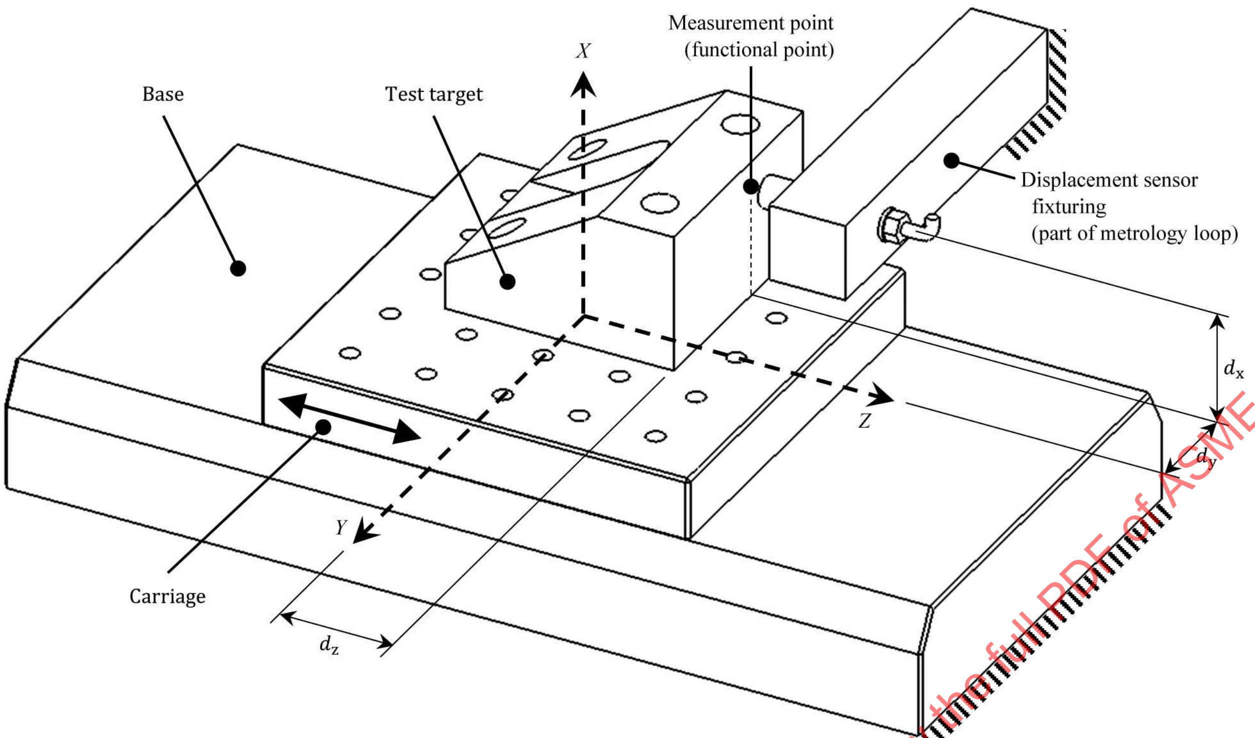
7-2.2.1 Equipment. The equipment used for measurements in the in-position jitter test are as follows:

(a) displacement sensor — a laser interferometer, capacitance sensor, or other type of sensor with adequate resolution, accuracy, measurement bandwidth, and low measurement uncertainty can be used (see para. 7-2.2.5)
(b) displacement sensor target and fixtures as needed to complete the metrology loop
(c) data acquisition system
(d) post-processing software
(e) environmental sensors

7-2.2.2 Measurement Setup. Figure 7-2.2.2-1 shows a schematic of an in-position jitter test setup using a displacement sensor targeting the functional point on the moving carriage of a single-axis linear positioning system. Measurement in the direction of motion is the most typical measurement case for in-position jitter. However, measurements in directions that are not in the direction of motion may also be useful to characterize. In all measurement cases, the direction of the measurement and location of the measurement point should be reported with the measurement results.

7-2.2.3 Measurement Target Location(s). The measurement should be performed at each functional point (see Section 5) or other location(s) agreed upon by the user and the manufacturer/supplier. If this point is unknown or not agreed upon, then the measurement point should be chosen by the user to represent the location where a process may occur (e.g., a certain distance above the moving carriage of the linear positioning system). In all cases, the location of each measurement point should be reported with the measurement results.

Figure 7-2.2.2-1
Example Measurement Setup for In-Position Jitter Test in the *Z*-Direction at Point (d_x, d_y, d_z)



7-2.2.4 Servo State. The measurement should be performed in the same "state" that the positioning system will be used in the final application or end-process. For example, if the end-process requires the motors to be disabled and an external brake applied to the axis, then the measurement should be performed in this state. The state of the servo should be agreed upon by the user and the manufacturer/supplier of the equipment. If the final application servo state is unknown, the measurement should be performed with the positioning axis under servo control (motors enabled) and no external brakes applied to the axis. In all cases, the servo state should be reported with the measurement results.

7-2.2.5 Measurement Bandwidth. The selection of the measurement bandwidth is critical to ensure that the dynamics of the positioning axis are adequately captured in the measurement. Because applications and processes can be vastly different, no single default measurement bandwidth is defined as part of this Standard. The user and the manufacturer/supplier of the positioning equipment need to determine the sensitivity of the end-process to motion over a specified spectral range. This should then be used to agree upon the measurement bandwidth for this measurement. It is recommended that, if possible, the measurement bandwidth be at least 10 times greater than the highest frequency required by the end process. If the application or end-process is unknown or not specified, it is recommended that a measurement bandwidth that adequately captures the dynamics of the system under test be used. Also, the measurement does not always need to occur from DC (0 Hz) to a certain frequency. Some applications may require that this measurement be performed from a non-zero frequency to a second higher frequency (e.g., 5 Hz to 800 Hz). In all cases, the measurement bandwidth must be reported with the measurement results.

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.

(a) Start of Test. The test should start after the axis has settled by criteria defined by subsection 7-3 (move-and-settle test). If no pretest motion profile is specified or known, then the axis should be tested when fully stabilized in the environment that the measurement is intended to occur.

(b) *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 a 100 data points (to ensure an adequate statistical sample size).

For all measurements, the starting criteria and measurement time should be reported with the measurement results.

7-2.2.7 Fixturing Design. The fixturing used to secure the displacement sensor in place shall be designed according to the required measurement uncertainty. It is worth noting that some applications require measurement of in-position jitter over many seconds, minutes, or even hours. In these cases, thermal drift of the metrology loop can dominate the measured value. Therefore, it is very important that care be given to design the metrology loop, so these effects are mitigated when desired. Also, the static and dynamic structural stiffness of the metrology loop should be commensurate with the level of in-position jitter desired from the measurement. That is, the metrology loop fixtures needed to measure nanometer-level in-position jitter should have much higher stiffness than those needed to measure micrometer-level in-position jitter.

7-2.3 Measurement Procedure

For the in-position jitter test, the sensor output is nulled as relevant at the functional point and then data is collected according to the general measurement setup (see para. 7-2.2). Repetitions or warm-up cycles may be used if agreed upon between the user and the manufacturer/supplier.

7-2.4 Data Analysis

The measurement data will need to be post-processed to evaluate in-position jitter. The required algorithms are commonly available in several commercial and open-source numerical analysis software packages. The data file will typically contain the sensor data output that is time-stamped to the data-acquisition unit clock. If the data are filtered in post-processing (to obtain a certain measurement bandwidth, e.g., to eliminate long-term drift), the type of filter used should be reported in sufficient detail to allow its reproduction.

The main result of this measurement, the in-position jitter, should be reported as a sample standard deviation, s, of the measured time signal over a given time and measurement bandwidth. Alternatively, the in-position jitter can be reported as a peak-to-peak value, if agreed upon between the user and the manufacturer/supplier. The standard deviation, s, and peak-to-peak value, d_{pk-pk}, of the measured data, d_i, at each sample time, t_i, are defined as

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(d_i - \bar{d})^2} \tag{7-2-1}$$

$$d_{pk-pk} = \max[d(t)] - \min[d(t)] \tag{7-2-2}$$

where

n = the number of data points in the measurement
$\bar{d}$ = the sample average of all measured values

Alternate presentations of the data that may assist in a deeper interpretation include histograms and spectral analyses.

7-2.5 Uncertainty Analysis

Uncertainties associated with the measurement of the in-position jitter are related to uncertainties of the used measurement systems and uncertainties of the axis under test. These uncertainties should be considered when specifying measurement sampling rates and parameters, to avoid situations where neither conformance nor nonconformance to specifications can be demonstrated. Potential measurement uncertainty contributors include

(a) measurement uncertainty of the test equipment
(b) 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
(c) uncertainty in the sensor calibration factor, u_{CAL}
(d) uncertainty due to the sensor resolution/noise, u_{SR} — evaluated via a sensor noise floor test
(e) uncertainty due to setup repeatability, u_{Δ} — relatively small due to motion being very small
(f) uncertainty of the probe spacing distance, u_L, when measuring angular in-position jitter
(g) uncertainty due to nonstationary (time-varying) processes or disturbances

(h) uncertainty due to fixturing vibrations, u_{VIB}

7-2.6 Presentation of Results

Figure 7-2.6-1 shows an example of an in-position jitter test report that includes the standard deviation, s, and the peak-to-peak value, d_{pk-pk}, of the measured data and its expanded uncertainty at a certain measurement bandwidth. The example test report also shows an optional cumulative root-mean-square plot, which is helpful to identify areas of contribution to the overall measurement value. For example, in Figure 7-2.6-1, there appears to be a large increase in the root-mean-square-value around 500 Hz. This could be due to a mechanical resonance in the positioning axis under test or in the metrology fixturing used in the measurement.

7-3 MOVE-AND-SETTLE TEST

7-3.1 General

Subsection 7-3 presents techniques for quantifying move-and-settle performance. The move-and-settle test quantifies the time required for a servo-controlled axis to move a specified distance and settle within a specified position tolerance. For a complete move-and-settle specification, three values shall be reported: displacement, position tolerance, and time. The reported performance uses the metrics of moving average error, moving standard deviation, and moving peak error defined over a particular process time. With appropriate time windows, the techniques can be applied either offline or in real time. This methodology can also be applied to measurements collected at any location in the system. The measurements are most commonly taken from the position sensor used for feedback but can also be recorded from an independent sensor measuring directly at the functional point. Though not directly addressed here, the technique can be expanded to multiaxis systems through requirements that multiple axes meet particular settling criteria before an overall "settled" state is achieved. Additional topics not covered but that may be considered are randomized move-and-settle tests that attempt to determine biases based on step size and location within the positioning volume of the system.

7-3.2 Measurement Setup

7-3.2.1 Equipment. Position may be measured by the position feedback device(s) used for axis servo control or by an independent displacement measuring device aligned with a specified functional point and the axis of motion, which is the setup used for characterizing in-position jitter (see subsection 7-2). It should be noted, however, that the position error measured by the position feedback device in a properly tuned controller will eventually converge to zero, whereas when measured at the functional point, a convergence to zero may not be possible due to sensor or system drift or unmeasured error motions in the mechanical system.

7-3.2.2 Measurement Target Location. The measurement location shall be agreed upon by the user and the manufacturer/supplier.

7-3.2.3 Measurement Bandwidth. The measurement bandwidth shall be agreed upon by the user and the manufacturer/supplier.

7-3.2.4 Sampling Rates. Each measurement device/equipment shall collect data with a sampling rate agreed upon between the user and the manufacturer/supplier. To avoid aliasing for a given application, the sampling rate shall be at least 2 times the highest frequency component present in the input to the measuring device that is significant to its output. This is related to, but not the same as, the bandwidth of the measuring device. Specifically, the sampling rate shall be at least 2 times the bandwidth of the measuring device but may need to be higher than the bandwidth of the measuring device depending upon its output filter characteristics and the magnitudes of the input signals above the bandwidth of the measuring device that affect its output. Note that one practical way to identify aliasing is to change the sampling rate and observe any shifts in frequencies of spectral components of the output signal.

7-3.3 Measurement Procedure

For the move-and-settle test, the linear positioning system is commanded to move the axis from a state of rest to a new position while position data is collected. The position data will be processed with metrics, and the axis is settled when the metric remains below a chosen position tolerance for the chosen process window time. The position tolerance and process window time are determined by mutual agreement between the user and the manufacturer/supplier. Also, the decision for whether the process window begins, is centered, or ends at a given measurement time shall be agreed upon between the user and the manufacturer/supplier. Finally, any axis calibration maps, or environmental correction factors shall be applied before the data is used for analysis.

Figure 7-2.6-1
Example of an In-Position Jitter Test Report

In-Position Jitter Test Report

Positioning System

Manufacturer: ABC	Model No.: XX	Serial No.: XX
Type: Linear	Max. travel: 300 mm	Max. velocity: 250 mm/s

Controller/drive unit to power the positioning system: ABC P100 S/N 1234

Measurement Setup

Functional point: X = 0 mm, Y = 0 mm, and Z = 35 mm (35 mm above center of tabletop)

Axis position: 150 mm (axis is at mid-travel position)

System location: 300 mm × 1.2 m × 1.2 m granite base with passive air isolation

Load: 0 kg

Servo state: Servo enabled during test

Pretest conditions: Axis stabilized for 10 min from a cold start prior to measurements

Temperature during test: 20.2°C

Data acquisition system: Acme D100 S/N 5678

Displacement sensor: Acme S100 S/N 91011

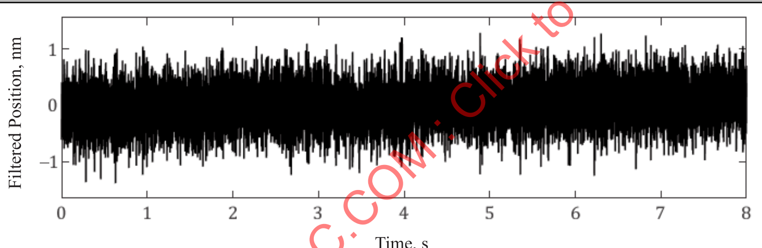
Sampling rate: 4 096 Hz

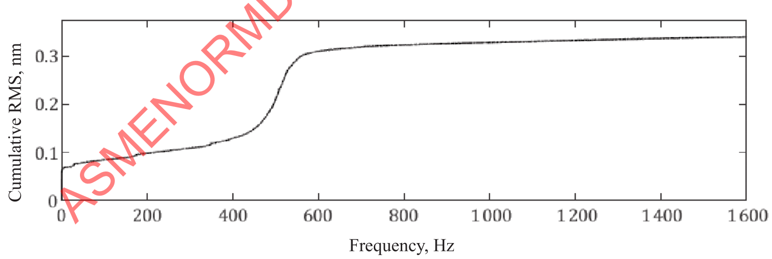
Measurement time: 8 s

Data filter: Second-order Butterworth low-pass filter with a 1 600 Hz cutoff frequency

Comments: Hamming window used for cumulative RMS and broadband (power) correction applied

Filtered Data Plots





In-Position Jitter Test Results

In-Position Jitter Metric	Metric Value, nm
Standard deviation	0.34 ± 0.10 (k = 2)
Peak-to-peak value	2.68 ± 1.9 (k = 2)

7-3.4 Data Analysis

7-3.4.1 Position Error Metrics. The settling criteria defined for a positioning system shall account for both the position error as well as the chosen process window time. A process window time is required to eliminate zero-crossing triggers (position error oscillations during settling may lead to multiple times when the error is identically zero) and to potentially represent different process times used in different industries. For example, the typical exposure time of a lithography system is likely to be shorter than the time required for laser drilling a hole.

Three metrics are used with the measured position error data and chosen parameters to determine when the axis is settled. The following metrics are for a process window centered around the nominal time, t. First, the dynamic positioning deviation, $x(t)$, is defined as

$$x(t) = P_{\text{actual}}(t) - P_{\text{target}} \tag{7-3-1}$$

for the actual position, P_{actual}, at time t and the constant target position, P_{target}. Then, the moving average error (MAE) is defined as

$$\text{MAE}(t) = \frac{1}{T}\int_{t-T/2}^{t+T/2} x(\tau)d\tau \tag{7-3-2}$$

and is the average of all position error samples over a process window time T with the window centered around the nominal time t. The moving standard deviation (MSD) is defined as

$$\text{MSD}(t) = \sqrt{\frac{1}{T}\int_{t-T/2}^{t+T/2} [x(\tau) - \text{MAE}(t)]^2 d\tau} \tag{7-3-3}$$

and quantifies the amount of jitter over the process window (Butler, 2011). Finally, the moving peak error (MPE) is the largest absolute error measured over the process window; that is,

$$\text{MPE}(t) = \max(|x(\tau)|: t - T/2 < \tau < t + T/2) \tag{7-3-4}$$

Note that the peak measured value of a stochastic signal (i.e., jitter during settling) depends heavily on the frequency response of the sensor used to make the measurement. Thus, the MPE is more susceptible to setup variations than the MAE and MSD. However, the MPE is commonly used in practice with the feedback device (e.g., the position encoder) used to gather the measurement data.

Although these metrics are written in the continuous time domain, they can also be implemented with sampled data. When the data is captured and processed offline, the process window can start anywhere in the data if the entire data set is available. In that case, the process window may begin at the current time (the "forward" calculation direction), be centered at the current time (the "centered" calculation direction), or end at the current time (the "backward" calculation direction). It may also be advantageous to compute these metrics in real time, in which the process window ends at the current time (the "backward" calculation direction). Real-time analyses allow the user to command a move and wait for it to be settled against the positioning criteria before moving to the next step in a process. However, real-time analysis with a process window is only approximately real time, since data collected before the current time is used in the analysis; specifications must be written taking this fact into account. In contrast, real-time implementation highlights the need for a process window to avoid false triggers at zero crossings during a typical move-and-settle process.

7-3.4.2 Metrics Example. To demonstrate the move-and-settle test, the test was implemented and repeated on a typical positioning axis. Six hundred individual move-and-settle tests were performed with a step size of 10 mm moving over an axis travel length of 600 mm: 60 forward-direction sequential steps, followed by 60 reverse-direction sequential steps, repeated five times.

Examples of the three position error metrics (MAE, MSD, and MPE) are plotted with the position error data in Figures 7-3.4.2-1, 7-3.4.2-2, and 7-3.4.2-3, respectively. In this case, a process window time of 50 ms centered on the current time is used.

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.

Figure 7-3.4.2-1
Example Moving Average Error, Calculated With a Process Window Time of 50 ms

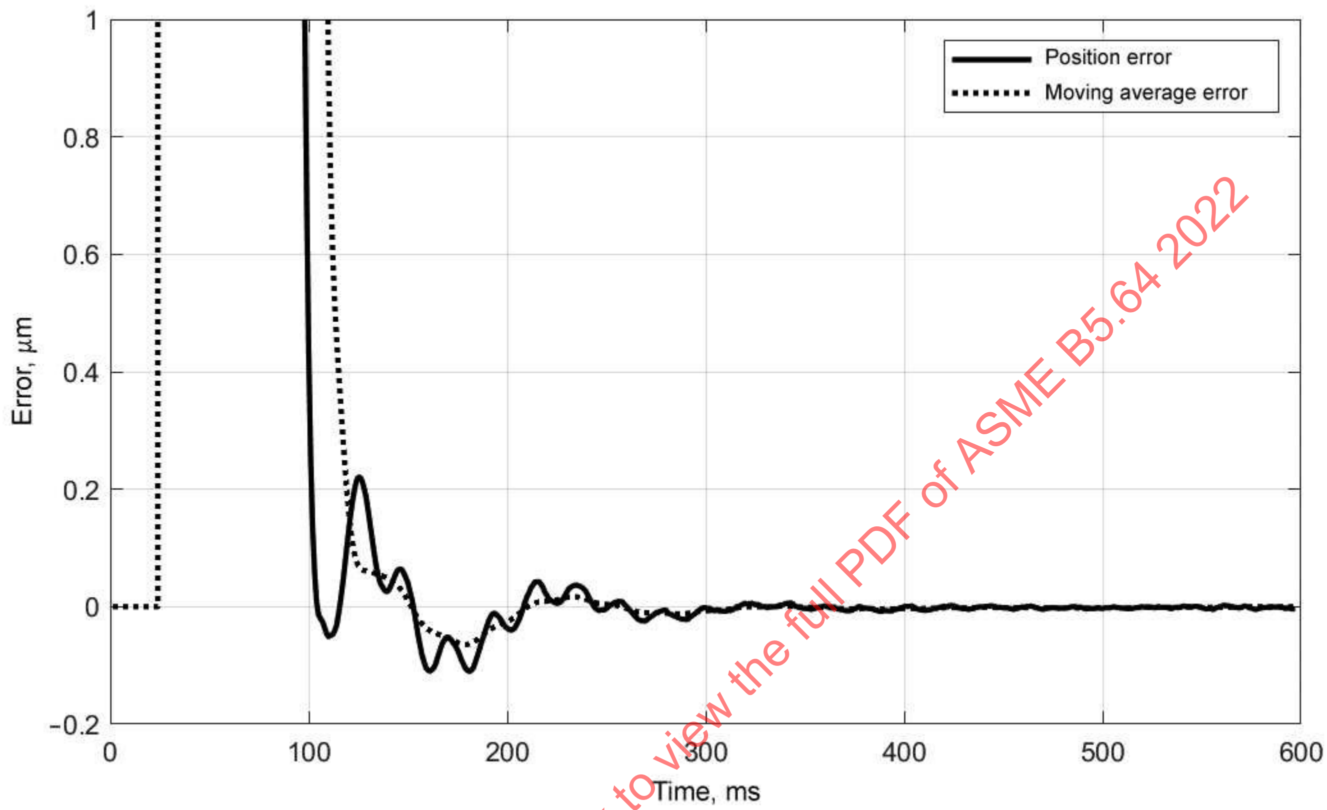


Figure 7-3.4.2-2
Example Moving Standard Deviation, Calculated With a Process Window Time of 50 ms

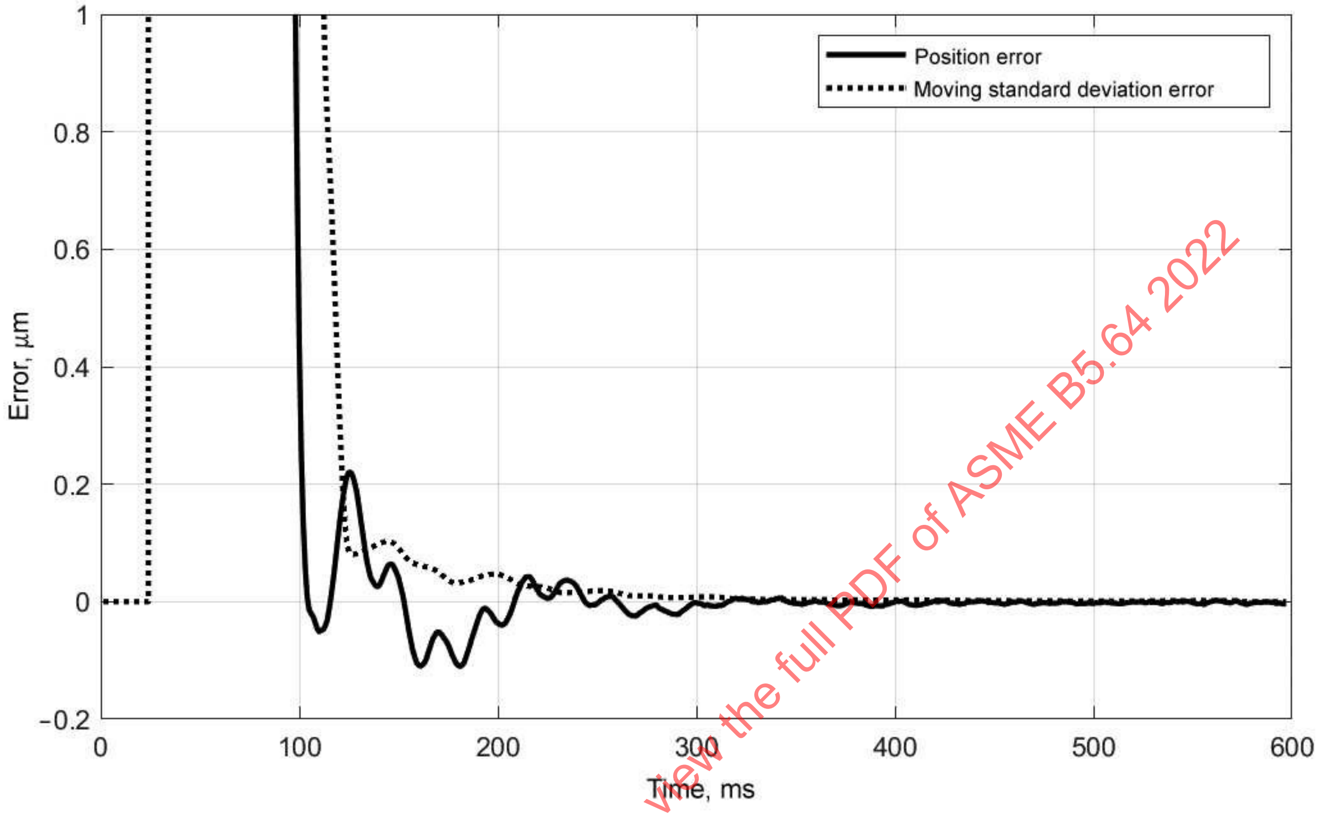


Figure 7-3.4.2-3
Example Moving Peak Error, Calculated With a Process Window Time of 50 ms

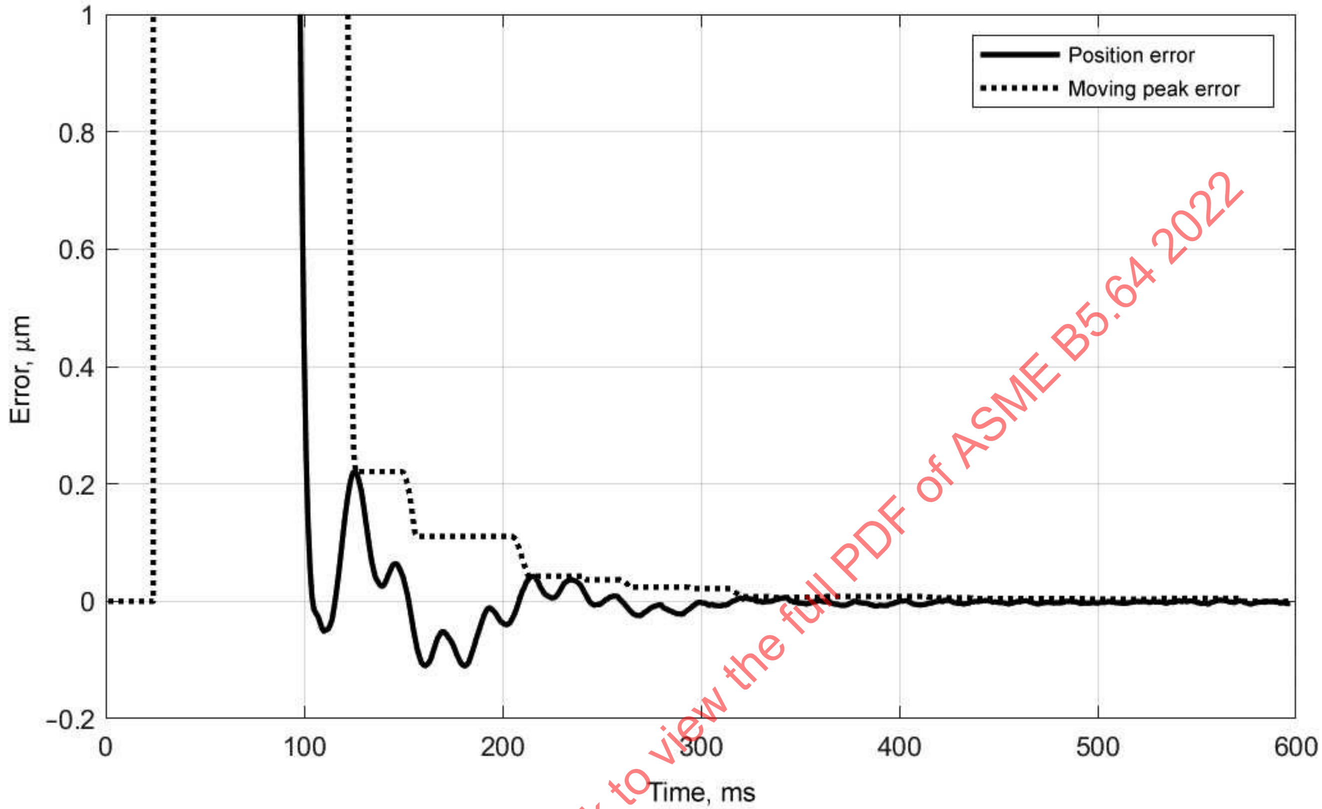


Table 7-3.4.3-1
Move-and-Settle Times for Various Metrics Using a Settling Criteria of 0.05 μm for a Process Window Time of 50 ms

Settle Metric	Move-and-Settle Time, ms
Moving average error	115
Moving standard deviation error	147
Moving peak error	189

Table 7-3.4.3-1 shows the move-and-settle time for each of the three metrics (see Figures 7-3.4.2-1 through 7-3.4.2-3) for the example dataset from para. 7-3.4.2 with a process window time of 50 ms and a position tolerance of 0.05 μm. In general, a different position tolerance may be used to determine the move-and-settle time for each metric, and each position tolerance should be noted in the test report (see para. 7-3.6). As Table 7-3.4.3-1 illustrates, the move-and-settle time depends on the metric chosen to evaluate the move-and-settle test. The appropriate metric should be chosen based on the requirements of the application this test seeks to replicate.

7-3.5 Test Uncertainty Analysis

Uncertainties associated with the measurements for the move-and-settle test are related to uncertainties of the used measurement systems and uncertainties of the axis under test. These uncertainties should be considered when specifying measurement sampling rates and parameters, to avoid situations where neither conformance nor nonconformance to specifications can be demonstrated. Potential measurement uncertainty contributors include

(a) uncertainties of geometric error motions of the linear axis
(b) measurement uncertainty of the test equipment
(c) 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
(d) uncertainty in the sensor calibration factor, u_{CAL}
(e) uncertainty due to the sensor resolution/noise, u_{SR} — evaluated via a sensor noise floor test
(f) uncertainty due to setup repeatability, u_{Δ} — relatively small due to motion being very small
(g) uncertainty due to fixturing vibrations, u_{VIB}

The uncertainty in the position error or the move-and-settle time of the move-and-settle test can be estimated. For example, given a suitably large number of move-and-settle tests, various uncertainty components can be estimated. Figure 7-3.5-1 shows the moving average error of numerous move-and-settle tests captured at multiple starting locations. It is to be expected that the uncertainty of the move-and-settle time increases as the position threshold decreases. Also, there are times near zero crossings for which the average position error is very small. For example, the errors are relatively low at about 150 ms in Figure 7-3.5-1. This type of information can allow a user to make better decisions in designing their overall automation process.

7-3.6 Presentation of Results

Figure 7-3.6-1 shows an example of a move-and-settle test report that includes the move-and-settle time and its expanded uncertainty for each of the metrics.

7-4 INCREMENTAL STEP TEST AND MINIMUM INCREMENTAL MOTION TEST

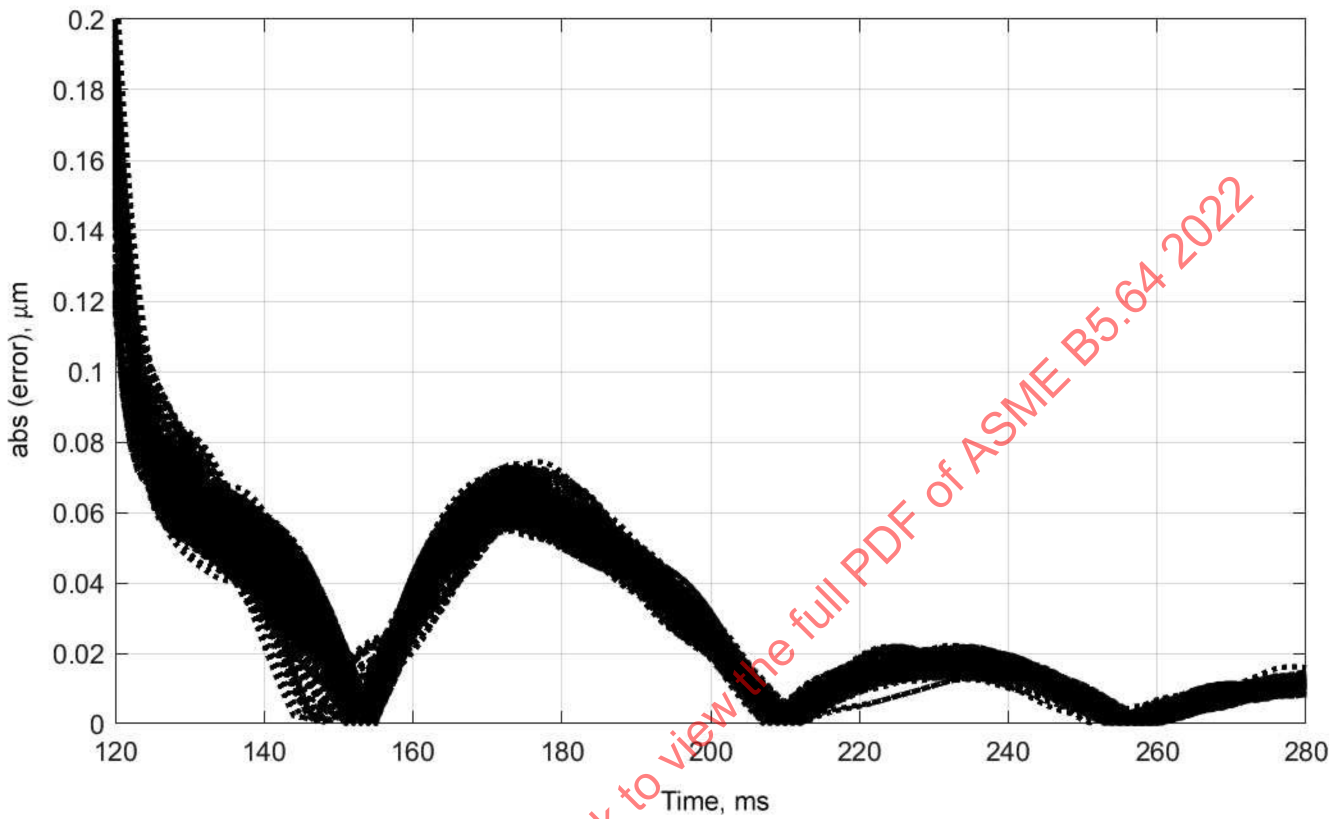
7-4.1 General

Subsection 7-4 describes a series of tests to determine whether a linear positioning system can reliably perform a commanded step. A step size is selected, and the axis is commanded to perform a series of steps. Based on the criteria outlined in subsection 7-4, the axis either is able to perform this commanded step, satisfying the given criteria, or is not able to perform this command step, failing the given criteria. In addition, tests are described that allow a user or manufacturer/supplier of a linear positioning system to determine the minimum incremental motion of an axis. The minimum incremental motion is defined as the size of the smallest reliably detectable step that the positioning system can execute.

7-4.2 General Measurement Setup

7-4.2.1 Equipment. The equipment used to perform the incremental step test and minimum incremental motion test should be the same equipment used for the in-position jitter test. Refer to subsection 7-2 for details.

Figure 7-3.5-1
Moving Average Error for Multiple Move-and-Settle Tests



GENERAL NOTE: Moving average error for multiple move-and-settle tests (overlaid) to show the dataset from which certain uncertainty components of position error or move-and-settle time can be estimated.

Figure 7-3.6-1
Example of a Move-and-Settle Test Report

Move-and-Settle Test Report

Positioning System

Manufacturer: ABC	Model No.: XX	Serial No.: XX
Type: Linear	Max. travel: 200 mm	Max. velocity: 250 mm/s

Controller/drive unit to power the positioning system: ABC P100 S/N 1234

Measurement Setup

Functional point: X = XX mm, Y = XX mm, and Z = XX mm

Axis positions: 0 mm, 10 mm, 20 mm, …600 mm

Load: XX kg

System location: 300 mm × 1.2 m × 1.2 m granite base with passive air isolation

Temperature during test: 22°C

Data acquisition system: Acme D100 S/N 5678

Displacement sensor: Acme S100 S/N 91011

Sampling rate: 10 kHz

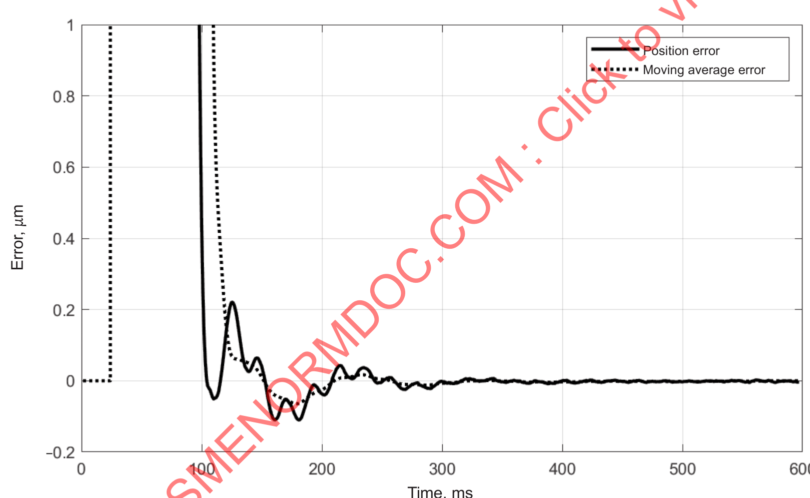
Commanded move distance: 10 mm

Process window time: 50 ms

Position tolerance: 0.05 μm

Process window calculation direction: Centered

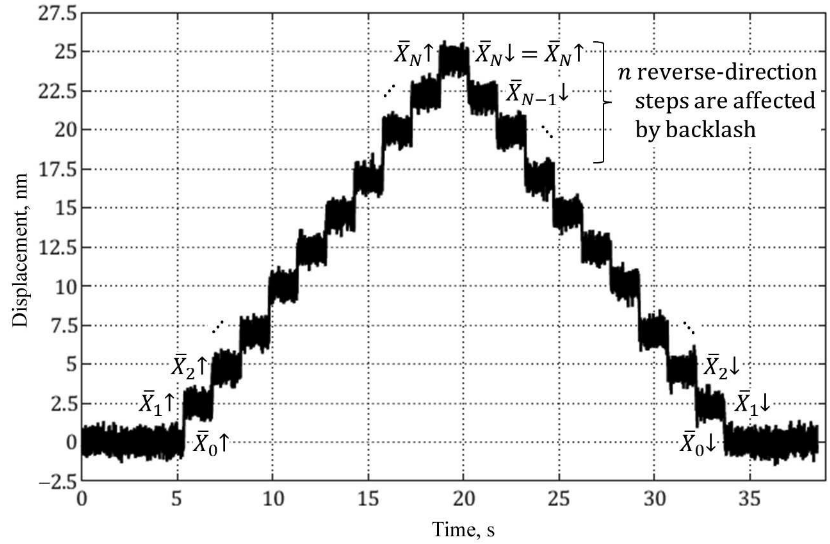
Plot of Data



Move-and-Settle Test Results

Settle Metric	Move-and-Settle Time, ms
Moving average error	115 ± 5.2 (k = 2)
Moving standard deviation error	147 ± 4.9 (k = 2)
Moving peak error	189 ± 9.2 (k = 2)

Figure 7-4.3.1-1
Example Displacement Vs. Time Plot for an Incremental Step Test With a 2.5 nm Commanded Step Size



7-4.2.2 Measurement Setup. The measurement setup for the incremental step test and minimum incremental motion test is the same setup used for characterizing in-position jitter. Refer to subsection 7-2 for details regarding measurement setups for linear positioning systems.

7-4.2.3 Measurement Target Location(s). The measurement shall be performed at a measurement point (see Section 5) or at multiple measurement points agreed upon by the user and the manufacturer/supplier. If measurement points are not agreed upon, then three measurement points, located at the center and close to the two ends of travel, allowing a direction reversal move to remove backlash from the starting location, shall be used. The distance from the carriage surface to the measurement points shall be chosen to represent the nominal location where processes may occur by end users. In all measurement cases, the locations of measurement points shall be reported with the measurement results.

7-4.2.4 Measurement Bandwidth. The required measurement bandwidth shall be equal to the bandwidth used in characterizing in-position jitter (see subsection 7-2). Measurement bandwidth shall be reported with the measurement results for the incremental step test and the minimum incremental motion test.

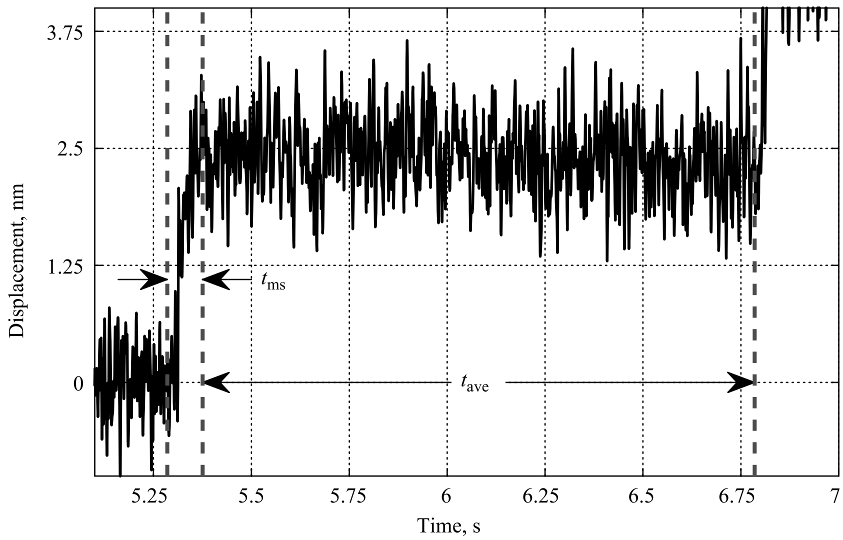
7-4.3 Incremental Step Test

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 7-4.3.1-1 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.

A step size, X_{CS}, (e.g., 2.5 nm) for the incremental step test shall be agreed upon between the user and the manufacturer/supplier of the positioning system. If a step size is not agreed upon, then the minimum specified step size shall be used. Also, the number of forward steps and the number of reverse steps shall be agreed upon between the user and the manufacturer/supplier of the positioning system. If the numbers of steps are not agreed upon, then ten steps shall be used for either the forward or reverse direction. The selected step size and the numbers of steps shall be reported with the measurement results.

The average time, t_{ave}, is shown in Figure 7-4.3.1-2 and must be determined for the step size, X_{CS}, before the measurement procedure can begin. The average time, t_{ave}, is defined as the amount of time the data points are averaged when the motion is settled to determine the mean step position of the ith step, $\bar{X}_i$. The average time, t_{ave}, shall be at least 2 times greater than t_{ms}, the move-and-settle time, which shall be determined for the given step size based on the procedure in subsection 7-3. The settle metric (see subsection 7-3) used to determine t_{ms} shall be agreed upon between the user and the

Figure 7-4.3.1-2
Illustration of Move-and-Settle Time, t_{ms}, and Average Time, t_{ave}



manufacturer/supplier. Also, a minimum of a 100 data points shall be collected within the average time, t_{ave}, to ensure an adequate statistical sample size.

Finally, the in-position jitter (see subsection 7-2), s, shall be characterized before performing the incremental step test. The results from the in-position jitter test shall be used in the data analyses performed for the incremental step test (see para. 7-4.3.3).

7-4.3.2 Measurement Procedure. Before data collection, the axis is commanded to approach the start point (the position at the initial time in Figure 7-4.3.1-1) in the forward direction, whether positive or negative in direction with respect to the axis, to eliminate backlash and hence a reversal error for the first step in the forward direction. Then, data is collected as the axis performs the forward steps and then the reverse steps, as desired, e.g., as seen in Figure 7-4.3.1-1. Additional steps or warm-up cycles may be used if agreed upon between the user and the manufacturer/supplier, for example, to allow for the exclusion of the first step, or multiple number of initial steps, in the reserve direction that are affected by backlash.

7-4.3.3 Data Analysis. The incremental step size, $X_{\text{inc},i}$, for the forward (↑) and reverse (↓) directions are defined as

$$X_{\text{inc},j}\uparrow = |\overline{X}_i\uparrow - \overline{X}_{i-1}\uparrow| \tag{7-4-1}$$

$$X_{\text{inc},j}\downarrow = |\overline{X}_i\downarrow - \overline{X}_{i-1}\downarrow| \tag{7-4-2}$$

for $i \geq 1$, where $\overline{X}_i\uparrow$ or $\overline{X}_i\downarrow$ are the mean step position of the ith step in the forward direction or reverse direction, respectively. Every $\overline{X}_i\uparrow$ or $\overline{X}_i\downarrow$ is the average position calculated from the data within the window of the average time, t_{ave}, that was determined before the measurement procedure began (see para. 7-4.3.1). Also, because the axis continued motion in the forward direction from $\overline{X}_0\uparrow$ to $\overline{X}_i\uparrow$, $\overline{X}_i\downarrow$ will not contain a reversal error. In contrast, the first n reverse-direction steps, $X_{\text{inc,N+1}-i}\downarrow$ for $i \in [1, n]$ (see Figure 7-4.3.1-1), are affected by backlash due to the reversal in motion from the final position in the forward direction. The number, n, of reverse-direction steps that are affected by backlash is known approximately as

$$n = \text{ceil}(B/X_{CS}) \tag{7-4-3}$$

where B is the system reversal error and ceil(x) is the ceiling function that maps its argument x to the least integer greater than or equal to x. The n reverse-direction steps may be neglected in the subsequent analysis, to ensure that the analysis is for motion that is free from any backlash or machine hysteresis, and if so, the lack of use of those n reverse-direction steps shall be reported in the presentation of results (see para. 7-4.7).

The sample mean, $\overline{X}_{inc}$, and sample standard deviation, s_{inc}, of the incremental step sizes are calculated for the forward and reverse directions as follows:

$$\overline{X}_{inc}\uparrow = \frac{1}{N\uparrow}\sum_{1}^{N\uparrow} X_{inc,i}\uparrow \tag{7-4-4}$$

$$\overline{X}_{inc}\downarrow = \frac{1}{N\downarrow}\sum_{1}^{N\downarrow} X_{inc,i}\downarrow \tag{7-4-5}$$

$$s_{inc}\uparrow = \sqrt{\frac{1}{N\uparrow - 1}\sum_{1}^{N\uparrow}\left(X_{inc,i}\uparrow - \overline{X}_{inc}\uparrow\right)^2} \tag{7-4-6}$$

$$s_{inc}\downarrow = \sqrt{\frac{1}{N\downarrow - 1}\sum_{1}^{N\downarrow}\left(X_{inc,i}\downarrow - \overline{X}_{inc}\downarrow\right)^2} \tag{7-4-7}$$

where $N\uparrow$ and $N\downarrow$ are the number of steps performed in the forward direction and reverse direction, respectively. The sample mean and sample standard deviation of the combined forward and reverse steps are calculated as follows:

$$\overline{X}_{inc} = \frac{1}{N_T}\left(\sum_{1}^{N\uparrow} X_{inc,i}\uparrow + \sum_{1}^{N\downarrow} X_{inc,i}\downarrow\right) \tag{7-4-8}$$

$$s_{inc} = \sqrt{\frac{1}{N_T - 1}\left(\sum_{1}^{N\uparrow}\left(X_{inc,i}\uparrow - \overline{X}_{inc}\right)^2 + \sum_{1}^{N\downarrow}\left(X_{inc,i}\downarrow - \overline{X}_{inc}\right)^2\right)} \tag{7-4-9}$$

where N_T is the total number of steps performed in the test; that is, $N_T = N\uparrow + N\downarrow$.

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 used 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 used to determine whether the axis performed the commanded incremental step in a certain direction if agreed upon between the user and the manufacturer/supplier.

(a) Unidirectional Incremental Step Criteria. To determine if the linear positioning system performed the commanded incremental step in a unidirectional manner, for either the forward or reverse direction, the following criteria must be met for the chosen direction:

(1) Criterion A1. Four times the standard deviation of the in-position jitter, s, must be less than the commanded incremental step size:

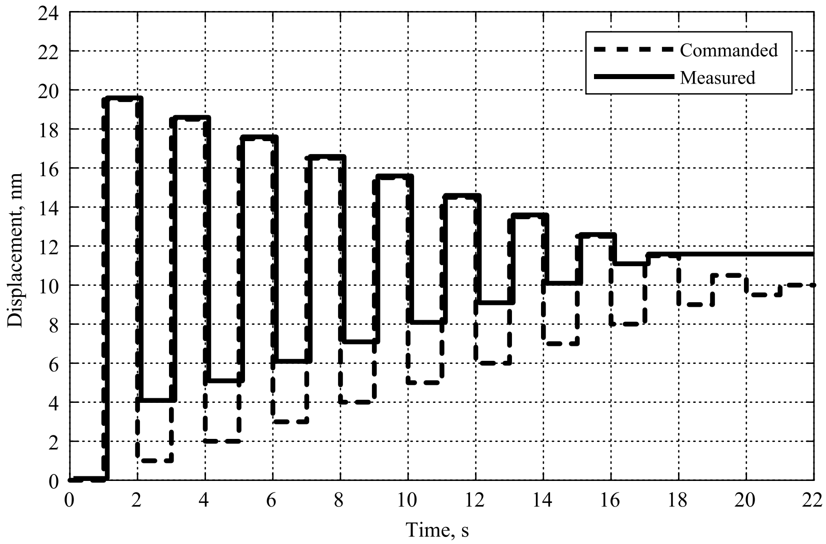
$$4s < X_{CS} \tag{7-4-10}$$

(2) Criterion A2. The sample mean of the unidirectional incremental step sizes compared to the incremental commanded step size must be less than 10% of the incremental commanded step size:

$$\begin{aligned}\frac{|X_{CS} - \overline{X}_{inc}\uparrow|}{X_{CS}} &< 0.10 \text{ for forward direction, or}\\ \frac{|X_{CS} - \overline{X}_{inc}\downarrow|}{X_{CS}} &< 0.10 \text{ for reverse direction}\end{aligned} \tag{7-4-11}$$

(3) Criterion A3. Four times the standard deviation of the unidirectional incremental step size must be less than the incremental commanded step size:

Figure 7-4.4-1
Successively Decreasing Steps Used to Measure the Incremental Step Reversal Error



$$4s_{\text{inc}}\uparrow < X_{CS} \text{ for forward direction, or}$$
$$4s_{\text{inc}}\downarrow < X_{CS} \text{ for reverse direction} \qquad (7\text{-}4\text{-}12)$$

(b) Bidirectional Incremental Step Criteria. To determine whether the linear positioning system performed the commanded incremental step in a bidirectional manner, the following criteria must be met:

(1) Criterion B1. Same as Criterion A1.

(2) Criterion B2. The maximum sample mean of the forward- and reverse-direction incremental step sizes compared to the incremental commanded step size must be less than 10% of the incremental commanded step size:

$$\max\left[\left(\frac{|X_{CS} - \overline{X}_{\text{inc}}\uparrow|}{X_{CS}}\right), \left(\frac{|X_{CS} - \overline{X}_{\text{inc}}\downarrow|}{X_{CS}}\right)\right] < 0.10 \qquad (7\text{-}4\text{-}13)$$

(3) Criterion B3. Four times the maximum standard deviation of the forward- and reverse-direction incremental step sizes must be less than the incremental commanded step size:

$$4\max(S_{\text{inc}}\uparrow, S_{\text{inc}}\downarrow) < X_{CS} \qquad (7\text{-}4\text{-}14)$$

If both the forward- and reverse-direction results satisfy the unidirectional criteria, but the bidirectional criteria is not satisfied, then the incremental step reversal error (see para. 7-4.4) must be determined and presented with the results of this test. Also, for the bidirectional data to satisfy the criteria in that case, the backlash would have to be reduced.

Alternatively, if the n reverse-direction steps were neglected in the previous analysis, then the incremental step reversal error (see para. 7-4.4) must be determined and presented with the results of this test.

7-4.4 Incremental Step Reversal Error

To determine the incremental step reversal error, alternating successive steps starting at a step size much larger than the commanded incremental step are performed as illustrated in Figure 7-4.4-1. However, especially for nanometer-level displacements, the performance is affected by warm-up cycles, ramp rates, dwell times, the approach direction, among other factors. Hence, the setup should be agreed upon between the user and the manufacturer/supplier, and the setup should be fully documented including its corresponding computer files.

The incremental step reversal error, B_{inc}, is calculated as one half of the commanded incremental step size for which the step error is closest to equaling 50% of the commanded incremental step size:

$$B_{\mathrm{inc}} = \frac{X_{CS,i}}{2} \text{ when } \frac{|X_{\mathrm{CS},i} - X_{\mathrm{inc},i}|}{X_{CS,i}} \approx 0.50 \tag{7-4-15}$$

where $X_{\mathrm{CS},i}$ is the commanded incremental step at the ith step. If the step error is greater than 50% for all steps taken, then the starting step size chosen was not large enough. In that case, the starting step size shall be increased, and the test is repeated until a step error of approximately 50% of the step size is achieved.

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 para.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 para. 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 para. 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 para. 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 para. 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.

7-4.6 Test Uncertainty Analysis

Uncertainties associated with the measurement of incremental steps, the incremental step reversal error, and the minimum incremental motion are related to uncertainties of the used measurement systems and uncertainties of the axis under test. These uncertainties should be considered when specifying measurement sampling rates and parameters, to avoid situations where neither conformance nor nonconformance to specifications can be demonstrated. Potential measurement uncertainty contributors include:

(a) uncertainties of geometric error motions of the linear axis
(b) measurement uncertainty of the test equipment
(c) 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
(d) uncertainty in the sensor calibration factor, u_{CAL}
(e) uncertainty due to the sensor resolution/noise, u_{SR} — evaluated via a sensor noise floor test
(f) uncertainty due to setup repeatability, u_{Δ}— relatively small due to motion being very small
(g) uncertainty due to fixturing vibrations, u_{VIB}
(h) uncertainty of the probe spacing distance

7-4.7 Presentation of Results

Figure 7-4.7-1 shows an example of an incremental step test and minimum incremental motion test report.

7-5 STATIC POSITIONING ACCURACY AND REPEATABILITY

Subsection 7-5 describes test methods used to evaluate the static positioning accuracy and repeatability of single-axis linear positioning systems. It addresses error deviations in the axis direction of motion for stationary target positions. The techniques and methods described apply to linear positioning systems. When multiple axes are tested simultaneously, the methods described here do not apply.

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

Figure 7-4.7-1
Example of an Incremental Step Test and Minimum Incremental Motion Test Report

Incremental Step Test and Minimum Incremental Motion Test Report

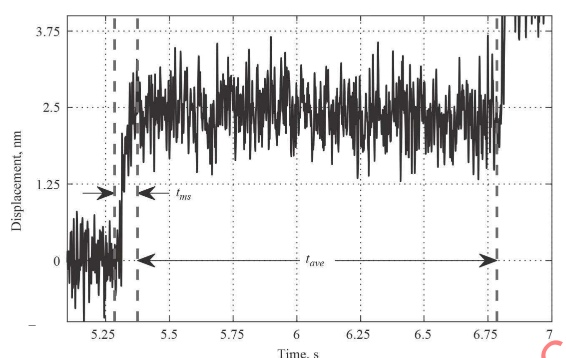
Positioning System

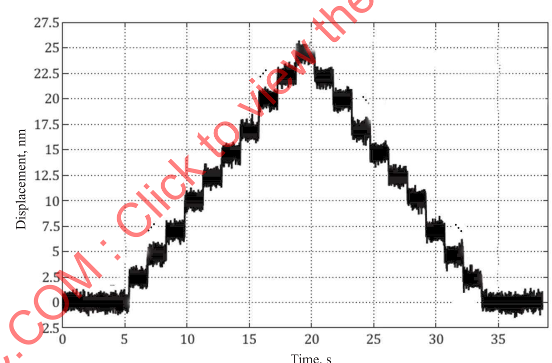
Manufacturer: ABC	Model No.: XX	Serial No.: XX
Type: Linear	Max. travel: 200 mm	Max. velocity: 250 mm/s
Controller/drive unit to power the positioning system: ABC P100 S/N 1234		

Measurement Setup

Functional point: X = XX mm, Y = XX mm, and Z = XX mm
Starting axis position: 100 mm
Load: XX kg
System location: 300 mm × 1.2 m × 1.2 m granite base with passive air isolation
Temperature during test: 22°C
Commanded step size: 2.5 nm
Number of forward/reverse steps: 10/10
Programmed velocity between steps: 50 nm/s
Data acquisition system: Acme D100 S/N 5678
Displacement sensor: Acme S100 S/N 91011
Sampling rate: 10 kHz
Data filter: Second-order Butterworth low-pass filter with a 500 Hz cutoff frequency
Move-and-settle time, t_{ms}: 0.10 s
Average time, t_{ave}: 1.4 s
In-position jitter: 0.9 nm

Plots of Filtered Data





Incremental Step Test Results

	Direction of Motion		
	Forward	Reverse	Combined
Sample Mean, $\overline{X}_{inc}$, nm	2.51	2.53	2.52
Sample Standard Deviation, s_{inc}, nm	0.051	0.074	0.065

Direction of Motion	Criteria			Criteria Satisfied?	Criteria			Criteria Satisfied?
	A1	A2	A3		B1	B2	B3	
Forward	Yes	Yes	Yes	Yes				
Reverse	Yes	Yes	Yes	Yes				
Combined					Yes	Yes	Yes	Yes

Minimum Incremental Motion Test Results

Unidirectional minimum incremental motion = 2.0 nm move-and-settle test described in subsection 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 Measurement Setup

The measurement setup is designed to measure the relative displacements between the moving element of the axis under test in the direction of motion and a reference frame that is fixed to the stationary element of the positioning system.

7-5.2.1 Equipment. Linear displacement shall be measured along a line that is parallel to the axis average line of motion of the axis under test and that passes through a series of measurement points. The position of the measurement points shall be agreed upon between the user and manufacturer/supplier and include, among others, the chosen target positions, and the distance with respect to a reference surface (see subsection 5-1). Alignment of the measuring instrument to the axis motion should be such that the cosine error is minimized to a level that meets the required test uncertainty. The contribution of the cosine error to the standard measurement uncertainty should be determined (see para. 12-6.2).

A variety of measuring devices can be used to measure the position of the measured point. A summary of such measurement devices and the usage of them can be found in Section 11.

7-5.2.2 Definition of Travel Range and the Measurement Range. In this Standard, the travel range, L_t, is used to describe the maximum range of a linear path over which the carriage can be controlled for the measurements described here. The measurement range, L_m, is the part of the travel range used for the evaluation of relevant measurands. The measurement range is defined specifically so that the first and the last target positions can be approached from either side (i.e., bidirectionally).

It is important to distinguish the measurement range from the travel range. The measurement range is the range for which data points are being evaluated. This range shall be defined in a manner that allows for bidirectional approach of the endpoints (see para. 7-5.2.2). For the linearity evaluation, points within the travel range but outside the measurement range are measured even if these points cannot be approached bidirectionally. All data will be saved, but the points measured beyond the measurement range will only be used in certain parts of the evaluation.

The measurement range can be calculated from the full travel range as follows:

$$L_m = L_t - 2Q \tag{7-5-1}$$

where Q is any length that ensures that all points within the travel range can be approached bidirectionally. This value should be as small as possible to achieve a maximum measurement range.

7-5.2.3 Selecting the Target Position. If every target position, P_i, can be freely selected (no customer specifications) and sampling should be performed in an evenly spaced sequence, the selection should follow

$$P_i = (i - 1)p + Q \tag{7-5-2}$$

where

i = the number of the current target position, starting with 1 and ending with the number of points m

p = the nominal interval based on uniform distribution of the target points within the measurement range, e.g., m points result in $p = L_m/(m - 1)$

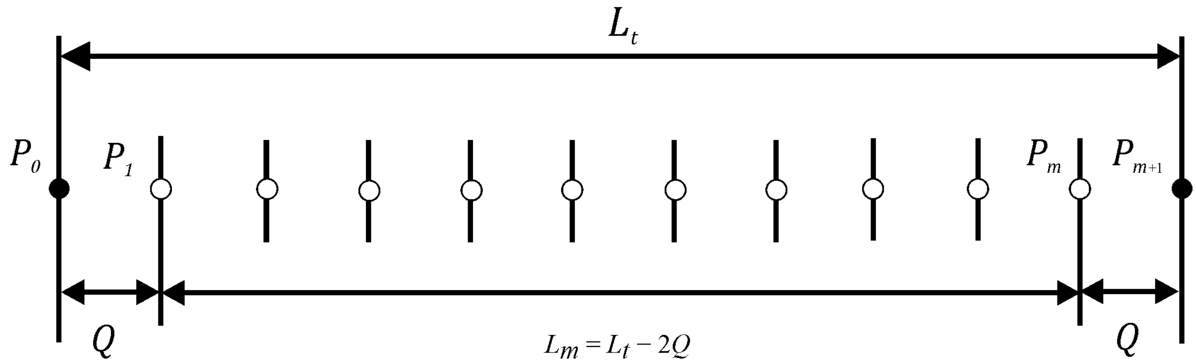
Target positions are required over the full travel range. If the full travel range is to be sampled in equidistant steps such that $Q = p$, the nominal interval is $p = L_t/(m + 1)$. If Q is not defined explicitly, Q shall equal p, provided that p is large enough that P_1 and P_m can be approached bidirectionally.

An illustration of the relationship between the travel range, the measurement range, and the target positions is shown in Figure 7-5.2.3-1.

If sampling is performed using random target positions, an example for a pseudo-random sequence can be found in para. 7-5.10.2.

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 para. 7-5.11).

Figure 7-5.2.3-1
Illustration of Travel Range and Measurement Range



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, e.g., a displacement measuring interferometer (DMI), the position of the target points shall be chosen in a way that ensures 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.

7-5.3 Measurement Procedure

The system is to be warmed up prior to measuring according to the procedure agreed upon between the user and the manufacture/supplier. The procedure may include monitoring and recording the temperature of the moving element until the temperature stabilizes. The warm-up procedure is to be documented in the test report.

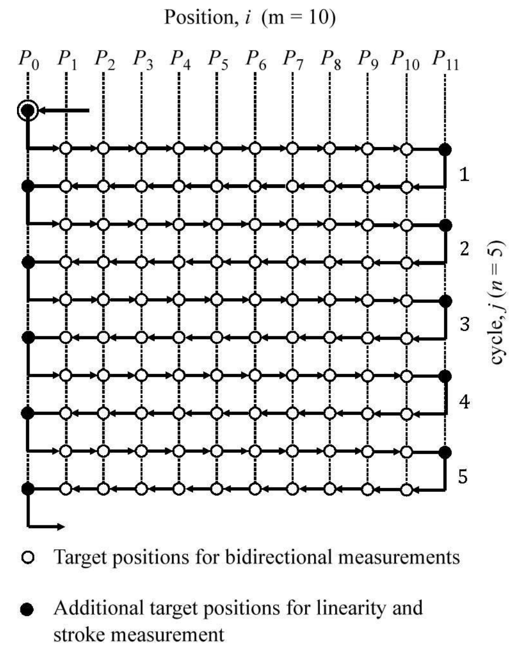
Because the measurement is quasi-static, low-pass filtering or oversampling of the measurement data is allowed. The filter frequency or oversampling rate shall be recorded and presented with the measurement results. The measurements described in this section include the periodic error, which is a component of the total error; para. 7-5.9 describes a test for periodic errors. For digitally controlled systems, the measurement data can be used to compensate for errors of the system.

A typical sampling pattern is shown in Figure 7-5.3-1. The measurement cycle is repeated at least 5 times, resulting in 10 full traversals of the axis as shown. That is, at each target position in the measurement range, at least 10 measurements will be collected (five per direction).

Because the end-of-travel target positions P_0 and P_{m+1} are approached only once (unidirectionally) for measurement, whereas the intermediate measurement range target positions P_1 and P_m are approached twice (bidirectionally), there are $2(m + 1)$ measurement points collected during one round trip measurement sweep. If the data are stored in arrays with equal length for forward and backward directions, keep in mind that both of the arrays have length $(m + 1)$, but the corresponding data for forward and backward directions are offset by one position in the arrays because there is a unidirectional datum at the end of the forward array, whereas it is at the beginning of the backward array when the arrays are indexed as shown in Figure 7-5.3-1. The first data point measured at P_0 at the beginning is a single data point.

When a measurement point is reached during the test cycle, an appropriate delay or trigger will be applied as discussed in para. 7-5.1. At least one measurement from the external measuring system is to be recorded for each point. Oversampling in the measuring system is permissible.

Figure 7-5.3-1
Example Test Cycle Having *m* = 10 Points Measured Bidirectionally 5 Times, 5 per Direction and Each Endpoint Measured Unidirectionally 5 Times



7-5.4 Data Analysis

7-5.4.1 Calculating Position Error. The deviation of position at the *i*th target position for the *j*th measurement cycle, $x_{ij}\uparrow$ or $x_{ij}\downarrow$, corresponds to the actual position, P_{ij}, reached by the object to be measured, minus the target position P_i (commanded position), where *i* ranges from 1 to *m*. The symbols ↑ and ↓ signify a value for the approach of the target position in either positive (↑) or negative (↓) direction, respectively. The deviation will be computed for each *j*th measurement cycle at the *i*th target position as

$$x_{ij} = P_{ij} - P_i \tag{7-5-3}$$

In terms of the analysis, "unidirectional" describes test series in which only the target positions that are approached in one direction of the axis are analyzed. The term "bidirectional" describes test series in which the target positions that are approached in both directions of the axis are analyzed. Although target positions P_0 and P_{m+1} are approached unidirectionally, they are not included in any position error calculation.

7-5.4.2 Calculation Rules for Measuring Open-Loop Systems. Often, when an open-loop system is to be measured, a position command value corresponds only indirectly to a physical position. For example, the applied voltage is the typical commanded value in piezo systems. For this reason, the commanded value, Z_i, needs to be converted to a commanded (or expected) position, P_{iE}, with the help of the conversion factor, a_E, in a consistent system of units to enable the required calculation procedures. This leads to

$$P_{iE} = a_E Z_i \tag{7-5-4}$$

The deviation of position is then defined as

$$x_{ij} = P_{ij} - P_{iE} \tag{7-5-5}$$

The conversion factor can either be computed from the system design data or be experimentally determined prior to the actual measurement procedure. Based on the standard measurement process, it is also possible to derive the correction factor from the maximum change of the measured position divided by the maximum change of the command values.

Measurement errors computed in subsequent sections of this Standard will include errors associated with determination of the correction factor. This must be considered when calculating the measurement uncertainty.

EXAMPLE: The system is controlled in open-loop operation with a command voltage (volt) and the measurement is conducted with an interferometer, yielding position values in micrometers (μm). At a voltage of 0 V, the interferometer measures a position of 0 μm, and a voltage of 100 V results in a position of 80 μm. Consequently, the conversion factor a_E is 0.8 μm/V.

7-5.4.3 Thermal Drift and Correction of Thermal Drift. Thermal drift during a test cycle can influence the measured actual position and the deviation of position because the change of temperature and the effects of thermal expansion cause movement of the test system and measurement system components relative to each other. This thermal drift will especially influence the measurement results for high precision positioning systems. Therefore, precautions must be taken to limit this thermal drift. The following are the two options for handling the thermal drift:

(a) Limit the temperature variation during the measurement procedure. The maximum allowed temperature variation and the procedure to measure this temperature variation will be based on the agreement between the user and the manufacturer/supplier.

(b) If the temperature cannot be controlled sufficiently for the measurement application, a correction algorithm as described in para. 7-5.10.3 can be applied to the measured position values to correct for the thermal drift. Note that this correction algorithm captures not only drift due to temperature variation, but also drifts due to any other reason. This correction method shall be used only upon agreement between the user and the manufacturer/supplier.

7-5.4.4 Correcting Abbe Error. The calculated deviations or the data resulting from the thermal drift correction (see para.7-5.10.3) can be corrected for Abbe error. Abbe error is caused by the combination of tilting of the moving element (e.g., due to pitch and yaw) and a distance offset between the functional/working point of the system under test (e.g., the surface of a stage) and the measurement point, as shown in Figure 7-5.4.4-1. Ideally, the functional point and the measuring point should be identical. The described Abbe correction can be used if such a measurement setup is not possible. The Abbe error correction is used to transform the collected data from the measurement point to the functional/working point. A typical example arises due to target mirror tilt in an interferometer. Depending on the position of the measurement mirror, a tilt error may occur in one or two directions. To correct for Abbe error, in addition to the linear position measurement, an autocollimator (or any other suitable angle-measuring device) may be applied simultaneously and at the same linear position to measure the tilt displacement angles. If simultaneous linear and angular measurements are not made, then angle measurements correlated with linear position should be made separately.

The variables α_{ij} and β_{ij} denote the angles resulting from the angular measurement. In the same manner, l_α and l_β denote the distance between the pivot points (e.g., from the mirror), as shown in Figure 7-5.4.4-1. The distances l_α and l_β are assumed to be constants that are independent of position P_{ij}. The new corrected values, x_{ij}^{A}, for sufficiently small angles are approximated as

$$x_{ij}^{\mathrm{A}} = x_{ij} + l_\alpha\ \alpha_{ij} + l_\beta\ \beta_{ij} \tag{7-5-6}$$

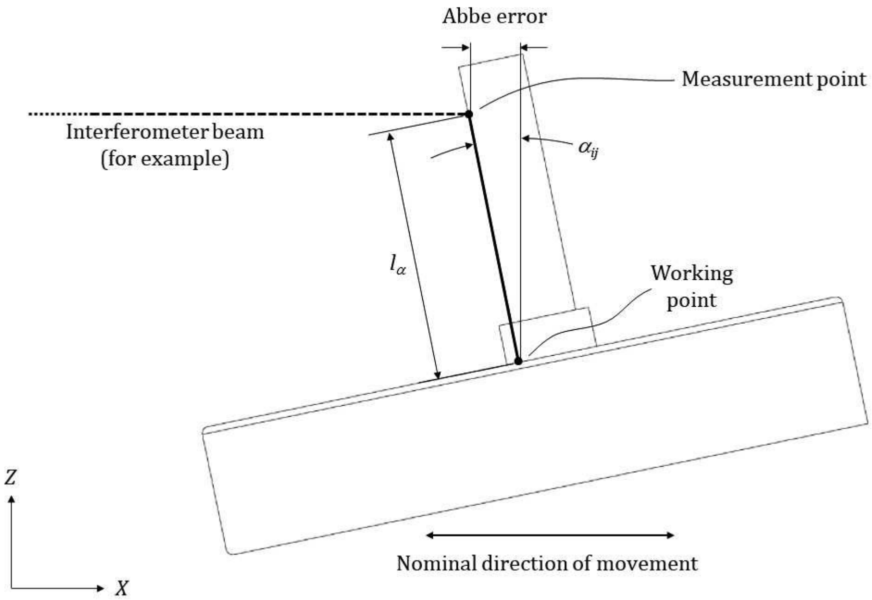
The corrections are positive for the angles and offsets shown in Figure 7-5.4.4-1; that is, $x_{ij}^{\mathrm{A}} > x_{ij}$.

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.

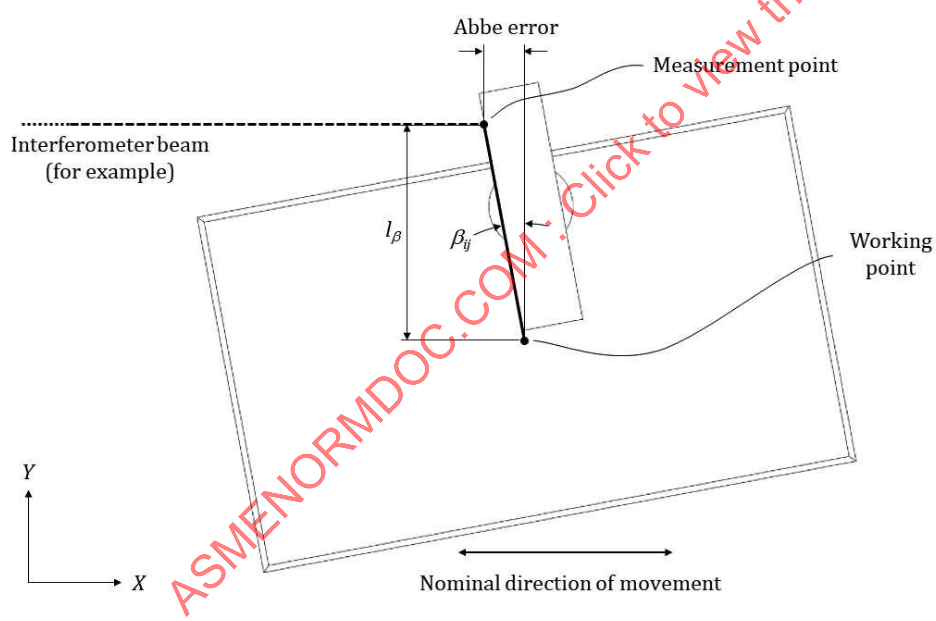
Figure 7-5.4.5-1 illustrates the two normalization methods. Figure 7-5.4.5-1, illustration (a) shows a set of measurement data without any corrections along with a line calculated to pass through the endpoints of the data and a line calculated according to a least-squares linear regression. To correct the measured data, one or the other calculated line is subtracted from the measurement data. In Figure 7-5.4.5-1, illustration (b), the line through the endpoints has been subtracted from the data. Under this normalization, the data endpoints have zero deviation. In Figure 7-5.4.5-1, Illustration (c), the least-squares fit regression line has been subtracted from the data. Under this normalization, the total deviation has been minimized in a least-squares sense.

7-5.4.6 Detailed Procedure for Linear Normalization. Linear normalization is used based on the assumption that there is an underlying linear relationship between the target position and the positioning deviation. Then, the deviation of position may be viewed in terms of deviation from this linear relationship. To normalize the positioning deviations, as

Figure 7-5.4.4-1
Abbe Error for Both Pitch Angle, α_{ij}, and Yaw Angle, β_{ij}, for the Case of Measuring With an Interferometer



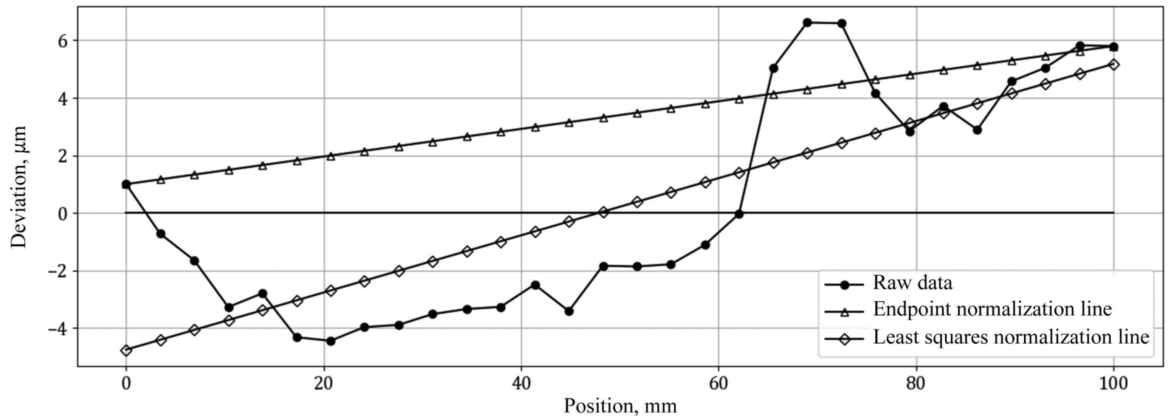
(a) Abbe Error for Pitch Angle, α_{ij}



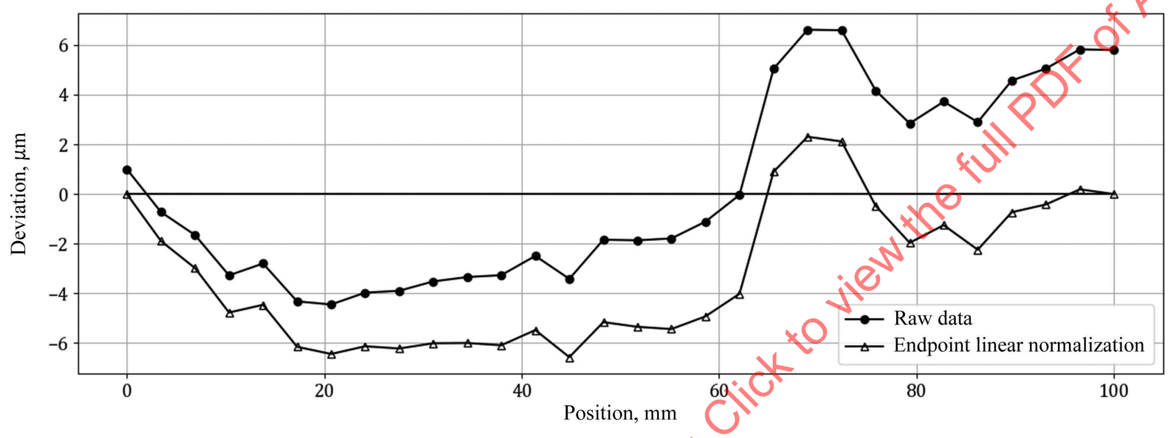
(b) Abbe Error for Yaw Angle, β_{ij}

GENERAL NOTE: The distances from the measuring point to the working point are l_α and l_β.

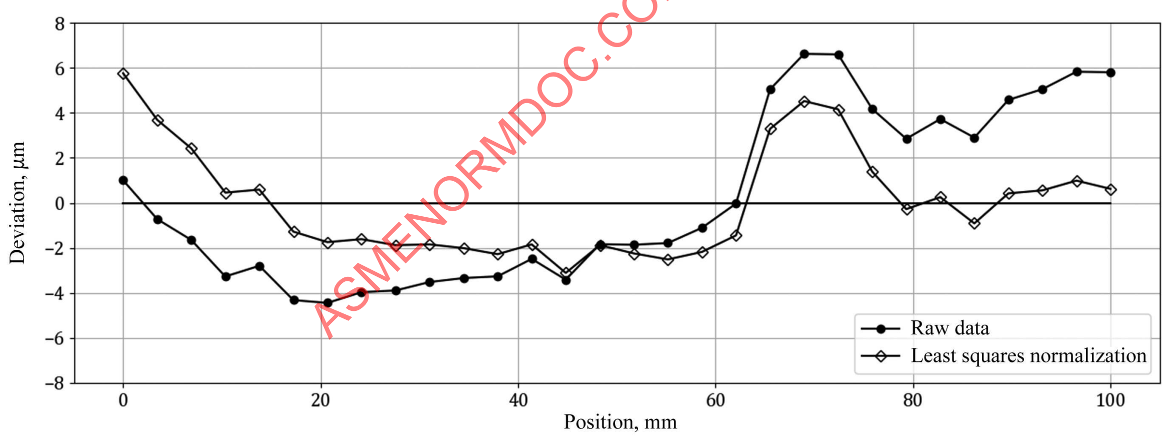
Figure 7-5.4.5-1
Examples of Measurement Data With Different Normalizations



(a) [Note (1)]



(b) [Note (2)]



(c) [Note (3)]

NOTES:
(1) Plot of the raw data along with lines determined by the endpoint normalization method and the least-squares normalization method.
(2) Plot of measurement data and data normalized using endpoint normalization.
(3) Plot of measurement data and data normalized using least-squares linear normalization.

discussed in para. 7-5.4.5, either the least-squares normalization line or the endpoint normalization line is subtracted from the positioning deviations in relation to the commanded target positions. Either normalization line is calculated based on the mean values of all measurands for each position for all repetitions. If endpoint linear normalization is used, the target positions P_0 and P_{m+1} will be included in the calculation. However, the most commonly used method for linear normalization is least-squares linear normalization applied to the mean deviation, $\bar{x}_i$, at the commanded positions P_1 to P_m. The mean deviation of position used for the least-squares regression is calculated as

$$\bar{x}_i = \frac{1}{2n}\sum_{j=1}^{n}\left(x_{ij}\uparrow + x_{ij}\downarrow\right) \tag{7-5-7}$$

where n is the number of bidirectional measurement cycles, e.g., n = 5.

This linear normalization as a correction method should not be confused with the calculation of the linearity of a system. In contrast, the purpose of the normalization of the dataset is to remove an underlying linear dependence to enable calculations as described in para. 7-5.5.

7-5.4.7 Nomenclature for Corrected Data. For further calculations, x_{ij} will denote the uncorrected positioning deviations. The values with drift correction, tilt error correction, or linear normalization are denoted by the appropriate superscripts to clearly distinguish among the corrected data types. The symbol $x^{\mathrm{L}}{}_{ij}$ denotes the linearly normalized deviations. The deviation values subjected to linear normalizations can either be the uncorrected values or the values corrected for thermal drift, Abbe error, or both, namely, $x^{\mathrm{D}}{}_{ij}$, $x^{\mathrm{A}}{}_{ij}$, or $x^{\mathrm{DA}}{}_{ij}$, respectively. If data is corrected for both thermal drift and Abbe error and then normalized to a linear relationship, the corrected data is denoted as $x^{\mathrm{DAL}}ij$.

7-5.5 Calculation of the Static Positioning Error, Reversal Error, Repeatability and Accuracy

This section describes the data analysis procedure that must be performed to calculate the positioning error, the reversal error, the repeatability, and the accuracy of single-axis linear positioning systems.

The mean unidirectional positioning deviation at a position, $\bar{x}_i\uparrow$ or $\bar{x}_i\downarrow$, is the average value of positioning deviations for a series of n unidirectional approaches to the target positions, where i is an integer from 1 to m. These values are calculated as

$$\bar{x}_i\uparrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij}\uparrow \tag{7-5-8}$$

and

$$\bar{x}_i\downarrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij}\downarrow \tag{7-5-9}$$

The mean bidirectional positioning deviation at a position, $\bar{x}_i$, is the average value of the mean unidirectional deviations at a position, $\bar{x}_i\uparrow$ and $\bar{x}_i\downarrow$; that is,

$$\bar{x}_i = \frac{\bar{x}_i\uparrow + \bar{x}_i\downarrow}{2} \tag{7-5.10}$$

The mean bidirectional positioning error, M, is the difference between the algebraic maximum and minimum values of the mean bidirectional deviations within the measurement range:

$$M = \max(\bar{x}_i) - \min(\bar{x}_i) \tag{7-5-11}$$

The unidirectional systematic positioning error, $E\uparrow$ or $E\downarrow$, is the difference between the algebraic maximum and minimum values of the mean unidirectional positioning deviations $\bar{x}_i\uparrow$ and $\bar{x}_i\downarrow$ at any target position within the measurement range:

$$E\uparrow = \max(\bar{x}_i\uparrow) - \min(\bar{x}_i\uparrow) \tag{7-5-12}$$

and

$$E\downarrow = \max(\bar{x}_i\downarrow) - \min(\bar{x}_i\downarrow) \tag{7-5-13}$$

The bidirectional systematic positioning error, E, is the difference between the algebraic maximum and minimum values of the mean unidirectional positioning deviations $\bar{x}_i\uparrow$ and $\bar{x}_i\downarrow$ for both approach directions within the measurement range:

$$E = \max[(\bar{x}_i\uparrow;\ \bar{x}_i\downarrow)] - \min[(\bar{x}_i\uparrow;\ \bar{x}_i\downarrow)] \tag{7-5-14}$$

The reversal deviation at a position, B_i, is the difference between the average unidirectional positioning deviations from the two directions of approach to the target position:

$$B_i = \bar{x}_i\uparrow - \bar{x}_i\downarrow \tag{7-5-15}$$

The system reversal error, B, is the maximum of absolute values $|B_i|$ at all target positions:

$$B = \max(|B_i|) \tag{7-5-16}$$

The average reversal error, $\overline{B}$, is the arithmetic average value of the reversal deviations at all target positions:

$$\overline{B} = \frac{1}{m}\sum_{j=1}^{m} B_i \tag{7-5-17}$$

The estimator for the unidirectional axis positioning repeatability at a position, $s_i\uparrow$ or $s_i\downarrow$, is the estimated value of the positioning deviation's standard uncertainty for n unidirectional approaches to the target positions; that is,

$$s_i\uparrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(x_{ij}\uparrow - \bar{x}_i\uparrow\right)^2} \tag{7-5-18}$$

and

$$s_i\downarrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(x_{ij}\downarrow - \bar{x}_i\downarrow\right)^2} \tag{7-5-19}$$

The extended unidirectional positioning repeatability at a position, $R_i\uparrow$ or $R_i\downarrow$, is a value calculated from applying the coverage factor of 2 to the estimated value of the unidirectional positioning repeatability at a position; that is,[1]

$$R_i\uparrow = 4s_i\uparrow \tag{7-5-20}$$

and

$$R_i\downarrow = 4s_i\downarrow \tag{7-5-21}$$

The bidirectional positioning repeatability at a position, R_i, is calculated from the extended repeatability at the positions:

$$R_i = \max[(2s_i\uparrow + 2s_i\downarrow + |B_i|;\ R_i\uparrow;\ R_i\downarrow)] \tag{7-5-22}$$

The unidirectional positioning repeatability, $R\uparrow$ or $R\downarrow$, is the maximum value of the positioning repeatability at any target position; that is,

$$R\uparrow = \max(R_i\uparrow) \tag{7-5-23}$$

and

$$R\downarrow = \max(R_i\downarrow) \tag{7-5-24}$$

The bidirectional positioning repeatability, R, is the maximum value of the repeatability at any target position:

$$R = \max(R_i) \tag{7-5-25}$$

The maximum of the unidirectional positioning repeatability, R_m, is the maximum value of the unidirectional positioning repeatability, $R\uparrow$ or $R\downarrow$:

$$Rm = \max[(R\downarrow;\ R\uparrow)] \tag{7-5-26}$$

[1] A coverage factor of 2 corresponds approximately to a ±2σ value and a 95% confidence interval for a normal distribution, where σ is the standard deviation.

The average unidirectional positioning repeatability, $\overline{R}\uparrow$ or $\overline{R}\downarrow$, is the average value of the repeatability at any target position; that is,

$$\overline{R}\uparrow = \frac{1}{m}\sum_{i=1}^{m} R_i\uparrow \tag{7-5.27}$$

and

$$\overline{R}\downarrow = \frac{1}{m}\sum_{i=1}^{m} R_i\downarrow \tag{7-5.28}$$

The average value of the average unidirectional positioning repeatability, $\overline{R}$, is the average value of the average unidirectional positioning repeatability:

$$\overline{R} = \frac{\overline{R}\uparrow + \overline{R}\downarrow}{2} \tag{7-5.29}$$

The unidirectional positioning accuracy, $A\uparrow$ or $A\downarrow$, is the value calculated from the combination using the mean unidirectional positioning deviation at a position plus applying the coverage factor of 2 to the estimator for the unidirectional axis positioning repeatability at a position:

$$A\uparrow = \max(\bar{x}_i\uparrow + 2s_i\uparrow) - \min(\bar{x}_i\uparrow - 2s_i\uparrow) \tag{7-5-30}$$

and

$$A\downarrow = \max(\bar{x}_i\downarrow + 2s_i\downarrow) - \min(\bar{x}_i\downarrow - 2s_i\downarrow) \tag{7-5-31}$$

The bidirectional positioning accuracy, A, is the value calculated from the combination using the mean bidirectional positioning deviation at a position plus applying the coverage factor of 2 to the estimator for the bidirectional axis positioning repeatability at a position:

$$A = \max[(\bar{x}_i\uparrow + 2s_i\uparrow;\ \bar{x}_i\downarrow + 2s_i\downarrow)] - \min[(\bar{x}_i\uparrow - 2s_i\uparrow;\ \bar{x}_i\downarrow - 2s_i\downarrow)] \tag{7-5-32}$$

An example for individual values is given in Figure 7-5.5-1.

7-5.6 Stroke of Axis

The testing of a single-axis linear positioning system shall evaluate whether the entire travel range can be used, which means that the axis being tested can reach every numerically controlled target position. To ensure that, the stroke, which is a measure for the complete travel range, is calculated based on the test data.

The average value of the measured starting point, $\overline{P}_0$, of the travel range is

$$\overline{P}_0 = \frac{1}{n}\sum_{j=1}^{n} P_{0j} \tag{7-5-33}$$

The average value of the measured endpoint, $\overline{P}_{(m+1)}$, of the travel range is

$$\overline{P}_{(m+1)} = \frac{1}{n}\sum_{j=1}^{n} P_{(m+1)j} \tag{7-5-34}$$

The stroke, S, is the difference of the average value of the travel range's measured endpoint and the travel range's measured starting point; that is,

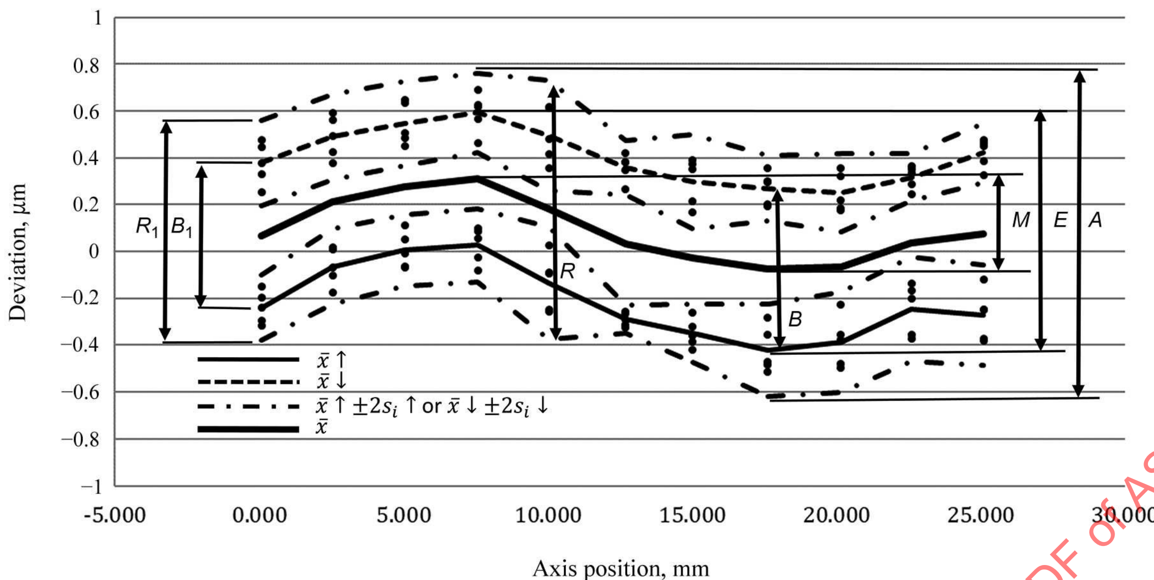
$$S = \overline{P}_{(m+1)} - \overline{P}_0 \tag{7-5-35}$$

7-5.7 Nomenclature for Performance Metrics Calculated With Corrected Data

If a drift correction is performed on the raw data and the bidirectional systematic positioning deviation is based on the drift-corrected data, the value will be identified with a superscript(s) as discussed in para. 7-5.4.7, e.g., E^{D}. If a drift and Abbe tilt error correction is performed, the value is identified as E^{DA}. If a linear normalization is to be applied, a standardized accuracy, or "on-axis accuracy" may be calculated. The terms are denoted as follows:

A^{L} = the standardized bidirectional positioning accuracy
E^{L} = the standardized bidirectional systematic positioning error

Figure 7-5.5-1
Example Mean Bidirectional Positioning Error and Calculation Results



Legend:
- A = bidirectional positioning accuracy
- B = system reversal error
- E = bidirectional systematic positioning error
- M = mean bidirectional positioning error
- R = bidirectional positioning repeatability

M^{L} = the standardized value of the mean bidirectional positioning error

Pursuant to this, the indices will be specified in the documentation and in protocols if corrections have been performed.

7-5.8 Linearity and Hysteresis

The linearity,[2] 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 para. 7-5.4, shall be agreed upon between the user and the manufacturer/supplier. Also, the corrected positioning deviations, x^{l}_{ij}, used to evaluate the linearity are calculated separately for each repetition of each travel back and forth[3] 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.

The average unidirectional linearly corrected positioning deviations, $\bar{x}^{l}_{i}\uparrow$and $\bar{x}^{l}_{i}\downarrow$, are calculated as

$$\bar{x}^{l}_{i}\uparrow = \frac{1}{n}\sum_{j=1}^{n} x^{l}_{ij}\uparrow \tag{7-5-36}$$

and

$$\bar{x}^{l}_{i}\downarrow = \frac{1}{n}\sum_{j=1}^{n} x^{l}_{ij}\downarrow \tag{7-5-37}$$

[2] Linearity is distinct from linear normalization.
[3] 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.

The mean bidirectional positioning deviation at a linearly corrected position, $\bar{x}_i^l$, is the mean value of the average unidirectional linearly corrected positioning deviation from the two approach directions, $\bar{x}_i^l\uparrow$and $\bar{x}_i^l\downarrow$, and is calculated according to

$$\bar{x}_i^l = \frac{\bar{x}_i^l\uparrow + \bar{x}_i^l\downarrow}{2} \tag{7-5-38}$$

The forward linearity, $L\uparrow$, is the result of

$$L\uparrow = \max(|\bar{x}_i^l\uparrow|) \tag{7-5-39}$$

The backward linearity, $L\downarrow$, is the result of

$$L\downarrow = \max(|\bar{x}_i^l\downarrow|) \tag{7-5-40}$$

Consequently, the bidirectional maximum linearity, L, is

$$L = \max[(L\uparrow;\ L\downarrow)] \tag{7-5-41}$$

The linear hysteresis, H_i, at a position is the difference between the average unidirectional linearly corrected positioning deviations from the two approach directions at the target position P_i:

$$H_i = \bar{x}_i^l\uparrow - \bar{x}_i^l\downarrow \tag{7-5-42}$$

The hysteresis, H, of the system is the maximum of absolute values, $|H_i|$, at all target positions; that is,

$$H = \max(|H_i|) \tag{7-5-43}$$

NOTE: Hysteresis H is analogous to the system reversal error B. However, unlike B, the hysteresis H includes the measurement data at the travel endpoints P_0 and P_{m+1}.

Linearity data computed from values corrected for drift and Abbe error is designated according to the appropriate superscripts, e.g., H^{DA} and L^{DA}.

An example of linearly corrected positioning deviations via endpoint linear normalization is shown in Figure 7-5.8-1.

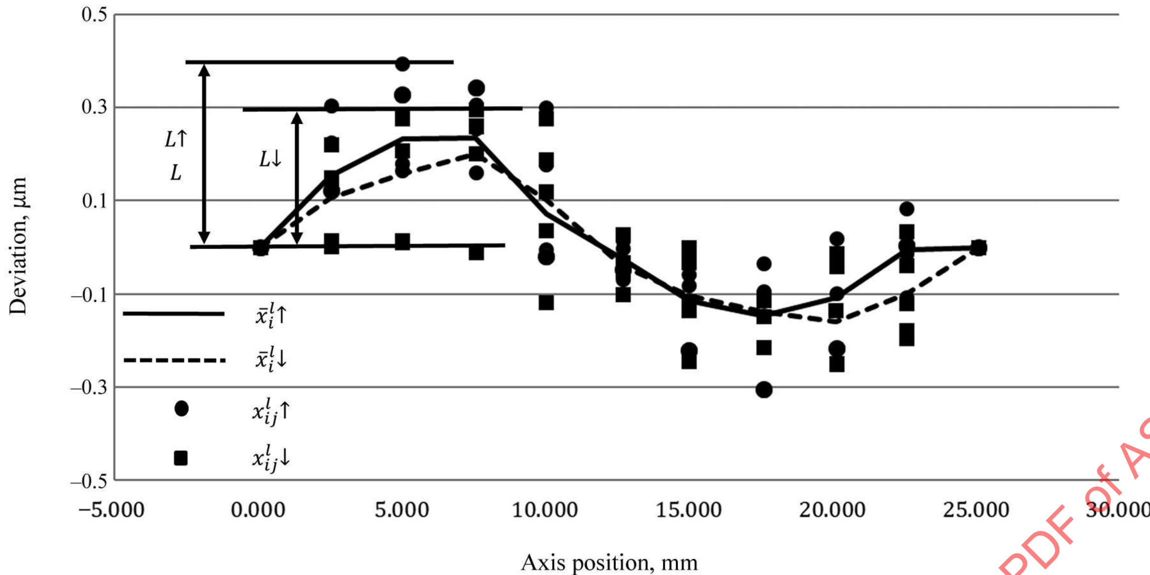
7-5.9 Periodic Error of Linear Motion (Partial Travel)

7-5.9.1 General. A periodic (i.e., repetitively occurring) component of the positioning deviation is determined by selecting a set of closely spaced target points on a small subrange of the travel range of the linear positioning system. For systems with leadscrews, the screw lead is the typical subrange for such periodic deviation measurements. For systems with encoders, the subrange typically is the signal period of the encoder system, and for systems with laser interferometers, the subrange is typically the wavelength of the light or a $1/2^n$ fraction of it. Systems may have more than one source of periodic deviations, e.g., systems relying on both a leadscrew and an encoder, in which case the subrange of periodic deviation measurements needs to consider both sources and their potential interactions. If the periodic components are known and recur within the full travel range, then this error can be compensated using, for example, a one-period look-up table applied to the axis position modulo the period.

7-5.9.2 Method for Defining Measurement Target(s) Location(s). The frequency of the periodic component of the positioning deviation is usually relatively constant over the full travel range, whereas the magnitude of the deviations can be different for different points. To get a full characterization of the device, the measurement should, in principle, be performed for all points of the travel range. Subsets of such a measurement sequence could include different specific subsets of the travel range (e.g., beginning, middle, and end). To reduce the measurement time, the standard measurement for correcting the periodic deviations is performed in the middle of the travel range. Additional measurement subsets can be defined based on the agreement between the user and the manufacturer/supplier.

EXAMPLES:
(1) For a system with a leadscrew, the measurement subset would be the screw lead.
(2) For a system with a linear or an angular encoder, the measurement subset would be the line spacing or a fraction thereof (typically a factor of 2 or 4).
(3) For laser interferometer measuring systems, the measurement subset would be the wavelength of light or a fraction thereof (typically a factor of 2 or 4).

Figure 7-5.8-1
Plot of Linearly Corrected (via Endpoint Linear Normalization) Positioning Deviations Illustrating the Calculation of Linearity of the Axis



To characterize the periodic deviations, a set of at least 21 evenly spaced target points is to be selected spanning two periods of the expected periodic deviations.

7-5.9.3 Setup and Instrumentation. The setup and instrumentation can be identical to that used for the positioning accuracy test over the full travel range.

7-5.9.4 Measurement Procedure. Before starting the measurements, the system shall execute a warmup sequence according to the agreement between the user and manufacturer/supplier. It is recommended that a minimum of two backward-forward movements between the first and last target points be executed at the anticipated measurement speed. The next five sets of measurements are made unidirectionally at the same target positions as for the positioning accuracy test.

Due to the relatively high resolution demanded of the measuring device for the measurement of periodic deviations, the measurement result can include the combined effects of the nonlinearity of the measuring device and of the system under test. To help separate the two effects and minimize the effect of the periodicity of the measuring device, it is permissible to take measurements spaced according to the expected periodicity of the measuring device itself (see para. 7-5.1).

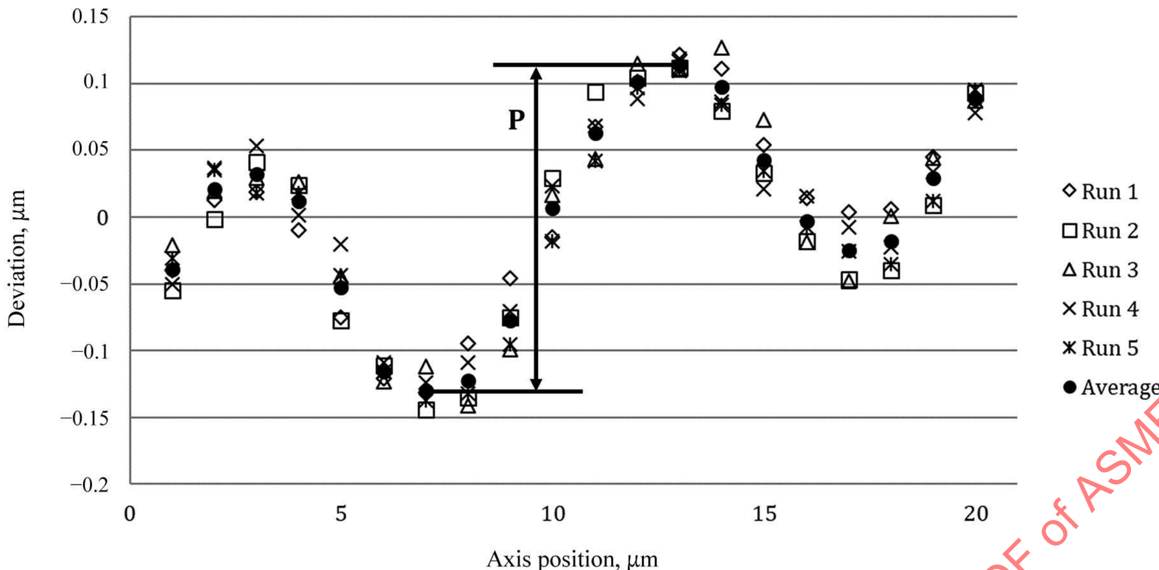
EXAMPLE: The periodic error of the linear axis under test is 20 µm. The measuring device is a four-beam DMI with a signal period of 632.8 nm/4 = 158.2 nm. Under these circumstances, it is permissible to set the points at which the data is recorded in integer multiples of 158.2 mm to mitigate the effect of any periodic error in the interferometer (see Section 11).

7-5.9.5 Data Analysis and Reported Parameters. The periodic error is computed in the same manner as the unidirectional systematic deviation of positioning $E\uparrow$, as described in para. 7-5.5. Thus, the periodic linear motion error, P, is

$$P = \max(\bar{x}_i\uparrow) - \min(\bar{x}_i\uparrow) \tag{7-5-44}$$

The calculated deviations shall be plotted as shown in Figure 7-5.9.5-1. The periodic error is the total maximum minus the minimum of the average of the deviations as shown in Figure 7-5.9.5-1.

Figure 7-5.9.5-1
Plot of Calculated Positioning Deviations Illustrating the Periodic Error *P* of a Linear Axis



7-5.10 Alternate Informative Methods

7-5.10.1 Step Test Cycle. This section addresses the application of the step test cycle, an optional test cycle (see Figure 7-5.10.1-1) in which each measurement position is sampled repeatedly before moving onto the next position. The step test cycle is in contrast with the standard scheme depicted in Figure 7-5.3-1.

The results from tests made using this method could be different from those obtained from the standard test cycle shown in Figure 7-5.3-1.

With the standard test cycle, the extreme target positions are approached from opposing directions with large time separation (e.g., there is a large time interval between sampling $x_{1j}\uparrow$ and $x_{1j}\downarrow$). With the step test cycle, however, the target positions are approached from either direction within the same, short time intervals while it takes a longer time between the measurements of the first and the last target positions, e.g., $x_1j\uparrow$ and $x_{mj}\uparrow$.

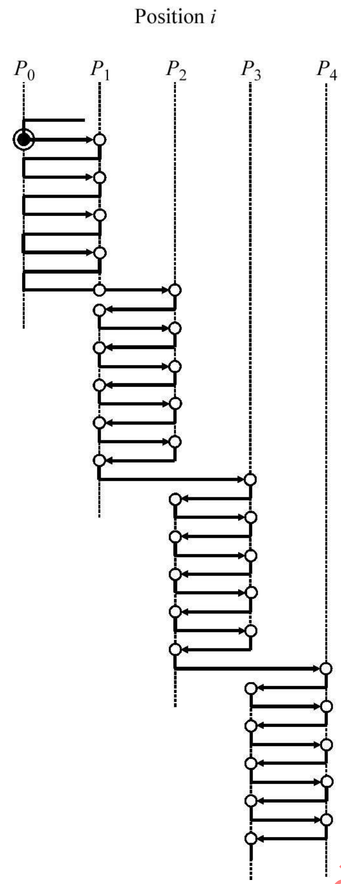
Due to the large time interval between opposite-direction measurements for extreme target positions according to the standard test cycle, thermal influences could be amplified, which affect the various target positions by variable amounts along the axis under test. Hence, when using the standard cycle (see Figure 7-5.3-1), the thermal influences during the measurements could affect both the backlash values and the repeatability values.

On the other hand, in the case of the step test cycle, thermal influences could affect the mean bidirectional positioning deviation whereas the reversal values and repeatability will be only slightly affected by thermal effects.

7-5.10.2 Pseudo-Random Position Sequences. Instead of standard evenly spaced sequences as defined in para. 7-5.2.3, pseudo-random sequences can be used to determine the target points. The suggested method to calculate such pseudo-random sequences is the Sobol sequence algorithm. Other pseudo-random sequence generators may be used. The Sobol algorithm is deterministic, i.e., using the algorithm several times with the same initial conditions yields the same results. This ensures that both the manufacturer and customer can calculate the same target points for the measurement, provided they start with the same initial conditions. Implementations of this algorithm can be found in commercial numerical analysis and symbolic mathematics software packages (Press et al., 1992).

The algorithm for the Sobol sequences delivers a set of pseudo-random numbers, $p_{\mathrm{rn},i}$, in the range of 0 to 1. By scaling, these numbers shall be mapped to target points P_i inside the full travel range of the stage. For a linear positioning system with a minimum travel position, $L_{t,\min}$, a maximum travel position, $L_{t,\max}$, and a total travel range of $L_t = L_{t,\max} - L_{t,\min}$, the new target points, P_i, can be calculated as

Figure 7-5.10.1-1
Step Test Cycle



$$P_i = (p_{\mathrm{rn},i} \times L_t) + L_{t,\min} \tag{7-5-45}$$

The data may be corrected for drift, Abbe error, and linearity according to para. 7-5.4. The measurement procedure, data analysis, and presentation of the results shall then be performed according to para. 7-5.5.

If a pseudo-random position algorithm is used, the type of algorithm shall be stated in the protocol. In Table 7-5.10.2-1, a list of the first 40 position values based on a Sobol sequence calculation is given. When the Sobol positions are used as target positions for a procedure as described in para. 7-5.3, they should be sorted in an ascending order. In addition, positions should be selected in sets that represent the travel range without bias. For example, from Table 7-5.10.2-1, one would pick the first three members to characterize the range divided into increments of 0.25, the first seven members to characterize increments of 0.125, and so on. It would be improper to select the first 5 members, because that would cause bias toward the maximum end of travel.

7-5.10.3 Drift Correction Method. Because thermal drift may occur during the time the measurements are performed, it is permitted to correct the actual position for drift. The drift correction applied to the measured positions results in the correction of the deviation of position values, because the commanded (or expected) position values do not drift. The drift correction is to be applied prior to any other correction, e.g., due to Abbe tilt error.

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

Table 7-5.10.2-1
First 40 Position Values Based on a Sobol Sequence Calculation

Number	Position	Number	Position
1	0.500000	21	0.968750
2	0.750000	22	0.718750
3	0.250000	23	0.218750
4	0.375000	24	0.156250
5	0.875000	25	0.656250
6	0.625000	26	0.906250
7	0.125000	27	0.406250
8	0.187500	28	0.281250
9	0.687500	29	0.781250
10	0.937500	30	0.531250
11	0.437500	31	0.031250
12	0.312500	32	0.046875
13	0.812500	33	0.546875
14	0.562500	34	0.796875
15	0.062500	35	0.296875
16	0.093750	36	0.421875
17	0.593750	37	0.921875
18	0.843750	38	0.671875
19	0.343750	39	0.171875
20	0.468750	40	0.234375

assumption is not agreed upon between the user and the manufacturer/supplier, then the following thermal drift correction method should not be applied.

The thermal drift correction uses the endpoint linear normalization method as described in para. 7-5.4.3, but applied to the starting points of successive repetitions, P_{0j} and $P_{0(j+1)}$. To correct the linear drift, the endpoint normalization line with respect to time is calculated for each repetition between the points P_{0j} and $P_{0(j+1)}$. That is, the relative change in the initial position of sequential cycles is assumed to vary linearly with time, and the time-dependent change is subtracted from the position values for the jth measurement cycle as a function of the timestamp of each measurement.

The reference deviation for all repetitions is chosen to be the initial deviation, $(P_{00} - P_0)$, which is the first measurement of the standard test sequence (see Figure 7-5.3-1) minus the 0th target position. Accordingly, after the endpoint linear normalization step using P_{0j} and $P_{0(j+1)}$ for each jth measurement cycle, $(P_{00} - P_0)$ is added to the normalized data to yield the positioning deviations corrected for drift.

The procedure is illustrated in Figure 7-5.10.3-1. In Figure 7-5.10.3-1, illustration (a), the uncorrected actual positions with respect to time for five repetitions are shown. For each repetition, the linear drift is corrected individually with an endpoint normalization line calculated between P_{0j} and $P_{0(j+1)}$ In Figure 7-5.10.3-1, illustration (b), the corrected actual positions are shown after the application of the time-dependent drift correction method. The starting positioning deviation for each repetition P_{0j} equals $(P_{00} - P_0)$. From these corrected data, the deviation of position x_{ij} can be calculated to get the corrected deviation of position $x^D ij$, where the superscript D indicates that a drift correction has been applied.

7-5.11 Presentation of Results

Figure 7-5.11-1 shows an example of a static positioning error and linearity test report.

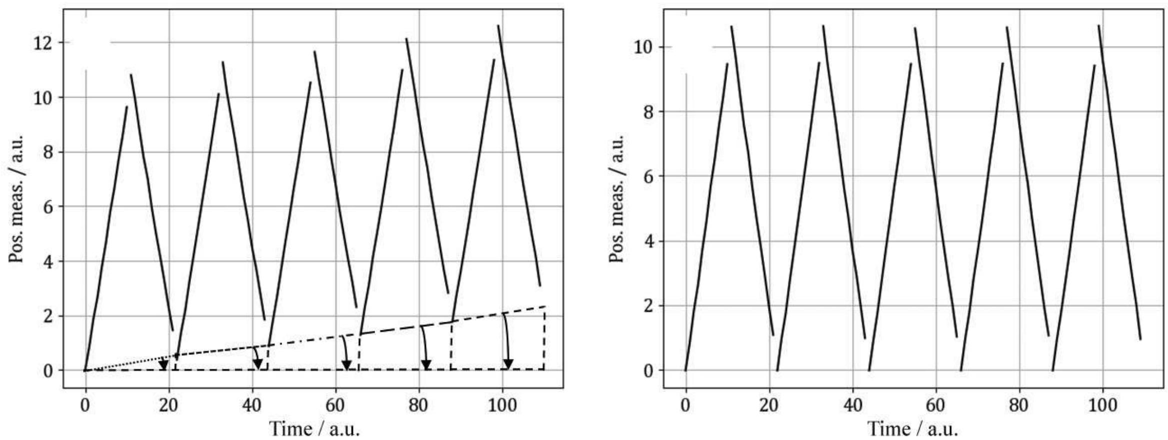
7-6 CONSTANT VELOCITY AND ACCELERATION TEST

7-6.1 General

The test method described in this section is modeled after the linear and rotary axes feed rate and acceleration tests described in ASME B5.54, para. 7.10.5. This Standard also provides a template for reporting the velocity and acceleration, and a numerical procedure for determining the points of transition between acceleration and constant-velocity regimes.

This test is designed to capture a velocity profile, from which the user can identify the following:

Figure 7-5.10.3-1
Example of Position Data Corrected for Drift



NOTE: (1) The raw position measurement graph includes endpoint normalization lines for each repetition.

(a) the acceleration profiles of the axis for a programmed velocity profile, including the maximum accelerations and the average accelerations

(b) the velocity profile of the axis for a programmed steady-state motion, including the velocity accuracy and variability

7-6.2 Method for Defining Measurement Targets

A linear axis positioning system must be commanded to execute a simple motion. The travel distance between the two endpoints should allow the axis to accelerate, then move at constant velocity for a defined distance, and then decelerate to stop. The travel distance, constant velocities, constant velocity distances, acceleration and deceleration rates, and loads shall be agreed upon between the user and the manufacturer/supplier of the linear axis positioning system. When the travel distance is not agreed upon a priori, the travel distance shall be the maximum possible travel distance. When predefined velocities are not agreed upon a priori, two different tests shall be conducted at 10% and 100% of the maximum steady-state speed, which is the maximum speed achievable where the constant-velocity distance is at least 50% of the travel distance used for both speeds. When the loads or payloads are not agreed upon a priori, no load or payload shall be used for the tests.

7-6.3 Measurement Setup

For proper use of each sensor, decisions must be made regarding the measurement setup, specifically about the following:

(a) *Sensor Type.* Does the sensor measure displacement, velocity, or acceleration?
(b) *Sensor Location.* Is the sensor located at the functional point or a different point of interest?
(c) *Sampling Rate.* What is the maximum positional resolution?
(d) *Sensor Feedback.* Is the sensor used within the position feedback loop?
(e) *Measurement Frame.* Is the measurement relative to the machine frame or an inertial frame?
(f) *System Condition.* Are the measurements collected in the nominal state of the linear axis?

7-6.3.1 Sensor Types

(a) The displacement, velocity, or acceleration could be measured to yield the velocity profile. A laser interferometer, linear encoder, or capacitive displacement sensor (for sufficiently small travel distances) shall measure the axis position as a function of time, or a laser Doppler velocimeter shall measure the axis velocity as a function of time. The linear encoder may be external or internal, whether used or not within the control system of the linear axis. In addition to a laser

Figure 7-5.11-1
Example of a Static Positioning Error and Linearity Test Report

Static Positioning Error and Linearity Test Report

Positioning System

Manufacturer: ABC	Model No.: XX	Serial No.: XX
Type: Linear, axis X	Max. travel: 200 mm	Max. velocity: 250 mm/s

Controller/drive unit to power the positioning system: ABC E712 S/N 1234

Measurement Setup

Measurement device and serial number: Interferometer XYZ S/N 1234

Sampling rate: 10 kHz

Data filter: xx-order Butterworth low-pass filter with a xx Hz cutoff frequency

Oversampling: ~~yes~~/no

Measurement program: Program XYZ

System location: 300 mm × 1.2 m × 1.2 m granite basewith passive air isolation

Functional point: X = XX mm, Y = XX mm, and Z = XX mm

Load: XX kg

Temperature during test: 22°C

Travel range: 25 mm

Measurement range: 20 mm

Pseudorandom sequence positions: ~~yes~~/no

Distance, Q: 2.5 mm

Nominal interval: 2.5 mm

Abbe correction: ~~yes~~/no

Linear normalization: ~~yes~~/no

Drift correction: yes/no

Number of repetitions: 5

Programmed velocity to move between measurement points: 50 mm/s

Dwell time: 1 s

Number of target positions, m: 9

Target positions: 0.0 mm, 2.5 mm, 5.0 mm, 7.5 mm, 10.0 mm, 12.5 mm, 15.0 mm, 17.5 mm, 20.0 mm, 22.5 mm, 25.0 mm

Measurement Data Static Positioning

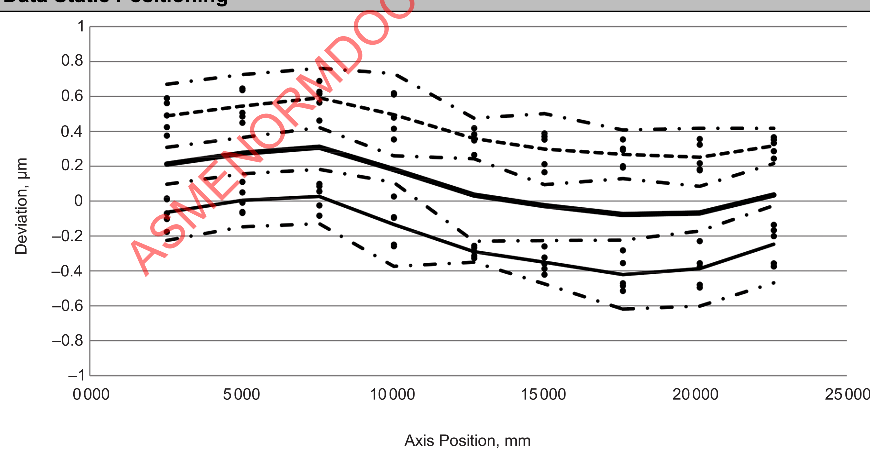
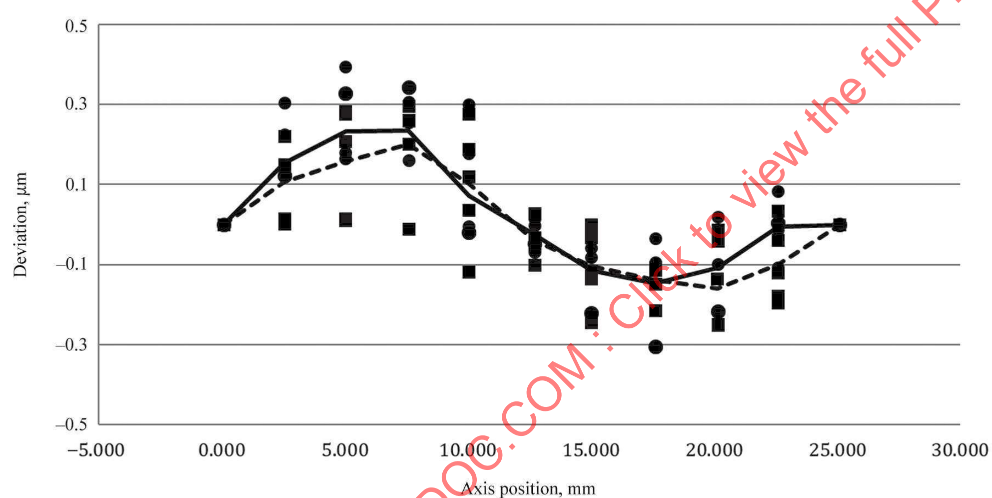


Figure 7-5.11-1
Example of a Static Positioning Error and Linearity Test Report (Cont'd)

Static Positioning Test Results

Metric	Symbol	Result, µm
Mean bidirectional positioning error	M	0.39
Bidirectional systematic positioning error	E	1.01
System reversal error	B	0.69
Average reversal error	$\bar{B}$	0.61
Unidirectional positioning repeatability, forward direction	$R\uparrow$	0.48
Unidirectional positioning repeatability, backward direction	$R\downarrow$	0.47
Bidirectional positioning repeatability	R	1.10
Bidirectional positioning accuracy	A	1.38

Measurement Data Linearity



Linearity Test Results

Metric	Symbol	Result, µm
Linearity, forward	$L\uparrow$	0.39
Linearity, backward	$L\downarrow$	0.30
Bidirectional maximum linearity	L	0.39

interferometer or linear encoder, a velocity transducer or accelerometer may be used simultaneously. Hence, at least one of the following equipment options should be used for the tests:

(1) laser interferometer with data acquisition software
(2) linear encoder (external or internal)
(3) capacitive displacement sensor
(4) velocity transducer or accelerometer with option (1) or (2)
(5) laser Doppler velocimeter with data acquisition software

(b) If position data is measured in options (a)(1) through (a)(3), the velocity may be estimated via differentiation, as outlined in para. 7-6.5.2. With option (a)(4), the velocity profile may be refined via use of the velocity transducer or accelerometer data. For example, the acceleration may be integrated to yield velocity changes, which can then be fused with the velocity profile from the position data, to eliminate the inherent amplification of noise from differentiation.

(c) Finally, it is assumed that the controller is sufficiently open, such that controller data may be collected to define the times when the acceleration/deceleration phase of the move begins or ends, and hence when the constant-velocity phase of motion begins or ends. Therefore, in addition to the sensor data, the following controller data shall be collected for the tests:

(1) commanded time when the acceleration phase begins
(2) commanded time when the acceleration phase ends and the constant-velocity phase begins
(3) commanded time when the constant-velocity phase ends and the deceleration phase begins
(4) commanded time when the deceleration phase ends

7-6.3.2 Sensor Locations. The sensor location may be either at the function point or at a separate location. If angular error motion data exists, then the velocity may be transformed from a separate location to the functional point via a rigid-body transformation (see Mandatory Appendix I). However, in certain cases, a rigid-body assumption is not valid specifically to achieve a relatively high measurement performance. Nonetheless, the sensor location must be noted in the test report.

7-6.3.3 Sampling Rates. Each measuring device/equipment shall collect data at axis positions with a positioning interval agreed upon between the user and the manufacturer/supplier. For example, if it is agreed upon to collect data with a positioning interval of 1 mm and the linear axis is programmed to move at a maximum speed of 500 mm/s, then the measuring device/equipment must sample data with a rate of at least 500 Hz. No smoothing or averaging techniques should be used for the raw data collection. The data may be collected at axis positions with either uniform spacing (i.e., from distance-based sampling) or non-uniform positioning intervals (i.e., from time-based sampling).

Sampling rates shall be agreed upon between the user and the manufacturer/supplier. Each equipment may measure at different sampling rates, and if possible, all data shall be timestamped in a synchronized fashion to the same reference clock. If no sampling rate is agreed upon a priori, then a time-based sampling rate coinciding with a positioning interval of at most 0.1% of the total travel distance shall be used, depending upon the constant velocity. For example, if the linear axis is programmed to move at a maximum speed of 500 mm/s for a total travel distance of 1 000 mm, a default sampling rate of at least 500 Hz shall be used, coinciding with a positioning interval of 1 mm (= 0.1% of 1 000 mm) at the maximum speed.

Measurement time intervals shall be agreed upon between the user and the manufacturer/supplier. Measurement time intervals shall include the complete motion with enough data collected before/after acceleration/deceleration to satisfy the user that the linear axis is nominally at rest.

7-6.3.4 Sensor Feedback. The sensors may be external (i.e., not used for closed-loop feedback) or internal (i.e., used as the measurement in a closed-loop feedback system). At least one external sensor is desired as an independent measurement of the velocity profile, but an internal sensor (a linear encoder) may be used per para. 7-6.3.1.

Collecting data synchronously may prove to be difficult, especially if collecting data from both external and internal sources. Nonsynchronous data may be collected and then synchronized afterwards via correlation analysis. The recommended approach to correlate two signals is to identify the times in both signals whenever the same physical event occurs and to shift one signal by a constant temporal offset to align the signals. The least-squares method may be used to determine the time shift based on minimizing the differences in the timing of the discrete physical events.

7-6.3.5 Measurement Frame. The velocity profile is preferred to be measured relative to the base of the linear positioning system, but measurement of the velocity relative to an inertial frame is also acceptable, if the relative velocity of the base to an inertial frame is sufficiently small.

7-6.3.6 System Condition. The test method described in this section should be carried out in similar conditions to those for straightness and angular error motion tests (see subsections 8-1 and 8-2). Additionally, the test shall be conducted at a programmed velocity and load that best replicates the nominal conditions of the application or process in which the positioning system is intended to be used. These conditions are application dependent and should be agreed upon between the user and the manufacturer/supplier of the positioning system. Particular attention should be given to the duty cycle for the system under test, which is the percentage of time that the system is moving, since the system will warm up from a state of rest. The agreed-upon duty cycle should be representative of the duty cycle for the intended application. For example, an agreement may be reached to run the system with a specific load with a duty cycle of 50% for 30 min before data collection. Furthermore, because the velocity and acceleration performance are functions of the entire motion system including the bus voltage, amplifier, controller, resolution, etc., the single-axis linear positioning system should not be changed during the tests.

7-6.4 Measurement Procedure

The measurement procedure is as follows:

Step 1. Align the measuring equipment with the axis under test.

Step 2. Exercise the positioning system following the recommendation in para. 7-6.3.6.

Step 3. The linear axis must be commanded to execute a simple motion. The travel distance used for both speeds should be the same, unless otherwise agreed upon by the user and the manufacturer/supplier.

Step 4. The test should be carried out in both positive and negative directions. For each direction, all measurements shall be recorded synchronously with each other, as much as possible; that is, if possible, the measurements shall be timestamped in a synchronized fashion to the same reference clock. Otherwise, the nonsynchronous data shall be collected and then synchronized afterwards.

Step 5. The tests must be repeated a minimum of three times.

7-6.5 Data Analysis

7-6.5.1 Test Uncertainty Analysis. Uncertainties associated with the measurement of velocity are related to uncertainties of the used measurement systems and uncertainties of the axis under test. These uncertainties should be considered when specifying measurement sampling rates and parameters to avoid situations where neither conformance nor nonconformance to specifications can be demonstrated. Potential measurement uncertainty contributors include

(a) uncertainties of geometric error motions of the linear axis
(b) measurement uncertainty of the test equipment [e.g., see (ASME B89.1.8-2011)]
(c) misalignment of the measurement axis and the axis under test
(d) fixturing vibrations at the measurement points
(e) differences in functional point motions at which the position and velocity are measured
(f) data analysis, especially noise amplification from differentiation

7-6.5.2 Data Analysis for Three Phases of Motion. Figure 7-6.5.2-1 shows the velocity profile for a typical motion. Each motion consists of three phases: an acceleration phase, a constant-velocity phase, and a deceleration phase. The acceleration phase is whenever the linear axis is speeding up from rest to its constant velocity, represented as the sampled times between the open diamond and closed diamond in Figure 7-6.5.2-1. Similarly, the deceleration phase is whenever the linear axis is slowing down from constant velocity to rest, represented as the sampled times between the closed square and open square in Figure 7-6.5.2-1. The four transition points, noted in Figure 7-6.5.2-1, shall be based on controller data.

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 (Press et al., 1992) as

$$v_q = (p_{q+1} - p_q)/(t_{q+1} - t_q) \tag{7-6-1}$$

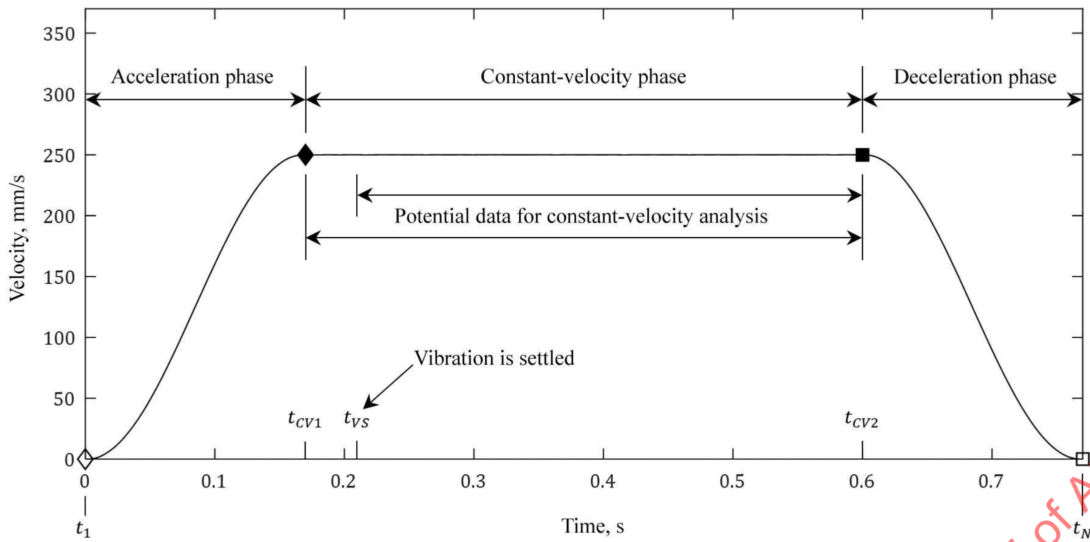
where

q = the iteration number
p_q = the actual position at the qth time value t_q
= $P_{\text{actual}}(t_q)$
v_q = the estimated velocity at t_q

Note that q ranges from 1 to N-1, where N is the total number of sampled data points.

The inherent noise in the sampled position p_q is amplified in the estimated velocity v_q according to the finite difference approximation of eq. (7-6-1). The smaller the time steps, the greater the noise amplification that increases the test uncertainty and may corrupt the velocity variation results (see Figure 7-6.5.3-1). Therefore, filtering with a zero-

Figure 7-6.5.2-1
Example of a Velocity Profile for a Test Motion



phase filter may be necessary for analysis. Use of a specific filter or no filter depends upon agreement between the user and the manufacturer/supplier.

If a first order Savitzky-Golay filter (Savitzky and Golay, 1964) is agreed upon for usage, the filter shall have a frame length equal to the odd number of samples that is closest to representing a distance agreed upon by the user and the manufacturer/supplier when the axis is traveling at its desired constant speed. For example, if the linear axis is programmed to move at a maximum speed of 100 mm/s, data is sampled at 500 Hz, and the filter frame length of 1.0 mm is agreed upon, then a frame length of 5 samples [= 1.0 mm/(100 mm/s/500 samples/s)] is used for the first-order Savitzky-Golay filter. It is advised that if a ballscrew is used within the linear axis, that the distance representing the filter frame length be at most 10% of the lead of the ballscrew. For example, if the lead of the ballscrew is 20 mm, then a distance of 2 mm or less should be used to determine the frame length for the Savitzky-Golay filter. Therefore, the fundamental frequency to be expected in the velocity data will not be removed by the filter.

The unfiltered velocity $v(t)$ is then filtered with the filter, $\mathrm{filt}(v_q)$, to yield the filtered velocity $\tilde{v}(t)$ as

$$\tilde{v}_q = \mathrm{filt}(v_q) \tag{7-6-2}$$

If no filter is to be used, then $\mathrm{filt}(v_q)$ represents a perfect pass-through filter; that is, a filter that does not change the inputted signal. Similarly, if not measured, the acceleration shall be estimated by a finite difference approximation as

$$a_q = (\tilde{v}_{q+1} - \tilde{v}_q)/(t_{q+1} - t_q) \tag{7-6-3}$$

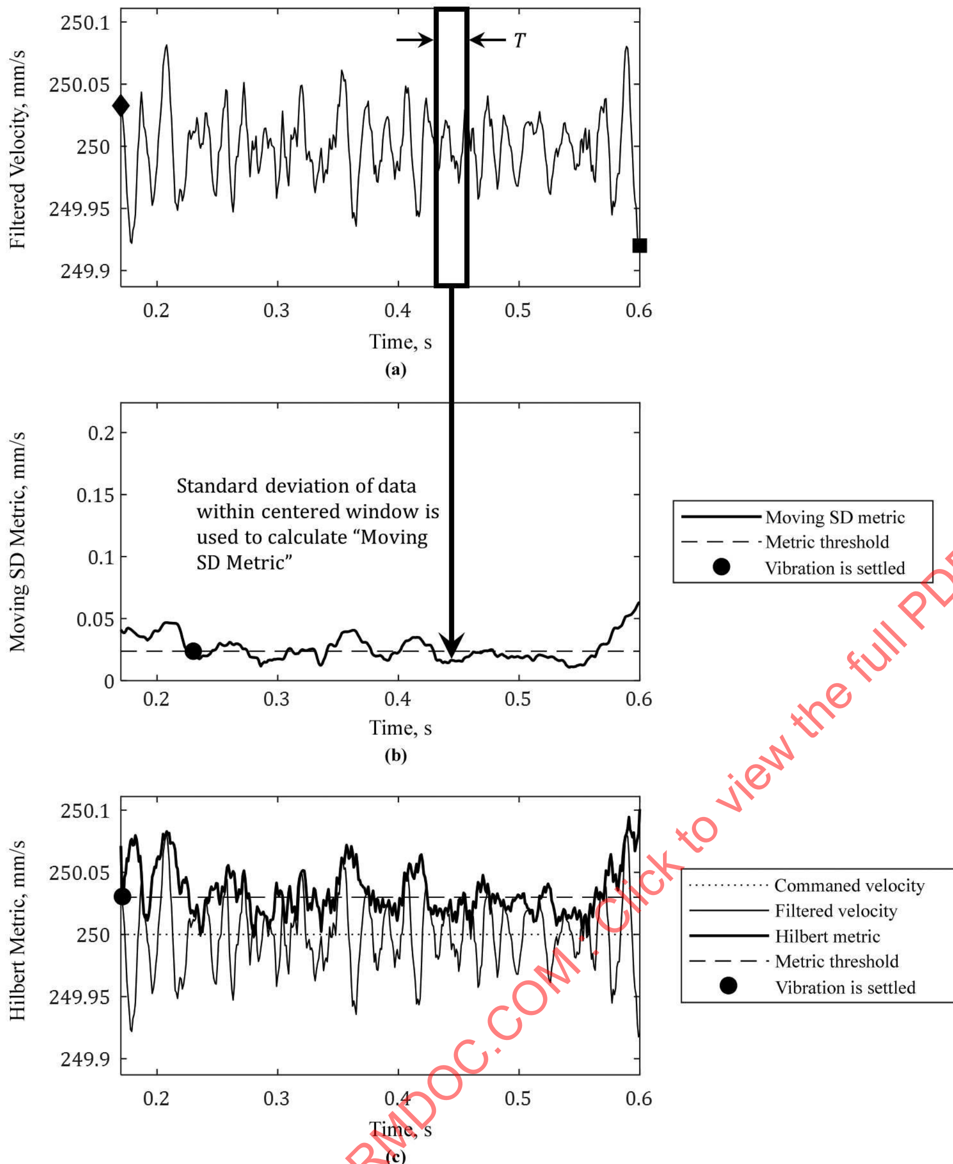
where a_q is the estimated acceleration at the qth time value t_q. The acceleration in eq. (7-6-3) is then filtered with the same filter to yield the filtered acceleration $\tilde{a}(t)$ as

$$\tilde{a}_q = \mathrm{filt}(a_q) \tag{7-6-4}$$

Results will be reported based on the filtered vibration, but some transient-vibration data during the constant-velocity phase of motion may not be used for final analysis. After the acceleration phase ends, the induced vibrations may take time to settle to lie within the constant-velocity phase. Consequently, the user and the manufacturer/supplier may agree to not use some data representing the transient settling of vibration for final analysis within the reporting of results. If no settling time is agreed upon, then all data within the two constant-velocity transition times shall be used for analysis. These two possibilities are shown in Figure 7-6.5.2-1.

If the data collected during the settling of vibration is to be neglected for final analysis, then the time must be determined when the vibration is settled, as seen in Figure 7-6.5.2-1. The filtered velocity $\tilde{v}(t)$, as shown in Figure 7-6.5.2-2, illustration (a), is used to determine when vibration is settled. The filtered velocity $\tilde{v}(t)$ is processed with either a moving

Figure 7-6.5.2-2
Example of Velocity Settling for a Test Motion



GENERAL NOTE: In this example of velocity settling for a test motion, the filtered velocity within the constant-velocity phase is analyzed with a moving standard deviation metric or a Hilbert metric.

standard deviation (SD) window, as seen in Figure 7-6.5.2-2, illustration (b), or a Hilbert transform, as seen in Figure 7-6.5.2-2, illustration (c), to determine the time when vibration is settled. Choice of either method depends upon agreement between the user and the manufacturer/supplier.

Use of the moving SD window to determine when vibration is settled begins with calculating the moving standard deviation (MSD) as

$$\mathrm{MSD}(t) = \sqrt{\frac{1}{T}\int_{t_{W1}}^{t_{W2}} [\tilde{v}(\tau) - \mathrm{MM}(t)]^2 d\tau} \tag{7-6-5}$$

where the moving mean (MM) is defined as

$$\mathrm{MM}(t) = \frac{1}{T}\int_{t_{W1}}^{t_{W2}} \tilde{v}(\tau) d\tau \tag{7-6-6}$$

and the minimum window time t_{W1} and the maximum window time t_{W2} are

$$t_{W1} = \max(t_{\mathrm{CV1}}, t - T/2) \tag{7-6-7}$$

$$t_{W2} = \min(t_{\mathrm{CV2}}, t + T/2) \tag{7-6-8}$$

for a window length T, which has the dimension of time. As seen in Figure 7-6.5.2-2, illustration (a), a window of length T is centered around the time t for which the moving SD metric is calculated according to eq. (7-6-5). For any time t, the standard deviation of the data within the window defines the moving SD metric. One caveat is that the window contracts according to eqs. (7-6-7) and (7-6-8) whenever the time t is sufficiently close to the beginning or end of the constant-velocity phase, to avoid the inclusion of transient data during the acceleration/deceleration phase. Collection of the metric values within the constant-velocity phase of motion yields the plot shown in Figure 7-6.5.2-2, illustration (b). Then, a metric threshold is calculated as the median of the metric values within the constant-velocity phase, as noted by the dashed line in Figure 7-6.5.2-2, illustration (b). Finally, the vibration is determined to be settled whenever the metric is first less than the metric threshold, as noted by the filled circle in Figure 7-6.5.2-2, illustration (b).

Note that the moving SD metric, and hence its use to determine vibration settling, depends on selection of the window length T. In general, T should be greater than the temporal period of the dominant frequency of vibration during the constant-velocity phase. For the example of Figure 7-6.5.2-2, illustration (a), a window length of 0.025 s was used. If no agreement for the value of T is reached between the user and the manufacturer/supplier, a moving SD window with a window length of the smaller of 0.025 s or 5% of the constant-velocity phase time shall be used.

Another method to determine when vibration is settled is to use the Hilbert transform (Feldman, 2011). The Hilbert transform $\Delta\tilde{v}_H(t)$ of the relative filtered velocity $\Delta\tilde{v}(t)$ is defined as

$$\Delta\tilde{v}_H(t) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{\Delta\tilde{v}(\tau)}{t - \tau} d\tau \tag{7-6-9}$$

where the relative filtered velocity $\Delta\tilde{v}(t)$ is

$$\Delta\tilde{v}(t) = \tilde{v}(t) - \tilde{v}_{\mathrm{CV}} \tag{7-6-10}$$

and $\tilde{v}_{CV}$ is the mean filtered velocity during the constant-velocity phase, defined as

$$\tilde{v}_{\mathrm{CV}} = \frac{1}{t_{\mathrm{CV2}} - t_{\mathrm{CV1}}}\int_{t_{\mathrm{CV1}}}^{t_{\mathrm{CV2}}} \tilde{v}(\tau) d\tau \tag{7-6-11}$$

where t_{CV1} and t_{CV2} are when the constant-velocity phase begins and ends, respectively, as seen in Figure 7-6.5.2-1. Next, the Hilbert metric $\tilde{v}_H(t)$ of the filtered velocity $\tilde{v}(t)$ is defined as

$$\tilde{v}_H(t) = \tilde{v}_{\mathrm{CV}} + |\Delta\tilde{v}_H(t)| \tag{7-6-12}$$

where $|x|$ is the magnitude of the complex argument x. As seen in Figure 7-6.5.2-2, illustration (c), the Hilbert metric in eq. (7-6-12) is an upper envelope of the filtered velocity $\tilde{v}(t)$, created from the Hilbert transform, which is the complex envelope of the original signal $\tilde{v}(t)$. Then, a metric threshold is calculated as the median of the metric values within the constant-velocity phase, as noted by the dashed line in Figure 7-6.5.2-2, illustration (c). Finally, the vibration is determined to be settled whenever the metric is first less than the metric threshold, as noted by the filled circle in Figure 7-6.5.2-2, illustration (c).

The moving SD metric and the Hilbert metric, as shown in Figure 7-6.5.2-2, illustrations (b) and (c), respectively, are very similar in form except for some differences. Due to the lack of a window for analysis, the Hilbert metric depends only on the vibration state at any specific time and does not have "edge effects" from window contraction near t_{CV1} and t_{CV2}. In contrast, the moving SD metric relies on use of a centered moving window that contracts to exclude data during the acceleration/deceleration phases. Consequently, the Hilbert metric is generally more complex but also more accurate for determination of when vibration is settled. As seen in Figure 7-6.5.2-2, illustration (b) compared to Figure 7-6.5.2-2, illustration (c), the vibration is determined for the given example to be settled significantly earlier via use of the Hilbert metric than for the moving SD metric.

The analysis procedure for each test, whether for the positive or negative direction, uses the filtered velocity and filtered acceleration in eqs. (7-6-2) and (7-6-4), respectively, as follows:

(a) Plot the filtered velocity, $\tilde{v}(t)$, as shown in Figure 7-6.5.2-1.

(b) Identify the two constant-velocity transition times, t_{CV1} and t_{CV2}, when the constant-velocity phase begins and ends.

(c) Determine the constant-velocity data to be used for final analysis. Based on agreement between the user and the manufacturer/supplier, the data for constant-velocity analysis begins at the settling time, t_{VS}, when either

(1) the constant-velocity phase begins

(2) the moving SD metric is first less than its threshold value, or

(3) the Hilbert metric is first less than its threshold value

The data for constant-velocity analysis ends at t_{CV2} when the constant-velocity phase ends.

(d) For the agreed-upon constant-velocity data for analysis, calculate the following metrics:

(1) mean filtered speed, $|\tilde{v}_{mean}|$, where the mean filtered velocity, $\tilde{v}_{mean}$, is

$$\tilde{v}_{mean} = \frac{1}{t_{CV2} - t_{VS}} \int_{t_{VS}}^{t_{CV2}} \tilde{v}(\tau) d\tau$$

(2) standard deviation of the filtered velocity, $\tilde{v}_{sd}$

$$\tilde{v}_{sd} = \sqrt{\frac{1}{t_{CV2} - t_{VS}} \int_{t_{VS}}^{t_{CV2}} [\tilde{v}(\tau) - \tilde{v}_{mean}]^2 d\tau}$$

(3) coefficient of variation = $\tilde{v}_{sd}/|\tilde{v}_{mean}|$, expressed as percentage

(4) absolute filtered speed error = $|\tilde{v}_{mean}|$, − |programmed velocity|

(5) relative filtered speed error = (absolute filtered velocity error)/|programmed velocity|, expressed as a percentage

(e) Identify the two transition points for the acceleration phase, t_1 and t_{CV1}, when the acceleration phase begins and ends, respectively, and the two transition points for the deceleration phase, t_{CV2} and t_N, when the deceleration phase begins and ends, respectively. These four transition points are identified based on controller data. Unlike for the constant-velocity phase, no data is ignored for this step, because the acceleration and deceleration phases of motion are inherently transient processes.

(f) For the sampled times within each acceleration/deceleration phase, calculate the following metrics

(1) mean filtered acceleration amplitude, $|\tilde{a}_{mean}|$:

$$|\tilde{a}_{mean}| = \left| \frac{1}{t_{CV1} - t_1} \int_{t_1}^{t_{CV1}} \tilde{a}(\tau) d\tau \right| \text{ for the acceleration phase}$$

$$|\tilde{a}_{mean}| = \left| \frac{1}{t_N - t_{CV2}} \int_{t_{CV2}}^{t_N} \tilde{a}(\tau) d\tau \right| \text{ for the deceleration phase}$$

(2) maximum filtered acceleration amplitude, $\tilde{a}_{max}$:

$$\tilde{a}_{max} = \max(|\tilde{a}(t)|) \text{ from } t = t_1 \text{ to } t = t_{cv1} \text{ for the acceleration phase}$$

$$\tilde{a}_{max} = \max(|\tilde{a}(t)|) \text{ from } t = t_{cv2} \text{ to } t = t_N \text{ for the deceleration phase}$$

(3) impulse factor = $\tilde{a}_{max}/|\tilde{a}_{mean}|$, expressed as a percentage

Finally, the average metrics of each motion type are calculated by averaging the individual trial metrics. For acceptance purposes of a new positioning system, the user and the manufacturer/supplier must agree beforehand on the specifications to be met for these tests.

7-6.5.3 Presentation of Results. Figure 7-6.5.3-1 shows an example of a constant velocity and acceleration test report for a single motion. One such report should be created for each motion, whether positive or negative. Figure 7-6.5.3-2 shows an example of average metrics for the collected constant velocity and acceleration test reports.

7-7 DYNAMIC POSITIONING TESTS

7-7.1 General

Subsection 7-7 describes test methods used to evaluate the dynamic position accuracy of single-axis linear positioning systems. The test methods presented in subsection 7-7 are an extension of subsection 7-6. The test methods are also related to the following tests from ASME B5.54-2005 (R2020):

– linear and rotary axes feed rate and acceleration tests described in para. 7-10.5
– contouring performance using circular tests described in subsection 7-11

Unlike the test described in subsection 7-6 to capture a velocity profile, which does not require knowledge of the target position, the tests described in subsection 7-7 require that the target position of the linear positioning system is available or measured.

These tests are designed to capture dynamic positioning profiles that can be used to evaluate the following:

(a) the dynamic positioning error (DPE), which is the maximum absolute deviation. The DPE is analogous to contouring errors presented in Koren, 1997 and Koren and Lo, 1992.

(b) the magnitude of the steady-state dynamic positioning deviation, also known as the following error (Tlusty, 2000), which is the target speed divided by the forward loop positional gain.

(c) observation of positional overshoot at velocity changes including stopping, to enable control parameter adjustment or machine design changes.

(d) frictional effects if observable in the collected data, but their evaluations are beyond the scope of this Standard.

The dynamic positioning profiles used in the dynamic positioning tests are linear ramp, sinusoidal motion, and general user-defined motion.

The test results for all dynamic positioning profiles may be heavily influenced by the machine and control algorithms (Koren, 1997; Koren and Lo, 1992), yet all systems will exhibit some errors as a function of time that may be identified by the test methods presented in this subsection.

7-7.2 Method for Defining Measurement Targets

The linear axis positioning system under test must be commanded to execute one or more of the dynamic positioning profiles described in paras. 7-7.2.1 through 7-7.2.3.

7-7.2.1 Linear Ramp Motion. This motion profile is the same as that described in para. 7-6.2.

7-7.2.2 Sinusoidal Motion. This motion profile is intended to be similar to the circular test prescribed in ASME B5.54-2005 (R2020), para. 7.11, except that the motion profile described here is for a single axis instead of two perpendicular axes.

The linear axis must be commanded to execute a sinusoidal motion. A linear interpolation can be used as an alternative to the sinusoid. The axis is commanded to move in three complete sinusoids, where each sinusoid is equivalent to a full period of the sinusoid. However, a different number of sinusoids may be performed, as agreed upon by the user and the manufacturer/supplier, to allow for structural dynamics and control response to stabilize. It should be noted that in operations where velocity and acceleration are key performance indicators, the maximum velocity and maximum acceleration of the motion should be in conformance with specified machine limits, unless otherwise agreed upon between the user and the manufacturer/supplier.

When predefined test parameters are not agreed upon a priori, the sinusoidal tests should be conducted with velocity maximums at 10% and 100% of the maximum command velocities, the sinusoidal motion should be centered at 25% and 75% of the axis travel, and the amplitude of the sinusoid should equal 15% of the travel range.

7-7.2.3 General User-Defined Motion. This motion profile is optional and intended to measure the dynamic positioning performance for a general user-defined path that is agreed upon by the user and the manufacturer/supplier. Examples include motion profiles with simultaneous components of different frequencies.

Figure 7-6.5.3-1
Example of a Constant Velocity and Acceleration Test Report for a Single Motion

Constant Velocity and Acceleration Test Report for a Single Motion

Positioning System

Manufacturer: ABC	Model No.: XX	Serial No.: XX
Type: Linear	Max. travel: 200 mm	Max. velocity: 250 mm/s

Test Setup

Programmed travel: 150 mm	Programmed velocity: 250 mm/s
Sampling rate: 1 000 Hz	
Functional point: X = XX mm, Y = XX mm, and Z = XX mm	Load: XX kg

Filtered Velocity and Filtered Acceleration Plots

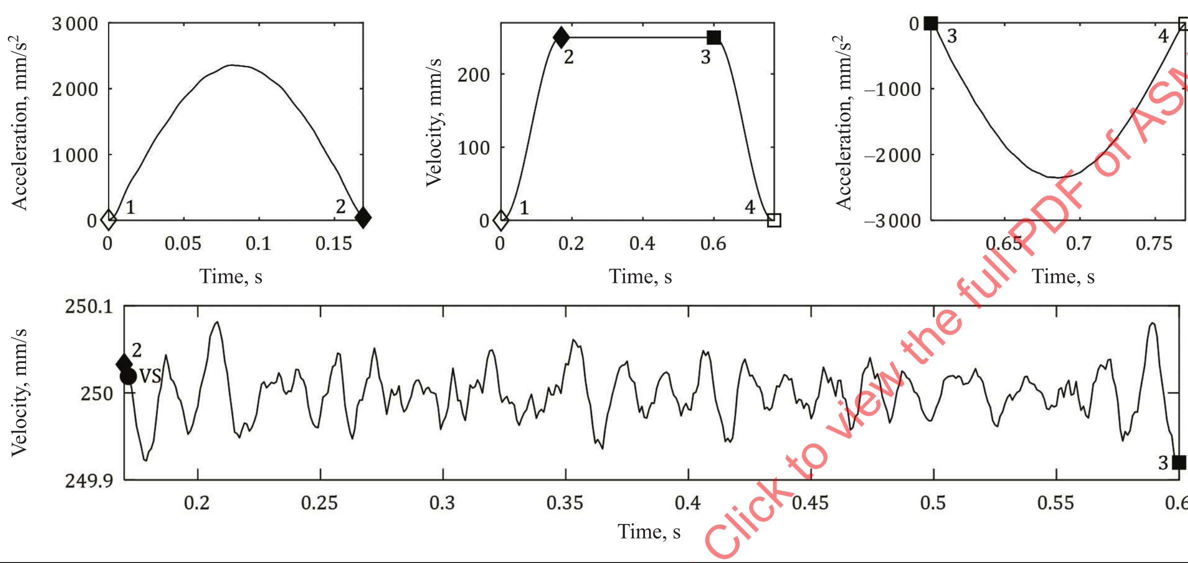


Table of Transition Points

Location	1	2	VS	3	4
Time, s	0	0.170	0.172	0.600	0.770
Measured position, mm	0	21.4326	21.9327	128.9321	149.9998
Measured filtered velocity, mm/s	0.0011	250.0449	249.9435	249.8702	−0.0037
Method to determine "Vibration is settled" (VS) point:			Hilbert Metric		

Results of Filtered Data

Acceleration Phase	Constant-Velocity Phase	Deceleration Phase
Mean: 1 470.49 mm/s²	Mean speed: 249.9990 mm/s	Mean: 1 470.02 mm/s²
Max. amplitude: 2 358.07 mm/s²	Standard deviation: 0.0286 mm/s	Max. amplitude: 2 354.92 mm/s²
Impulse factor: 1.6036	Coefficient of variation: 0.0114%	Impulse factor: 1.6020
	Absolute error: −0.001 mm/s	
	Relative error: −0.0004%	

Figure 7-6.5.3-2
Example of Average Metrics for Constant Velocity and Acceleration Test Report

Average Metrics for Constant Velocity and Acceleration Test Reports

Positioning System

Manufacturer: ABC	Model No.: XX	Serial No.: XX
Type: Linear	Max. Travel: 200 mm	Max. velocity: 250 mm/s

Test Setup

Programmed travel: 150 mm	Programmed velocity: 250 mm/s	
Functional point: X = XX mm, Y = XX mm, and Z = XX mm	Load: XX kg	Sampling rate: 1 000 Hz

Acceleration Phase Metrics for Forward and Reverse Single Motions

Motion	Mean, mm/s²	Max. Amplitude, mm/s²	Impulse Factor
Forward #1	1 470.49	2358.07	1.6036
Forward #2	1 470.49	2358.07	1.6036
Forward #3	1 470.49	2358.07	1.6036
Forward Average	**1 470.49**	**2358.07**	**1.6036**
Reverse #1	1 465.84	2348.42	1.6021
Reverse #2	1 465.84	2348.42	1.6021
Reverse #3	1 465.84	2348.42	1.6021
Reverse average	1 465.84	2348.42	1.6021

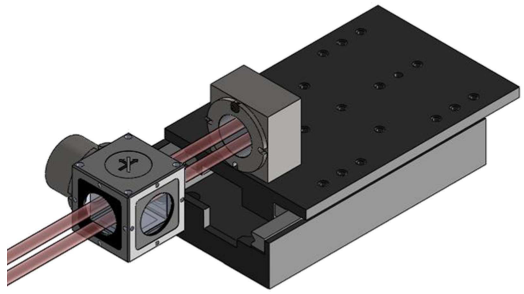
Constant-Velocity Phase Metrics for Forward and Reverse Single Motions

Motion	Mean Speed, mm/s	Standard Deviation, mm/s	Coefficient of Var., %	Abs. Error, mm/s	Rel. Error, %
Forward #1	249.9990	0.0286	0.0114	−0.001	−0.0004
Forward #2	249.9990	0.0286	0.0114	−0.001	−0.0004
Forward #3	249.9990	0.0286	0.0114	−0.001	−0.0004
Forward Average	**249.9990**	**0.0286**	**0.0114**	**−0.001**	**−0.0004**
Reverse #1	250.0005	0.0268	0.0107	0.0005	0.0002
Reverse #2	250.0005	0.0268	0.0107	0.0005	0.0002
Reverse #3	250.0005	0.0268	0.0107	0.0005	0.0002
Reverse Average	**250.0005**	**0.0268**	**0.0107**	**0.0005**	**0.0002**

Deceleration Phase Metrics for Forward and Reverse Single Motions

Motion	Mean, mm/s²	Max. Amplitude, mm/s²	Impulse Factor
Forward #1	1 470.02	2 354.92	1.6020
Forward #2	1 470.02	2 354.92	1.6020
Forward #3	1 470.02	2 354.92	1.6020
Forward Average	**1 470.02**	**2 354.92**	**1.6020**
Reverse #1	1 473.43	2 362.12	1.6031
Reverse #2	1 473.43	2 362.12	1.6031
Reverse #3	1 473.43	2 362.12	1.6031
Reverse Average	**1 473.43**	**2 362.12**	**1.6031**

Figure 7-7.3.1-1
Laser Interferometer Example Setup



The linear axis must be commanded to execute any arbitrary motion specified between the user and the manufacturer/supplier. The measurement setup and method defined within this section are applicable to any general user-defined motion. It is recommended that the user and the manufacturer/supplier agree upon the needed position, control parameters, velocity, acceleration, jerk, etc.

7-7.3 Measurement Setup

The measurement setup is designed to measure the relative displacements between a target mounted to the moving element of the positioning system and a displacement sensor fixed to the base of the positioning system.

7-7.3.1 Sensor Types. Paragraph 7-6.3.1 contains guidance on decisions related to sensors. An independent measuring system should be used, when possible, but it is recognized that, in some applications, a fully independent measurement system may not be feasible. However, whenever possible, the preferred method is to use an external measurement system, unless otherwise agreed upon between the user and the manufacturer/supplier. Accordingly, at least one of the following equipment options should be used for the dynamic positioning tests:

(a) Laser Displacement Interferometer. A retroreflector or target mirror should be mounted to the moving element of the positioning system, and the interferometer should be fixtured to the stationary base of the positioning system. For example, see Figure 7-7.3.1-1.

(b) Capacitive Displacement Sensor. The capacitance target or a flat artifact should be mounted to the moving element of the positioning system and the capacitive displacement sensor should be fixtured to the stationary base of the positioning system. Care should be taken to maintain the required electrical ground loop over the required range of displacement. Inadequate ground loops can cause error and extraneous noise in the measurement.

(c) Other Sensor. Any independent measurement system may be used to measure position, if agreed upon between the user and the manufacturer/supplier. However, sensors that are used internally for feedback within the control loop structure, such as motor encoders or linear scales, will not provide independent validation of the prescribed motion.

7-7.3.2 Sensor Locations. The sensor location may be either at the functional point or at a separate measurement point with a subsequent transformation (see Mandatory Appendix I) whenever dynamic influences during testing are negligible. In either case, the sensor location must be noted in the test report.

The dynamic positioning test is a dynamic performance test, influenced by system mode shapes, natural frequencies, and the inherent response of the control system. Careful consideration should be given to avoid dynamic measurement error influenced by the target selection, location, and mounting method, which are application-dependent and should be agreed upon by the user and the manufacturer/supplier. If significant structural dynamics are observed within the dynamic positioning tests and it is not possible to eliminate the effects, corrections and filtering adjustments may be used if agreed upon between the user and the manufacturer/supplier. While outside the scope of this Standard, application of appropriate filtering, modal analysis, and other engineering methods may be conducted to help determine the sources of errors.

7-7.3.3 Sampling Rates. The same framework in para. 7-6.3.3 for sampling rate selection is applied in this section of the standard. The sensor's accuracy, resolution, sampling latency, linearity, and harmonic distortion within the measurement frequency bandwidth should be considered to ensure that a satisfactory test uncertainty ratio of at least 4:1 is achieved (ISO/IEC 17025:2017).

7-7.3.4 Sensor Feedback. The sensors may be internal (i.e., used as the measurement in a closed-loop feedback system) or external (i.e., not used for closed-loop feedback). At least one external sensor is preferable as an independent measurement of the motion profile within the dynamic positioning test. The user of the equipment must be aware that any structural dynamics that exist outside the control loop will not be observable by an internal measurement system.

7-7.3.5 Measurement Frame. Each motion profile is preferred to be measured relative to the base of the linear positioning system, but measurement relative to an inertial frame is also acceptable, if the relative measurement differences of the base to an inertial frame are sufficiently small.

7-7.3.6 System Condition. Paragraph 7-6.3.6 prescribes the system conditions that shall be used for this test. Furthermore, because the velocity and acceleration performance are functions of the entire motion system including the bus voltage, amplifier, controller, resolution, etc., the entire system should remain unchanged during the tests.

7-7.4 Measurement Procedure

The measurement procedure for any motion profile is as follows:

Step 1. Align the measuring equipment with the axis under test.

Step 2. For linear ramp motion, in the case of backlash existing in the axis, the backlash should be removed by a back-and-forth reversal move to positively preload in the direction of motion.

Step 3. Conduct the test for the desired dynamic positioning profiles as described in para. 7-7.2 for either linear ramp motion, sinusoidal motion, or general user-defined motion.

Step 4. For linear ramp motion, the test should be carried out in both positive and negative directions. For each direction, all measurements shall be recorded synchronously with each other, as much as possible; that is, if possible, the measurements shall be time stamped in a synchronized fashion to the same reference clock. Otherwise, the non-synchronous data shall be collected and then synchronized afterwards.

Step 5. The tests must be repeated a minimum of three times.

7-7.5 Data Analysis

For any motion profile (linear ramp, sinusoidal, or general user-defined), the target position is denoted as $P_{\text{target}}(t)$ and the actual position is denoted as $P_{\text{actual},c}(t)$, where c indicates the number of the control configuration (e.g., 0, 1, or 2). Consequently, the dynamic positioning deviation, $x_c(t)$, between the actual position and the target position for the cth control configuration is calculated as

$$x_C(t) = P_{\text{actual},c}(t) - P_{\text{target}}(t) \tag{7-7-1}$$

The sign convention chosen in eq. (7-7-1) is consistent with that in ISO 230-2:2014. However, the results may be shown for the opposite sign convention, as agreed upon between the user and the manufacturer/supplier. Furthermore, the deviation in velocity and the deviation in acceleration may be calculated for each control configuration in a manner similar to the calculation of the deviation in position. Generally, the definition for position deviation in ISO 230-2:2014 is defined where time, t, is sufficiently large to reach a stationary position. In this case, the position is sampled as time increases, and the dynamic positioning error (DPE) is defined as the maximum absolute deviation; that is,

$$\text{DPE} = \max[|x_C(t)|] \tag{7-7-2}$$

7-7.5.1 Ramp Motion Characteristics. In addition to dynamic deviations of position, velocity, and acceleration, some other common performance characteristics can be calculated from the ramp motion test. Additional ramp motion characteristics include constant velocity, overshoot, and following error. Figure 7-7.5.1-1 shows the dynamic positioning deviations, $x_0(t)$ and $x_2(t)$, for two control configurations as well as annotations illustrating the constant velocity, overshoot, and following error. The DPE location is shown for both control configuration responses. In the second case, the DPE is equal to the following error. This is common for critically damped or underdamped systems. It is noted that the user and manufacturer/supplier must determine if any of these metrics are an issue within the process being evaluated.

7-7.5.2 Examples for Linear Ramp Motion. Figure 7-7.5.2-1 shows examples of linear ramp motion responses as a function of time for three control configurations, and Figure 7-7.5.2-2 shows a zoomed-in portion of the positioning deviations to better visualize them for comparison purposes. The examples shown in both figures are for a system that is commanded to move a linear ramp motion for a total distance of 20 mm. The system reaches 20 mm at about 0.2 s after initiation of the motion command. As can be seen in Figure 7-7.5.2-2, $x_2(t)$ is for the control configuration with the lowest gain, which results in a positioning deviation of nearly 2 mm in magnitude at t = 0.2 s. Similarly, $x_0(t)$ has a magnitude of slightly less than 1 mm at t = 0.2 s. Also, the position for the zeroth control configuration reaches 20 mm before the

Figure 7-7.5.1-1
Linear Ramp Motion General Characteristics

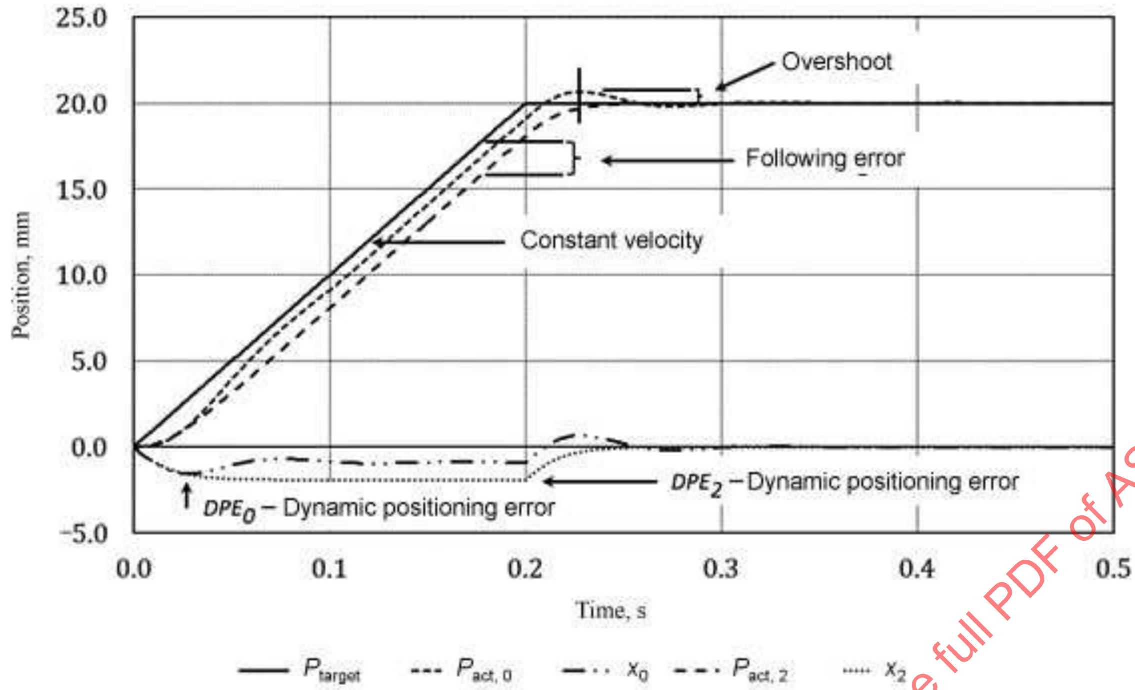


Figure 7-7.5.2-1
Example Linear Ramp Motion and Dynamic Positioning Deviation for Three Control Configurations

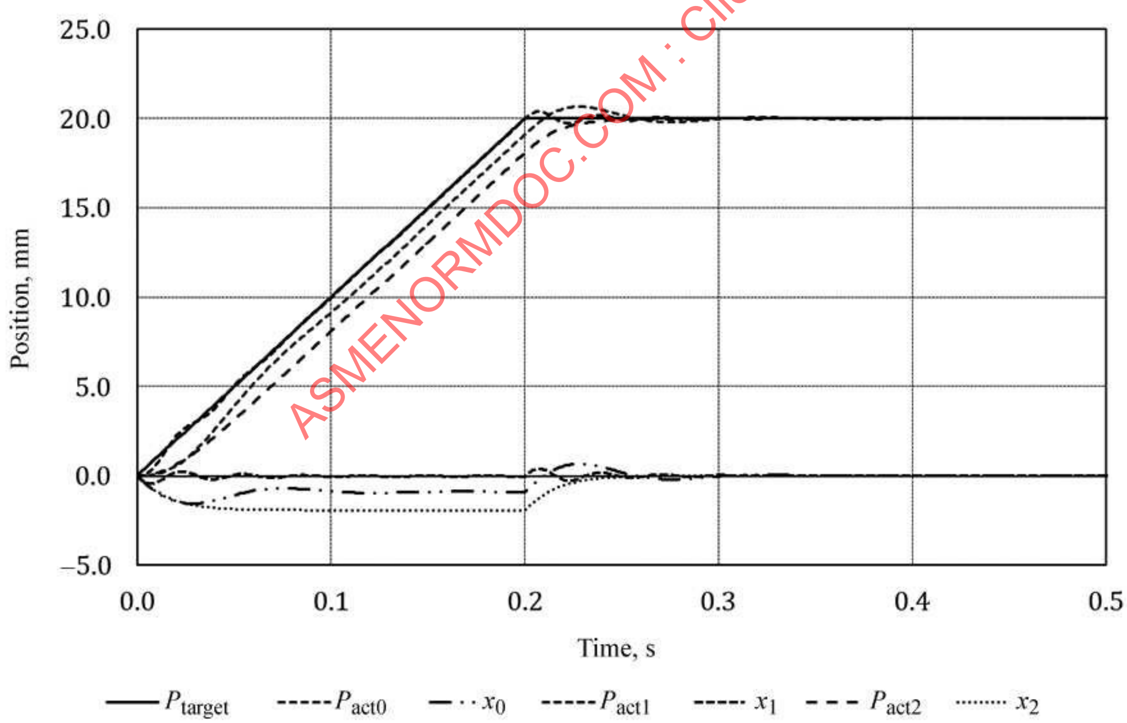
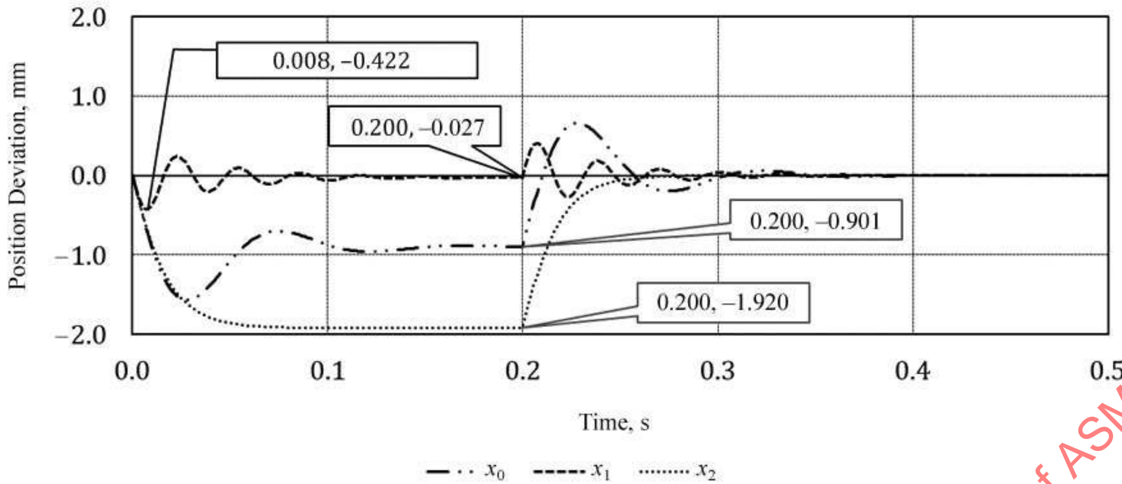


Figure 7-7.5.2-2
Zoomed-In Portion of Example Dynamic Positioning Deviation for Three Control Configurations for Linear Ramp Target Motion



response for the second control configuration. In contrast, as seen in Figure 7-7.5.2-2, the response of the stiffest control system (c = 1) yields a positioning deviation of less than 0.03 mm in magnitude at t = 0.2 s. Hence, Figures 7-7.5.2-1 and 7-7.5.2-2 show how the results may be displayed to illustrate the positioning deviations from a target path as a function of time.

Figure 7-7.5.2-3 shows a zoomed-in portion of the linear ramp motion responses seen in Figure 7-7.5.2-1. As can be seen in Figure 7-7.5.2-3, the first control configuration leads to an overshoot while reaching the final target position after t = 0.2 s, which is a trade-off compared to that configuration resulting in the smallest magnitude of positioning deviation at t = 0.2 s (see Figure 7-7.5.2-2) compared to the zeroth and second control configurations. Full characterization and documentation of this motion is important for the user and the manufacturer/supplier to understand and evaluate, since the allowable result for each motion response is upon agreement between the user and manufacturer/supplier. For example, the linear ramp motion may be modified to test the largest deviation from the target prescribed motion.

7-7.5.3 Sinusoidal Motion Characteristics. Similar to the ramp motion, the sinusoid motion has general characteristics that may be calculated from dynamic positioning test data. In addition to the dynamic position deviation, $x_2(t)$, the dynamic position error, following error, time shift, and actual peak-to-peak values are illustrated in Figure 7-7.5.3-1.

7-7.5.4 Examples for Sinusoidal Motion. Figure 7-7.5.4-1 shows examples of sinusoidal motion responses as a function of time for two control configurations, and Figure 7-7.5.4-2 shows a zoomed-in portion of the positioning deviations to better visualize them for comparison purposes. Additionally, Figure 7-7.5.4-3 shows the target velocity and target acceleration along with the actual velocity and actual acceleration for two control configurations. This test is valuable to compare the target velocities and target accelerations to the actual respective results; the results will be analyzed further in the presentation of results section.

7-7.6 Test Uncertainty Analysis

See subsection 7-6 for a discussion of the test uncertainty, which is related to uncertainties of the measurement systems used and uncertainties of the axis under test.

Figure 7-7.5.2-3
Zoomed-In Portion of Example Dynamic Positioning Deviation Near the Final Target Position After t = 0.2 s

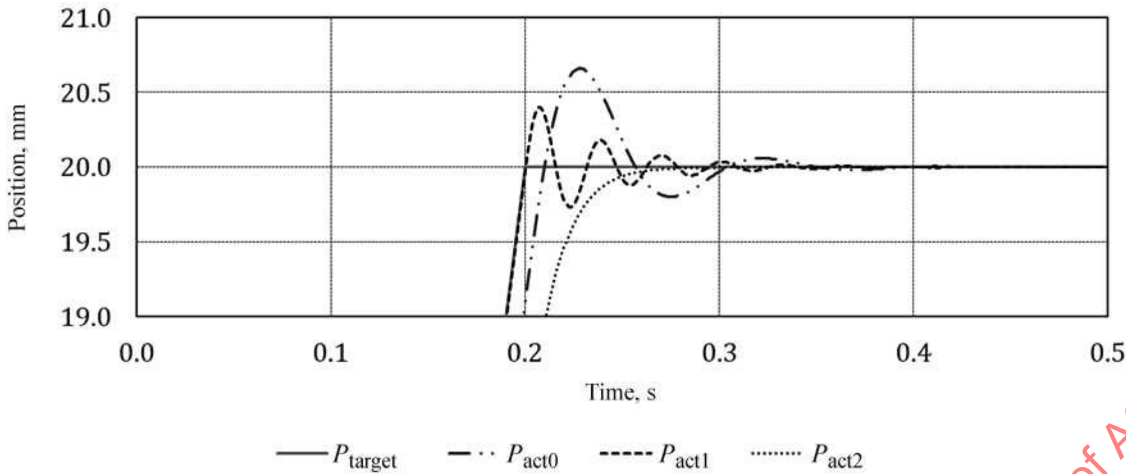


Figure 7-7.5.3-1
Sinusoidal Motion General Characteristics

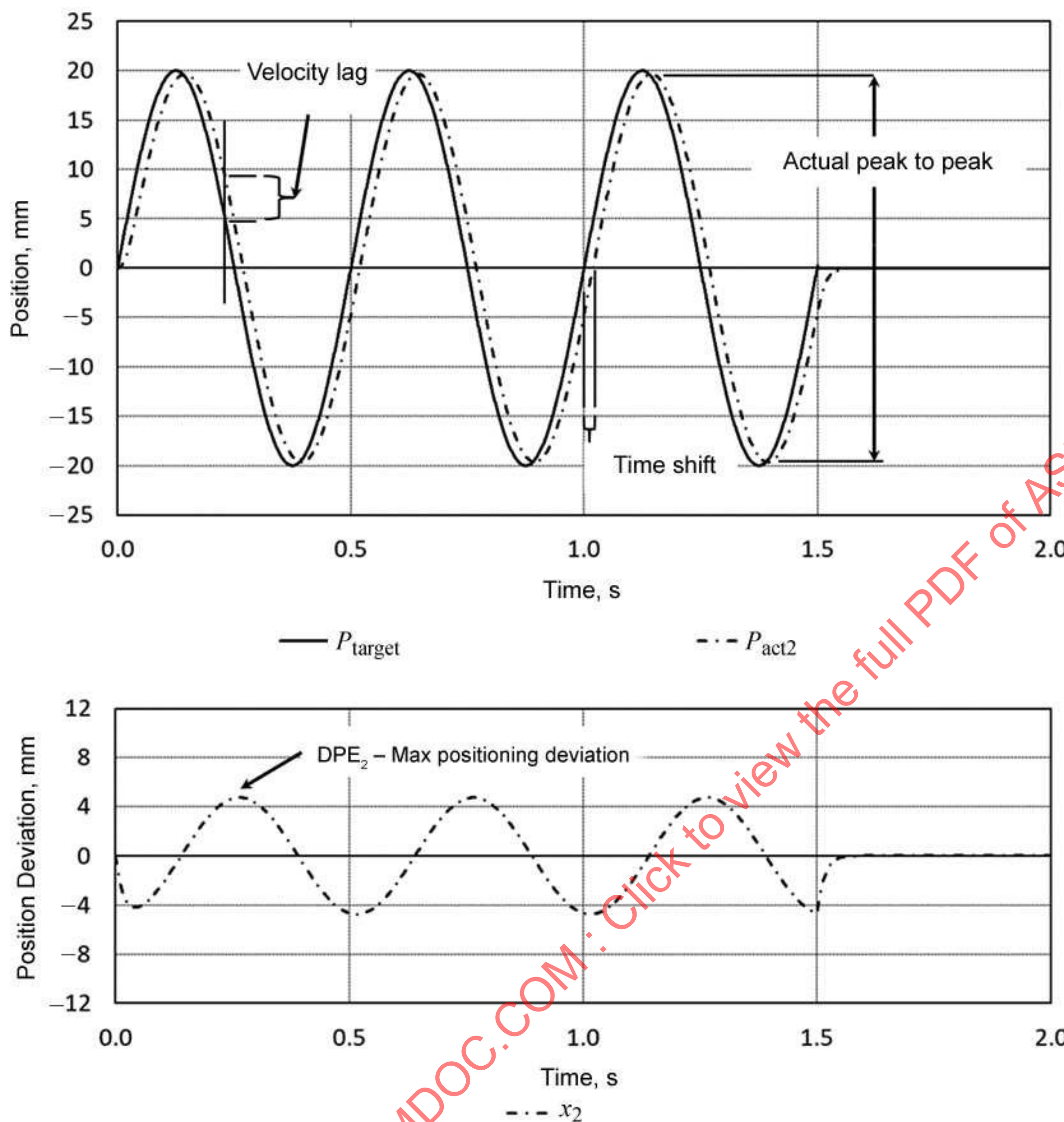


Figure 7-7.5.4-1
Example Sinusoidal Motion and Dynamic Positioning Deviation for Two Control Configurations

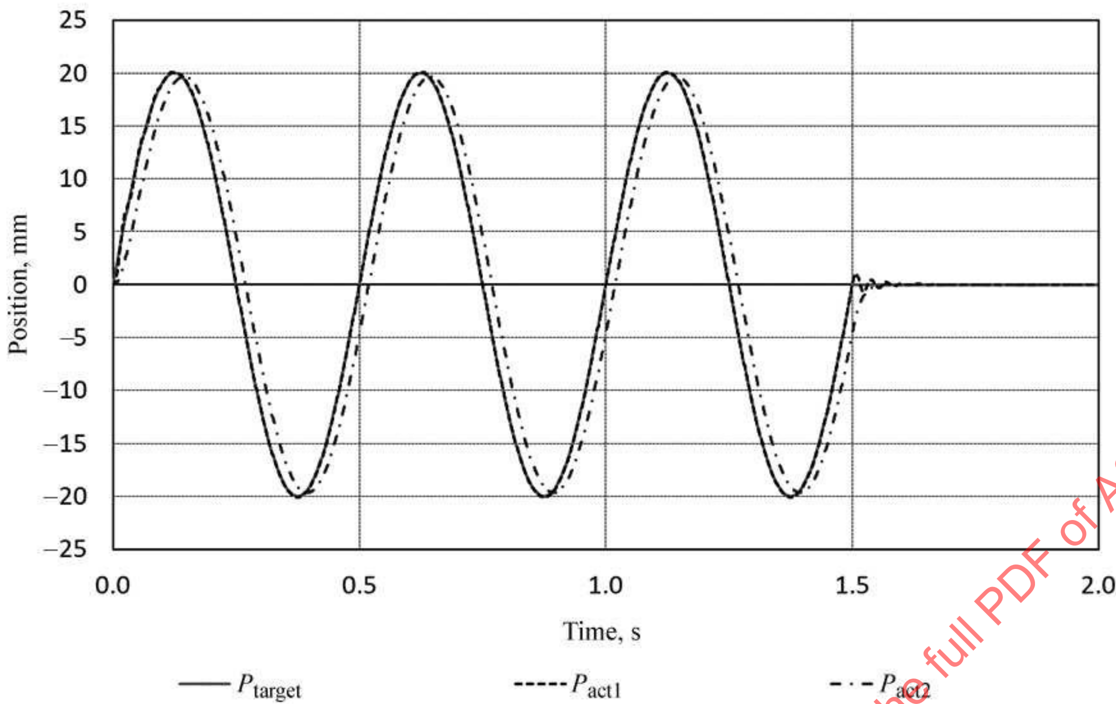


Figure 7-7.5.4-2
Zoomed-In Portion of Example Dynamic Positioning Deviation for Two Control Configurations for Sinusoidal Target Motion

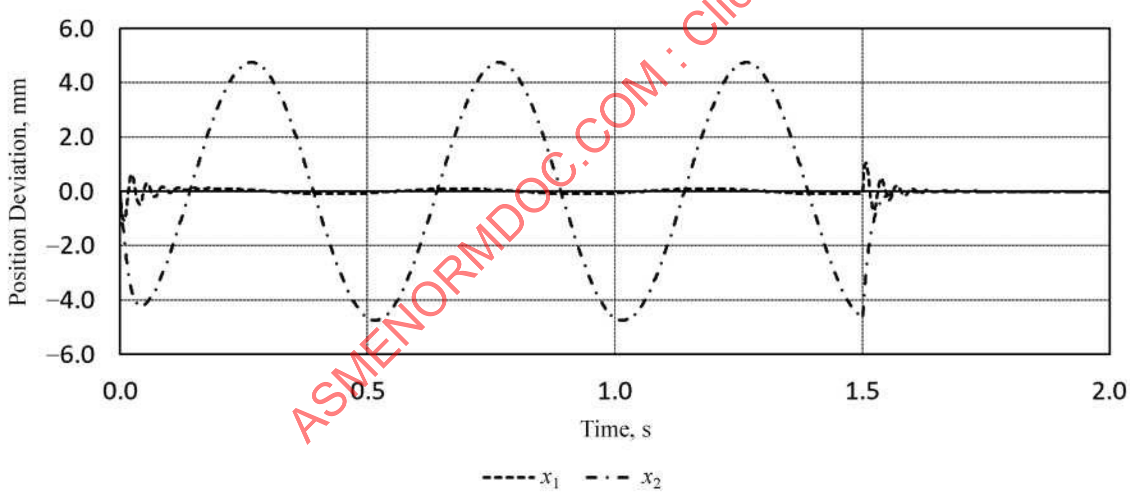
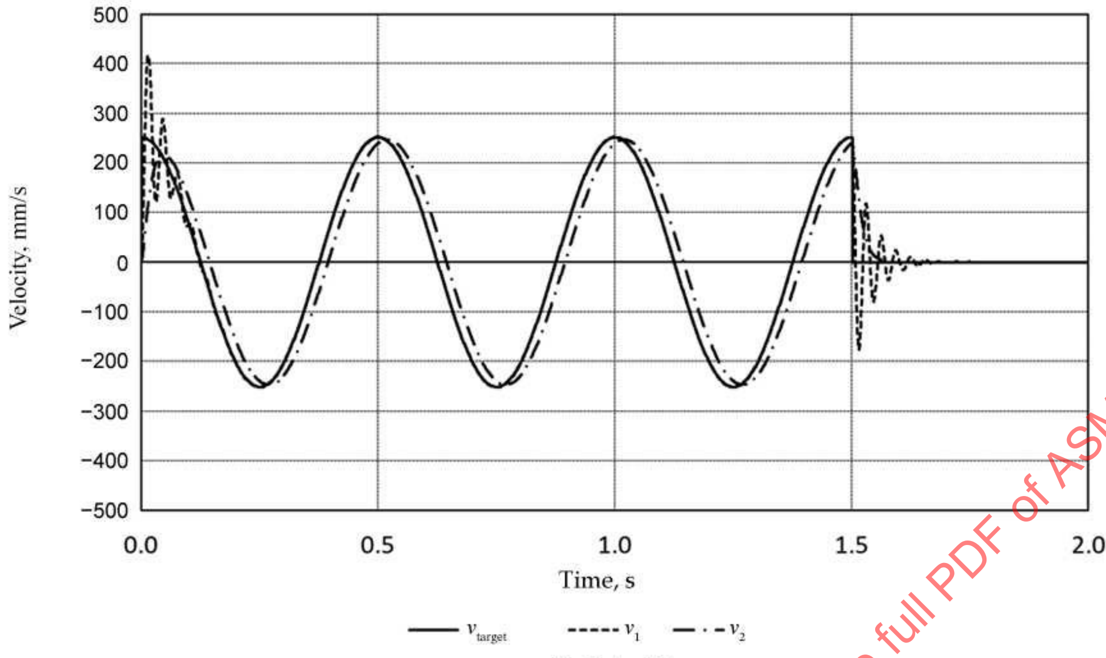
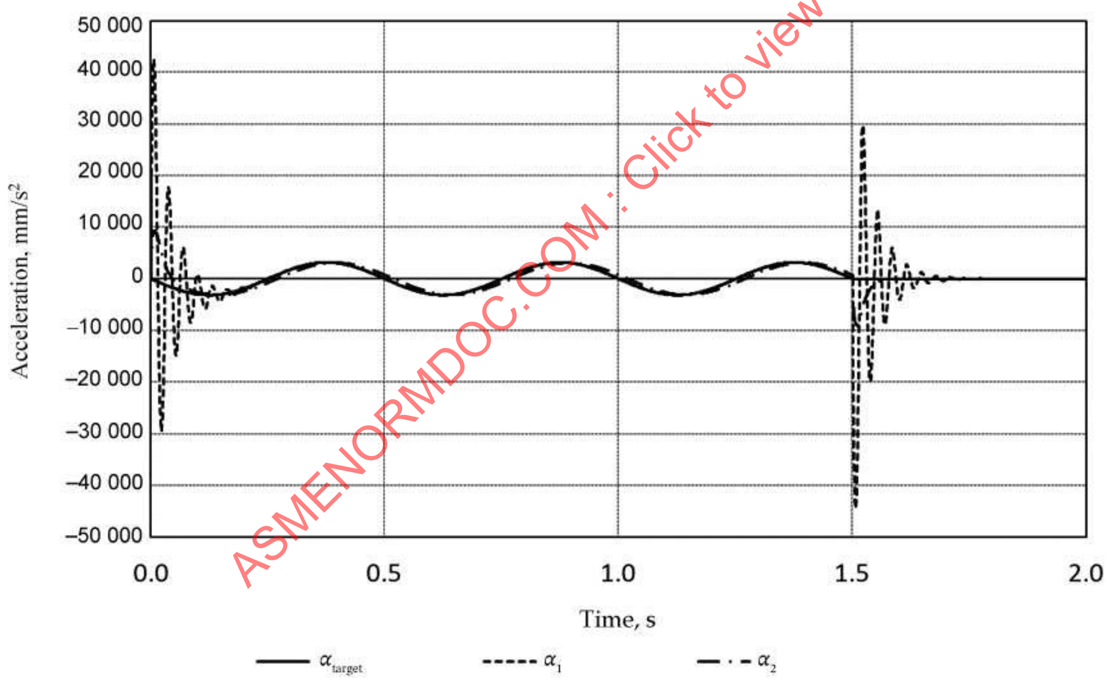


Figure 7-7.5.4-3
Example Sinusoidal Target Velocity and Target Acceleration for Two Control Configurations



(a) [Note (1)]



(b) [Note (2)]

NOTES:
(1) Example of sinusoidal target velocity with actual velocity for two control configurations.
(2) Example of sinusoidal target acceleration with actual acceleration for two control configurations.

7-7.7 Presentation of Results

One report should be created for each motion, whether positive or negative, and for each tested control configuration. The report shall show the deviation between the actual position path and the target position and the associated metrics. Reports for various control configurations may be used to demonstrate the influence of the control system on performance. Any changes to control parameters should be recorded to ensure repeatability of these tests.

7-7.7.1 Linear Ramp Motion. Figure 7-7.7.1-1 shows an example of a dynamic positioning test report for a linear ramp motion. As seen in this example report, the actual position is underdamped compared to the target position. The metrics of dynamic positioning error, following error, and overshoot are noted in Figure 7-7.7.1-1. Other metrics and issues are not specifically addressed in this example report but may be observable and noted in similar reports.

7-7.7.2 Sinusoidal Motion. shows an example of a dynamic positioning test report for a sinusoidal motion. In this example, the largest position deviation is recorded. Other locations are also noted as those results may be important. Specifically, while a sinusoid was prescribed, both the positive and negative peaks are recorded. Additional or alternative results of significance may be noted as agreed upon between the user and manufacturer/supplier. Furthermore, additional derivatives of position are observable and may be reported. For example, Figures 7-7.7.2-1 and 7-7.7.2-3 show examples of reports for the velocity and acceleration, respectively.

Figure 7-7.7.1-1
Example of a Dynamic Positioning Test Report for a Linear Ramp Motion

Dynamic Positioning Test Report for a Linear Ramp Motion

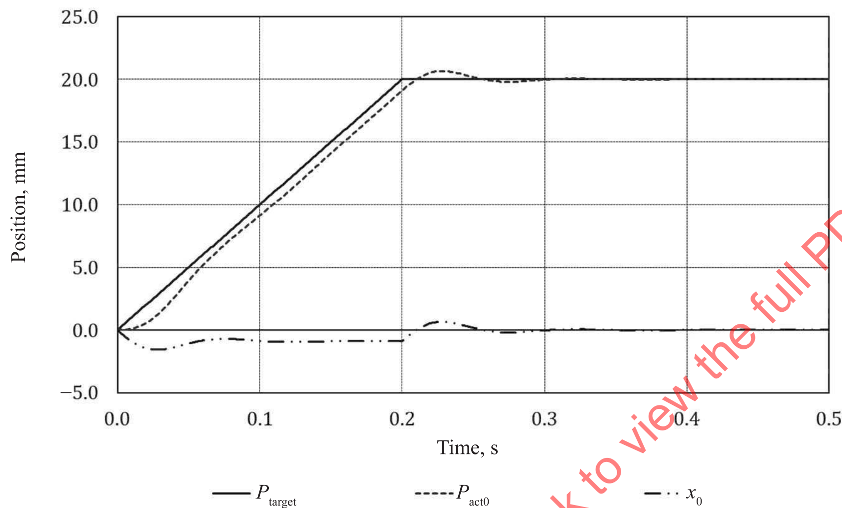
Positioning System

Manufacturer: ABC	Model No.: XX	Serial No.: XX
Type: Moderate damping	Max. travel: 200 mm	Max. velocity: 250 mm/s

Test Setup

Programmed travel: 20 mm	Programmed velocity: 100 mm/s
Sampling rate: 1 000 Hz	
Functional point: X = XX mm, Y = XX mm, and Z = XX mm	Load: 0 kg

Position and Position Deviation



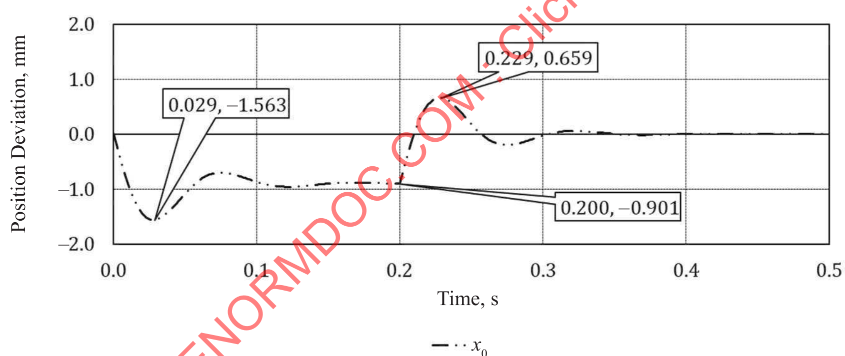
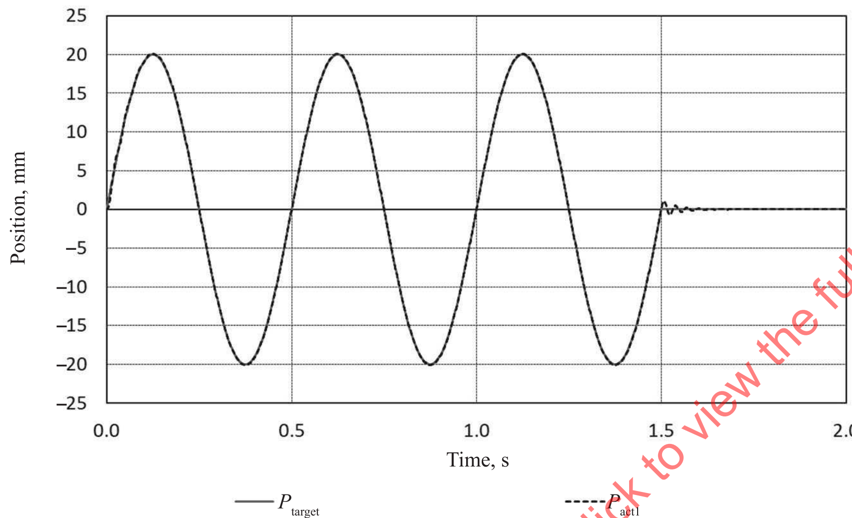


Table of Results

Metric	Dynamic Positioning Error (DPE)	Following Error	Overshoot
Time, s	0.029	0.2	0.229
Target position, mm	2.90	20	20
Metric value, mm	1.563	0.901	0.659
Method to determine value	User and manufacturer/supplier agreement		Manual selection

Figure 7-7.7.2-1
Example of a Dynamic Positioning Test Report for a Sinusoidal Motion

Dynamic Positioning Test Report for a Sinusoidal Motion		
Positioning System		
Manufacturer: ABC	Model No.: XX	Serial No.: XX
Type: High damping	Max. travel: 200 mm	Max. velocity: 1 000 mm/s
Test Setup		
Programmed travel: 20 mm amplitude		Programmed velocity: 250 mm/s
Sampling rate: 1 000 Hz		
Functional point: X = XX mm, Y = XX mm, and Z = XX mm		Load: 0 kg:
Position and Position Deviation		



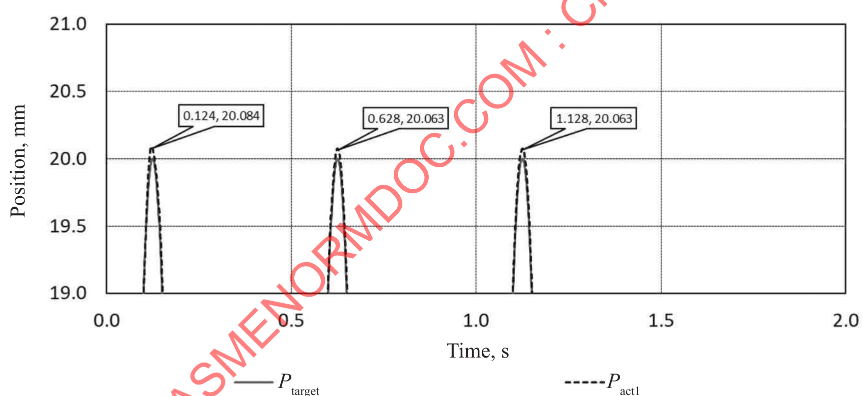
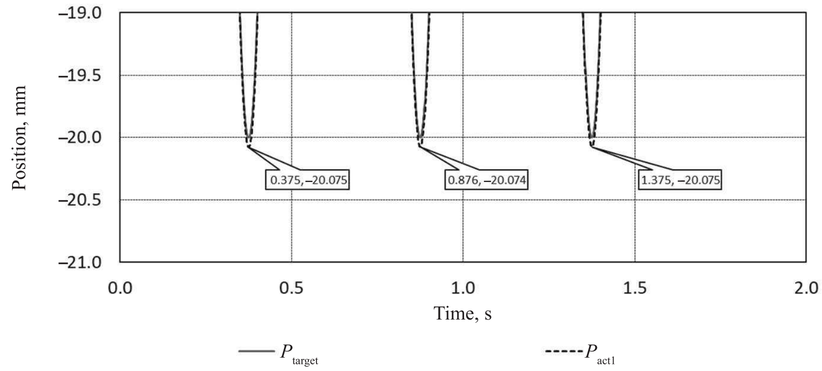


Figure 7-7.7.2-1
Example of a Dynamic Positioning Test Report for a Sinusoidal Motion (Cont'd)

Position and Position Deviation (Cont'd)



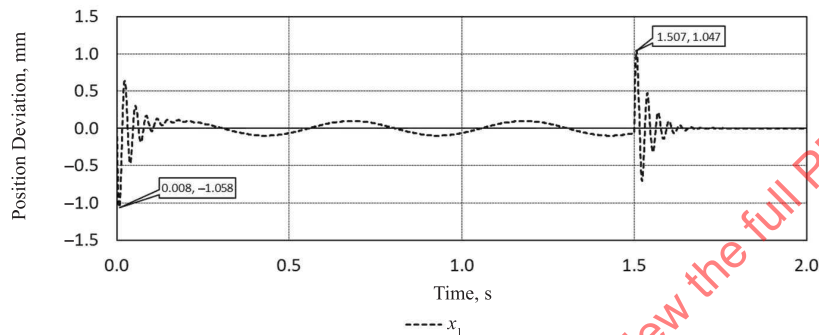


Table of Results

Metric	Max. Actual Position	Min. Actual Position	Dynamic Positioning Error (DPE)
Time, s	0.124	0.375	0.008
Target position, mm	≅ 20	≅ −20	≅ 0
Metric value, mm	20.084	−20.075	1.058

Figure 7-7.7.2-2
Example of a Dynamic Velocity Test Report for a Sinusoidal Motion

Dynamic Velocity Test Report for a Sinusoidal Motion

Positioning System

Manufacturer: ABC	Model No.: XX	Serial No.: XX
Type: Stiff control	Max. travel: 200 mm	Max. velocity: 1 000 mm/s

Test Setup

Programmed travel: 20 mm amplitude	Programmed velocity: 250 mm/s
Sampling rate: 1 000 Hz	
Functional point: *X* = XX mm, *Y* = XX mm, and *Z* = XX mm	Load: 0 kg

Velocity

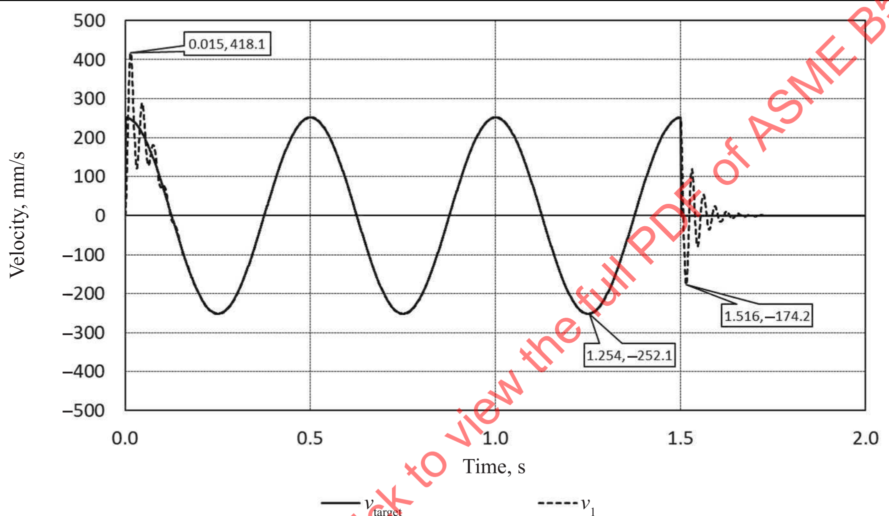


Table of Results

Metric	Max. Actual Velocity	Min. Actual Velocity	Max. Velocity Deviation	Min. Velocity Deviation
Time, s	0.015	1.254	0.015	1.516
Target velocity, mm/s	≦ 250	≦ −250	≦ 250	0
Metric value, mm/s	418	−252	168	−174
Method to determine value	User and manufacturer/supplier agreement			

Figure 7-7.7.2-3
Example of a Dynamic Acceleration Test Report for a Sinusoidal Motion

Dynamic Acceleration Test Report for a Sinusoidal Motion

Positioning System

Manufacturer: ABC	Model No.: XX	Serial No.: XX
Type: Stiff control	Max. travel: 200 mm	Max. velocity: 1 000 mm/s

Test Setup

Programmed Travel: 20 mm amplitude	Programmed velocity: 250 mm/s
Sampling rate: 1 000 Hz	
Functional point: X = XX mm, Y = XX mm, and Z = XX mm	Load: 0 kg

Acceleration

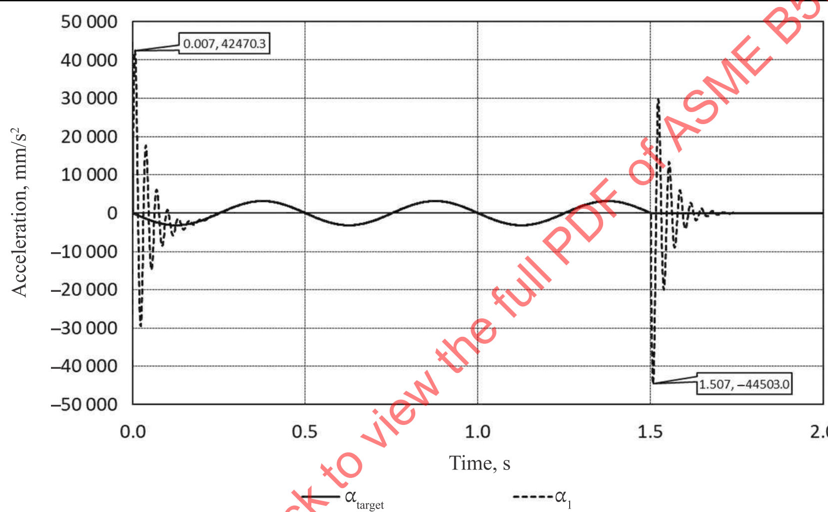


Table of Results

Metric	Max. Actual Acceleration	Min. Actual Acceleration	Max. Acceleration Deviation	Min. Acceleration Deviation
Time, s	0.007	1.507	0.007	1.507
Target acceleration, mm/s²	−788	0	−788	0
Metric value, mm/s²	42 470	−44 503	43 258	−44 503

Section 8
Geometric Accuracy

8-1 STRAIGHTNESS ERRORS

8-1.1 General

As the carriage of a linear positioning system is moved, there are unwanted deviations in the lateral directions orthogonal to the system's nominal straight linear path. These unwanted deviations are called straightness errors. The straightness of a single-axis linear positioning system is characterized by these lateral motions of a specified measurement point that is fixed with respect to the carriage of the system (see Section 5). As shown in Figure 8-1.1-1, if the direction of nominal motion is chosen as the X-direction, then the straightness errors are in the Y- and Z-directions, respectively, and are called the lateral and vertical straightness error motions and represented by symbols E_{YX} and E_{ZX}, respectively. The straightness errors vary as a function of the axis position X.

This Section describes how to measure the static and dynamic straightness errors as functions of the axis position. The intended applications for single-axis positioning systems may vary among users. Similarly, the forces and moments acting on the positioning systems may differ between applications. A few examples include the orientation of the positioning system with respect to gravity, the mass of the payload, and the rate/method in which the payload is traversed, i.e., dynamic motion. In all cases, the forces and moments acting on the positioning system can alter the straightness error motions. For these reasons, this Section describes a static straightness test (see para. 8-1.5) and a dynamic straightness test (see para. 8-1.7).

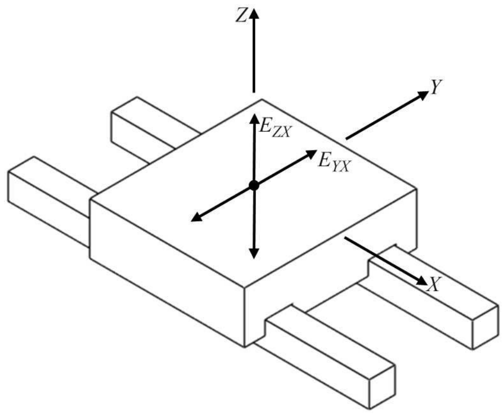
8-1.2 Measurement Setup

8-1.2.1 Sensor Locations. Straightness measurements shall be taken in two directions along axes of the specified fixed coordinate system csF (see Section 5), with both axes orthogonal to the nominal motion direction. The values obtained for the straightness errors depend on the location of the measured point fixed relative to the moving carriage (coordinate system csM, per Section 5). This is because straightness measurements are affected by the angular errors as well as the nonrigid body behavior of the positioning system's components. Because straightness errors change with point location, it is recommended that the location of the measured point corresponds to the location of the functional point, i.e., the point where work of the intended application is occurring. Spatial constraints, however, may limit the ability to measure straightness errors at the functional point. Thus, it is recommended that the measured point be located as close to the functional point as possible, the point's location with respect to the carriage be well documented, and the measurements of the carriage's angular errors made as well (see subsection 8-2). Resulting straightness data should then be transformed (see Mandatory Appendix I) to represent the straightness errors at the functional point of the intended application.

8-1.2.2 Fixed or Moving Sensors. Straightness measurements can be performed in either a fixed- or moving-sensor setup. For example, Figures 8-1.2.2-1 and 8-1.2.2-2 show both the fixed- and moving-sensor configurations when a straightedge or a straightness interferometer is used, respectively.

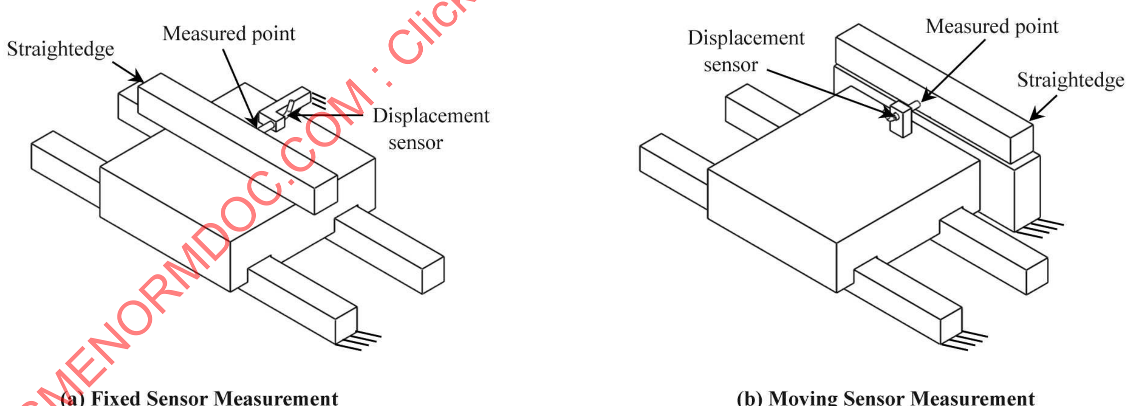
In the fixed-sensor configuration, the sensor is fixed with respect to the base and the reference straightedge or straightness reflector is placed on the moving carriage, as seen in Figure 8-1.2.2-1, illustration (a) or Figure 8-1.2.2-2, illustration (a), respectively. The displacement sensor or Wollaston prism is held stationary (fixed to the base of the positioning system) and measures against a traversing straightedge or reflector attached to the traversing element of the positioning system. The location of the measured point with respect to the moving carriage is not constant and varies as a function of axis position. A transformation (see Mandatory Appendix I) of the data with the appropriate angular positioning errors (see subsection 8-2) is required to represent the measurements as the straightness of a single measurement point, as for the moving-sensor setup.

Figure 8-1.1-1
Straightness Error Motions, E_{YX} and E_{ZX}, of a Linear Positioning System Designed to Traverse in the *X*-Direction



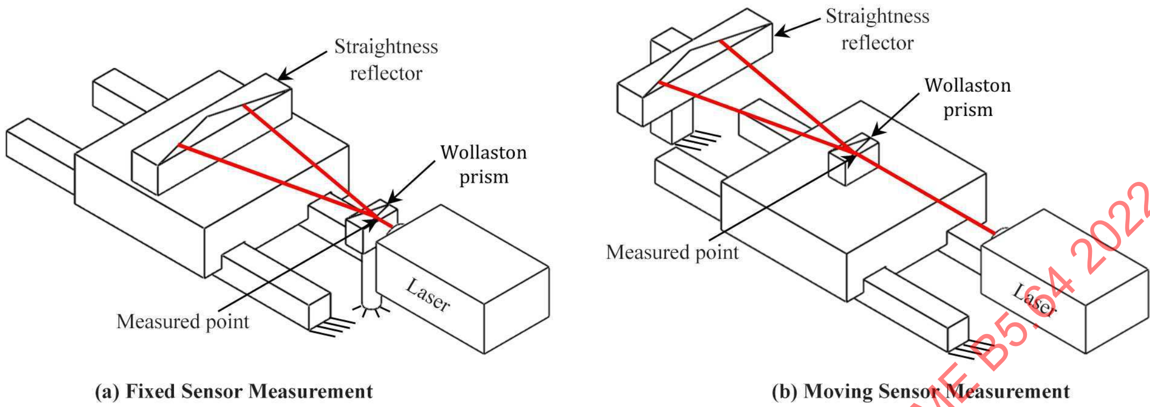
GENERAL NOTE: Figure is adapted from "Methods for Performance Evaluation of Single Axis Positioning Systems: Dynamic Straightness," by R. Fesperman, B. O'Connor, and J. Ellis, 2013, Proceedings of the 28th ASPE Annual Meeting, Vol. 56, pp. 505–509. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=914434. Courtesy of the National Institute of Standards and Technology, U.S. Department of Commerce. Not copyrightable in the United States.

Figure 8-1.2.2-1
Setups for Measuring Straightness Using a Displacement Sensor and a Straightedge With Either a Fixed-Sensor Measurement or a Moving-Sensor Measurement



GENERAL NOTE: Figure is adapted from "Methods for Performance Evaluation of Single Axis Positioning Systems: Dynamic Straightness," by R. Fesperman, B. O'Connor, and J. Ellis, 2013, Proceedings of the 28th ASPE Annual Meeting, Vol. 56, pp. 505–509. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=914434. Courtesy of the National Institute of Standards and Technology, U.S. Department of Commerce. Not copyrightable in the United States.

Figure 8-1.2.2-2
Setup for Measuring Straightness Using a Straightness Interferometer With Either a Fixed-Sensor Measurement or a Moving-Sensor Measurement



GENERAL NOTE: Figure is adapted from "Methods for Performance Evaluation of Single Axis Positioning Systems: Dynamic Straightness," by R. Fesperman, B. O'Connor, and J. Ellis, 2013, Proceedings of the 28th ASPE Annual Meeting, Vol. 56, pp. 505–509. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=914434. Courtesy of the National Institute of Standards and Technology, U.S. Department of Commerce. Not copyrightable in the United States.

In the moving-sensor configuration, the sensor is attached to the carriage and the reference straightedge or straightness reflector is mounted stationary with respect to the base, as seen in Figure 8-1.2.2-1, illustration (b) or Figure 8-1.2.2-2, illustration (b), respectively. The displacement sensor or prism is attached to the carriage of the positioning system and measures against a stationary straightedge or straightness reflector fixed to the base of the positioning system (coordinate system csF, per Section 5). The location of the sensor or prism (in csM) represents the location of the measurement point. Throughout the duration of the measurement, the location of the measured point with respect to the moving carriage is constant and the resulting measurement data reflects the straightness of the point's trajectory. Also, displacement sensors with attached cables may experience false readings due to cable movements. Thus, cable management should be considered for the moving-sensor setup, or a fixed-sensor setup should be used to eliminate false cable-influenced readings.

Although a linear positioning system can be characterized by measuring in either a fixed- or moving-sensor setup, the moving sensor method should be chosen, unless otherwise agreed upon by the user and the manufacturer/supplier or if the functional point of the intended use does not move with the carriage.

8-1.3 Measurement Setup

8-1.3.1 Test Equipment. In general, a straightness measurement may require the following equipment, which should be chosen to reflect the expected performance of the positioning system and the results of an uncertainty evaluation:

(a) displacement sensor with straightedge
(b) laser and Wollaston prism with laser straightness reflector
(c) laser and lateral-effect sensor (geometry laser)
(d) fixturing
(e) data acquisition system
(f) post-processing software
(g) environmental sensors

8-1.3.2 Sensor Types. Common methods of straightness measurement use displacement sensors, straightedges, reflectors, laser straightness interferometers, and geometry lasers in fixed-sensor setups and/or moving-sensor configurations:

(a) Displacement Sensor With Straightedge. A common straightness measurement uses a displacement sensor with a straightedge, as seen in Figure 8-1.2.2-1. The straightedge is aligned nominally parallel to the axis of motion and should be minimally constrained to minimize deformations along the straightedge's functional surface. The straightness error is measured with a displacement sensor/indicator or a plane mirror interferometer (if the straightedge has an optical quality reflective surface). When an interferometer is used as the measurement sensor, the air gap between the interferometer and the straightedge should be kept as small as possible to avoid effects of ambient air turbulence. If air

turbulence exists, then methods should be employed to minimize their effects. If turbulence is unavoidable, then a displacement sensor that is not sensitive to air turbulence should be used. Since interferometer measurements are differential and the air gap is small, in many cases it is not necessary to make corrections for errors in laser wavelength due to atmospheric conditions such as temperature and pressure. For the lowest measurement uncertainty conditions, corrections should be made (see Section 12) and the contribution to the measurement uncertainty should be calculated (ASME B89.1.8-2011).

The calibration chart of the straightedge should be used to determine if its accuracy is adequate compared to the straightness specification of the positioning system under test. If the straightedge is not accurate enough, in that a test uncertainty ratio of at least 4:1 is not possible (ISO/IEC 17025:2017), then the calibration chart or a technique called straightedge reversal (Evans et al., 1996) should be used to eliminate the effects of straightedge errors from the measurements. However, the straightedge reversal technique does not work when measuring the vertical straightness of a horizontal axis when the sag of the straightedge due to gravity is significant. In such cases, the straightedge should be characterized separately (e.g., with a flatness interferometer or profiler) and under the same constraints and in the same orientation in which it will be used for straightness measurements (Estler, 1985).

(b) Laser Straightness Interferometer. The most used laser straightness interferometers consist of a Wollaston prism and a straightness reflector, as seen in Figure 8-1.2.2-2. Extreme care must be taken in fixturing this reflector, particularly in situations where table bending is suspected. Any local bending will cause the centerline of the reflector to change its position, potentially corrupting the straightness measurements. This situation can be partially rectified by mounting the reflector to a secondary surface that is kinematically supported over the table.

(c) Laser and Lateral-Effect Sensor. A geometry laser may also be used, in which straightness is measured by a laser and a lateral-effect sensor, e.g., a four-quadrant photodiode, without the use of interferometry. In this case, a laser source is held stationary and fixtured to the base of the positioning system with the laser beam aligned parallel to the axis of motion. A lateral-effect sensor capable of measuring lateral motion is attached to the moving carriage of the positioning system and located as near as possible to the functional point. These measurements are representative of a moving-sensor measurement. Alternatively, the laser source can be mounted to the moving carriage and the lateral effect sensor is fixed to the base of the positioning system. In either case, thermal perturbations from the laser source and sensor electronics should be minimized to limit gradient effects.

8-1.3.3 Anti-Aliasing Filter. If an anti-aliasing filter is not an integral part of the data acquisition unit, it must be configured external between the sensor and data acquisition system so that the analog filtering occurs before the signal is digitized.

8-1.4 Static Straightness Measurement Procedure

8-1.4.1 General. Static straightness measurements are used to characterize the straightness error of a positioning system without the added effects of inertial forces due to accelerations. These measurements are performed statically, with the system held at position with no programmed movement.

8-1.4.2 Measurement Targets. A series of evenly, unevenly, or randomly spaced target positions are required over the full travel of the positioning system. The target intervals shall be no more than 1/10 of the axis travel. Generally, smaller intervals are preferred to yield more information about the straightness error motions of the system. The same target positions shall be used for repetitive measurements. Ultimately, the targets shall be agreed upon between the user and the manufacturer/supplier of the linear axis positioning system.

8-1.4.3 System Condition. Before data acquisition, the positioning system shall be run through a warm-up exercise sequence of at least five back-and-forth runs that include all target positions. The programmed accelerations, velocity, and position dwells used should be the same as for the static straightness measurement.

Alternative warm-up sequences and techniques should be agreed upon between the user and the manufacturer/supplier of the positioning system.

8-1.4.4 Measurement Procedure. The test shall be conducted at a programmed velocity and payload that best replicates the nominal conditions of the application or process in which the positioning system is intended to be used. These conditions are application-dependent and shall be agreed upon between the user and the manufacturer/supplier of the linear axis positioning system. The measurement procedure is as follows:

Step 1. Align the measuring equipment with the axis under test.

Step 2. Exercise the linear positioning system following the recommendation in para. 8-1.4.3.

Step 3. The positioning system shall be programmed to position the axis under test at a series of target positions (see para. 8-1.4.2). The default traverse velocity shall be the system's maximum programmable velocity or a velocity that is negotiated between the user and the manufacturer/supplier.

Step 4. At each target position, the measurement data can be acquired with the system stationary (static measurement) based on the move-and-settle time (see subsection 7-3).

Step 5. Five sets of bidirectional measurements are made at all the target positions, unless otherwise agreed upon between the user and the manufacturer/supplier. For some applications, unidirectional measurements may be agreed upon to be sufficient. A set of measurement data shall consist of the target positions and the corresponding displacement readings for straightness.

8-1.5 Static Straightness Data Analysis

8-1.5.1 Error Motions. To determine the actual straightness error motions, a straight line shall be removed from every motion data. The straight line shall be determined by the least-squares method, unless otherwise agreed upon between the user and the manufacturer/supplier. The data used for least-squares method shall be, by default, the entire set of forward-motion straightness data, or the entire set of bidirectional motion straightness data if agreed upon between the user and the manufacturer/supplier. Because the same straight line is removed from each individual motion straightness data, the reversal error is preserved between the forward- and reverse-motion data.

8-1.5.2 System Straightness Values. After linear correction (i.e., slope removal) (see para. 8-1.5.1), a straightness error value shall be calculated for each unidirectional motion data or each set of bidirectional motion data (a forward-motion data curve and its corresponding reverse-motion data curve) by subtracting its minimum value from its maximum value. The result for bidirectional measurements is a unique set of straightness values for the forward-, reverse-, and bidirectional-motion data, with each of the three sets containing at least five values, one for each repeated measurement at the target positions. Specifically, the forward-motion straightness error, reverse-motion straightness error, and bidirectional straightness error are defined, respectively, as

$$E_{\beta\alpha,E\uparrow} = \max(E_{\beta\alpha}\uparrow) - \min(E_{\beta\alpha}\uparrow) \quad \text{(8-8-1)}$$

$$E_{\beta\alpha,E\downarrow} = \max(E_{\beta\alpha}\downarrow) - \min(E_{\beta\alpha}\downarrow) \quad \text{(8-1-2)}$$

$$E_{\beta\alpha,\mathrm{E}} = \max[(E_{\beta\alpha}\uparrow;\ E_{\beta\alpha}\downarrow)] - \min[(E_{\beta\alpha}\uparrow;\ E_{\beta\alpha}\downarrow)] \quad \text{(8-1-3)}$$

where α denotes the axis direction (e.g., X) and β denotes the straightness error direction (e.g., Y or Z). The average value for each set may be considered the static straightness error of the system for that data type, and the standard deviation for each set may be used for the uncertainty analysis of the straightness errors.

8-1.5.3 Test Uncertainty Analysis. Uncertainties associated with the measurement of static straightness errors are related to uncertainties of the used measurement systems among other factors. These uncertainties should be considered when specifying measurement sampling rates and parameters, to avoid situations where neither conformance nor nonconformance to specifications can be demonstrated. Potential measurement uncertainty contributors include

(a) uncertainty due to the sensor calibration, u_{CAL}
(b) uncertainty due to the sensor resolution, u_{SR}
(c) uncertainty due to sensor correction error, u_{SCE}
(d) uncertainty due to the straightness reference error, u_{SRE}
(e) uncertainty due to sensor misalignment, u_{MA}
(f) uncertainty due to setup repeatability, u_{Δ}
(g) uncertainty due to the thermal drift of the measurement setup, u_{TD}
(h) uncertainty due to the linear axis position repeatability, u_{AR}
(i) uncertainty due to triggering, u_{TR}
(j) uncertainty due to the data acquisition system noise, u_{DAQ}

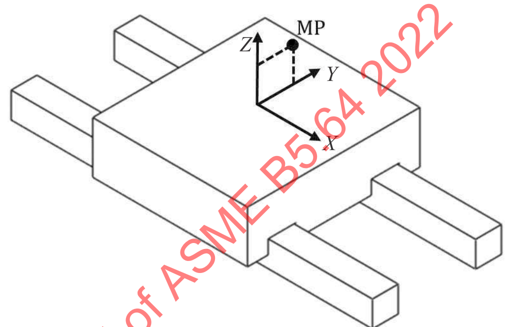
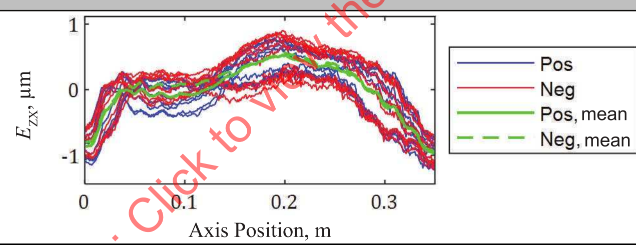
8-1.6 Presentation of Static Results

The average and expanded uncertainty of the straightness values shall be reported with a plot of the static straightness error motions. Figure 8-1.6-1 shows an example of a static straightness report.

8-1.7 Dynamic Straightness Measurement Procedure

8-1.7.1 General. Forces and moments inherent in dynamic systems affect the straightness errors. Some forces and moments are due to the drive forces that occur during acceleration and deceleration of the positioning system. The acceleration and deceleration at each axis position are based on the positioning profile. During constant-velocity motions,

Figure 8-1.6-1
Example of a Static Straightness Test Report

Static Straightness Test Report		
Positioning System		
Manufacturer: ABC	Model No.: XX	Serial No.: XX
Type: Linear	Max. travel: 350 mm	Max. velocity: 500 mm/s
Controller/drive unit to power the positioning system: ABC P100 S/N 1234		
Measurement Setup		
Functional point: X = XX mm, Y = XX mm, and Z = XX mm Load: XX kg System location: 300 mm × 1.2 m × 1.2 m granite base Temperature during test: 22°C Axis travel: 350 mm Number of forward/reverse motions: 10/10 Direction of measurement/motion: Z-axis/X-axis Commanded axial positioning interval: 1 mm Dwell time for averaging: 5 s Measurement point (MP): (X, Y, Z) = (0 mm, 30 mm, 25 mm) Data acquisition system: Acme D100 S/N 5678 Displacement sensor: Acme S100 S/N 91011 Data filter: None	 	
Static Straightness Plots		
 		
Static Straightness Test Results		
	Axis positions: Every 1 mm from 0.001 m to 0.349 m $E_{ZX,E\uparrow}$ = 1.56 µm ± 0.21 µm (k = 2) $E_{ZX,E\downarrow}$ = 1.57 µm ± 0.23 µm (k = 2) $E_{ZX,E}$ = 1.62 µm ± 0.18 µm (k = 2)	

the acceleration and deceleration regions occur at the beginning and end of travel and their lengths are a function of the programmed speed, acceleration, and deceleration, as explained in subsection 7-6. With other positioning profiles, such as contouring and raster scanning, acceleration and deceleration may occur throughout the profile and may vary in magnitude (e.g., a sinusoidal profile). In addition to drive forces, straightness errors may also be affected by gravity or loaded conditions such as the mass of the material that the positioning system is intended to carry. For these reasons, the positioning profile and load that best represents the intended use of the positioning system should be used during dynamic straightness measurements. These conditions shall be agreed upon between the user and the manufacturer/supplier.

8-1.7.2 Measurement Targets. Because accelerations and decelerations can affect the dynamic straightness error, the constant-velocity and acceleration regions of the positioning profile should be identified. A linear axis positioning system must be commanded to execute a simple motion. The travel distance between the two endpoints should allow the axis to accelerate, then move at constant velocity for a defined distance, and then decelerate to stop. These regions can be identified by measuring the position or velocity during the dynamic straightness measurement (see subsection 7-6). The acceleration and deceleration regions of the velocity profile should be referenced when reporting the dynamic straightness. The travel distance, constant velocities, constant velocity distances, acceleration and deceleration rates, and loads shall be agreed upon between the user and the manufacturer/supplier of the linear axis positioning system. When the travel distance is not agreed upon a priori, the travel distance shall be the maximum possible travel distance. When predefined velocities are not agreed upon a priori, two different tests shall be conducted at 20% and 80% of the maximum steady-state speed, which is the maximum speed achievable where the constant-velocity distance is at least 50% of the travel distance used for both speeds.

8-1.7.3 Sampling Rates. Each measurement device/equipment shall collect data at axis positions with a positioning interval agreed upon between the user and the manufacturer/supplier. For example, if it is agreed upon to collect data with a positioning interval of 1 mm and the linear axis is programmed to move at a maximum speed of 500 mm/s, then the measurement device/equipment must sample data with a rate of at least 500 Hz. No smoothing or averaging techniques should be used for the raw data collection. The data may be collected at axis positions with either uniform spacing (i.e., from distance-based sampling) or nonuniform positioning intervals (i.e., from time-based sampling).

Sampling rates shall be agreed upon between the user and the manufacturer/supplier. Each equipment may measure at different sampling rates, and if possible, all data shall be timestamped in a synchronized fashion to the same reference clock. If no sampling rate is agreed upon a priori, then a time-based sampling rate coinciding with a positioning interval of at most 0.1% of the total travel distance shall be used, depending upon the constant velocity. For example, if the linear axis is programmed to move at a maximum speed of 500 mm/s for a total travel distance of 1 000 mm, a default sampling rate of at least 500 Hz shall be used, coinciding with a positioning interval of 1 mm (= 0.1% of 1 000 mm) at the maximum speed.

Measurement time intervals shall be agreed upon between the user and the manufacturer/supplier. Measurement time intervals shall include the complete motion with enough data collected before/after acceleration/deceleration to satisfy the user that the linear axis is nominally at rest.

8-1.7.4 System Condition. Before data acquisition, the positioning system shall be run through a warm-up exercise sequence of at least five back-and-forth movements between the first and last target points. The programmed accelerations, velocity, and position dwells used should be the same as for the dynamic straightness measurement. Alternative warm-up sequences and techniques should be agreed upon between the user and the manufacturer/supplier of the positioning system.

8-1.7.5 Measurement Procedure. The measurement procedure is as follows:

Step 1. Align the measuring equipment with the axis under test.

Step 2. Exercise the linear positioning system following the recommendation in para. 8-1.7.4.

Step 3. The linear axis must be commanded to execute a simple motion. The travel distance used for both speeds should be the same, unless otherwise agreed upon by the user and the manufacturer/supplier.

Step 4. The test should be carried out in both positive and negative directions. For each direction, all measurements shall be recorded synchronously with each other, as much as possible; that is, if possible, the measurements shall be timestamped in a synchronized fashion to the same reference clock. Otherwise, the non-synchronous data shall be collected and then synchronized afterwards.

Step 5. The tests must be repeated a minimum of five times, unless otherwise agreed upon between the user and the manufacturer/supplier. For some applications, unidirectional measurements are sufficient. The sets of bidirectional data shall consist of time, axis position, and the corresponding displacement readings for straightness.

8-1.8 Dynamic Straightness Data Analysis

8-1.8.1 Error Motions. Post-process filtering may be performed on the raw data, upon agreement between the user and the manufacturer/supplier, and if so, the filter used should be reported (see para. 8-1.9). Then, the dynamic straightness error motions shall be determined as for the static straightness error motions (see para. 8-1.5.1), except that the data used shall be either that for the full travel or that collected within the constant-velocity phase (see subsection 7-6), as agreed upon between the user and the manufacturer/supplier. Without an agreement, only the data collected within the constant-velocity phase shall be used; that is, data collected during axis acceleration or deceleration shall not be used for determination of the dynamic straightness error motions in that case.

8-1.8.2 System Straightness Values. For the test data at the agreed-upon axis positions, the dynamic straightness error values shall be determined as in para. 8-1.5.2 for the static straightness error values.

8-1.8.3 Test Uncertainty Analysis. Uncertainties associated with the measurement of dynamic straightness error are related to uncertainties of the used measurement systems among other factors, with at least the same uncertainty contributors as those for the static straightness error (see para. 8-1.5.3). Additional measurement uncertainty contributors for the dynamic straightness error include

(a) uncertainty due to temporal synchronization of position and error motion data, u_{SYNC}

(b) uncertainty due to fixturing vibrations of the measurement points, u_{VIB}

8-1.9 Presentation of Dynamic Results

The average and expanded uncertainty of the straightness values shall be reported with a plot of dynamic straightness error motions and a velocity profile plot that identifies the acceleration/deceleration phases and the constant-velocity phase. The dynamic straightness plot should contain the five measurement runs and the two parallel lines, if used to determine the straightness values. Also, when filtered data is used for analysis, the filter parameters shall be provided. Figure 8-1.9-1 shows an example of a dynamic straightness test report.

8-2 ANGULAR ERRORS

8-2.1 General

As the carriage of a linear positioning system is moved, there are unwanted rotations with respect to the system's nominal orientation along the straight linear path. These unwanted rotations are called angular errors. The angular errors of a single-axis linear positioning system are characterized by these rotational motions of a measurement frame that is fixed with respect to the carriage of the system (see Section 5). As shown in Figure 8-2.1-1, if the direction of nominal motion is chosen as the *X*-direction, then the angular errors are in the *X*-, *Y*-, and *Z*-directions, respectively, and are called the roll, pitch, and yaw angular error motions and represented by symbols E_{AX}, E_{BX}, and E_{CX}, respectively. The angular errors vary as a function of the axis position *X*.

This Section describes how to measure the static and dynamic angular errors as functions of the axis position. The intended applications for single-axis positioning systems may vary among users. Similarly, the forces and moments acting on the positioning systems may differ between applications. A few examples include the orientation of the positioning system with respect to gravity, the mass of the payload, and the rate/method in which the payload is traversed, i.e., dynamic motion. In all cases, the forces and moments acting on the positioning system can alter the angular error motions. For these reasons, this Section describes a static angular error test (see para. 8-2.5) and a dynamic angular error test (see para. 8-2.8).

8-2.2 Measurement Setup

8-2.2.1 Sensor Locations. Angular measurements shall be taken in three directions along axes of the specified fixed coordinate system csF (see Section 5), with the axes orthogonal to the nominal motion direction. Under the assumption of rigid bodies, the location of the angle sensors should not influence the measurements. However, if there is evidence of significant nonrigid body behavior, then the location of the angular measurements becomes important, and thus, it is recommended that the location of the measured point corresponds to the location of the functional point, i.e., the point where work of the intended application is occurring. Either way, the point's location with respect to the carriage should be well documented.

8-2.2.2 Fixed or Moving Sensors. Some angular error measurements can be performed in either a fixed- or moving-sensor setup. See subsection 8-1 for details about the differences between these two types of configurations. These differences are critical for straightness measurements to understand the effects of angular motion on the error motions but are generally not as significant for angular error measurements. Nonetheless, selection of sensor configurations shall be agreed upon by the user and the manufacturer/supplier.

8-2.3 Measurement Setup

8-2.3.1 Test Equipment. In general, an angular measurement may require the following equipment, which should be chosen to reflect the expected performance of the positioning system and the results of an uncertainty evaluation:

(a) reference target or straightedge

(b) angle sensor or laser

(c) fixturing

Figure 8-1.9-1
Example of a Dynamic Straightness Test Report

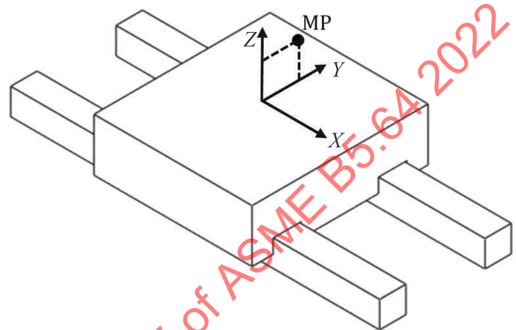
Dynamic Straightness Test Report

Positioning System

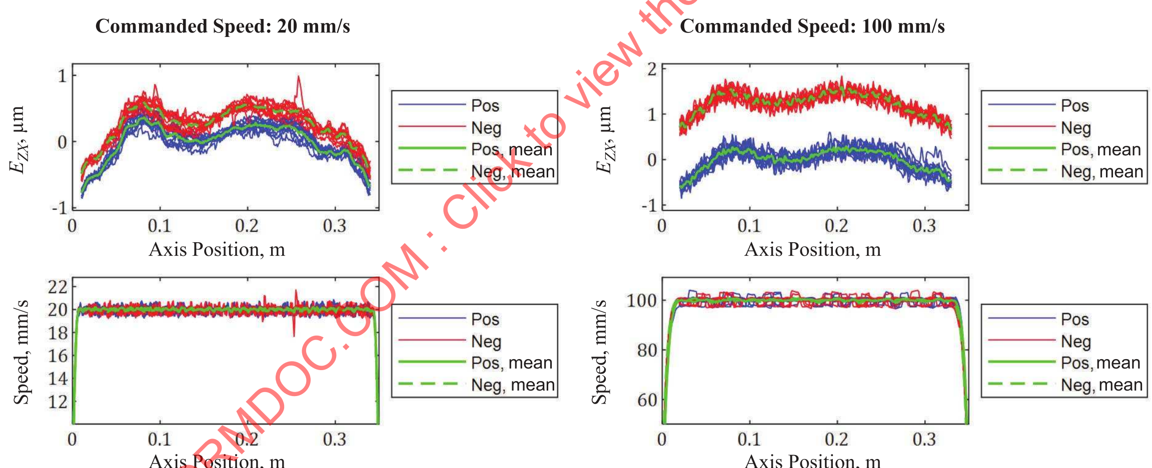
Manufacturer: ABC	Model No.: XX	Serial No.: XX
Type: Linear	Max. travel: 350 mm	Max. velocity: 500 mm/s
Controller/drive unit to power the positioning system: ABC P100 S/N 1234		

Measurement Setup

Functional point: X = XX mm, Y = XX mm, and Z = XX mm
Load: XX kg
System location: 300 mm × 1.2 m × 1.2 m granite base
Temperature during test: 22°C
Axis travel: 350 mm
Commanded speed(s): 20 mm/s and 100 mm/s
Number of forward/reverse motions: 10/10
Direction of measurement/motion: Z-axis/X-axis
Measurement Point (MP): (X, Y, Z) = (0 mm, 30 mm, 25 mm)
Data acquisition system: Acme D100 S/N 5678
Displacement sensor: Acme S100 S/N 91011
Sampling rate: 1 kHz
Data filter: None



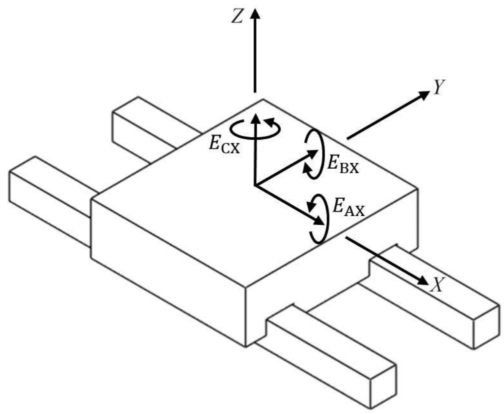
Dynamic Straightness Plots



Dynamic Straightness Test Results

Constant Speed: 20 mm/s	Constant Speed: 100 mm/s
Axis positions: 0.01 m to 0.34 m	Axis positions: 0.02 m to 0.33 m
$E_{ZX,E\uparrow}$ = 1.18 µm ± 0.12 µm (k = 2)	$E_{ZX,E\uparrow}$ = 1.17 µm ± 0.18 µm (k = 2)
$E_{ZX,E\downarrow}$ = 1.20 µm ± 0.29 µm (k = 2)	$E_{ZX,E\downarrow}$ = 1.16 µm ± 0.14 µm (k = 2)
$E_{ZX,E}$ = 1.48 µm ± 0.27 µm (k = 2)	$E_{ZX,E}$ = 2.43 µm ± 0.19 µm (k = 2)

Figure 8-2.1-1
Angular Error Motions, E_{AX}, E_{BX}, and E_{CX}, of a Linear Positioning System Designed to Traverse in the X-Direction



(d) data acquisition system
(e) post-processing software
(f) environmental sensors

8-2.3.2 Sensor Types. Common methods of angular measurement use differential displacement sensing relative to a straightedge (differential straightness), laser angle interferometers, autocollimators, electronic levels, and polarization reference angle sensors.

(a) Differential Straightness Sensors. Angle measurements using a differential straightness technique are directly analogous to the methods described for mechanical straightedges in para. 8-1.3.2, except that the angular error is measured with the difference of two separate straightness measurements collected by a pair of displacement sensors/indicators in two different locations. The calibration chart of the straightedge should be used to determine if its accuracy is adequate compared to the angular specification of the positioning system under test. If the straightedge is not accurate enough, in that a test uncertainty ratio of at least 4:1 is not possible (ISO/IEC 17025:2017), then the calibration chart or a technique called straightedge reversal (Evans et al., 1996) should be used to eliminate the effects of straightedge errors from the measurements. However, the straightedge reversal technique does not work when measuring the pitch error motion of a horizontal axis when the sag of the straightedge due to gravity is significant. In such cases, the straightedge should be characterized separately (e.g., with a flatness interferometer or profiler) and under the same constraints and in the same orientation in which it will be used for the angle measurements (Estler, 1985).

(b) Laser Angle Interferometers. The most used laser angle interferometers consist of a polarizing beam splitter with a turning mirror and a pair of retroreflector targets mounted with a known spacing between them. Laser angle interferometers are typically used to measure the pitch error motion, E_{BX}, and the yaw error motion, E_{CX}, for an axis nominally traversing along the X-direction of a Cartesian coordinate system. The retroreflector targets should be mounted to the moving carriage of the positioning system and the polarizing beam splitter should be held stationary and fixtured to the base of the positioning system. In most cases it is not necessary to make corrections for errors in laser wavelength due to atmospheric conditions such as temperature and pressure. For the lowest measurement uncertainty conditions, corrections should be made (see Section 12) and the contribution to the measurement uncertainty should be calculated (ASME B89.1.8-2011).

(c) Autocollimators. Autocollimators are generally used in a fixed-sensor setup for measuring E_{BX} and E_{CX} for an axis nominally traversing along the X-direction of a Cartesian coordinate system. The autocollimator is fixtured to the base of the linear axis system and the target is fixtured at the functional point on the moving stage.

(d) Electronic Levels. Electronic levels are generally used in a differential setup for measuring the roll error motion, E_{AX}, or pitch error motion, E_{BX}, for an axis nominally traversing along the X-direction of a Cartesian coordinate system. One level is fixtured to the base of the linear axis system and the other level is fixtured at the functional point on the moving stage. The relative output of the moving sensor to the fixed sensor is the error motion. Care should be taken to avoid acceleration and deceleration effects as the levels must settle after motion has ceased.

(e) Polarization Reference Angle Sensors. The polarization angle of an optical beam can be used to measure E_{AX} for an axis nominally traversing along the *X*-direction of a Cartesian coordinate system. A polarized laser source is typically mounted to the base and a target that changes the polarization angle or degree of polarization as a function of angle change is mounted at the functional point on the moving stage. The target reflects the optical beam from the polarized sources, and the reflected polarization angle is then detected relative to the initial polarization angle.

8-2.3.3 Anti-Aliasing Filter. If an anti-aliasing filter is not an integral part of the data acquisition unit, it must be configured external between the sensor and data acquisition system so that the analog filtering occurs before the signal is digitized.

8-2.4 Static Angular Measurement Procedure

8-2.4.1 General. Static angular measurements are used to characterize the angular error of a positioning system without the added effects of inertial forces due to accelerations. These measurements are performed statically, with the system held at position with no programmed movement.

8-2.4.2 Measurement Targets. A series of evenly, unevenly, or randomly spaced target positions are required over the full travel of the positioning system. The target intervals shall be no more than one-tenth of the axis travel. Generally, smaller intervals are preferred to yield more information about the angular error motions of the system. The same target positions shall be used for repetitive measurements. Ultimately, the targets shall be agreed upon between the user and the manufacturer/supplier of the linear axis positioning system.

8-2.4.3 System Condition. Before data acquisition, the positioning system shall be run through a warm-up exercise sequence of at least five back-and-forth runs that include all target positions. The programmed accelerations, velocity, and position dwells used should be the same as for the static angular measurement. Alternative warm-up sequences and techniques should be agreed upon between the user and the manufacturer/supplier of the positioning system.

8-2.4.4 Measurement Procedure. The test shall be conducted at a programmed velocity and payload that best replicates the nominal conditions of the application or process in which the positioning system is intended to be used. These conditions are application-dependent and shall be agreed upon between the user and the manufacturer/supplier of the linear axis positioning system. The measurement procedure is as follows:

Step 1. Align the measuring equipment with the axis under test.

Step 2. Exercise the linear positioning system following the recommendation in para. 8-2.4.3.

Step 3. The positioning system shall be programmed to position the axis under test at a series of target positions (see para. 8-2.4.2). The default traverse velocity shall be the system's maximum programmable velocity or a velocity that is negotiated between the user and the manufacturer/supplier.

Step 4. At each target position, the measurement data shall be acquired with the system stationary (static measurement) based on the move-and-settle time (see subsection 7-3).

Step 5. Five sets of bidirectional measurements are made at all the target positions, unless otherwise agreed upon between the user and the manufacturer/supplier. For some applications, unidirectional measurements may be agreed upon to be sufficient. A set of measurement data shall consist of the target positions and the corresponding angle readings for angular errors.

8-2.5 Static Angle Data Analysis

8-2.5.1 Error Motions. To determine the actual angular error motions, an offset value shall be removed from every motion data. The offset value shall be determined by the average deviation at the target position closest to the home position of the positioning system, unless otherwise agreed upon between the user and the manufacturer/supplier. The data used for offset value shall be, by default, the entire set of forward-motion angle data, or the entire set of bidirectional motion angle data if agreed upon between the user and the manufacturer/supplier. Because the same offset value is removed from each individual motion angular error data, the reversal error is preserved between the forward- and reverse-motion data.

8-2.5.2 System Angular Error Values. An angular error value shall be calculated for each unidirectional motion data or each set of bidirectional motion data (a forward-motion data curve and its corresponding reverse-motion data curve) by subtracting its minimum value from its maximum value. The result for bidirectional measurements is a unique set of angular error values for the forward-, reverse-, and bidirectional-motion data, with each of the three sets containing at least five values. Specifically, the forward-motion angular error, reverse-motion angular error, and bidirectional angular error are defined, respectively, as

$$E_{\beta\alpha,\mathrm{E}\uparrow} = \max(E_{\beta\alpha}\uparrow) - \min(E_{\beta\alpha}\uparrow) \tag{8-2-1}$$

$$E_{\beta\alpha,\mathrm{E}\downarrow} = \max(E_{\beta\alpha}\downarrow) - \min(E_{\beta\alpha}\downarrow) \tag{8-2-2}$$

$$E_{\beta\alpha,\mathrm{E}} = \max[(E_{\beta\alpha}\uparrow;\ E_{\beta\alpha}\downarrow)] - \min[(E_{\beta\alpha}\uparrow;\ E_{\beta\alpha}\downarrow)] \tag{8-2-3}$$

where α denotes the axis direction (e.g., X) and β denotes the angular error direction (A, B, or C, as described in Section 5). The average value for each set may be considered the static angular error of the system for that data type, and the standard deviation for each set may be used for the uncertainty analysis of the angular errors.

8-2.5.3 Test Uncertainty Analysis. Uncertainties associated with the measurement of static angular errors are related to uncertainties of the used measurement systems among other factors. These uncertainties should be considered when specifying measurement sampling rates and parameters, to avoid situations where neither conformance nor nonconformance to specifications can be demonstrated. Potential measurement uncertainty contributors include

(a) uncertainty due to the sensor calibration, u_{CAL}
(b) uncertainty due to the sensor resolution, u_{SR}
(c) uncertainty due to sensor correction error, u_{SCE}
(d) uncertainty due to the straightness reference error, u_{SRE}
(e) uncertainty due to the distance between displacement sensors, u_{DDS}
(f) uncertainty due to sensor misalignment, u_{MA}
(g) uncertainty due to setup repeatability, u_{Δ}
(h) uncertainty due to the thermal drift of the measurement setup, u_{TD}
(i) uncertainty due to the linear axis position repeatability, u_{AR}
(j) uncertainty due to triggering, u_{TR}
(k) uncertainty due to the data acquisition system noise, u_{DAQ}

8-2.6 Presentation of Static Results

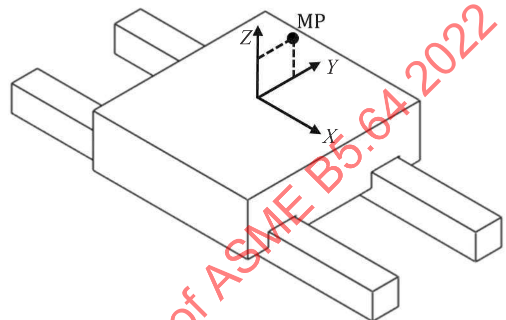
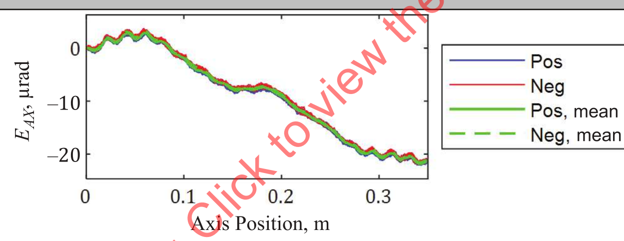
The average and expanded uncertainty of the angular error values shall be reported with a plot of the static angular error motions. Figure 8-2.6-1 shows an example of a static angular error report.

8-2.7 Dynamic Angular Measurement Procedure

8-2.7.1 General. Forces and moments inherent in dynamic systems affect the angular errors. Some forces and moments are due to the drive forces that occur during acceleration and deceleration of the positioning system. The acceleration and deceleration at each axis position are based on the positioning profile. During constant-velocity motions, the acceleration and deceleration regions occur at the beginning and end of travel and their lengths are a function of the programmed speed, acceleration, and deceleration, as explained in subsection 7-6. With other positioning profiles, such as contouring and raster scanning, acceleration and deceleration may occur throughout the profile and may vary in magnitude (e.g., a sinusoidal profile). In addition to drive forces, angular errors may also be affected by gravity or loaded conditions such as the mass of the material that the positioning system is intended to carry. For these reasons, the positioning profile and load that best represents the intended use of the positioning system should be used during dynamic angular measurements. These conditions shall be agreed upon between the user and the manufacturer/supplier.

8-2.7.2 Measurement Targets. Because accelerations and decelerations can affect the dynamic angular error, the constant-velocity and acceleration regions of the positioning profile should be identified. A linear axis positioning system must be commanded to execute a simple motion. The travel distance between the two endpoints should allow the axis to accelerate, then move at constant velocity for a defined distance, and then decelerate to stop. These regions can be identified by measuring the position or velocity during the dynamic angular measurement (see subsection 7-6). The acceleration and deceleration regions of the velocity profile should be referenced when reporting the dynamic angular errors. The travel distance, constant velocities, constant velocity distances, acceleration and deceleration rates, and loads shall be agreed upon between the user and the manufacturer/supplier of the linear axis positioning system. When the travel distance is not agreed upon a priori, the travel distance shall be the maximum possible travel distance. When predefined velocities are not agreed upon a priori, two different tests shall be conducted at 20% and 80% of the maximum steady-state speed, which is the maximum speed achievable where the constant-velocity distance is at least 50% of the travel distance used for both speeds.

Figure 8-2.6-1
Example of a Static Angular Error Test Report

Static Angular Error Test Report		
Positioning System		
Manufacturer: ABC	Model No.: XX	Serial No.: XX
Type: Linear	Max. travel: 350 mm	Max. velocity: 500 mm/s
Controller/drive unit to power the positioning system: ABC P100 S/N 1234		
Measurement Setup		
Functional Point: X = XX mm, Y = XX mm, and Z = XX mm Load: XX kg System location: 300 mm × 1.2 m × 1.2 m granite base Temperature during test: 22°C Axis travel: 350 mm Number of forward/reverse motions: 10/10 Direction of measurement/motion: X-axis/X-axis Commanded axial positioning interval: 1 mm Dwell time for averaging: 5 s Measurement point (MP): (X, Y, Z) = (0 mm, 30 mm, 25 mm) Data acquisition system: Acme D100 S/N 5678 Displacement sensor: Acme S100 S/N 91011 Data filter: None		
Static Angular Error Plots		
		
Static Angular Error Test Results		
Axis positions: Every 1 mm from 0.001 m to 0.349 m $E_{AX,E\uparrow}$ = 24.9 μrad ± 0.29 μrad (k = 2) $E_{AX,E\downarrow}$ = 25.0 μrad ± 0.33 μrad (k = 2) $E_{AX,E}$ = 25.3 μrad ± 0.32 μrad (k = 2)		

8-2.7.3 Sampling Rates. Each measurement device/equipment shall collect data at axis positions with a positioning interval agreed upon between the user and the manufacturer/supplier. For example, if it is agreed upon to collect data with a positioning interval of 1 mm and the linear axis is programmed to move at a maximum speed of 500 mm/s, then the measurement device/equipment must sample data with a rate of at least 500 Hz. No smoothing or averaging techniques should be used for the raw data collection. The data may be collected at axis positions with either uniform spacing (i.e., from distance-based sampling) or nonuniform positioning intervals (i.e., from time-based sampling).

Sampling rates shall be agreed upon between the user and the manufacturer/supplier. Each equipment may measure at different sampling rates, and if possible, all data shall be timestamped in a synchronized fashion to the same reference clock. If no sampling rate is agreed upon a priori, then a time-based sampling rate coinciding with a positioning interval of at most 0.1% of the total travel distance shall be used, depending upon the constant velocity. For example, if the linear axis is programmed to move at a maximum speed of 500 mm/s for a total travel distance of 1 000 mm, a default sampling rate of at least 500 Hz shall be used, coinciding with a positioning interval of 1 mm (= 0.1% of 1 000 mm) at the maximum speed.

Measurement time intervals shall be agreed upon between the user and the manufacturer/supplier. Measurement time intervals shall include the complete motion with enough data collected before/after acceleration/deceleration to satisfy the user that the linear axis is nominally at rest.

8-2.7.4 System Condition. Before data acquisition, the positioning system shall be run through a warm-up exercise sequence of at least five back-and-forth movements between the first and last target points. The programmed accelerations, velocity, and position dwells used should be the same as for the dynamic angular measurement. Alternative warm-up sequences and techniques should be agreed upon between the user and the manufacturer/supplier of the positioning system.

8-2.7.5 Measurement Procedure. The measurement procedure is as follows:

Step 1. Align the measuring equipment with the axis under test.

Step 2. Exercise the linear positioning system following the recommendation in para. 8-2.7.4.

Step 3. The linear axis must be commanded to execute a simple motion. The travel distance used for both speeds should be the same, unless otherwise agreed upon by the user and the manufacturer/supplier.

Step 4. The test should be carried out in both positive and negative directions. For each direction, all measurements shall be recorded synchronously with each other, as much as possible; that is, if possible, the measurements shall be timestamped in a synchronized fashion to the same reference clock. Otherwise, the non-synchronous data shall be collected and then synchronized afterwards.

Step 5. The tests must be repeated a minimum of five times, unless otherwise agreed upon between the user and the manufacturer/supplier. For some applications, unidirectional measurements are sufficient. The sets of bidirectional data shall consist of time, axis position, and the corresponding angle readings for angular errors.

8-2.8 Dynamic Angle Data Analysis

8-2.8.1 Error Motions. Post-process filtering may be performed on the raw data, upon agreement between the user and the manufacturer/supplier, and if so, the filter used should be reported (see para. 8-2.9). Then, the dynamic angular error motions shall be determined as for the static angular error motions (see para. 8-2.5.1), except that the data used shall be either that for the full travel or that collected within the constant-velocity phase (see subsection 7-6), as agreed upon between the user and the manufacturer/supplier. Without an agreement, only the data collected within the constant-velocity phase shall be used; that is, data collected during axis acceleration or deceleration shall not be used for determination of the dynamic angular error motions in that case.

8-2.8.2 System Angular Error Values. For the test data at the agreed-upon axis positions, the dynamic angular error values shall be determined as in para. 8-2.5.2 for the static angular error values.

8-2.8.3 Test Uncertainty Analysis. Uncertainties associated with the measurement of dynamic angular error are related to uncertainties of the used measurement systems among other factors, with at least the same uncertainty contributors as those for the static angular error (see para. 8-2.6). Additional measurement uncertainty contributors for the dynamic angular error include

(a) uncertainty due to temporal synchronization of position and error motion data, u_{SYNC}

(b) uncertainty due to fixturing vibrations of the measurement points, u_{VIB}

8-2.9 Presentation of Dynamic Results

The average and expanded uncertainty of the angular error values shall be reported with a plot of dynamic angular error motions and a velocity profile plot that identifies the acceleration/deceleration phases and the constant-velocity phase. The dynamic straightness plot should contain the five measurement runs. Also, when filtered data is used for analysis, the filter parameters shall be provided. Figure 8-2.9-1 shows an example of a dynamic angular error test report.

Figure 8-2.9-1
Example of a Dynamic Angular Error Report

Dynamic Angular Error Test Report

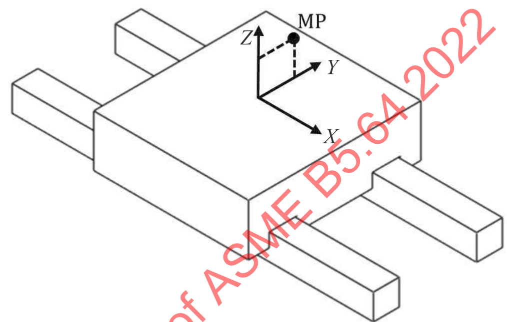
Positioning System

Manufacturer: ABC	Model No.: XX	Serial No.: XX
Type: Linear	Max. travel: 350 mm	Max. velocity: 500 mm/s

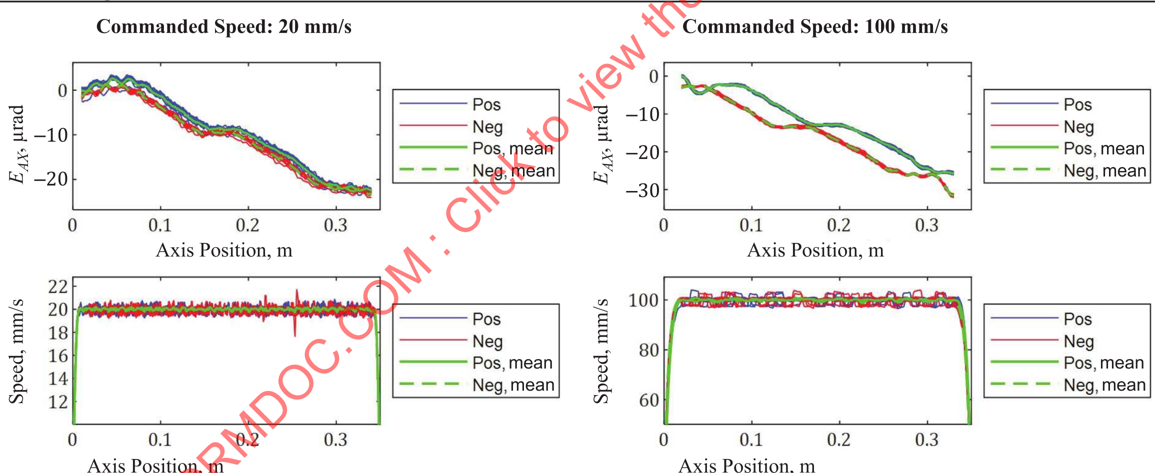
Controller/drive unit to power the positioning system: ABC P100 S/N 1234

Measurement Setup

Functional point: X = XX mm, Y = XX mm, and Z = XX mm
Load: XX kg
System location: 300 mm × 1.2 m × 1.2 m granite base
Temperature during test: 22°C
Axis travel: 350 mm
Commanded speed(s): 20 mm/s and 100 mm/s
Number of forward/reverse motions: 10/10
Direction of measurement/motion: X-axis/X-axis
Measurement point (MP): (X, Y, Z) = (0 mm, 30 mm, 25 mm)
Data acquisition system: Acme D100 S/N 5678
Displacement sensor: Acme S100 S/N 91011
Sampling rate: 1 kHz
Data filter: None



Dynamic Angular Error Plots



Dynamic Angular Error Test Results

Constant Speed: 20 mm/s	Constant Speed: 100 mm/s
Axis positions: 0.01 m to 0.34 m	Axis positions: 0.02 m to 0.33 m
$E_{AX,E\uparrow}$ = 25.5 μrad ± 0.94 μrad (k = 2)	$E_{AX,E\uparrow}$ = 25.8 μrad ± 0.45 μrad (k = 2)
$E_{AX,E\downarrow}$ = 24.8 μrad ± 0.61 μrad (k = 2)	$E_{AX,E\downarrow}$ = 29.0 μrad ± 0.79 μrad (k = 2)
$E_{AX,E}$ = 26.2 μrad ± 0.27 μrad (k = 2)	$E_{AX,E}$ = 31.6 μrad ± 0.85 μrad (k = 2)

Section 9
Point Repeatability Test

9-1 GENERAL

Section 9 describes the point repeatability test to determine the point repeatabilities of the position of a functional point. The point repeatability is characterized by repeatedly moving a functional point on a single-axis linear positioning system to a defined target position where the three-dimensional variation of the functional point's position is recorded by an adequate sensor setup. The resulting dataset is used to quantify the point repeatability of the functional point in all three orthogonal directions.

9-2 MEASUREMENT SETUP

9-2.1 General Measurement Setup

The following application-specific system-level components or characteristics may affect the point repeatability and thus should be defined and documented:

(a) control system/drive electronics
(b) control system tuning algorithms
(c) base mounting surface or reference frame
(d) payload
(e) motion profile (commanded velocity, acceleration, and jerk)
(f) environmental conditions
(g) sensor model, serial number, and uncertainty

For the default case, the settings should be chosen such that their influences on the point repeatability are insignificant, and consequently, the point repeatability represents the performance of stage mechanics. For example, the payload should be minimized except for the required mass of fixtures, and the motion profile should avoid mechanical or thermal instability in the results.

9-2.2 Equipment

(a) The suggested equipment required for the point repeatability test are as follows:
(1) positioning system and drive electronics
(2) linear displacement sensor(s)
(3) displacement sensor fixture(s)
(4) artifact or fixture representing a functional point
(5) data acquisition system
(6) post-processing software
(7) environmental sensors

(b) Each linear displacement sensor is not restricted to one form or type of measuring device and may include, but is not limited to, the following:
(1) laser interferometer
(2) capacitive gauge
(3) linear variable differential transformer (LVDT) sensor
(4) confocal white light sensor
(5) a dial indicator with a straightedge

(c) Each linear displacement sensor selected must have an acceptable test uncertainty ratio (TUR) for the actual measured performance.

9-2.3 Functional Point(s), Target position(s), and Sensor Location

The quantity and location of functional points are defined in the coordinate system fixed to the moving element of the positioning system. The quantity and location of target positions are defined as positions along the axis of travel of the positioning system under test. The sensor setup of linear displacement sensors is fixtured such that the functional point will be in each sensor's measurement range when the axis is positioned at a specific target position.

The point repeatability test is valid for both fixed- and moving-sensor configurations. For a fixed-sensor configuration, the artifact is mounted to the moving element and the sensor nest is stationary. For a moving-sensor configuration, the sensor nest is mounted to the moving element of the positioning system, representing the functional point, and the sensor nest is translated to the defined target position where a stationary artifact is measured. The chosen configuration shall be agreed upon between the user and the manufacturer/supplier of the linear axis positioning system.

In the case where there are more than one functional point or target position, the artifact and/or sensor nest are to be moved to new fixture positions to capture the multiple datasets that will characterize all combinations of functional points at all target positions. The option to define single or multiple functional points and target positions results in four possible test cases listed below and shown in Figure 9-2.3-1:

(a) *Case A.* A single moving functional point is tested at a single target position.
(b) *Case B.* Multiple moving functional points are tested at a single target position.
(c) *Case C.* A single moving functional point is tested at multiple target positions.
(d) *Case D.* Multiple moving functional points are tested at multiple target positions.

The functional points and target positions should be defined to represent the application or process in which the positioning system is intended to be used. The functional points and target positions shall be agreed upon between the user and the manufacturer/supplier of the linear axis positioning system. For the case where there is no defined application or no information from an end user, the default test case is Case C where a single moving functional point is tested at multiple target positions. The default quantity of target positions is five and are at locations along the axis of travel of 5%, 25%, 50%, 75%, and 95% of the nominal travel, measured from the negative end of travel.

An important aspect of the point repeatability test is that it only characterizes the performances for the specific functional points and target positions tested. The performances for untested functional points and target positions cannot be inferred from any preexisting dataset of other defined functional points and target positions.

9-2.4 Setup Configuration

Each test setup is composed of the functional points, target positions, positioning system, and the equipment required to record data for the defined points. For a linear positioning stage, this test methodology characterizes the three-dimensional (*X*, *Y*, and *Z*) repeatability of the position of a functional point attached to the moving element of a motion system.

Figure 9-2.4-1 shows a linear positioning system with a moving carriage and a ball artifact acting as the functional point. A three-sensor nest of capacitive gauges is set up to measure the three-dimensional (*X*, *Y*, and *Z*) variations of the position of the artifact. The moving element of the positioning system will be commanded through a defined motion cycle. When the artifact is commanded to the target position, the data acquisition system will record the sensed position of the artifact. The test artifact and displacement sensors represented in Figure 9-2.4-1 are for visual purposes only; actual equipment used may differ.

The point repeatability test is by default a three-dimensional test. However, some applications may only require measurement of performance in one or two dimensions. For these applications, it is acceptable to test only the critical dimensions and present the related performance data. An example of the directional importance is an application where the repeatability performance in a plane (composed of the *X*-axis and *Y*-axis) is critical, but the *Z*-axis component is not critical and thus may be neglected from the test.

For such cases, nests with one or two displacement sensors (as opposed to a three-sensor nest) may be used to collect position data for one or two of the repeatability components individually. Figure 9-2.4-2 shows a test setup with a single sensor used to collect axial position data of a linear positioning system. Figure 9-2.4-3 shows a test setup with a two-sensor nest used to collect the repeatability components perpendicular to the axis of travel, the horizontal and vertical straightness repeatabilities, or the *Y*- and *Z*-axis repeatabilities, respectively. The setup in Figure 9-2.4-3, which uses a straightedge, has the benefit of being able to characterize multiple functional points (along the straightedge) with one test setup.

Figures 9-2.4-1 through 9-2.4-3 show measurement setups with a displacement sensor such as a capacitive gauge. While not shown, similar setups using other available displacement sensor technologies are permitted, given that the sensors can clearly characterize the *X*-, *Y*-, and *Z*-axis repeatability components of the measurement point.

Figure 9-2.3-1
The Four Possible Test Cases of the Point Repeatability Test Given the Options for Single or Multiple Functional Points and Target Positions

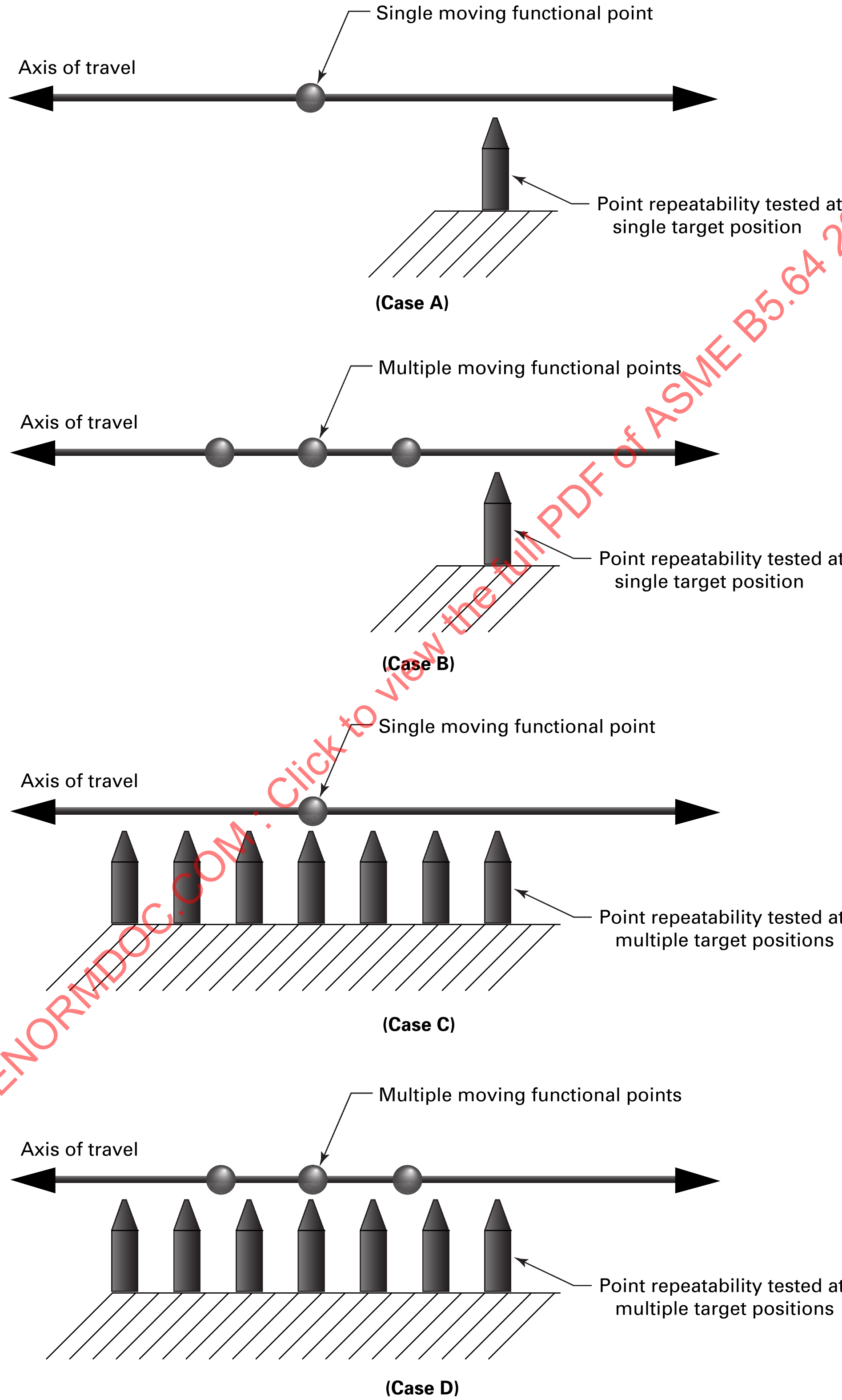
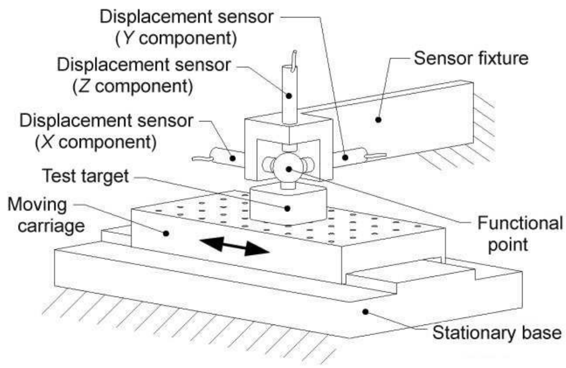
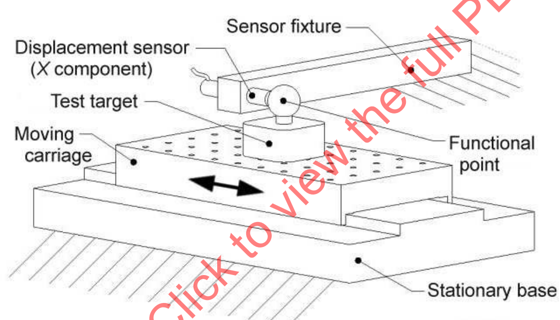


Figure 9-2.4-1
Setup Configuration — Three-Sensor Nest



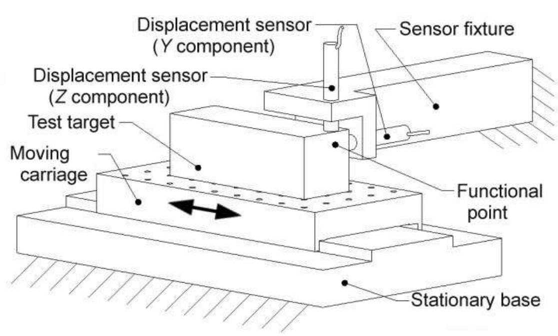
GENERAL NOTE: A three-sensor nest is used to collect the *X*, *Y*, and *Z* components in a single point repeatability test of a linear positioning system. This is also an example for a fixed sensor configuration.

Figure 9-2.4-2
Setup Configuration — Single Sensor



GENERAL NOTE: A single sensor is used to collect the axial component (or *X* component) of the point repeatability test of a linear positioning system.

Figure 9-2.4-3
Setup Configuration —Two-Sensor Nest



GENERAL NOTE: A two-sensor nest is used to collect the two straightness components (the *Y* and *Z* components) of the point repeatability test of a linear positioning system.

Furthermore, if the user does not have access to multiple sensors, it is permitted that a single sensor be used to collect the *X*-, *Y*-, and *Z*-axis component data through repeated tests performed sequentially, each with a different sensor orientation. The artifact remains fixed between tests with different sensor orientations. For example, in such a case, the *X*-axis data is collected, then the sensor is reoriented, the *Y*-axis data is collected, then the sensor is reoriented, and finally, the *Z*-axis data is collected. The data from this sequential data collection method can be presented as a single result, as if it was collected simultaneously.

9-2.5 Measurement Approach Direction(s)

The point repeatability test is by default a multidirectional test; it characterizes point repeatability for all possible approach directions to a target position. This multi-directional test aims to be a quick test that quantifies the simultaneous contributions of all repeatability errors (i.e., all repeatability and reversal errors) of a specific functional point, without quantifying the individual error components. This test differs from bidirectional repeatability tests that quantify unidirectional repeatability and reversal errors separately [ASME B5.54-2005 (R2020), ISO 230-2:2014].

For single-axis linear positioning systems, the approach direction to the target position should alternate between the positive approach and negative approach for the duration of the test.

For customer-specific applications such as pick-and-place applications, where only one direction of approach to a target position is performed, the point repeatability test may be conducted as a unidirectional test. Any data presented from a unidirectional test should be labelled as unidirectional point repeatability data.

9-2.6 Minimum Displacement

The motion of the moving element of the positioning system away from the target position between data collection cycles will impact the point repeatability data. The minimum displacement away from the target position should be defined to ensure that cyclic or random mechanical errors vary between successive measurements. Regardless of axis mechanics, the displacement away from the target position shall be a minimum of 20% of the nominal travel of the axis under test. This requirement applies for all measurement points, except target positions located within 20% (of the total travel) from either end of travel. For the default test locations at 5% or 95% of the total travel, the minimum displacement for the move toward the end of travel should be equal to the available travel in that direction. Alternatively, for applications where motion system repeatability is critical for small moves less than 20% of the total travel, the minimum displacement performed during the point repeatability test can be adjusted to match the actual application use, as agreed upon by the user and the manufacturer/supplier. In this case, the actual minimum displacement performed must be documented with the test results.

9-2.7 Axial Sensor — Special Cases

Certain sensor types, such as capacitive gauges, must be positioned axially in line with the artifact to measure the axial position variation for the point repeatability test. Axially located sensors with small measurement ranges will be an obstruction limiting travel of the moving element near the sensor and will prohibit conformance to the minimum displacement requirement above. When using sensors with these characteristics, either the test may be modified to a unidirectional test (and labelled as such) or the test can be performed as a multidirectional test with the following modification.

A multidirectional test may still be performed by adding an additional axis of travel that moves either the sensor nest or the artifact temporarily away from the primary motion axis between data collection cycles at the target position. With the potential for interference eliminated through this additional motion, the minimum displacement can be performed in the direction into the sensor. Once the minimum displacement of the axial move has been completed, the sensor nest or artifact that was moved off axis can be moved back into the target position to continue data collection.

This additional axis motion will induce additional errors not attributed to the primary axis under test. Thus, it will typically increase the magnitude of the point repeatability. Regardless, the results should be presented as measured without modification. The tester does have the option to perform a secondary point repeatability test by moving only the secondary axis, not the primary axis under test, to quantify the secondary axis point repeatability. While this secondary axis result can be included as additional information with the primary axis data, no calculations to separate the contributors of repeatability shall be used to modify the actual multidirectional test results.

Two examples illustrate this special case of a multidirectional test. In the first example, assume that an artifact is mounted to the moving element of the positioning system and a capacitive gauge sensor nest is stationary. Now assume that the positioning system under test is an *XY* stage but the axis under test is only the *X*-axis. The user may use the *Y*-axis to make a slight *Y*-axis motion such that the artifact would be free of interference with the stationary sensor nest. Then the *X*-axis could move in the direction toward (or into) the sensor nest without the artifact contacting the sensors. Once this move is complete and the X-axis is returned to the target position, the Y-axis is returned to the target position to collect the positional data. In the second example, assume that an artifact is mounted to the moving element of the positioning system and a capacitive gauge sensor nest is mounted to an axis perpendicular to the axis under test. The test process is similar to the first example, but the decoupled axis would move the sensor nest (not the artifact) out of the way of the minimum displacement move in the direction toward (or into) the sensor nest. Both examples meet the minimum displacement requirement for the primary axis under test and the secondary axis inherently affects the point repeatability.

9-3 MEASUREMENT PROCEDURE

9-3.1 General Measurement Procedure

At the ith test configuration (combination of functional point and target position) and jth measurement cycle, each qth measurement may be recorded for each orthogonal direction; that is,

$$dx_{i,j,q} = \text{discrete sensor measurement in } X \text{ direction} \tag{9-3-1}$$

$$dy_{i,j,q} = \text{discrete sensor measurement in } Y \text{ direction} \tag{9-3-2}$$

$$dz_{i,j,q} = \text{discrete sensor measurement in } Z \text{ direction} \tag{9-3-4}$$

where

i = test configuration number for the discrete combination of functional point and target position
j = cycle number at ith test configuration
q = measurement number at ith test configuration and jth cycle

Once the jth measurement cycle is complete, the (j+1)th measurement cycle may be performed. The total number of measurement cycles, n, conducted for each ith test configuration shall be 20, unless otherwise agreed upon between the user and the manufacturer/supplier of the linear axis positioning system. After the n cycles at the ith test configuration are complete, the test setup may be moved to the (i+1)th test configuration. The test equipment, artifact, and setup may not be moved or altered in any way between the first (j = 1) and the last (j = n) measurement cycles, to ensure that reversal errors influence the point repeatability. Test setups may only be changed between the ith and (i+1)th test configurations.

9-3.2 Number of Data Points and Sampling Rate

The number of data points, r, collected for any approach direction at the ith test configuration and jth measurement cycle should be a minimum of 100, for statistical purposes, unless otherwise agreed upon between the user and the manufacturer/supplier, e.g., whenever values from a dial indicator are manually recorded. The measurement number, q, is ranging from 1 to r. The sampling rate should be sufficient to collect the data in the desired time window. For example, for a measurement time of 2.0 s, a sampling rate of at least 50 Hz is required to collect 100 data points.

9-3.3 Data Collection Timing

Two timing parameters must be controlled during collection of the r data points at the ith test configuration and jth measurement cycle: the dwell time and the data collection time. First, the dwell time is the time between the end of a move to the sensor and the beginning of data collection, and related to that, the move-and-dwell time is the time between the start of a move to the sensor and the beginning of data collection. Because the position of the motion system should be settled and stable prior to data collection, the move-and-dwell time must be greater than or equal to the move- and-settle time (see subsection 7-3). Second, the data collection time is the total time for which data is collected at the ith test configuration and jth measurement cycle. The data collection time must be long enough to ensure that in-position jitter does not adversely or beneficially affect the test result. For instance, valid point repeatability results will be greater in magnitude than the system in-position jitter (see subsection 7-2).

A dwell time of 3.0 s and a data collection time of 2.0 s are defined as default timing parameters. While it is expected that these values will be acceptable for many motion systems, other values for the timing parameters may be agreed upon between the user and the manufacturer/supplier of the linear axis positioning system. Both timing parameters, the dwell time and the data collection time, must be reported with the presentation of results.

9-4 DATA ANALYSIS

The data analysis involves using the measured displacements to calculate the point repeatabilities for the various test configurations. For each test configuration, a point repeatability shall be calculated and reported for each available measurement direction (*X*, *Y*, or *Z*).

First, the total number, *r*, of discrete measurements at the *i*th test configuration and *j*th cycle are averaged to yield the average values; that is,

$$dx_{i,j} = \frac{1}{r} \sum_{q=1}^{r} dx_{i,j,q} \tag{9-4-1}$$

$$dy_{i,j} = \frac{1}{r} \sum_{q=1}^{r} dy_{i,j,q} \tag{9-4-2}$$

$$dz_{i,j} = \frac{1}{r} \sum_{q=1}^{r} dz_{i,j,q} \tag{9-4-3}$$

For the multidirectional test, the approach direction alternates between the positive and negative approach directions for consecutive measurement cycles. For the special case of the unidirectional test, the approach direction will be the same for all measurement cycles.

The mean value at the *i*th test configuration for the *n* cycles is defined as

$$\bar{d}x_i = \frac{1}{n} \sum_{j=1}^{n} dx_{i,j} \tag{9-4-4a}$$

$$\bar{d}y_i = \frac{1}{n} \sum_{j=1}^{n} dy_{i,j} \tag{9-4-5}$$

$$\bar{d}z_i = \frac{1}{n} \sum_{j=1}^{n} dz_{i,j} \tag{9-4-6}$$

Next, the deviation of each average data point from the mean is defined as

$$E'x_{i,j} = dx_{i,j} - \bar{d}x_i \tag{9-4-7}$$

$$E'y_{i,j} = dy_{i,j} - \bar{d}y_i \tag{9-4-8}$$

$$E'z_{i,j} = dz_{i,j} - \bar{d}z_i \tag{9-4-9}$$

It follows that, for the relative position deviations defined in eqs. (9-4-7) through (9-4-9), the mean values are zero. Therefore, the standard deviations of the *X*-, *Y*-, and *Z*-direction relative position deviations from eqs. (9-4-7) through (9-4-9) are defined as

$$sx_i = \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} \left(E'x_{i,j}\right)^2} \tag{9-4-10}$$

$$sy_i = \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} \left(E'y_{i,j}\right)^2} \tag{9-4-11}$$

$$sz_i = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(E'z_{i,j}\right)^2} \tag{9-4-12}$$

since the means of the relative position deviations equal zero.

Finally, the repeatability of the *X*-axis, *Y*-axis, and *Z*-axis components for the *i*th test configuration are derived from the expanded uncertainty of the position deviations with a coverage factor of $k = 2$:

$$PRx_i = 4sx_i \tag{9-4-13}$$

$$PRy_i = 4sy_i \tag{9-4-14}$$

$$PRz_i = 4sz_i \tag{9-4-15}$$

When a motion system is analyzed, the point repeatability of the system is presented as the maximum of the individual point repeatability of all test configurations; that is,

$$PRx = \max(PRx_i) \tag{9-4-16}$$

$$PRy = \max(PRy_i) \tag{9-4-17}$$

$$PRz = \max(PRz_i) \tag{9-4-18}$$

As stated above, the point repeatability test is a multidirectional test and eqs. (9-4-16) through (9-4-18) represent the multidirectional point repeatability performance. For the special case of the unidirectional test, where the approach direction is always the same for all measurement cycles, eqs. (9-4-16) through (9-4-18) should be replaced with eqs. (9-4-19) through (9-4-21) in the presentation of unidirectional data:

$$uPRx = \max(PRx_i) \tag{9-4-19}$$

$$uPRy = \max(PRy_i) \tag{9-4-20}$$

$$uPRz = \max(PRz_i) \tag{9-4-21}$$

9-5 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 nonconformance to specifications can be demonstrated. Potential measurement uncertainty contributors include

(a) uncertainties of geometric error motions of the linear axis

(b) measurement uncertainty of the test equipment

(c) 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

(d) uncertainty in the sensor calibration factor, u_{CAL}

(e) uncertainty due to the sensor resolution/noise, u_{SR} — evaluated via a sensor noise floor test

(f) uncertainty due to setup repeatability, u_{Δ}— relatively small due to motion being very small

(g) uncertainty due to fixturing vibrations, u_{VIB}

9-6 PRESENTATION OF RESULTS

Figure 9-6-1 shows an example point repeatability test report for testing of a single functional point at multiple target positions for a linear positioning system with a travel of 750 mm. The presented data represents a customer-specific application where eight equidistant data points were tested within the useable travel. The point repeatabilities, *PRx*, *PRy*, and *PRz*, are the only quantitative results that are required to be presented. However, additional tabular data for all target positions is also included in the test report. Also, in this example, a secondary axis was used to move the sensor nest away from the primary axis to enable multidirectional testing. The secondary axis (or moving sensor) point repeatability is also presented as reference information.

For the special case where only one or two repeatability components are measured, the available data should be presented. For example, if only the repeatability performance in a plane (composed of the *X*-axis and *Y*-axis) is critical, then only *PRx* and *PRy* will be included in the presentation of results.

Figure 9-6-1
Example of a Point Repeatability Test Report for a Linear Positioning System

Point Repeatability Test Report for a Single Functional Point

Positioning System

Manufacturer: ABC	Model No. XX	Serial No.: XX
Type: Linear	Max travel: 750mm	
Controller: DEF	Drive: GHI	

Test Setup

Sensor(s): Capacitive gauge	Measurement directions: *X*, *Y*, *Z*
Number of cycles per test: 20	Payload: 0.4 kg
Test type: Multidirectional	Minimum displacement move: 150 mm
Secondary axis used: Yes	Secondary axis mount: Moving sensor

Data Collection

Sampling rate: 1 000 Hz	Data collection time: 2.0 s
Dwell time: 3.0 s	

Point Repeatability

Test Case: Case C (single-moving functional point tested at multiple target positions.) Functional Point (*x*, *y*, *z*): (0 mm, 0 mm, 50 mm) [Defined from center of moving element.]

Target Positions: −350 mm, −250 mm, −150 mm, -50 mm, +50 mm, +150 mm, +250 mm, +350 mm

	PRx	PRy	PRz
Point Repeatability	35.8 nm	26.2 nm	17.1 nm

Tabular Data for All Target Positions (Optional Data)

Test Number	Target Position, mm	PRx_i, nm	PRy_i, nm	PRz_i, nm
$i = 1$	−350	25.7	19.1	7.0
$i = 2$	−250	25.7	11.3	5.1
$i = 3$	−150	32.1	13.9	5.0
$i = 4$	−50	29.0	26.2	9.5
$i = 5$	+50	26.4	18.7	17.1
$i = 6$	+150	30.0	4.6	12.8
$i = 7$	+250	35.8	13.4	13.6
$i = 8$	+350	24.6	12.6	3.6

Secondary Axis Point Repeatability (Optional Data)

An additional axis was used to move the sensor nest to enable multidirectional testng into the sensor direction. The data provided is for reference only.

	PRx, nm	PRy, nm	PRz, nm
Auxiliary Axis Point Repeatability	12.1	14.3	5.7

Section 10
Servo Characterization

10-1 GENERAL

Servo characterization as used in this Standard refers to the use of frequency response techniques to quantify performance and stability metrics for closed-loop feedback control systems. Closed-loop control systems rely on a measurement from a sensor to adjust the command to an actuator. They are distinct from open-loop control systems in which an actuator is given a command, but there is no further modification to the command based on measurement. The term bandwidth is often used to indicate the highest frequency that a servo system can respond to within certain error limits (e.g., a 3 dB reduction in the amplitude of the actual axis position over the commanded one). However, this definition is not particularly well quantified or meaningful on its own. A servomechanism generally has several different dynamic responses, depending on where the inputs are applied and where the outputs are measured. In addition, feedforward techniques can (and should) be used to improve the dynamic response to known inputs such as a reference trajectory. Feedforward techniques are largely open-loop methods that generate a command to the actuator that, based on a system model, should generate the desired motion of the axis. Frequency response methods are used because they require no detailed underlying knowledge of a system model, they are well suited to experimental implementation, and — although they are primarily linear techniques — they can be used to provide information about nonlinear behavior in a system. In this Standard, several frequency response measurements used in characterizing servomechanisms are defined in addition to metrics for performance and stability robustness, which is a measure for the stability on the system with respect to uncertainty in its dynamic response.

10-2 TECHNICAL BACKGROUND

10-2.1 Signals and Systems

A "signal" in the context of this Standard is a mathematical encoding of information about the behavior or nature of some phenomenon. Signals are transformed into other signals through the action of a "system." That is, systems operate on and transform signals. These definitions are very broad, yet a more rigorous treatment may be found in Oppenheim et al., 1983. In a typical motion control application, the reference trajectory is a signal, transformed into the actual movement of the axis through the action of the closed-loop servomechanism (the system). These systems and signals can be continuous or discrete, or most likely a combination of both. This Standard will make the distinction only when important, otherwise it can be assumed that analogous techniques exist for both.

10-2.2 Linearity and Time Invariance

Commonly used dynamic system models possess the properties of linearity and time invariance. A linear system exhibits superposition. That is, if an input signal is the weighted sum of several other signals, then the output signal will likewise be the weighted sum of their individual responses. This allows us to predict the response to an arbitrarily complex signal by deconstructing the signal into simpler forms and summing the response of the system to each of them. Time-invariant systems possess the property that a time shift to the input signal leads to a corresponding shift to the output signal, with no other change to the signal itself. Neither of these properties holds strictly true for high-performance motion systems. However, the tools that these assumptions enable are so useful that they are applied even with knowledge of their limitations.

10-2.3 Frequency Response

The frequency response of a system describes its steady-state response to a sinusoidal input. For a linear system, this response is another sinusoid of the same frequency, but shifted in magnitude and phase. If the input signal, $u(t)$, is

$$u(t) = \sin(2\pi ft) \tag{10-2-1}$$

then the output of the system, $y(t)$, will be

$$y(t) = A\sin(2\pi ft + \phi) \tag{10-2-2}$$

The magnitude multiplier A and phase shift ϕ in eq. (10-2-2) are both functions of the frequency, f. Thus, frequency response plots (which are also sometimes referred to as Bode plots in the literature) consists of two traces, the magnitude and the phase shift both versus frequency. A frequency response plot is complete only if it displays both magnitude and phase characteristics.

Figure 10-2.3-1 shows a lumped-parameter model of a spring-mass-damper system, and Figure 10-2.3-2 shows its frequency response plot with force as the input and position as the output. This model is commonly used to describe the performance of a positioning system as it captures the dominant dynamics of system after closed-loop control has been applied. The variable m represents the mass, k represents a spring stiffness, b represents viscous damping, u is the applied force, and y represents the position of the mass. There are a few important features to note. The magnitude plot clearly shows the units of the response, meters per Newton in this case. It is also very common to express the magnitude in terms of decibels (dB). When decibels are used, however, the plot should still indicate the underlying units of the gain. The horizontal frequency axis is conventionally plotted on a logarithmic scale for both magnitude and phase plots, while the vertical axis scaling depends on the measurand. Magnitude is plotted on a logarithmic scale unless presented in decibels, in which case a linear axis is used, and phase is plotted on a linear axis. Note again that a complete frequency response plot always includes both the magnitude and phase characteristics.

Figure 10-2.3-1
Lumped-Parameter Model of a Mass-Spring-Damper System Driven by a Force

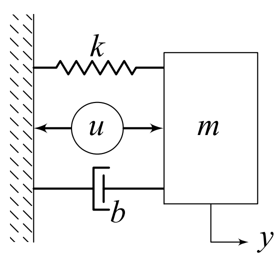
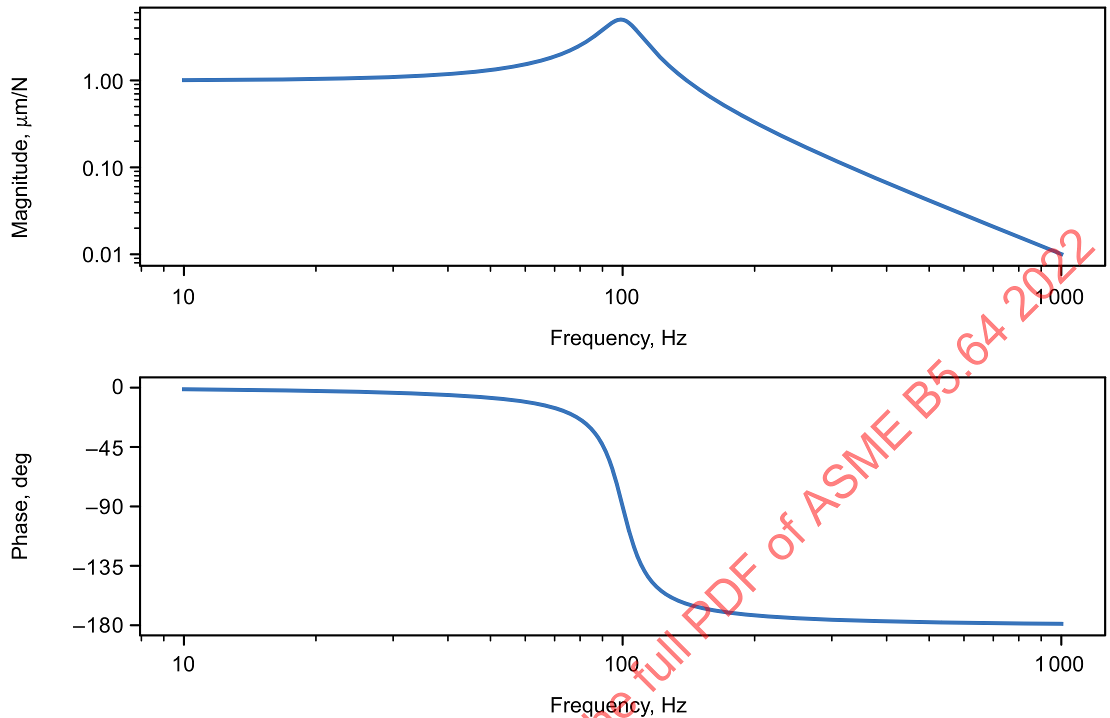


Figure 10-2.3-2
Frequency Response Plot for an Underdamped Mass-Spring-Damper System



GENERAL NOTE: A frequency response plot shows the frequency-dependent displacement of an underdamped mass-spring-damper system when driven by a sinusoidally varying force at a range of different frequencies.

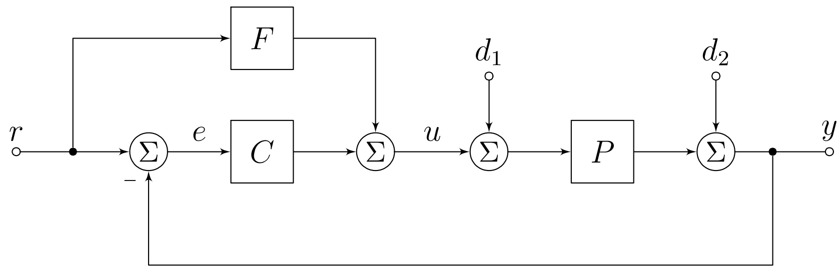
10-2.4 Inputs and Outputs

Dynamic systems are often described by the number of inputs and outputs they contain. A linear motion stage with one motor and one position sensor is described as a single-input, single-output (SISO) system. An active vibration isolation system controlling a payload in six degrees of freedom may have six (or more) actuators and a dozen or more sensors. This is properly described as a multiple-input, multiple-output (MIMO) system. In many cases, a coupled multivariable system like this can be mathematically reduced through appropriate coordinate transformations to appear as a series of SISO systems. This is quite often the case in practice and allows familiar SISO techniques to be applied just as readily to complex systems as to simple ones. The techniques described in this Standard apply most directly to SISO feedback systems, or to those MIMO systems that can be transformed into SISO equivalents.

10-2.5 Categorizing Frequency Responses

10-2.5.1 A Basic Control Scheme. Figure 10-2.5.1-1 shows a block diagram of the basic control scheme used by many single-axis positioning systems. Many single-axis servomechanisms can be adequately represented by three interconnected systems, as shown in Figure 10-2.5.1-1. The plant P is generally understood to be the moving elements and actuators, the feedback controller C is the algorithm that modifies the control effort in response to measurements of the system state, and the feedforward controller F is the algorithm that modifies the control effort solely in response to known changes in the reference profile. The block diagram of the setup shown in Figure 10-2.5.1-1 is often called a two-degree-of-freedom controller, since the servo system designer has the ability to modify two different algorithms (C and F) to meet the overall performance requirements. From this basic block diagram, several useful systems that transform input signals to output signals are defined. For simplicity, the transfer functions of the plant, feedforward controller, and feedback controller will be denoted henceforth by their italicized symbols P, F, and C, respectively. The blocks F and C are generally algorithms contained within the motion control software, while P captures the dynamics of the power amplifier and stage system. In a typical closed-loop positioning system, the disturbance d_1 would represent a so-called process disturbance — such as a cutting force in a machining application — while the output disturbance d_2 would capture the influence of noise or inaccuracy on the position sensor as well as the effect of floor vibrations. The variable r is the commanded position (the reference) and y is the measured position.

Figure 10-2.5.1-1
Basic Control Scheme Used by Many Single-Axis Positioning Systems



GENERAL NOTE: The basic two-degree-of-freedom control scheme used by many single-axis positioning systems includes a plant, *P*; a feedforward controller, *F*; and a feedback controller, *C*.

10-2.5.2 Loop Transmission. The loop transmission, *L*, is the combined response of all systems in a path around the feedback loop. This function captures the response of each system, physical or algorithmic, in the chain from an actuator command through the plant response, the state measurement, feedback control algorithm, and finally back to a new actuator command. The loop transmission in our basic control scheme example can be expressed as

$$L = -CP \tag{10-2-3}$$

where *C* and *P* denote the transfer functions of the feedback controller and plant, respectively. This is the frequency response used to quantify stability metrics (see subsection 10-4) as used in determining the amount of variation that can occur in the loop before instability occurs. For example, over what range of payloads will the system be stable. The loop transmission is closely related to the open-loop transfer function but differs in the important point that measuring the frequency response while the system is under closed-loop control also captures any time delays in the complete feedback loop.

10-2.5.3 Output Sensitivity. The output sensitivity shows the closed-loop servomechanism response to a disturbance, d_2, added at the output of the plant, as shown in Figure 10-2.5.1-1. This is often classified as a measurement disturbance. These disturbances cannot be known in advance (as the reference position can be) and so the control algorithm can only respond after the disturbance occurs. The output sensitivity *S* is defined as the reciprocal of one minus the loop transmission:

$$S = \frac{1}{1 + CP} \tag{10-2-4}$$

and a plot of its magnitude versus frequency shows frequency bands where the servo system attenuates disturbances (generally at low frequencies) and regions where the servo system amplifies disturbances (generally at high frequencies, or regions of mechanical resonances). It is generally good practice to design the servo controller to limit the disturbance amplification to a factor of 2 (or equivalently, a peak magnitude of the sensitivity curve of about 6 dB).

10-2.5.4 Process Sensitivity. The process sensitivity, sometimes called the input sensitivity, shows the closed-loop servomechanism response to a disturbance, d_1, added at the input of the plant, as shown in Figure 10-2.5.1-1. Some examples of these disturbances include mechanical sources, such as cutting forces or bearing friction, and electronic noise in the power electronics that govern motor current. When possible, the disturbances should be modeled and corrected for via feedforward control. The process sensitivity characterizes the response to the remaining inputs that are not known in advance. The process sensitivity S_P is defined as

$$S_P = \frac{P}{1 + CP} \tag{10-2-5}$$

and in many instances has units that are equivalent to a mechanical compliance (or an inverse stiffness). It is often instructive to compare the process sensitivity with the open-loop plant response to determine the frequency bands in which the control algorithm effectively increased stiffness (usually at low frequencies) or decreased stiffness. Stiffness here is defined as the amount of disturbance force required to displace the tool or workpoint by a given amount. Higher stiffness generally results in reduced tracking errors.

10-2.5.5 Complementary Sensitivity. The complementary sensitivity, T, shows the output response to a reference input under only feedback control. Feedforward control is not active in this case. Defining complementary sensitivity as

$$T = \frac{CP}{1 + CP} \tag{10-2-6}$$

One can see that the output sensitivity and complementary sensitivity are related through $S + T = 1$. At every individual frequency, the sum of the output sensitivity and the complementary sensitivity must equal unity.

10-2.5.6 Closed-Loop Response. The closed-loop response shows the output response to a reference input including both feedback and feedforward control algorithms. The closed-loop response G is defined as

$$G = \frac{FP + CP}{1 + CP} \tag{10-2-7}$$

and with perfect (but practically unobtainable) model matching, one can set $F = P^{-1}$ and arrive at $G = 1$ for all frequencies, where F denotes the transfer function of the feedforward controller. In practice, it is usually more practical to design the feedforward filter to invert the plant response as closely as possible at low frequencies, and to attenuate the plant response at high frequencies where the uncertainty in the model is greater.

10-3 FREQUENCY RESPONSE MEASUREMENTS

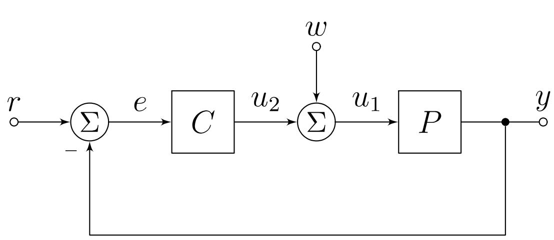
10-3.1 Equipment

Most users and suppliers will measure the frequency response of a system using commercially available tools. One such tool could be a standalone dynamic signal analyzer, but increasingly, software-only tools provided by manufacturers of the motion controllers are used. A software-only tool may be a necessity as an overwhelmingly digital network may not have available analog inputs to allow a standalone external device to be used. The particular dynamic signal analyzer, whether standalone or not, used to measure the frequency response should be mutually agreed upon between the user and the manufacturer/supplier. Frequency response measurements are part of a rich field of study called "system identification," and the interested reader is referred to Pintelton and Schoukens, 2001 and Ljung, 1999 for greater detail.

10-3.2 Loop Transmission Measurement Procedure

The preferred technique for characterizing the servo performance in a motion system is through a loop transmission measurement. Figure 10-3.2-1 shows the point in the loop where the known, commanded disturbance, w, is injected, and the corresponding outputs u_1 and u_2 that are used to measure the loop transmission. The variable r is the reference command, y is the measurement of the controlled variable, and e is the error, or difference between them. Exact operating procedures are necessarily dependent on the specifics of the dynamic signal analyzer used to perform the measurement, but Table 10-3.2-1 lists the set of test parameters that should be specified.

Figure 10-3.2-1
Disturbance Signal, *w*, Injected Into a System Following the Control Algorithm but Before the Power Amplifier Stage



GENERAL NOTE: In many motion control systems, a disturbance will effectively appear as either a disturbance in current, force, or torque.