ASME B5.57-2012
[Revision of ASME B5.57-1998 (R2006)]

Methods for Performance Evaluation of Computer Numerically Controlled Lathes and Turning Centers

AN AMERICAN NATIONAL STANDARD

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Two Park Avenue • New York, NY • 10016 USA

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The American Society of Mechanical Engineers
Two Park Avenue, New York, NY 10016-5990

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FOREWORD

The primary purpose of this Standard is to provide procedures for the performance evaluation of computer numerically controlled (CNC) lathes and turning centers. These procedures are used to evaluate conformance to specifications, to compare machines, to periodically reverify the suitability of production machines, and to reverify performance of machines after repair or modification. Definitions, environmental requirements, and test methods are specified. This Standard defines the test methods capable of yielding adequate results for most turning centers but is not intended to supplement more complete tests that may be required for particular special applications. This Standard does not address issues of machine safety.

Suggestions for improvement of this Standard are welcome. They should be sent to The American Society of Mechanical Engineers; Attn: Secretary, B5 Standards Committee; Two Park Avenue; New York, NY 10016-5990.

This revision was approved as an American National Standard on November 30, 2012.

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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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Proposing Revisions. Revisions are made periodically to the Standard to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Standard. Approved revisions will be published periodically. The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Proposing a Case. Cases may be issued for the purpose of providing alternative rules when justified, to permit early implementation of an approved revision when the need is urgent, or to provide rules not covered by existing provisions. Cases are effective immediately upon ASME approval and shall be posted on the ASME Committee Web page.

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Attending Committee Meetings. The B5 Standards Committee regularly holds meetings, which are open to the public. Persons wishing to attend any meeting should contact the Secretary of the B5 Standards Committee.

METHODS FOR PERFORMANCE EVALUATION OF COMPUTER NUMERICALLY CONTROLLED LATHES AND TURNING CENTERS

1 SCOPE

This Standard establishes requirements and methods for specifying and testing the performance of CNC lathes and turning centers. In addition to clarifying the performance evaluation of lathes and turning centers, this Standard seeks to facilitate performance comparisons between machines by unifying terminology, general machine classification, and the treatment of environmental effects. The Standard defines testing methods capable of yielding adequate performance results for the majority of turning centers and is not intended to replace more complete tests. It is not the intent of this Standard to place limits on, or to enforce 100%-testing of, any individual machine tool in accordance with this Standard. This shall be the subject of contractual agreement between the Supplier and the User.

The actual specification for turning centers is divided into the following six logical areas:

(a) General Definitions. Definitions provided in this Standard are generally consistent with the usage in other referenced documents related to machine tools and metrology, although some are specific to their use in this Standard.

(b) Machine Environmental Specifications and Responses. Environmental specifications and responses include thermal, electrical, and vibration specifications and tests, as well as requirements on utility air and other externally supplied services.

(c) Machine Accuracy Performance as a Machine Tool. Machine accuracy performance as a machine tool includes positioning accuracy and repeatability for linear and rotary axes, angular error motion of linear axes, spindle axis of rotation analysis, machine thermal tests, critical alignments, and contouring performance using circular tests.

(d) Machine Cutting Performance and Short-Term Reliability. Machine cutting performance and short-term reliability includes tests of spindle idle run losses and maximum metal-removal capability. Additionally, the machine is run for approximately 24 h to determine short-term reliability.

(e) Additional Machine Performance. Additional performance sections are provided for axis of rotation alignment, tail stock alignment, subsystems repeatability, tool-setting performance, CNC performance, and machine performance as a measuring tool.

(f) Machining Test Parts. This Standard provides for the machining of test parts for a particular manufacturing application. These test parts shall be fully specified as part of the original purchasing agreement between the User and the Supplier. Such specification shall include, but not be limited to, material, tooling, machining sequence, and inspection procedure.

This Standard is rather comprehensive, and for smaller, less-expensive machines, a shorter series of tests for conformance to specification is given in Nonmandatory Appendix B.

1.1 Performance Forms (Sample)

A schematic of the machine with axis directions should be provided along with Forms 1 through 8.

1.2 Alternatives

Where specifications use definitions and procedures different than those in this Standard, the alternative items shall be identified and made part of the machine specification. Such procedures should follow the philosophy outlined in the previous paragraphs and be specified in equivalent detail.

This Standard allows parts of the environmental test section to be deferred or bypassed, and only the performance test to be carried out. This alternative is allowable only if it is acceptable to both the User and the Supplier and if deferred according to the procedures outlined in para. 6.1.

FORM 1 MACHINE DESCRIPTION

Linear Axes

Axis Name	Full Travel mm	Full Travel in.	Control Resolution mm	Control Resolution in.	Minimum Programming Increment mm	Minimum Programming Increment in.
X						
Y						
Z						

Axis Name	Maximum Programmable Feed Rate mm/min	Maximum Programmable Feed Rate in./min	Rapid Traverse Speed mm/min	Rapid Traverse Speed in./min	Acceleration/Deceleration mm/s^2	Acceleration/Deceleration $in./sec^2$
X						
Y						
Z						

Rotary Machining Axes

Axis Name	Full Travel, deg	Control Resolution, deg	Minimum Programming Increment, deg	Maximum Programmable Feed Rate, deg/min	Rapid Traverse Speed, deg/min	Acceleration/ Deceleration, deg/s^2	Time to Rotate, s 90°	Time to Rotate, s 180°
A								
B								
C								

Rotary Positioning Axes

Axis Name	Full Travel, deg	Minimum Index Increment, deg	Time to Index, s 90°	Time to Index, s 180°
A				
B				
C				

Principal Spindle Parameters (for Each Spindle)

Spindle Range	Rotation Speed, rpm Min.	Rotation Speed, rpm Max.	Spindle Power Continuous Duty kW	Spindle Power Continuous Duty hp
1				
2				

FORM 1 MACHINE DESCRIPTION (CONT'D)

Workpiece or tool spindle: ☐ headstock ☐ tool
Minimum programmable speed: ___________ rpm

Supplier shall furnish torque/power curves for each spindle range. Intermittent duty cycle details for each spindle range shall be supplied if applicable.

Tool holder type: ________________

Other

Tool-indexing time — all turrets
  Tool change time (where applicable): _____ s
  Pocket-to-pocket: _____ s
  Longest time: _____ s
Tool-setting system measurement time (where applicable): ______ s
Pallet change time (where applicable): ______ s
Axis indexing time (where applicable): ______ s

Machine Tool Probes (for Each Probe)

Probe type

☐ Part probe ☐ Tool-setting probe
☐ Contact ☐ Noncontact
☐ Switching ☐ Proportional ☐ Nulling
☐ 1D ☐ 2D ☐ 3D

Operating parameters

Probe approach rate: ______ mm/s (______ in./sec)
Probe approach distance: ______ mm (______ in.)
Settling time (proportional probes only): ______s

Software

☐ Allows only 1D measurements
☐ Allows only 2D measurements
☐ Allows 3D measurements

List of Compensation Tables in the Controller

Supplier shall provide a technical description of the machine compensation system (where applicable), as well as a statement describing User access to compensation system parameters.

Compensation Description	Accessible by User, Yes/No	Information Attached, Yes/No

FORM 2 ENVIRONMENTAL SPECIFICATIONS GUIDELINES

Thermal Information (para. 5.2)

	°C	°F
Mean ambient temperature		
Minimum safe operating temperature		
Maximum safe operating temperature		
Daily (24-h) temperature cycling amplitude, ±		

Superimposed cycle(s)

Amplitude: ± _______ °C (± ________ °F)

Frequency: _______ cycles/h

Maximum temperature gradients

Vertical: ________ °C/m (_________ °F/ft)

Horizontal: ________ °C/m (_________ °F/ft)

Maximum mean air speed surrounding the machine: ________ m/s (_______ ft/sec)

Additional guidelines on machine component placement and special flow parameters, such as mean flow rate, shall be specified if appropriate.

Nominal Coefficient of Thermal Expansion of Linear Machine Feedback Device

Axis	Nominal Coefficient of Thermal Expansion	
	10^{-6} per °C	10^{-6} per °F
X		
Y		
Z		

Seismic Vibration Allowances (para. 5.3)

☐ Option 1 Response function data

(Detailed permissible vector vibration spectra shall be attached as a part of this specification.)

☐ Option 2 Broadband data [time history (para. D-3.2.2)]

Frequency Range, Hz		Peak-to-Peak Amplitude	
Min.	Max.	mm	in.

FORM 2 ENVIRONMENTAL SPECIFICATIONS GUIDELINES (CONT'D)

Electrical (para. 5.4)
(Equivalent specification is required for each electrical supply.)

Steady-state requirements

Nominal RMS voltage: _______ V Frequency:______ Hz Amperage: _____ A

______ Single-phase _____ Three-phase ______ Delta _____Wye

Allowable short-duration RMS voltage variations (instantaneous)

Voltage sag (8.3 ms to 500 ms):_________% of nominal

Voltage swell (8.3 ms to 500 ms):_______% of nominal

Allowable long-duration RMS variations

Overvoltages (> 1 min): __________ % of nominal

Undervoltages (> 1 min):_________ % of nominal

Allowable transient voltage (0.5 μs to 800 μs):________% of nominal

Utility Air, If Applicable (para. 5.5)
Pressure:________ MPa (_________ psi)
Flow rate: ________ dm^3/s (_________ SCFM)
Dew point: _______ °C (_________ °F)

Particulate removal requirements
Maximum particulate size: _______ μm (_______ μin.),________% removal

Other Services, If Applicable (para. 5.6)
Foundation/installation specifications (must be included by Supplier)

Construction drawings: ☐ Yes ☐ No

Supplier shall provide a technical description of the coolant system.

Coolant through spindle: ☐ Yes ☐ No

GENERAL NOTE: The parameters listed here are based on assumptions regarding normal air-conditioned rooms. Another set, if provided as part of the machine specification and agreed on between the Supplier and the User, shall be acceptable for the purposes of this Standard. In some cases, other fluids (rather than air) are used to provide thermal stability. In those cases, separate guidelines should also be provided.

FORM 3 ENVIRONMENTAL TESTS (SECTION 6)

Environmental Temperature Variation Error (para. 6.2)

Date: ____________

Time: ____________

Operator: __________________________

Axis	Location for *ETVE* Test (Machine Coordinates) mm or deg	in. or deg
X		
Y		
Z		
A		
B		
C		

Reported Result	Range Drift mm or arcsec	in. or arcsec
$ETVE_x$		
$ETVE_y$		
$ETVE_z$		
$ETVE_{xx}$		
$ETVE_{yy}$		

Relative Vibration Test (para. 6.3)

If the nominal location for this test is different from that of the environmental temperature variation test, the nominal location shall be recorded in this sheet.

Date: _________

Time: _________

Operator: __________________________

Direction	Relative Vibration mm	in.
X		
Y		
Z		

FORM 4 MACHINE PERFORMANCE (SECTION 7)

Machine Compliance and Hysteresis (Nonmandatory Appendix H)

Date: ___________

Time: ___________

Operator: __________________________

Location for Tests (Machine Coordinates)

Compliance	Location of Test (Machine Coordinates) X mm	X in.	Y mm	Y in.	Z mm	Z in.	A, deg	B, deg	C, deg
X									
Y									
Z									
A									
B									
C									

Machine Compliance and Hysteresis Measured Between Machine Spindle and Workpiece

Direction of Measured Compliance	Rotary Axis	Radius Offset (Rotary Axis)	Clamped or Servo Held	Axis That Generates the Force [Note (1)]	Compliance mm/N	Compliance in./lb	Hysteresis mm	Hysteresis in.
X	N/A	N/A	N/A					
Y	N/A	N/A	N/A					
Z	N/A	N/A	N/A					
□ X or □ Y	A							
□ X or □ Z	B							
□ Y or □ Z	C							

NOTE:

(1) Enter "N/A" if the force is applied using an external actuator such as a turnbuckle or hydraulic jack.

FORM 4 MACHINE PERFORMANCE (SECTION 7) (CONT'D)

Positioning Accuracy and Repeatability (para. 7.2)

Linear Axes

Date: ___________

Time: ___________

Operator: _____________________

Compensated: ☐ yes ☐ no

Axis	Maximum Unidirectional Systematic Deviation of Positioning, $E\uparrow$ or $E\downarrow$		Bidirectional Systematic Deviation of Positioning, E		Bidirectional Accuracy of Positioning, A		Periodic Error, P	
	mm	in.	mm	in.	mm	in.	mm	in.
X								
Y								
Z								

Axis	Maximum Unidirectional Repeatability, $R\uparrow$ or $R\downarrow$		Bidirectional Repeatability, R		Reversal Deviation, B	
	mm	in.	mm	in.	mm	in.
X						
Y						
Z						

Minimum ambient temperature: ________°C (___________°F)
Maximum ambient temperature: ________°C (___________°F)
Ambient air pressure: ____________ mm Hg (___________ in. Hg)
Relative humidity: ____________%
Machine temperature: __________°C (___________°F)
Feed rate of testing: ____________ mm/min (______ in./min)

Positioning Accuracy and Repeatability of Rotary Axes (para. 7.5)

Date: ___________

Time: ___________

Operator: _____________________

Compensated: ☐ yes ☐ no

Axis	Maximum Unidirectional Systematic Deviation of Positioning, $E\uparrow$ or $E\downarrow$, arcsec	Bidirectional Systematic Deviation of Positioning, E, arcsec	Bidirectional Accuracy of Positioning, A, arcsec	Periodic Error, P, arcsec
A				
B				
C				
Turret axis				

FORM 4 MACHINE PERFORMANCE (SECTION 7) (CONT'D)

Axis	Maximum Unidirectional Repeatability, $R\uparrow$ or $R\downarrow$, arcsec	Bidirectional Repeatability, R, arcsec	Reversal Deviation, B, arcsec
A			
B			
C			
Turret axis			

Minimum ambient temperature: ________°C (___________°F)
Maximum ambient temperature: ________°C (___________°F)
Rotary feed rate: _______________ deg/min

Angular Errors (Usually Yaw) of Linear Axes (para. 7.4)

Date: ___________

Time: ___________

Operator: _____________________

Compensated: □ yes □ no

Angular Error Designation	Maximum Unidirectional Systematic Deviation of Angular Error, $E_{ae}\uparrow$ or $E_{ae}\downarrow$, arcsec	Bidirectional Systematic Deviation of Angular Error, E_{ae}, arcsec	Maximum Unidirectional Repeatability, $R_{ae}\uparrow$ or $R_{ae}\downarrow$, arcsec	Bidirectional Repeatability, R_{ae}, arcsec
Yaw of X				

Spindle Axis of Rotation (for Each Spindle, para. 7.6)

Date: ___________

Time: ___________

Operator: _____________________

Spindle: _____________________

Structural Motion, Spindle Off (para 7.6.2)

	Machine Drives Off		Machine Drives On	
	mm	in.	mm	in.
Along X or Y direction				
Along Z direction				

FORM 4 MACHINE PERFORMANCE (SECTION 7) (CONT'D)

Work Spindle, Fixed Sensitive Direction

Date: ___________
Time: ___________
Operator: ______________________
Spindle: ______________________

		Percent of Maximum Speed		
		10%	50%	100%
Spindle speed	rpm			
Average radial error motion	mm			
	in.			
Asynchronous radial error motion	mm			
	in.			
Total axial error motion	mm			
	in.			
Average tilt error motion	arcsec			
Asynchronous tilt error motion	arcsec			

Tool Spindle, Rotating Sensitive Direction

Date: ___________
Time: ___________
Operator: ______________________
Spindle: ______________________

		Percent of Maximum Speed		
		10%	50%	100%
Spindle speed	rpm			
Average radial error motion	mm			
	in.			
Asynchronous radial error motion	mm			
	in.			
Total axial error motion	mm			
	in.			
Average tilt error motion	μrad			
Asynchronous tilt error motion	μrad			

FORM 4 MACHINE PERFORMANCE (SECTION 7) (CONT'D)

Machine Thermal Tests (para. 7.7)

Spindle Warm-Up and Transient Shutoff Test (for Each Spindle)

Date: ___________ Duration of test: __________

Time: ___________ Spindle speed: ___________

Operator: ____________________

Compensated: □ yes □ no

Coolant: □ on □ off

Spindle: ____________________

Displacement and Tilt of the Axis of Rotation

Error Motion	Drift During Warm-Up		Drift During Transient Shutoff	
	mm or µrad	in. or µrad	mm or µrad	in. or µrad
Displacement in X, D_x				
Displacement in Y, D_y				
Displacement in Z, D_z				
Tilt around X, $D_{y,z}$				
Tilt around Y, $D_{y,z}$				

Thermal Distortion Caused by Moving Linear Axes (for Each Axis, para. 7.7.3)

Date: ___________ Duration of test: __________

Time: ___________

Operator: ____________________

Compensated: □ yes □ no

Axis	Range of Drift at Position 1 in Axis Direction				Range of the Drift at Position 2 in Axis Direction			
	Forward Direction ↑		Reverse Direction ↓		Forward Direction ↑		Reverse Direction ↓	
	mm	in.	mm	in.	mm	in.	mm	in.
X								
Y								
Z								

Composite Thermal Error (para. 7.7.4)

Date: ___________

Time: ___________

Operator: ____________________

Compensated: □ yes □ no

Duration of test: ______________

Distance between indicator 1 and indicator 2: ___________ mm (_________ in.)

Error Motion	Drift After 30 Min		Drift After ___ Min	
Displacement in X, in.				
Displacement in Y, in.				
Displacement in Z, in.				
Tilt around X, µrad				
Tilt around Y, µrad				

FORM 4 MACHINE PERFORMANCE (SECTION 7) (CONT'D)

Critical Alignments (para. 7.8)

Squareness errors between cross-slide (X-axis) and the work spindle axis (often a C-axis)

Date: ___________

Time: ___________

Operator: ______________________

Compensated: ☐ yes ☐ no

Measurement method (select one)

☐ Mechanical straightedge

☐ Test part

Soak-out time: ___________ min

Machining time: __________ min

Warm-up cycle must be specified.

Squareness Error	Error Magnitude, arcsec
XC squareness	

Parallelism of the longitudinal slide (Z-axis) with the work spindle (often a C-axis) and other linear axes

Date: ___________

Time: ___________

Operator: ______________________

Compensated: ☐ yes ☐ no

Measurement method (select one)

☐ Mechanical straightedge

☐ Test part

Soak-out time: ___________ min

Machining time: __________ min

Warm-up cycle must be specified.

☐ Laser for long-travel axes

☐ Mechanical straightedge (para. 7.8.3.1)

Parallelism Error	Error Magnitude, arcsec
Z–C parallelism in X–Z plane	
Z–C parallelism in Y–Z plane	
Z–W parallelism in X–Z plane	
Z–W parallelism in Y–Z plane	

FORM 4 MACHINE PERFORMANCE (SECTION 7) (CONT'D)

Contouring Performance Tests (para. 7.9)

Date: ___________

Time: ___________

Operator: ____________________

Compensated: ☐ yes ☐ no

A 360-deg test should be used where possible; otherwise, a 190-deg test should be used. If neither of those tests is possible, then a 100-deg test shall be allowed.

Plane: X–Z		360 deg		190 deg		100 deg	
Nominal radius	mm						
	in.						
Feed rate	% max	10%	80%	10%	80%	10%	80%
	mm/min						
	in./min						
Circular deviation, $G\uparrow$, clockwise	mm						
	in.						
Circular deviation, $G\downarrow$, counterclockwise	mm						
	in.						
Radial deviation, $F_{min}\uparrow$, clockwise	mm						
	in.						
Radial deviation, $F_{min}\downarrow$, counterclockwise	mm						
	in.						
Radial deviation, $F_{max}\uparrow$, clockwise	mm						
	in.						
Radial deviation, $F_{max}\downarrow$, counterclockwise	mm						
	in.						

Cutting Performance Tests (para. 7.10)

Date: ___________

Time: ___________

Operator: ____________________

Spindle Idle Run Losses (para. 7.10.2)

Report for each work and tool spindle.

Maximum spindle speed: ____________ rpm

% of Max. Speed	Lost Power, kW
20	
40	
60	
80	
100	

FORM 4 MACHINE PERFORMANCE (SECTION 7) (CONT'D)

Chatter Susceptibility and Maximum Torque Test (para. 7.10.3)

Detailed specifications and procedures shall be agreed upon between the User and the Supplier and made part of the machine specification.

Multifunction Cycle Test (para. 7.11)

Date: ___________

Time: ___________

Operator: ____________________

Duration of the test:___________min

Number of failures:___________

Maximum time required for correction:__________ min

FORM 5 COAXIALITY OF AXES OF ROTATION (PARA. 8.2)

For each of the tests below, the User may specify the specification zones with machine compensation on or off, or both.

Select one:

- ☐ Rim-and-face method (para. 8.2.1)
- ☐ Reverse indicator method (para. 8.2.2)
- ☐ Optical rotary axis alignment (para. 8.2.3)
- ☐ Two-sphere axis alignment (para. 8.2.4)
- ☐ Mechanical rotary axis alignment (para. 8.2.5.1)

Offset in the vertical direction, *VO*: _______ mm (_________ in.)

Offset in the horizontal direction, *HO*: _______ mm (_________ in.)

Parallelism, angularity in the vertical direction, *VA*: ___________ arcsec

Parallelism, angularity in the horizontal direction, *HA*: ___________ arcsec

FORM 6 SUBSYSTEMS REPEATABILITY (PARA. 8.3)

Tool-Change Repeatability (para. 8.3.1)

Date: ____________

Time: ____________

Operator: __________________________

Length from gage line for short tool: _____mm (_____ in.)

Length from gage line for long tool: _____mm (_____ in.) (100 mm is recommended.)

Error Direction	Tool-Change Repeatability			
	Short Tool		Long Tool	
	mm	in.	mm	in.
X				
Z				

Turret Repeatability (para. 8.3.2)

Date: ____________

Time: ____________

Operator: __________________________

Length from gage line for short tool: _____mm (_____ in.)

Length from gage line for long tool: _____mm (_____ in.) (100 mm is recommended.)

Error Direction	Tool-Change Repeatability			
	Short Tool		Long Tool	
	mm	in.	mm	in.
X				
Z				

Tool-Setting System Location and Repeatability (para. 8.4)

Date: ____________

Time: ____________

Operator: __________________________

Tool-setting X repeatability: ___________ mm (__________in.)

Tool-setting Z repeatability: ___________ mm (__________in.)

Tool-setting X location: ___________ mm (__________in.)

Tool-setting Z location: ___________ mm (__________in.)

FORM 7 CNC PERFORMANCE TESTS (PARA. 8.5)

Date: ___________
Time: ___________
Operator: __________________________

Maximum steady feed rate, V_{max}: _______________mm/min (_____________in./min)
Minimum block execution time, *MBET*: __________ s

FORM 8 MACHINE PERFORMANCE AS A MEASURING TOOL (PARA. 8.6)

	Feature Location Repeatability					
	1D		2D		3D	
Axis	mm	in.	mm	in.	mm	in.
X						
Y						
Z						

2D-feature measurement accuracy:______________ mm (__________in.)
3D-feature measurement accuracy:______________ mm (__________in.)

2D-probe lobing range: ________________ mm (__________in.)
3D-probe lobing range: ________________ mm (__________in.)

Linear measurement accuracy in X:_____________ mm (__________in.)
Linear measurement accuracy in Y:_____________ mm (__________in.)
Linear measurement accuracy in Z:_____________ mm (__________in.)

Volumetric measuring performance: _____________ mm (__________in.)
Circular profile measurement accuracy:___________ mm (__________in.)

Workpiece Location

	Workpiece Location Working Tolerance	
Axis	mm	in.
X		
Y		
Z		

2 REFERENCES

The following is a list of publications referenced in this Standard.

ANSI B5.54-2005, Methods for the Performance Evaluation of Computer Numerically Controlled Machining Centers

ANSI B89.3.4M-2010, Axes of Rotation

ANSI B89.6.2-1973, Temperature and Humidity Environment for Dimensional Measurement

ANSI/EIA-267-C-1990, Axis and Motion Nomenclature for Numerically Controlled Machines

Publisher: American National Standards Institute (ANSI), 25 West 43rd Street, New York, NY 10036 (www.ansi.org)

ASME B89.4.1.10360.2-2008, Acceptance Test and Reverification Test for Coordinate Measuring Machines (CMMs), Part 2: CMMs Used for Measuring Linear Dimensions (Technical Report)

Publisher: The American Society of Mechanical Engineers, Two Park Avenue, New York, NY 10016-5990; Order Department: 22 Law Drive, P.O. Box 2900, Fairfield, NJ 07007-2900 (www.asme.org)

ISO 1:2002, Geometrical Product Specifications (GPS) — Standard Reference Temperature for Geometrical Product Specification and Verification

ISO 230-2:2006, Test Code for Machine Tools — Part 2: Determination of Accuracy and Repeatability of Positioning Numerically Controlled Axes

ISO 230-3:2007, Test Code for Machine Tools — Part 3: Evaluation of Thermal Effects

ISO 230-4:2005, Test Code for Machine Tools — Part 4: Circular Tests for Numerically Controlled Machine Tools

ISO 554:1976, Standard Atmospheres for Conditioning and/or Testing — Specifications

ISO 841:2001, Industrial Automation Systems and Integration —- Numerical Control of Machines — Coordinate System and Motion Nomenclature

ISO 1940-1: 2003, Mechanical Vibration-Balance Quality Requirements for Rotors in a Constant (Rigid) State — Part 1: Specification and Verification of Balance Tolerances

ISO 3205:1976, Preferred Test Temperatures

ISO 10360-2:2001, Geometrical Product Specifications (GPS) — Acceptance and Reverification Tests for Coordinate Measuring Machines (CMM) — Part 2: CMMs Used for Measuring Size

ISO 13041-1:2004, Test Conditions for Numerically Controlled Turning Machines and Turning Centres — Part 1: Geometric Tests for Machines With Horizontal Workholding Spindle

ISO 13041-2:2008, Test Conditions for Numerically Controlled Turning Machines and Turning Centres — Part 2: Geometric Tests for Machines With Vertical Workholding Spindle

ISO 13041-3:2009, Test Conditions for Numerically Controlled Turning Machines and Turning Centres — Part 3: Geometric Tests for Machines With Inverted Vertical Workholding Spindle

ISO DIS 230-1:2009, Test Code for Machine Tools — Part 1: Geometric Accuracy of Machine Tools Operating Under No-Load or Quasi-Static Conditions

ISO/IEC Guide 98-3:2008, Uncertainty of Measurement — Part 3: Guide to the Expression of Uncertainty in Measurement [GUM:1995(E)]

ISO/IEC Guide 99:2007, International Vocabulary of Metrology — Basic and General Concepts and Associated Terms (VIM)

Publisher: International Organization for Standardization (ISO) Central Secretariat, 1, ch. de la Voie-Creuse, Case postale 56, CH-1211 Genève 20, Switzerland/Suisse (www.iso.org)

3 NOMENCLATURE

1D = one-dimensional
2D = two-dimensional
3D = three-dimensional
A = a computer-controlled rotary axis, other than a spindle axis[1]
A = bidirectional accuracy of positioning of an axis
$A\uparrow$ = unidirectional accuracy of positioning of an axis, forward direction
$A\downarrow$ = unidirectional accuracy of positioning of an axis, reverse direction
A_{ae} = bidirectional total angular error
$A_{ae}\uparrow$ = unidirectional total angular error, forward direction
$A_{ae}\downarrow$ = unidirectional total angular error, reverse direction
ANGF = angle measured in the forward direction, straightedge reversal
ANGR = angle measured in the reverse direction, straightedge reversal
a^+ = upper limit of a uniform distribution
a^- = lower limit of a uniform distribution
B = maximum of the absolute reversal values at all target positions along an axis
$\bar{B}$ = mean reversal value of an axis
B_{ae} = reversal deviation of angular error
B_i = reversal value at target position, *i*, along or around an axis
C = a programmable spindle axis
C_n = a programmable spindle axis on a machine with more than one spindle axis (n=1, 2,...)
CPMA = circular profile measurement accuracy

[1] In this Standard, "A" is used to symbolize two different quantities. This is done to conform with existing ISO and ANSI standards. The accuracy variable, *A*, is italicized. The axis designation, A, is not italicized. The usage is so different it is expected that no confusion will arise.

CX_n = mean X circle center at position $n = 1, 2$, two-sphere axis alignment
CY_n = mean Y circle center at position $n = 1, 2$, two-sphere axis alignment
$c(X_n,30)$ = X displacement at position n ($n = 1, 2,...$) after 30 min, composite thermal error test
$c(X_n,t)$ = X displacement at position n ($n = 1, 2,...$) after t min, composite thermal error test
$c(Y_n,30)$ = Y displacement at position n ($n = 1, 2,...$) after 30 min, composite thermal error test
$c(Y_n,t)$ = Y displacement at position n ($n = 1, 2,...$) after t min, composite thermal error test
$c(Z,30)$ = Z displacement after 30 min, composite thermal error test
$c(Z,t)$ = Z displacement after t min, composite thermal error test
D_c = diameter of a test cylinder
D_g = distance between two gages
D_i = gage reading during spindle warm-up test ($i = 1$ to 5)
D_x = spindle thermal drift, X direction
$D_{x,z}$ = spindle angular thermal drift of axis average line, X–Z plane
D_y = spindle thermal drift, Y direction
$D_{y,z}$ = spindle angular thermal drift of axis average line, Y–Z plane
D_z = spindle thermal drift, Z direction
DIA = diameter of a circle or part
E = bidirectional systematic deviation of positioning of an axis
$E\uparrow$ = unidirectional systematic deviation of position of an axis, forward direction
$E\downarrow$ = unidirectional systematic deviation of position of an axis, reverse direction
$E(X)$ = bidirectional systematic deviation of positioning, X-axis
$E(Z)$ = bidirectional systematic deviation of positioning, Z-axis
E_{ae} = bidirectional systematic angular error
$E_{ae}\uparrow$ = unidirectional systematic angular error, forward direction
$E_{ae}\downarrow$ = unidirectional systematic angular error, reverse direction
$ETVE$ = environmental temperature variation error
$e(x_n\uparrow)$ = range of thermal drift, target position n, X direction, forward, thermal distortion test
$e(x_n\downarrow)$ = range of thermal drift, target position n, X direction, reverse, thermal distortion test
$e(z_n\uparrow)$ = range of thermal drift, target position n, Z direction, forward, thermal distortion test
$e(z_n\downarrow)$ = range of thermal drift, target position n, Z direction, reverse, thermal distortion test
F = out-of-squareness angle between a straightedge and a spindle axis
$F_{max}\uparrow$ = radial deviation, maximum, clockwise direction, circular test
$F_{max}\downarrow$ = radial deviation, maximum, counterclockwise direction, circular test
$F_{min}\uparrow$ = radial deviation, minimum, clockwise direction, circular test
$F_{min}\downarrow$ = radial deviation, minimum, counterclockwise direction, circular test
$FM(X)$ = feature measurement accuracy, X direction
$FM(Z)$ = feature measurement accuracy, Z direction
FR_s = mean sag of face indicator, rim-and-face test
FRN = mean face reading at N, $N = 0, 3, 6, 9$, rim-and-face test
$G\uparrow$ = circular deviation, clockwise, circular test
$G\downarrow$ = circular deviation, counterclockwise, circular test
H = circular hysteresis, circular test
HA = horizontal angle between two axes of rotation, coaxiality of axes of rotation
HO = horizontal offset between two axes of rotation, coaxiality of axes of rotation
HO_n = horizontal offset at position n, $n = 1, 2$, two-sphere axis alignment
$INCR$ = increment length used to test block execution time
i = index of target position
j = index for number of measurements
k = coverage factor
L = dimension of workpiece at 20°C (68°F)
$L_{1,2}$ = distance between indicators 1 and 2 and spindle face, spindle thermal stability test
L_c = length of a test cylinder
L_{cte} = distance between the displacement indicators in the composite thermal error test
L_d = dimension between two gages used to calculate angle
L_s = dimension of the reference and/or working standard at 20°C (68°F)
L_T = dimension of an object at temperature $T \neq$ 20°C (68°F)
L_X = traverse length of the X-axis
L_Z = traverse length of the Z-axis
$LMA(X)$ = linear measurement accuracy, X direction
$MA(Z)$ = linear measurement accuracy, Z direction
LSC = least-squares circle center of a polar profile
$LUTM$ = length uncertainty due to temperature measurement
M = range of the mean bidirectional positional deviations of an axis
$Max[q]$ = maximum value of a quantity, q
$MBET$ = minimum block execution time
MIC = minimum inscribed circle center of a polar profile
$Min[q]$ = minimum value of a quantity, q
$MR(R)$ = measurement repeatability of a radius
$MR(X)$ = measurement repeatability, X direction
$MR(Z)$ = measurement repeatability, Z direction
MR_s = mean sag of the M gage, reverse indicator test

MRN = mean M gage reading at $N = 0, 3, 6, 9$, reverse indicator test
MRS = minimum radial separation center of a polar profile
m = total number of measurements of a specified quantity
N = Newton, unit of force
NDE = nominal differential expansion
NE = nominal thermal expansion of the object to be measured or calibrated
NE_s = nominal thermal expansion of the standard
n = number of measurements of the same quantity
P = periodic error of a linear or rotary axis
P_i = target position in the positioning tests, i^{th} position
P_{ij} = measured position at the j^{th} approach to the target position, P_i
q = a quantity to be measured, i.e., a measurand
$\overline{q}$ = mean of a set of measurements of a quantity, *q*
q_j = the j^{th} measurement of a quantity, *q*
R = bidirectional repeatability of a measurement
$R\uparrow$ = unidirectional repeatability for an axis, forward direction (maximum value)
$R\downarrow$ = unidirectional repeatability for an axis, reverse direction (maximum value)
R_A = radius of an artifact
R_{ae} = bidirectional repeatability of angular error
$R_{ae}\uparrow$ = unidirectional repeatability of angular error, forward direction
$R_{ae}\downarrow$ = unidirectional repeatability of angular error, reverse direction
R_i = bidirectional repeatability of positioning at position *i*
$R_i\uparrow$ = unidirectional repeatability of positioning in the forward direction at position *i*
$R_i\downarrow$ = unidirectional repeatability of positioning in the reverse direction at position *i*
R_{Mi} = measured radius of a part, $i = 1, 2$, machine performance as a measuring tool
R_{pi} = radius of a part, $i = 0, 1, 2, 180$, machine performance as a measuring tool
$\overline{R}_{pi}$ = average measured radius of a part, $i = 0, 1, 2, 180$, machine performance as a measuring tool
R_{sphere} = radius of a sphere
R_{xts} = tool change repeatability, X direction
RR_s = mean sag of rim indicator, rim-and-face test
RRN = mean rim reading at position *N*, $N = 0, 3, 6, 9$, rim-and-face test
$r(\theta)$ = radial error motion of a spindle
r_0 = radius of the eccentricity in rotating-sensitive-direction spindle testing
$r_n(\theta)$ = radial motion of a spindle measured by gage n ($n = 1, 2, ...$)
rpm = revolutions per minute
SMTC = significant mean temperature change
SOTR = safe operating temperature range
SR_s = mean sag of the S gage, reverse indicator test
SRN = mean S gage reading at $N = 0, 3, 6, 9$, reverse indicator test
SZ = specification zone for a quantity specified in this Standard
s_i = estimator of the standard uncertainty of a quantity measured at the i^{th} position
$s_i\uparrow$ = estimator of the standard uncertainty in the forward direction at position *i*
$s_i\downarrow$ = estimator of the standard uncertainty in the reverse direction at position *i*
T = temperature of the workpiece
T_s = temperature of the reference and/or working standard
TEI = thermal error index
t = time
$U_T(L)$ = expanded thermal uncertainty
UNDE = uncertainty of nominal differential expansion
UNE = uncertainty of nominal thermal expansion
UNE_s = uncertainty of nominal thermal expansion of a standard
$u(T)$ = uncertainty of temperature of the object being measured or calibrated
$u(T_s)$ = uncertainty of temperature of the reference and/or working standard
$u(\alpha)$ = uncertainty of the coefficient of thermal expansion of the object being measured or calibrated
$u(\alpha_s)$ = uncertainty of the coefficient of thermal expansion of reference standard and/or working standard
$u_{cT}(L)$ = combined standard thermal uncertainty
u_{ETVE} = standard uncertainty due to the environmental temperature variation
u_q = standard uncertainty of a quantity, *q*
u_{sub} = standard uncertainty of a measurement, denoted by the subscript *sub*
u_x = estimate of the standard uncertainty, X direction, tool change repeatability
$V_{\max}$ = maximum feed rate observed, minimum block execution time test
VA = vertical angle between two axes of rotation, coaxiality of axes of rotation
VMA = volumetric measurement accuracy
VO = vertical offset between two axes of rotation, coaxiality of axes of rotation
VO_n = vertical offset at position $n = 1, 2$, two-sphere axis alignment
W = out-of-squareness angle
X = a linear axis direction, usually the cross-slide
X_n = a linear machine axis on a machine with more than one X-axis ($n = 1, 2,...$)

x_i = bidirectional deviation of axis positioning at position i
$\bar{x}_i\uparrow$ = mean deviation of an axis positioning in the forward direction at the i^{th} position
$\bar{x}_i\downarrow$ = mean deviation of an axis positioning in the reverse direction at the i^{th} position
x_{ij} = positional deviation for the j^{th} measurement at the i^{th} position
$\overline{x_{ij}}\uparrow$ = j^{th} positional deviation at the i^{th} position along an axis, forward direction
$\overline{x_{ij}}\downarrow$ = j^{th} positional deviation at the i^{th} position along an axis, reverse direction
$\overline{x_t}$ = average X reading, tool-change repeatability
x_{ti} = i^{th} X reading, tool-change repeatability
Y = a linear direction on a lathe, usually the nonsensitive direction
$Y(\theta)$ = tilt degree of freedom for a rotary axis in the nonsensitive direction
Z = a linear axis direction, usually the in-feed
Z_{M0} = measured step height, machine performance as a measuring tool
Z_n = a linear machine axis on a machine with more than one Z-axis ($n = 1, 2, ...$)
Z_{p0} = average measured step height, machine performance as a measuring tool
α = coefficient of thermal expansion of the object being measured or calibrated
α_s = coefficient of thermal expansion of the reference and/or working standard
$\alpha(\theta)$ = axis of rotation angular error motion about the X direction as a function of the rotation angle
$\beta(\theta)$ = axis of rotation angular error motion about the Y direction as a function of the rotation angle
$\Delta_X(\theta)$ = axis of rotation translational error in the X direction as a function of the rotation angle
$\Delta_Y(\theta)$ = axis of rotation translational error in the Y direction as a function of the rotation angle
$\Delta_z(\theta)$ = axis of rotation translational error in the Z direction as a function of the rotation angle
$\gamma(\theta)$ = axis of rotation angular error motion about the Z direction as a function of the rotation angle
θ = angular position of a rotary axis (spindle axes included) or the angle between two lines
κ = thermal conductivity of a material
μm = micrometer, unit of length
τ = time constant of a physical quantity

4 DEFINITIONS

Abbe error: the measurement error resulting from angular motion of a movable component and an Abbe offset.

Abbe offset: the instantaneous value of the perpendicular distance between the line where the displacement is measured and the line where the displacement is to be determined.

Abbe principle: the displacement-measuring system should be in line with the functional point whose displacement is to be measured. If this 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.

accessory spindle: a spindle, other than the main spindle, that was supplied with a machine but not manufactured by the Supplier of the base machine and is, by the machine Supplier, considered an add-on.

accuracy: quantitative measure of the degree of conformance to recognize national or international physical standards and methods of measurement.[2]

accuracy (of measurement): closeness of the agreement between the result of a measurement and a true value of the measurand.

NOTES:
(1) *Accuracy* is a qualitative concept.
(2) The term *precision* should not be used for *accuracy*.

actual path: the path produced by the machine tool when programmed to move along a nominal path.

actual position, P_{ij}, ($i = 1$ to m; $j = 1$ to n): the measured position reached by the moving component on the j^{th} approach to the i^{th} target position.

ambient temperature: the temperature of the ambient air (or other working fluid, such as oil on an oil-showered machine) surrounding a machine. (See also *mean ambient temperature*.)

angular drift of axis average line: the change in angle of a spindle's axis average line caused by thermal effects due to spindle rotation.

artifact: a generic term used to describe a stable, physical object, used as a master in machine testing. Particularly used to describe a ball, a set of balls, or a mandrel in many tests in this Standard.

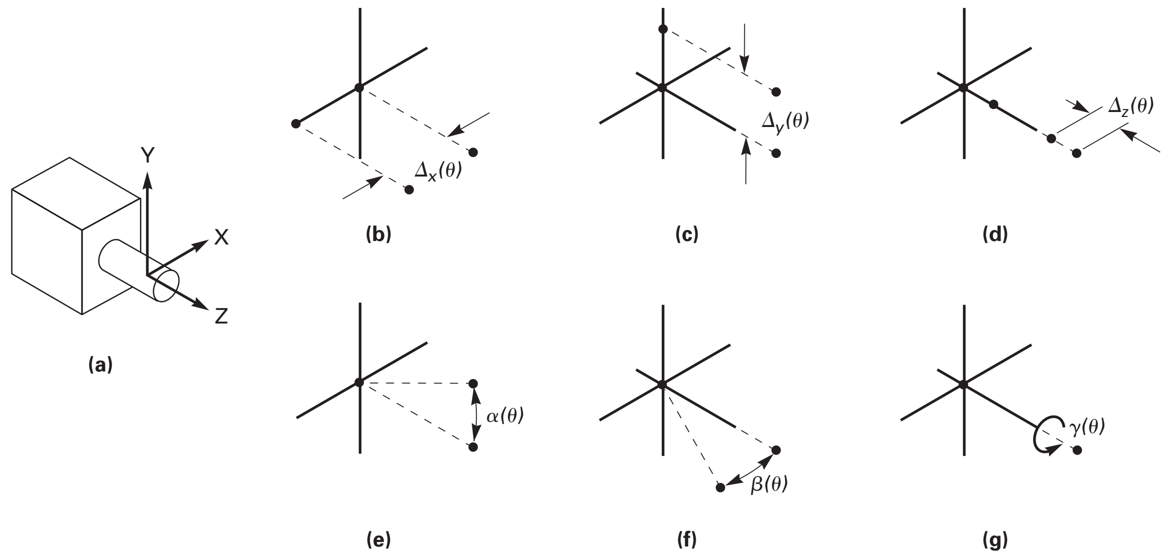
aspect ratio: for a turning center, the ratio of the travel of the longest linear axis to the shortest linear axis. A large aspect ratio machine is defined as having an aspect ratio greater than 3.

autocollimator: an 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.

auxiliary spindle: see *accessory spindle*.

[2] ISO defines *accuracy* (of measurement) as the closeness of the agreement between the result of a measurement and the true value of the measurand, with the conditions that accuracy is a qualitative concept and the term precision should not be used for accuracy. This ASME Committee does not concur that accuracy is a qualitative concept.

Fig. 4-1 The Six Basic Error Motions of an Axis of Rotation



average: the average value of a series of measurements. See also *mean*.

axial error motion: the error motion collinear with the Z reference axis of an axis of rotation [see Fig. 4-1, illustration (d)].

axis acceleration/deceleration: the rate at which the machine drive systems control the transition between different programmed axis feed rates.

axis average line: the average axis of rotation for a rotating spindle. The axis average line is obtained by least-squares fitting a line through the centers of several average error motion polar plots at different distances from the spindle face.

axis of rotation: a line about which rotation occurs.

axis travel: the maximum travel, linear or rotary, over which the movable component of a machine can move under numerical control.

backlash: a relative movement between interacting mechanical parts, resulting from looseness.

ball bar (magnetic, telescoping): a gage with two high-precision ball-and-magnetic-socket pairs held at the end of a telescoping rod, with an integral displacement sensor to measure the change of distance between the balls/sockets.

bearing error motion: the error motion of a rotary axis due to imperfect bearings.

bidirectional: refers to a parameter derived from a series of measurements in which the approach to a target position is made in either direction along or around the axis.

bidirectional accuracy of positioning of an axis, A: the range derived from the combination of the bidirectional systematic deviations and the estimator of the standard uncertainty of bidirectional positioning obtained using a coverage factor of 2.

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

bidirectional repeatability for an axis, R: the maximum value of the bidirectional repeatability positioning for an axis; that is, $R = \max.(R_i)$.

bidirectional repeatability of angular error, R_{ae}: the maximum value of the bidirectional repeatability of angular error for an axis.

bidirectional repeatability of positioning at a position, Ri: the maximum range representing the expanded uncertainty of bidirectional positional deviations, including the reversal deviation obtained using a coverage factor of 2, or 4 times the standard uncertainty in either direction at the position, whichever is larger; that is

$$R_i = \max.(2s_i\uparrow + 2s_i\downarrow + |B_i|;\ R_i\uparrow;\ R_i\downarrow)$$

where

B_i = the reversal deviation at position *i*

$R_i\uparrow = 4s_i\uparrow$

$R_i\downarrow = 4s_i\downarrow$

$s_i\uparrow, s_i\downarrow$ = the estimators of the standard uncertainty at that position

bidirectional systematic angular error, E_{ae}: the difference between the algebraic maximum and minimum of the mean unidirectional angular motions for both directions of approach at any position along a linear axis being measured. Computed in the same manner as the bidirectional systematic deviation of positioning of an axis, *E*.

bidirectional systematic deviation of positioning of an axis, E: the difference between the maximum and minimum of the mean unidirectional positional deviations for both approach directions (i.e., $E\uparrow$ and $E\downarrow$) at any position along or around the axis.

$$E = \max.(\bar{x}\uparrow, \bar{x}\downarrow) - \min.(\bar{x}\uparrow, \bar{x}\downarrow)$$

bidirectional total angular error, A_{ae}: the range derived from the combination of the bidirectional systematic angular error and the estimator of the standard uncertainty of bidirectional angular error, obtained using a coverage factor of 2. Computed in the same manner as the bidirectional accuracy of positioning of an axis, A.

block look-ahead limit: the number of part program blocks ahead of the block being executed that a CNC controller uses to plan motion.

broadband vibration amplitude: the amplitude (size) of vibration allowed over a specified frequency band, usually specified as the maximum vibration from a low-frequency, say 1 Hz, to an upper frequency of several thousand hertz.

Bryan principle: the straightness-measuring system should be in line with the functional point whose straightness is to be measured. If this is not possible, either the slideways that transfer the straightness must be free of angular motion, or angular-motion data must be used to calculate the consequences of the offset.

canned cycle: see *fixed cycle*.

cap test: a check for electrical noise and drift of a transducer, most commonly applied to displacement transducers, sensors, or indicators (see Nonmandatory Appendix I). In this Standard, the check is normally performed by placing a stable "cap" on a displacement indicator and monitoring its output over time. (See also *transducer drift check*.)

capacitance (cap) gage: a displacement measuring device of relatively short range and high resolution that functions by measuring the electrical capacitance between the probe tip and the surface being displaced.

catenary: the curve formed by a flexible string, wire, band, or cable suspended between two spatially separated points of equal height in a gravitational field. The form of the curve is determined primarily by the tension in the suspended element and its mass per unit length. In the context of this Standard, a catenary correction refers to the difference between this curve and a straight line between the two suspension points, measured in a vertical direction.

chatter: self-excited relative vibrations between the tool and the workpiece during the cutting process that may damage the cutting tool, the machine, or the part in roughing cuts and degrade the surface finish in finishing cuts.

circular deviation: the minimum radial separation of two concentric circles enveloping the actual path (minimum zone circles) in the circular test and that may be evaluated as the maximum radial range around the least-squares circle. It is equivalent to the total error motion value (see *error motion value*). Values are denoted $G\uparrow$ for clockwise rotations and $G\downarrow$ for counterclockwise rotations.

coefficient of thermal expansion: the true coefficient of expansion, α, at a temperature, T, of a body is the rate of change of the length of the body, L, with respect to temperature at the given temperature divided by the measured length at the given temperature, L_T.

$$\alpha = \frac{1}{L_T}\left(\frac{dL}{dT}\right)_T$$

cold machine: a machine at a stable operating temperature where during the last 2-h period

(*a*) the hydraulic systems and servos have been on

(*b*) the spindle has not been rotated above 10% of the maximum revolutions per minute

(*c*) the axes motions have been restricted to only those necessary to set up measurement equipment

A secondary definition is that the machine has been allowed to thermally stabilize for a Supplier- or User-specified soak-out time.

combined angular standard thermal uncertainty: for the purposes of this Standard, the combined angular standard thermal uncertainty for the angle measurement is given by

$$u_{cT}(A) = \sqrt{ETVE_A^2/12}$$

combined standard thermal uncertainty: for the purposes of this Standard, the combined standard thermal uncertainty for a length measurement made at a temperature other than 20°C (68°F) in a changing environment is given by

$$u_{cT}(L) = \sqrt{\begin{aligned}&u_{ETVE}^2 + L_s^2(T_s - 20)^2u^2(\alpha_s) + L^2(T-20)^2u^2(\alpha)\\ &+ L_s^2\alpha_s^2u^2(T_s) + L^2\alpha^2u^2(T)\end{aligned}}$$

command: an operative order to initiate a movement or a function.

command mode: a mode of operation of the command or data-entry device and display device in which entries are interpreted as functions to be executed.

comparator: any device used to perform the comparison of the part and the master. For the purposes of this Standard, the comparator can be a simple short-range indicating device, such as a gage block comparator, or a complex comparator, such as a coordinate measuring machine.

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

compliance: the displacement per unit static force between two objects, specified with respect to the structural loop, the location and direction of the applied forces, and the location and direction of the displacement of interest. The following terms can be applied when the structural loop contains an axis of rotation or a linear axis:

angular compliance: applicable when a pure moment is applied to a rotary axis in the direction of the designed angular displacement.

axial compliance: applicable when the force and the displacement are collinear with the Z reference axis.

face compliance: applicable when the force and displacement are parallel to the Z reference axis and at a specified radial location.

linear compliance: applicable when the force and displacement are applied to a machine axis designed for linear motion. Linear compliance can be in the direction of the slide axis or perpendicular to that direction.

radial compliance: applicable when the force and displacement directions are at 90 deg to the reference axis.

tilt compliance: applicable for a pure moment and a tilt displacement in a plane containing the Z reference axis.

computer numerical control (CNC): a numerical control system in which the data-handling sequence, the control functions, and the response to data input are determined primarily by a control program executed by a computer.

constant surface speed: in a turning application, the condition achieved by varying the speed of rotation of the workpiece relative to the tool inversely proportional to the distance of the tool from the center of rotation.

contouring control system: a system of control in which two or more controlled motions move in relation to each other so that the desired angular path or contour is generated.

contouring mode: a mode of operation of a CNC system that operates in one of the defined modes of interpolation, e.g., linear, circular, or parabolic.

control program: an order set of instruction in a computer language and a format that provide a computer base control system with the capability of properly executing system functions and commands of the machine program.

cosine error: the measurement error in the motion direction caused by angular misalignment between a linear displacement measuring system and the gage or displacement being measured.

coverage factor: a numerical factor used as a multiplier of the standard uncertainty to obtain an expanded uncertainty, normally denoted *k*.

cutter diameter (radius) compensation: a displacement normal to the cutter path to adjust for the difference between the actual and the programmed cutter radius or diameter.

cutter diameter (radius) offset: a displacement normal to the cutter path that is along a machine axis, to adjust for the difference between the actual and the programmed cutter radius or diameter.

cycle time: the period of time from starting one machine operation to starting another (in a pattern of continuous repetition).

deviation: in general, the difference between an actual value and the desired value, or commanded value, of a quantity. In this Standard, this word is used synonymously with error and refers to the average difference between an actual value and the desired value, unless otherwise specified. (See also *error*.)

deviation of position, x_{ij}: the actual position reached by the moving component minus the target position.

$$x_{ij} = P_{ij} - P_i$$

diagonal displacement: the displacement of the "tool" of a machine tool along a diagonal in its work zone. The diagonal may be either a face diagonal, that is, in a plane defined by two machine axes, or, in the general case, along a body diagonal defined by the displacement of three machine axes.

differential expansion: the difference between the expansion of the part and the expansion of the master from 20°C (68°F) to their time-mean temperatures at the time of the measurement.

displacement indicator: see *displacement transducer.*

displacement transducer: any one of a family of devices that measures displacement between a datum and a moving element. Such instruments could be, for example, capacitance gages, linear variable differential transformers (LVDTs), dial gages, laser interferometers, or eddy current probes. (See also *indicator* and *transducer*.)

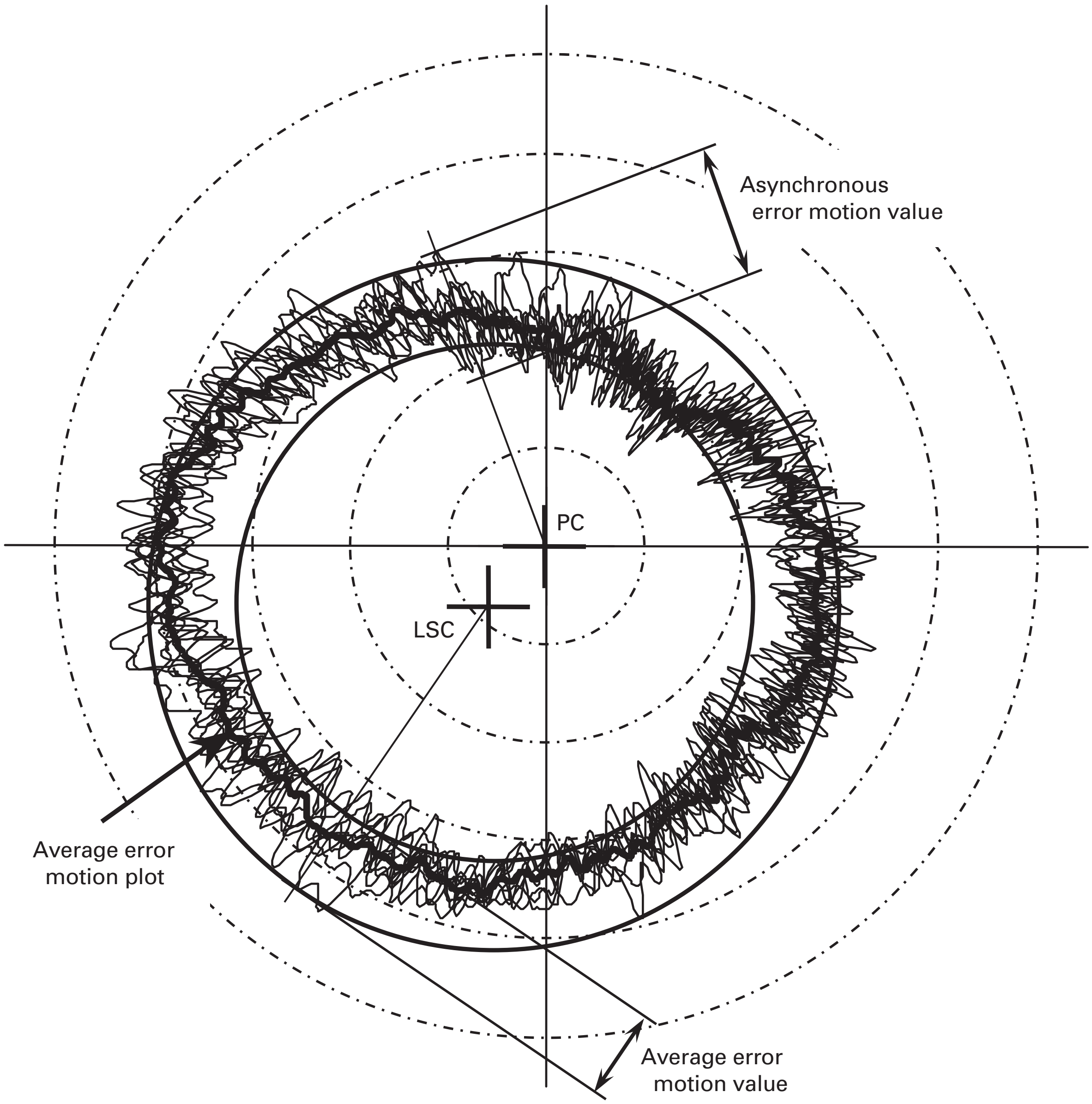
drift test: an experiment conducted to determine the actual drift inherent in a measurement system under normal operating conditions. This test usually consists of simultaneous recordings of drift and environmental temperatures. The recommended procedure for the conduct of a drift test is given in para. 6.2 for the measurement of environmental temperature variation error (*ETVE*).

drifts of axis average line: positional drifts of a spindle's axis average line caused by spindle thermal effects. For the purposes of this Standard, these drifts are defined as close to the chuck, part-holding device, or tool-holding device as is practical (see para. 7.1.3).

environmental temperature variation error (ETVE): an estimate of the maximum possible measurement uncertainty induced solely by deviation of the environment from average conditions. For the purposes of this Standard, it is assumed that the errors due to temperature variation are uniformly distributed with a total range equal to the measured *ETVE.* Since the *ETVE* is a total range, it must be converted to a standard uncertainty, as is discussed in para. 6.2.1.

error: the difference between the actual response of a machine to a command issued according to the accepted protocol of that machine's operation and the response to that command anticipated by that protocol. (See also *deviation*.)

Fig. 4-2 Error Motion Polar Plot Showing a Polar Chart Center, a Least-Squares-Circle Center, and Error Motion Values About These Centers



GENERAL NOTE: LSC = least-squares circle; PC = polar chart

error motion (of spindle): the change in position relative to the reference coordinate axes, of the surface of a perfect workpiece with its centerline coincident with the axis of rotation. Error motions are specified as to location and direction as shown in Fig. 4-1, illustration (a), and do not include motions due to thermal drift.

error motion measurements: a measurement record of error motion that should include all pertinent information regarding the machine, instrumentation, and test conditions.

error motion polar plot: a polar plot error motion made in synchronization with the rotation of the spindle. The following terms apply to the error motion polar plot and its components (see Fig. 4-2):

asynchronous error motion polar plot: the deviation of the total error motion polar plot from the average error motion polar plot.

average (synchronous) error motion polar plot: the mean contour of the total error motion polar plot averaged over a number of revolutions that can be divided into.

fundamental error motion polar plot: the best-fit reference circle fitted to the average error motion polar plot.

inner error motion polar plot: the contour of the inner boundary of the total error motion polar plot.

outer error motion polar plot: the contour of the outer boundary of the total error motion polar plot.

residual error motion polar plot: deviation of the average error motion polar plot from the fundamental error motion polar plot.

total error motion polar plot: the complete error motion polar plot as recorded.

error motion value: a magnitude assessment of error motion.

asynchronous error motion value: the maximum value of 4 times the standard uncertainty obtained during a spindle error motion measurement, after the average error motion has been subtracted from the error motion polar plot.

average error motion: the average (mean) error motion in the spindle performance test. At least 20 revolutions are required by this Standard.

average error motion value: the scale difference in radii of two concentric circles from a least-squares motion center just sufficient to contain the average error motion polar plot.

estimator of the unidirectional standard uncertainty of positioning at a position, $s_i\uparrow$ or $s_i\downarrow$: estimator of the standard uncertainty of the positional deviations obtained by a series of n unidirectional approaches at a position P_i.

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

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

expanded thermal uncertainty: in the case where the effective number of the degrees of freedom for each of the uncertainties in the combined standard thermal uncertainties is known, the expanded uncertainty should be computed following the example given in the latest version of ISO Guidelines. In the absence of such information, a coverage factor of $k = 2$ should be used to yield an expanded uncertainty of length measurement at approximately the 95% confidence level, due to temperature, $U_T(L)$, given by

$$\pm U_T(L) = \pm k u_{cT}(L) = \pm 2 u_{cT}(L)$$

expanded uncertainty: a quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values.

face error motion: error motion parallel to the Z reference axis at a specified radial location.

face runout: the runout of the face plate of a lathe as measured with an indicator in the tool position at some X distance off the axis of rotation.

feed function: a command defining a feed rate.

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

feed rate: the rate of motion of the feed axis of the tool relative to the workpiece, measured in millimeters per minute (mm/min) or millimeters per revolution (mm/rev).

fixed cycle: a preset series of operation that directs the machine axis movement and/or causes the spindle operation to perform a complex function (e.g., boring, drilling, tapping, probing, facing, or a combination thereof).

fixed zero: a reference position of the origin of the coordinate system not readily movable.

NOTE: This is typically a characteristic of a machine having absolute feedback elements.

floating zero: a characteristic of a numerical control system permitting the zero point on an axis to be established readily at any point; the control retains no information on the location of any previously established zeroes.

functional point: the point on the machine tool where a cutting tool would contact a part for the purposes of material removal.

fundamental error motion: in spindle testing, an error motion that is at the spindle rotation frequency.

gage: a mechanical artifact, often of high precision, used either for checking a part or for checking the accuracy of a machine, or a measuring device with a proportional range and some form of displacement indicator. When referring to a measuring device, the term gage is synonymous with displacement indicator or sensor, as used in this Standard.

grid encoder: a type of two-axis positioning readout sensor that, through the use of a two-dimensional grid or grating and an electronic read head, allows the position of the read head with respect to the grid to be accurately measured in two dimensions.

high-speed spindle: for the purposes of this Standard, any spindle that can operate at continuous duty at over 10,000 rpm.

hysteresis: a component of bidirectional repeatability caused by mechanisms such as drive train clearance, guide way clearance, mechanical deformations, friction, and loose joints. For the purposes of this Standard, two types of hysteresis are defined.

machine hysteresis: the hysteresis of the machine structure when subjected to specific loads.

setup hysteresis: the hysteresis of the various elements in a test setup, normally due to loose mechanical connections.

identification of axes: the identity of an axis moved to produce an actual path during machine testing.

incremental dimension: a dimension expressed with respect to the preceding point in a sequence of points.

incremental feed: a manual or automatic input of preset motion command for a machine axis.

indicator: a device used to measure displacements between a surface and a reference point. For the purposes of this Standard, an indicator could be a dial gage, an LVDT, or a capacitance gage.

initial position: a fixed point along an axis referenced with respect to a machine datum.

NOTE: This is typically used for start-up.

initialization: a sequence of operations establishing the starting point of a machine.

intermittent duty: with respect to motors, a measure of the time that the motor is operated as a fraction of 100% operation, continuous duty.

laser interferometer: a fringe counting interferometer for displacement measurement that uses a laser as a light source.

laser scales: machine scales that are based on laser interferometric principles.

lathe: any one of a class of machine tools where the part to be machined is rotated in a spindle to provide the surface speed necessary for material cutting.

length uncertainty due to temperature measurement: the use of this Standard requires that the measured length of a body be corrected to 20°C (68°F). This requires a measurement of the temperature of the body and an estimate of its thermal expansion coefficient. The uncertainty that the temperature measurement induces in the calculated length is called the length uncertainty due to temperature measurement (*LUTM*). In the case where there is a mechanical part and a mechanical master, it is given by

$$LUTM = \sqrt{\alpha^2 L^2 u(T)^2 + \alpha_s^2 L_s^2 u(T_s)^2}$$

where $u(T)$ and $u(T_s)$ are the standard uncertainties in temperature measurement of the part and the standard. In the case where the standard is a laser interferometer, α_s should be taken as 0.93×10^{-6} / °C.

level: the condition of perpendicularity between a surface and the force of gravity, or an instrument used to measure such perpendicularity.

linear variable differential transformer (LVDT): an electromagnetic device used for displacement measurement. Normally an LVDT has the capability to convert a displacement into a proportional electrical signal.

live tooling: a generic term used to refer to tooling on a turning center where the tool is rotated around a secondary axis of rotation for the purposes of milling, drilling, etc. Depending upon the machine, the spindle that holds the live tooling may be considered to be a main spindle or an accessory spindle.

load cell: a transducer that is used to measure force. Normally a load cell has the capability to convert a force into a proportional electrical signal.

machine coordinate system: the coordinate system that corresponds to the axes of the machine on which a part is to be manufactured. The coordinate system usually includes one or more linear axes designated X, Y, or Z (see ANSI/EIA-267-C). (The machine may also include rotary axes usually designated A, B, and C.)

machine datum: the built-in zero position of the machine elements used to establish the origin of the machine coordinate system.

machine home: a condition in a machine coordinate system where all machine elements are at home position (i.e., at the machine datum).

machine program: an ordered set of instructions in automatic control language and format sufficiently complete to affect the direct operation of an automatic control system.

machine tool duty rating (MTDR): the power level that a machine tool's spindle motor can operate above its continuous power rating for a short period of time (intermittent duty). This rating is supplied by the machine tool Supplier.

machine zero: the origin of the coordinates in the machine system.

main spindle: on a turning machine, the largest spindle equipped for the fixturing of parts with the purpose of turning such parts to provide surface speed for metal removal. In the case where there are two spindles capable of fixturing the same size of part, the main spindle shall be that spindle that is used more often or that is closest to the operator's left hand when the operator faces the machine.

master: the standard against which the desired dimension of the part is compared. The standard may be in the form of the wavelength of light, the length of a gage block, line standard, lead screw, etc.

mean: in this Standard, the average value of a physical quantity, denoted with a bar over the symbol for that quantity.

mean ambient temperature: the mean temperature of the ambient environment surrounding a machine as computed from at least two readings taken at the center of the machine's work zone during the interval required for the test.

mean bidirectional positional deviation at a position, $\bar{x}_i$*:* arithmetic mean of the mean unidirectional positional deviations, $\bar{x}_i\uparrow$ and $\bar{x}_i\downarrow$, obtained from the two directions of approach at a position, P_i.

$$\bar{x}_i = \frac{\bar{x}_i\uparrow + \bar{x}_i\downarrow}{2}$$

mean gage temperature: the mean temperature of a gage used for machine testing as computed from at least two readings taken on the gage during the interval required for a test.

mean reversal value of an axis, $\overline{B}$: the arithmetic mean of the reversal values, B_i, at all target positions along or around the axis.

$$\overline{B} = \frac{1}{m}\sum_{i=1}^{m} B_i$$

mean scale temperature: the mean temperature of a machine 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: the average temperature computed from a stated number of temperature measurements at equally spaced time intervals at a specified location.

mean unidirectional positional deviation at a position, $\overline{x}_i\uparrow$ or $\overline{x}_i\downarrow$: the arithmetic mean of the positional deviations obtained by a series of n unidirectional approaches to a position, P_i.

$$\overline{x}_i\uparrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij}\uparrow$$

and

$$\overline{x}_i\downarrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij}\downarrow$$

measurement line: a line in the work zone of a machine along which measurements are taken.

measurement point: a point in the work zone of a machine at which measurements are taken.

measurement travel: part of the axis travel that is used for data capture. It is selected so that the first and last target positions may be approached bidirectionally (see section 7).

minimum block execution time (MBET): the minimum time required by a CNC controller to execute one program block.

movable component: a major structural component that is movable relative to the machine base during measurement.

nominal coefficient of thermal expansion: an 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. Since the true coefficient for a given machine is not known, an uncertainty must be applied when making nominal differential expansion corrections (see para. 7.2.4). Following ISO practice, this Standard does not differentiate between the expected value of quantity and its actual value. Therefore, the nominal coefficient of expansion, in this Standard, will be denoted α.

nominal differential expansion (NDE):[3] the difference between the nominal expansion of the object to be calibrated and the standard.

$$NDE = NE - (NE)_s$$

When measuring at temperatures other than 20°C (68°F), corrections for the *NDE* must always be made. The *NDE* is a systematic error and cannot be considered to be an uncertainty.

nominal expansion (NE): an estimate of the expansion of an object from 20°C (68°F) to its time-mean temperature. It shall be determined from the following relationship:

$$NE = \alpha L(T - 20)$$

nominal path: a numerically controlled and programmed path defined by the machine's appropriate programming protocol. For the purposes of the circular tests, this path would be defined by its diameter or radius, the position of its center, and its orientation of the work zone of the machine. Nominal paths for the circular tests may either be full circles or partial arcs.

nonsensitive direction: any direction perpendicular to any sensitive direction. (See also *sensitive direction*.)

numerical control system: a special-purpose computer that processes primarily numeric data to control the movements and functions of a machine to which it is connected.

optical polygon: an optical element composed of a number of plane surface mirrors arranged to form a regular polygon.

outlier: a measured value that is greater than +2 times the repeatability or less than −2 times the repeatability from the average of all data values for the same quantity in the sample, where the repeatability of the machine is as defined in para. 7.2.7.

parametric: for the purposes of this Standard, refers to the measurement of any of the geometrical errors of a machine. These include, for example, angular errors, straightness errors, spindle errors, and alignment errors such as parallelism and squareness.

part: in a dimensional or geometric measurement process, the physical object for which a dimension is to be determined. (See also *workpiece*.)

part coordinate: the Cartesian (X, Y, Z) coordinate system in which the part is defined and in which the tool coordinates are specified.

part programming, computer-aided: the preparation of a part program to obtain a machine program using a computer and appropriate processor and post-processor.

[3] It is a requirement of this Standard that nominal differential expansion corrections always be made. See para. 7.2.4 for details.

part-trace test: a test that consists of cutting a part and then replacing the cutting tool with a displacement indicator (usually an LVDT) and repeating the original tool path indicating against the part with the spindle off.

performance test: any of a number of test procedures that are used to measure machine performance.

periodic error: an error in the linear or angular positioning of a machine that is periodic over an interval which normally coincides with the natural periodicity of the machine scales. 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.

pitch: the angular motion of a carriage, designed for linear motion, about an axis perpendicular to the motion direction and perpendicular to the yaw axis.

play: a condition of low or zero stiffness over a limited range of displacement due to clearance between members of the structural loop.

polar chart (PC) center: the center of the polar chart.

polar profile center: a center derived from the polar profile. In this Standard, the least-squares circle (LSC) center is used.

positional deviation: see *deviation of position*.

positioning control system: a numerical control in which

(a) each numerically controlled motion operates in accordance with instructions that specify only the next required position

(b) the movement in the different axes of motion are not necessarily coordinated with each other and may be executed simultaneously or consecutively

(c) velocities are not specified by the input

positioning mode: a mode of operation of an NC or CNC system that performs in accordance with the definition of a positioning control system.

probe: in this Standard, a device that establishes the location of the movable components of a machine tool relative to a measurement point. Three types of probes are discussed in this Standard.

nulling probe: a probe that, in reference to a workpiece, gives a signal which causes the machine to be driven to a position that will null the probe reading.

proportional probe: a probe that gives a signal proportional to a displacement of the probe from its free position.

switching probe: a probe that gives a binary signal as a result of contact with or being in proximity to a workpiece.

probe approach distance: the distance of approach to the part at which the machine traverse speed is reduced to the probe approach rate for measurement.

probe approach rate: the nominal speed of approach of the probe toward the part during the acquisition of data.

probe cycle: a fixed cycle using a probe.

probe lobing: a systematic error in the measuring accuracy of probing systems such that a measured value depends on the displacement direction of the probe tip.

pure radial motion: the concept of radial motion in the absence of tilt motion.

quadrant photodiode: a photodetector, used for measuring displacements in two dimensions, composed of four separate photodetectors arranged in a form that resembles the quadrants of a circle.

radial deviation: the deviation in radial direction between the actual path and the nominal circular path, where the center of the nominal path is obtained from either one of the following:

(a) the centering of the measuring instruments on the machine tool

(b) the least-squares centering analysis for a full circle only

radial error motion: error motion of a rotary axis perpendicular to the axis average line and at a specified orientation angle (see Fig. 4-1).

radial runout: the maximum reading obtained from a displacement sensor when the displacement sensor is set to read in the radial direction against a part rotated in a spindle. Customarily the spindle rotation is at low speed.

radian: the 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.

range: the difference between the maximum and minimum values of a set of measurements of nominally the same quantity.

reference coordinate axes: mutually perpendicular X, Y, and Z axes fixed with respect to an object.

relative vibration: for the purposes of this Standard, the nonzero-frequency relative motion between the position of a nominal tool and a nominal workpiece.

repeatability: for the purposes of this Standard, a measure of the ability of a machine to sequentially position a tool with respect to a workpiece under similar conditions. Repeatability is defined on a per-axis basis (see para. 7.2.7).

resolution: the lowest increment of a measuring device. On a digital instrument, the least significant bit.

retroreflector: an optical element with the property that an input light beam is reflected to return along the same angle as it was incident.

reversal deviation of angular error, B_{ae}: the maximum of the absolute reversal values at all target positions along a linear axis when measuring angular error. Computed similarly to the reversal value of an axis.

reversal value (error) at a position, B_i: the value of the difference between the mean unidirectional deviations obtained from the two directions of approach.

$$B_i = x_i\uparrow - x_i\downarrow$$

reversal value of an axis, B: the maximum of the absolute reversal values, $|B_i|$, at all target positions along or around the axis.

$$B = \max.\,(|B_i|)$$

roll: the angular motion of a carriage, designed for linear motion, about the linear motion axis.

rotary axis: any motion axis of a machine whose function is to provide a rotary motion either for the purposes of positioning or for moving a part or a tool to provide sufficient surface speed for cutting (i.e., a spindle). In this Standard, three types of rotary axes are defined.

rotary machining axis: a rotary axis where the axis can be used to provide continuous-path contour cutting in a rotary direction.

rotary positioning axis: a rotary axis that allows the rotation of a part into a new position for the purposes of cutting only; that is, this axis is not used to provide continuous, contour cutting, but only to reposition different faces of the part for the purpose of metal removal.

spindle: a device that provides an axis of rotation for the purposes of rapidly rotating a part or a tool to provide sufficient surface speed for cutting operations.

runout: the total range of displacements measured by an instrument sensing against a moving surface or moved with respect to a fixed surface.

safe operating temperature range: the temperature range at which a machine tool may be expected to operate without physical damage to the machine or its support systems (i.e., computers, controllers, etc.).

scale: the part of a transducer system that provides the linear or rotary position of a machine axis. For the purposes of this Standard, the transducer system could be a line scale, inductive scale, a shaft encoder, or any type of linear or rotary positional measuring device. Where temperature is mentioned in this Standard with respect to a scale, it refers to the temperature of the material that comprises the portion of the scale that establishes the unit of length. For example, in a line scale, it refers to the matrix on which the lines have been deposited; for a lead or ball screw, it refers to the temperature of the material composing the screw itself.

sensitive direction: the direction where relative motion between the tool and the workpiece causes one-for-one form errors to be cut into the workpiece. On lathes the error motion of the main spindle must be considered to be in the fixed sensitive direction. The error motions of tool spindles are in the rotating sensitive direction. Two types of sensitive directions are recognized.

fixed sensitive direction: the workpiece is rotated by the spindle, and the point of machining or gaging is fixed.

rotating sensitive direction: the workpiece is fixed, and the point of machining or gaging rotates with the spindle.

NOTE: A lathe has a fixed sensitive direction; a jig borer has a rotating sensitive direction. With a fixed sensitive direction, the reference coordinate axis is fixed; with a rotating sensitive direction, the reference coordinate rotates with the spindle.

sensor: a generic term used for an indicator that senses a particular physical quantity. In this Standard, the term sensor is normally used to mean a displacement indicator. (See also *displacement indicator*.)

sensor nest: a group of more than one sensor assembled together in a stable fixture to allow measurement in more than one direction.

sequence number: a number identifying blocks or a group of blocks in a machine program.

settling time: the time required between contact of a proportional probe with a measurement point and the time at which valid data may be taken.

significant mean temperature change: the change in the mean ambient temperature surrounding a machine that, in the Supplier's judgment, will cause sufficient degradation in machine performance such that performance evaluation (section 7) should be repeated.

soak out: one of the characteristics of an object is that it has a thermal "memory." When a change in environment is experienced, such as occurs when an object is transported from one room to another, there will be some period of time before the object completely "forgets" about its previous environment and exhibits a response dependent only on its current environment. The time elapsed following a change in environment until the object is influenced only by the new environment is called the soak-out time. After soak out, the object is said to be in equilibrium with the new environment. In cases where an environment is time variant, the response of the object is also a variable in time.

socket: a spherical cup that allows the accurate repositioning of one end of a telescoping ball bar.

specific power or specific force: the power or force required for the removal of a unit volume of a particular material per unit time in cutting.

specification zone (SZ): for the purposes of this Standard, the value specified in a machine specification for the result of a particular test.

spindle: see *rotary axis*.

tool spindle: a spindle whose purpose is to rotate a cutting tool to remove material from a workpiece.

work spindle: a spindle whose purpose is to rotate a workpiece to provide sufficient surface speed for the purposes of material removal by cutting.

spindle speed: the rate of rotation of a machine spindle, usually expressed in revolutions per minute.

spindle speed function: a command defining the spindle speed.

squareness: a plane surface is "square" to an axis of rotation if coincident polar profile centers are obtained for an axial and face motion polar plot at different radii. Also, for linear axes, the angular deviation from 90 deg measured between the best fit lines drawn through two sets of straightness data derived from two orthogonal axes in a specified work zone.

staging: the moving of a gage from a first position to a second position such that a series of measurements started in the first position may be continued in the second position.

standard uncertainty due to the environmental temperature variation error: the environmental temperature variation error (*ETVE*) is measured as the range of the total drift of the instrument/master/part system as described in section 6. To convert this to a standard uncertainty according to ISO Guidelines, it is assumed that this environmental error is uniformly distributed within this range for a given measurement. The resulting standard uncertainty, u_{ETVE}, is then given by

$$u_{ETVE} = \sqrt{\frac{ETVE^2}{12}}$$

standard uncertainty (of a quantity, q), u_q or u(q): given a set of n measurements of a quantity, q, the standard uncertainty in q is given as

$$u_q = u(q) = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(q_j - \overline{q})^2}$$

where

q = the mean of the set of measurements
q_j = the individual measurements

This quantity is also sometimes called the estimator of the standard uncertainty and commonly symbolized by s_q.

static error motion measurement: a special case of spindle error motion measurement in which the error motion is sampled with the spindle at rest at a series of discrete rotational positions.

steering mirror: a mirror used to steer the laser beam to the appropriate angle in the diagonal displacement measurement test.

step gage: a gage comprising a rigid bar with calibrated steps used for determining accuracy of distance measurements in a direction of linear motion.

stiffness: the reciprocal of compliance. Usually defined statically as a ratio of the applied force to the displacement of a machine element. For the purposes of this Standard, stiffness is defined with respect to the structural loop.

straightness error: the deviation from straight-line movement that a displacement indicator positioned perpendicular to a slide direction exhibits when it is either stationary and reading against a perfect straightedge supported on the moving slide, or moved by the slide along a perfect straightedge that is stationary.

NOTE: In some documents, the moving indicator against the stationary straightedge is called lateral deviation.

structural loop: an assembly of mechanical components that maintain relative position between specified objects. A typical pair of specified objects is the cutting tool and the workpiece; the structural loop would include the spindle shaft, the bearings and housing, the slideways and frame, possibly the foundation, and the tool and work-holding fixtures (see Fig. 4-3).

Supplier: a party who contracts, or indicates readiness to contract, to supply a machine tool to a User. Also called a vendor in some ISO documents.

synchronous error motion: another term for average error motion, used in spindle testing.

systematic error: the mean that will result from an infinite number of measurements of the same measurand carried out under repeatability conditions, minus a true value of the measurand.

NOTE: Systematic error is equal to error minus random error; like true value, systematic error and its causes cannot be completely known. For a measurement instrument, systematic error is often called bias.

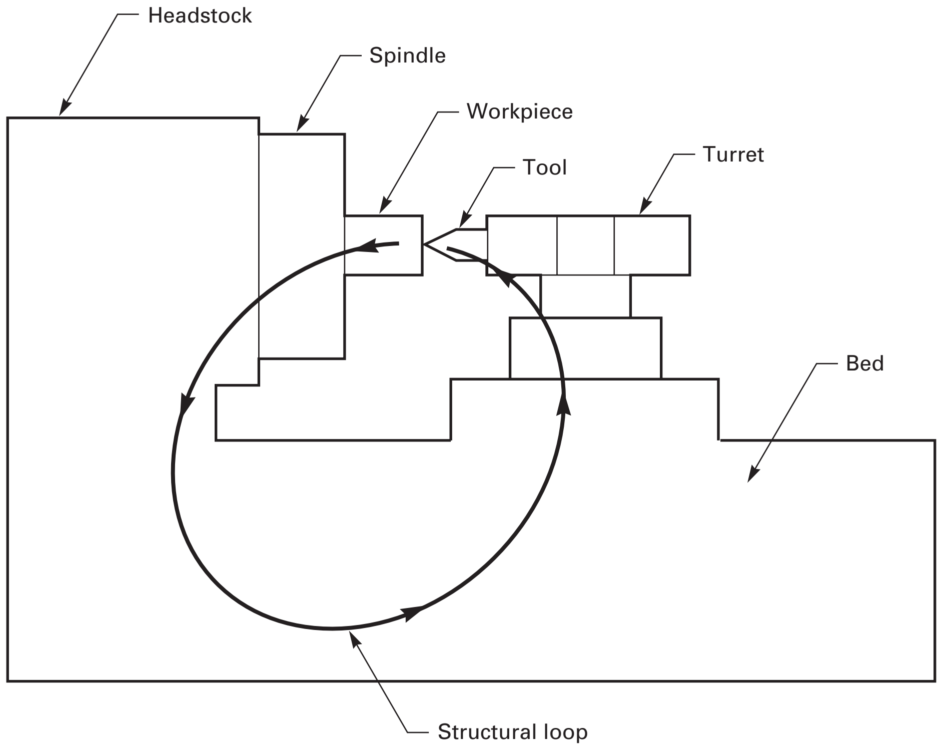
target position, P_i (i = 1 to m): position to which the moving component is programmed to move. The subscript i identifies the particular position among other selected target positions along or around the axis.

temperature at a point: when discussing a body that does not have a single uniform temperature, it is necessary to refer in some manner to the distribution of temperature throughout the body. Temperature at a point in a body is assumed to be the temperature of a very small volume of the body centered at that point. The material of which the body is composed is assumed to form a continuum.

temperature of a body: when the differences between the temperatures at all points in a body are negligible, the body is said to be at a uniform temperature. This temperature is then the temperature of the body.

instantaneous average temperature of a body: when the body is not at a uniform temperature at all points, but it is desirable to identify the thermal state of the body by a single temperature, the temperature that represents the total heat stored in the body may be used. When the body is homogeneous, this is called the instantaneous average temperature of the body. (This temperature is the average, over the volume of the body, of all point temperatures.)

Fig. 4-3 An Example of a Structural Loop Showing a Workpiece, Spindle, Machine Bed, and Tool



time-mean temperature of a body: the average of the average temperature of a body, over a fixed period of time. The fixed period is selected as appropriate to the measurement problem.

thermal error index (TEI): in some cases, particularly in factories, dimensional measurements are made at other than 20°C (68°F), corrections are not made for the nominal differential expansion between standard and part, and the environment is constantly changing. In such a case, there is a systematic error that is coupled with the thermal uncertainty index to give an overall estimate of the error made in manufacturing or measurement. Since the nominal differential expansion correction is a systematic error, it is not subject to statistical analysis. This Standard defines, in this particular case, a thermal error index that estimates the maximum possible percentage error that would be made in these conditions as the sum of the absolute value of the uncorrected differential expansion, *NDE*, and the expanded thermal uncertainty, $U_T(L)$, divided by the specification zone, *SZ*. That is

$$TEI = \{[|NDE| + U_T(L)]/SZ\}(100\%)$$

Here, *SZ* is the desired specification zone on the measurement.

thermal expansion: the difference between the length (or volume) of a body at one temperature and its length (or volume) at another temperature is called the linear (or volumetric) thermal expansion of the body.

thermally induced drift: drift caused by variations in the thermal environment or internal heat sources of the machine.

tilt error motion: error motion in the angular direction relative to the reference linear axis [see Fig. 4-1, illustrations (e) and (f)].

tolerance: for the purposes of this Standard, a range on either side of a desired dimension of a manufactured part or a gage. In some cases, tolerances are expressed as plus (+) or minus (–) a single value. That value is called the tolerance.

tool change under program control: the process on a machining center or work center where the cutting tool is exchanged, usually with its tool holder, for another tool under control of the part program (i.e., without human intervention).

tool function: a command identifying a tool.

tool (fixture) offset: a relative displacement that is applied to an axis of a machine for a specified portion or the whole of a program and causes a displacement in that axis only in the direction determined by the sign of the offset value.

NOTE: For example, the tool offsets are typically applied in pairs of independent values for *X*, *Y*, and *Z* for the tool tip location on turning machines, and individually or in combination on milling machines.

tool (length) offset: an incremental displacement in the axial direction of the tool.

NOTE: This is typically used on milling and drilling machines.

tool-setting system: an instrument supplied with a CNC lathe or turning center that allows for the measurement of X or Z tool offsets, or both, as part of a computer-controlled cycle. Sometimes called a tool-setter, a tool-gage, or a tool-setting probe(s).

tow-along carriage: a machine carriage that is positioned with the mechanical assistance of another machine carriage, thus the term tow-along.

transducer: any device that converts a measurand of one physical quantity into another physical parameter. For example, a strain gage that converts strain to an electrical signal would be considered a transducer. For the purposes of this Standard, most transducers discussed are displacement transducers.

transducer drift check: an experiment conducted to determine the drift in a displacement transducer and its associated amplifiers and recorders when it is subjected to a thermal environment similar to that being evaluated by the drift test itself. The transducer drift is the sum of the "pure" amplifier drift and the effects of the environment on the transducer, amplifier, etc. The transducer drift check is performed by blocking the transducer and observing the output over a period of time at least as long as the duration of the drift test to be performed. Blocking a transducer involves making a transducer effectively indicate on its own frame, base, or cartridge. In the case of a cartridge-type gage head, this is accomplished by mounting a small cap over the end of the cartridge so the plunger registers against the inside of the cap. Finger-type gage heads can be blocked with similar devices. Care must be exercised to ensure that the blocking is done in such a manner that the influence of temperature on the blocking device is negligible.

transfer function: for the purposes of this Standard, the ratio of the relative vibration between tool and workpiece to the input variable force acting between tool and workpiece as a function of frequency. The transfer function has both amplitude and phase (or a real and an imaginary part).

turning center: a CNC lathe with at least one workholding spindle (work spindle). Such a machine shall have a means of automatically introducing various tools to the workpiece by means of either an indexable turret or automatic tool-changer. In the most general case, such a turning center may also have "live" tooling.

type test: a machine performance test that is likely to yield nearly the same results for all machines of the same model or type, as long as the machine has been assembled to specification.

uncertainty of nominal coefficient of expansion: the uncertainty in the nominal thermal expansion coefficient of a body shall be denoted $u(\alpha)$ for the object being calibrated or measured and $u(\alpha_s)$ for the standard. This value, like that of α itself, must be an estimate. (See para. 6.2.2.2 for further explanation.)

uncertainty of nominal differential expansion (UNDE): the square root of the sum of the squares of the uncertainties of nominal expansion of the object to be calibrated or measured and the standard.

$$UNDE = \sqrt{(UNE)^2 + (UNE)_S^2}$$

uncertainty of nominal expansion (UNE): the uncertainty in the value chosen for the nominal expansion. It is determined by

$$UNE = L(T - 20)u(\alpha)$$

uncertainty of temperature measurement: the uncertainty associated with the measurement of the temperature of a body or the ambient environment. This uncertainty comes from the calibration of the thermometer, the thermometer-mounting procedures, and instrumental variations. (See para. 6.2.2 for further explanation.)

undulations per revolution (UPR): a term commonly used when referring to spindle error testing. It refers to the highest order (frequency) sine wave detected in a spindle error analysis (highest harmonic of the spindle speed). The bandwidth of a sensor used for spindle error detection should be several times higher than the product of the UPR and the revolutions per second of the spindle being tested. (See ANSI B89.3.4M for a more detailed explanation.)

unidirectional: refers to a series of measurements in which the approach to a target position is always made in the same direction along or around the axis. The symbol ↑ signifies a parameter derived from a measurement made after an approach in the positive direction, and ↓ one in the negative direction (e.g., $x_{ij}\uparrow$ or $x_{ij}\downarrow$).

unidirectional accuracy of positioning of an axis, $A\uparrow$ or $A\downarrow$: the range derived from the combination of the unidirectional systematic deviations and the estimator of the standard uncertainty of unidirectional positioning using a coverage factor of 2.

$$A\uparrow = \max.\ (x_i\uparrow + 2s_i\uparrow) - \min.\ (x_i\uparrow - 2s_i\uparrow)$$

and

$$A\downarrow = \max.\ (x_i -\downarrow + 2s_i\downarrow) - \min.\ (x_i\downarrow - 2s_i\downarrow)$$

unidirectional repeatabilities of angular error, $R_{ae}\uparrow$ and $R_{ae}\downarrow$: the maximum value of repeatability of angular error at any position along a linear axis. Computed similarly to unidirectional repeatability of positioning of an axis.

unidirectional repeatability of positioning at a position, $R_i\uparrow$ or $R_i\downarrow$: range derived from the expanded uncertainty of unidirectional positional deviations at a position, using a coverage factor of 2.

$$R_i\uparrow = 4s_i\uparrow$$

and

$$R_i\downarrow = 4s_i\downarrow$$

unidirectional repeatability of positioning of an axis, $R\uparrow$ or $R\downarrow$: the maximum value of the unidirectional repeatabilities of positioning at any position along or around an axis.

$$R\uparrow = \text{max.}\ (R_i\uparrow)$$

and

$$R\downarrow = \text{max.}\ (R_i\downarrow)$$

unidirectional systematic angular error, $E_{ae}\uparrow$ and $E_{ae}\downarrow$: the difference between the algebraic maximum and minimum of the mean unidirectional angular errors for both approach directions, at any position along a linear axis, determined using the procedures and under the conditions specified in this Standard. Computed similarly to unidirectional systematic deviation of positioning of an axis.

unidirectional systematic deviation of positioning of an axis, $E\uparrow$ or $E\downarrow$: the difference between the algebraic maximum and minimum of the mean unidirectional positional deviations for both approach directions (i.e., $x_i\uparrow$ or $x_i\downarrow$), at any position along or around the axis, determined using the procedures and under the conditions specified in this Standard.

$$E\uparrow = \text{max.}\ (x_i\uparrow) - \text{min.}\ (x_i\uparrow)$$

and

$$E\downarrow = \text{max.}\ (x_i\downarrow) - \text{min.}\ (x_i\downarrow)$$

unidirectional total(s) angular error, $A_{ae}\uparrow$ and $A_{ae}\downarrow$: the range derived from the combination of the unidirectional systematic angular error and the estimator of the standard uncertainty of unidirectional angular error, using a coverage factor of 2. Computed similarly to unidirectional accuracy of positioning of an axis.

User: a party who contracts to accept a machine tool from a Supplier.

vibration amplitude: the size (amplitude) of a given frequency component of a vibration spectrum. Common practice is to express the vibration amplitude in either displacement or acceleration units. (See also *broadband vibration amplitude.*)

volumetric performance: the ability of a machine tool to perform the intended multiaxis functions anywhere within the volume defined by the maximum travel of the machine linear axes.

wobble plate: a mechanical device that allows the tilting (wobbling) of a test fixture by adjustment screws.

workpiece: an object to be turned, machined, or measured.

work zone: the working (machining) volume of a machine as specified by the Supplier. More than one work zone may be specified for a given machine, and specification zones may be specified separately for each work zone.

yaw: the angular motion of a carriage, designed for linear motion, about a specified axis perpendicular to the motion direction. In the case of a carriage with horizontal motion, the specified axis shall be vertical unless explicitly specified. For a carriage that does not have horizontal motion, the axis shall be explicitly specified.

5 ENVIRONMENTAL SPECIFICATIONS

5.1 General

It shall be the responsibility of the User to provide an acceptable environment for performance testing of the machine tool at the installation site. Environmental parameters recommended in this Standard are given in Form 2 of section 1. The environment shall be considered acceptable if the requirements of sections 5 and 6 are met. The User shall be responsible for conducting all environmental tests at the installation site. The Supplier shall have a right to witness all tests. The Supplier shall, on request, supply test equipment as specified in section 9, and support for equipment and tests, at a price to be negotiated between the Supplier and the User.

5.2 Temperature

5.2.1 General. Temperature has a significant influence on the accuracy of machine tools and measuring instruments, and its effects are often misunderstood. The provisions of ANSI B89.6.2 form a part of this Standard, but interpretation is needed for application to machine tools. ANSI 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 (see para. 6.2) be a reasonable percentage of the specification zone. Acceptability of a thermal environment is specified in terms of its effects on the machine.

5.2.2 Thermal Environment Guidelines. The Supplier shall offer guidelines regarding what thermal environment should be acceptable for the machine. 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 machine, as listed in Form 2. The User shall be informed that the conformance to such guidelines does not guarantee an acceptable machine 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 Supplier. If the User chooses not to conform to the guidelines supplied, the tests of environmental sensitivity (see section 6) may lead to an increase in the acceptable specification zone for a given performance test. In this second case, the degradation in performance shall be solely the responsibility of the User.

5.2.2.1 Time Variations. Particular attention should be given to time variations of temperature, although this Standard does not offer specific guidelines in this area. Machine tools are composed of numerous elements, each with different thermal behavior. For example, the ram of a machine may have a short thermal time constant and the bed of the machine a very long thermal time constant. Therefore, when the machine is in an environment with time variations of the temperature, the resulting response in terms of spindle motion with respect to the table can be quite complex. Furthermore, when a part is being machined, there are other time constants due to the part and the part fixture, which also serve to complicate this problem. Efforts should be made to keep the time variations of temperature either much faster than the fastest time constant in the system or to reduce them to acceptable levels.

5.2.2.2 Thermal Radiant Energy. The machine shall not be exposed to direct sunlight or other powerful radiant energy sources. Other direct radiant energy sources (e.g., fluorescent lighting, radiant heaters, and high-intensity lamps) shall be as far from the machine as possible, to reduce their effects on the machine's thermal behavior. Where this distance requirement is impractical, indirect lighting designed for diffuse reflection and increased path length shall be used. Users and Suppliers should be aware that lights in the machine enclosure supplied by the Supplier may sometimes have unwanted thermal influence.

5.3 Seismic Vibration

5.3.1 General. The support surface (floor, foundation, isolation pad, etc.) upon which the machine will be mounted can have motion induced as a result 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 machine, has a degrading effect on the overall accuracy and repeatability of a machine tool by causing relative motions between the tool and the workpiece. Improperly installed or designed isolators can also cause excessive motions. In addition, certain excessive motion amplitudes can cause damage to the machine. Several major American corporations have developed extensive standards for vibration analysis on machine tools. These standards have been conceived of for purposes that are primarily diagnostic. This Standard in no way supersedes these other standards.

5.3.2 Responsibilities. The User shall be responsible for site selection, environmental shock and vibration analysis, and additional special isolators required to ensure compliance with the maximum permissible vibration levels specified by the Supplier. All questions of compliance shall be determined at the interface between the support system provided by the User and the machine system provided by the Supplier. Functional tests for measuring the relative vibration are described in para. 6.3.

5.3.3 Seismic Vibrational Parameters. The Supplier shall provide, as part of the machine specification, a statement of the acceptable vibration spectra at the User–Supplier interface. (This interface may vary depending on details of the contractual arrangement between the Supplier and the User. For example, if the machine is supplied with isolators, the interface will be between the foundation and those isolators. However, if the User provides an isolation system from another source, the interface shall be at the connection between those isolators and the machine. In any event, it is a requirement of this Standard that the appropriate interface be defined as part of the machine specification.) This statement can contain a complete description of the allowable vibration displacement amplitude as a function of frequency for each vector component of the vibration spectrum, or can be simply a limit on the total vibrational displacement amplitude over a specified frequency range. In lieu of vibration displacements, accelerations or velocities shall also be acceptable. The sample specification form, Form 1, allows for the displacement options. Users desiring to specify a machine in terms of accelerations or velocities shall create forms and test procedures in equivalent detail. The statement of acceptable vibration spectra applies with the machine in place. It is recognized that in some highly atypical cases it is physically possible that the vibration spectrum of the foundation or floor may be significantly altered by the installation of the machine, particularly large or very heavy machines. In such cases, the party (User or Supplier) contracted to supply the vibration isolation system shall be responsible for achieving an acceptable vibration environment for the machine.

5.4 Electrical

5.4.1 General. The electrical power supplied to a machine can have an effect on its ability to perform accurate and repeatable machining operations. This is especially true with today's modern machines, which typically incorporate electronic and electrical components that can be sensitive to voltage variations. For this reason, it is necessary to characterize the machine in the range of the electrical environment in which it will operate. It is also necessary to know the operating range in which the machine was designed to operate.

5.4.2 Responsibilities. It shall be the responsibility of the User to provide electrical power meeting typical requirements as specified by current standards. The Supplier shall be responsible for providing a specification for which the equipment will operate properly.

5.4.3 Electrical Parameters. The Supplier shall provide, as part of the machine specification, a statement of the steady state requirements, including voltage(s), frequency, and amperage for the machine; allowable short- and long-term root mean square (RMS) voltage variations; and allowable transient voltages expressed in percent of nominal voltage.[4] These parameters are listed in the sample specification form, Form 1.

5.5 Utility Air

5.5.1 General. Air supplies to machines can affect their accuracy and useful working life. Temperature variations in the utility air can generate thermal gradients in the machine; and particulates, oils, and water can degrade bearing performance, increase friction, and accelerate wear.

5.5.2 Responsibilities. For all machines requiring utility air, it shall be the responsibility of the User to supply utility air meeting the requirements specified by the Supplier.

5.5.3 Specifications. For utility air, the Supplier shall provide specification for all air parameters required for the proper operation and maintenance of the machine to be supplied. For air-bearing machines, these should include mean temperature, permissible temperature variation, pressure, and pressure variations. Further, on some machines, the acceptable dew point and the particulate content shall be specified. These parameters are listed in the environmental specification form, Form 2. Air quality parameters, such as particulate, oil, and water content, are the sole responsibility of the User, although the Supplier shall offer guidelines.

5.6 Other

5.6.1 General. Just as air supplies can affect the accuracy and useful working life of a machine, so can hydraulic supplies, coolant supplies, foundations, and the like. For example, temperature variations caused by pumping can generate large thermal gradients in the machine, and, of course, particulates, oil, and water can degrade machine performance and accelerate wear. Large machine tools also often rely on a User-supplied foundation for their stiffness, and improperly installed foundations can significantly increase a machine's compliance. Both the Supplier and the User recognize the importance of foundations when the machine design utilizes the foundation as an integral part of the structure. It should be anticipated that test data collected at the Supplier or User facility will likely be affected if static stiffness tests or horsepower cuts are attempted and the foundation at the Supplier or User facility does not comply to the foundation specification, which was generated as part of the machine design. In new installations it is particularly important to pay attention to the inherent instability and cure time of hydraulic concrete, as this material can lead to unstable machine structures if improperly installed. For further discussions related to foundations, see Nonmandatory Appendix F.

5.6.2 Responsibilities. For all machines requiring hydraulics or other services, it shall be the responsibility of the Supplier to provide for proper filtering and temperature control such that these services do not degrade machine performance. If, for some reason, hydraulics, coolants, or other services are to be supplied by the User, then the User shall be responsible for meeting all requirements as specified by the Supplier. In the case of foundations, the responsibility for foundation design and installation shall be negotiated as part of the original contract, but foundation specifications, including construction drawings (where applicable), shall be supplied by the Supplier.

6 ENVIRONMENTAL TESTS

6.1 General

As stated previously, it is the philosophy of this Standard that the environment is the responsibility of the machine User. However, if the User follows the guidelines supplied by the machine Supplier, that responsibility reverts to the machine Supplier. The following tests are designed to reflect that philosophy, but if because of economic or other considerations the machine User chooses not to conform to the Supplier's environmental specifications, this Standard provides a derating procedure on the machine performance. This is particularly true in the case of nonconformance of the thermal environment.

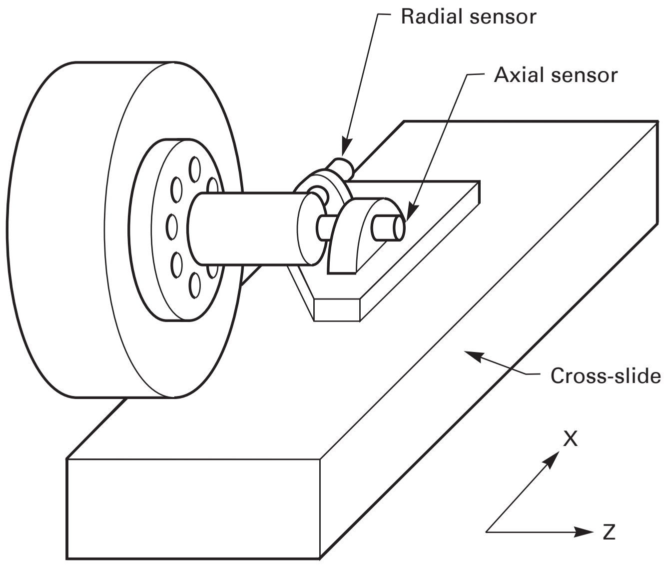
In general, these environmental tests should be performed before the performance tests to verify the suitability of the environment for machine testing. However, for machines with large specification zones, the effects of the environment may be deemed acceptable by the Supplier without the testing specified below. In these cases, specific environmental tests may be deferred. If measurements on the machine are within the specified specification zones in the performance tests, the deferred tests may be eliminated. If the performance fails, the environmental tests may be performed as part of the diagnostic process. The thermal computations (see para. 6.2.2) should not be deferred or eliminated.

6.2 Environmental Thermal Test and Computations

The thermal test shall be performed under conditions equivalent to those pertaining during machine performance tests (see section 7).

[4] Percentage of nominal voltage is the percentage of the remaining voltage. For example, a reduction in voltage of 15% would be expressed as 85% of nominal voltage.

Fig. 6.2.1.4-1 Setup Showing Two Displacement Sensors Used to Measure the Environmental Temperature Variation Error (*ETVE*) Between a Nominal Tool Location and a Work Spindle



6.2.1 Environmental Temperature Variation Error, *ETVE*. This test is designed to measure the response of a machine to its ambient environment, and not the response of a machine to its internal heat sources. (This test shall therefore be run with the machine in a start-up, cold condition, unless some other agreement is reached between the User and the Supplier. Further tests to determine the effects of machine-induced thermal behavior are described in para. 7.7.)

If the Supplier elects to defer the *ETVE* test, the value of *ETVE* shall be set to zero for computing *TEI*. If the *ETVE* test is performed later, then the measured value shall be used after the test.

ETVE shall be determined by a drift test. The choice of displacement sensor for this test depends on the environment. Any displacement-measuring device meeting the requirements of section 9 may be used.

6.2.1.1 Equipment. The following equipment should be used:

(*a*) test artifact
(*b*) two (or three) displacement sensors
(*c*) gage-holding fixture
(*d*) data-recording system or software (as required)
(*e*) air temperature sensor
(*f*) metal surface-temperature sensor

6.2.1.2 Machine Warm-Up

(*a*) The machine shall be stabilized to "cold machine" condition. All systems that normally operate while the machine is idle (including systems to control effects of environmental temperature) shall be operating.

(*b*) To detect the effects of spatial temperature gradients across the machine work volume, the location of the machine axes during warm-up shall be as far as possible from the position selected by the machine Supplier for the *ETVE* test.

6.2.1.3 Test Location

(*a*) The location for the *ETVE* test may be specified by the machine Supplier. The description shall include the location of the test artifact with respect to the spindle and the position of each axis.

(*b*) The default location of the test artifact shall be on the spindle centerline, approximately 150 mm (6 in.) from the spindle face.

6.2.1.4 Measurement Procedure. The following procedure should be used (see Fig. 6.2.1.4-1; for the procedure using three displacement sensors, see Fig. 6.2.1.4-2):

Step 1: Place the test artifact in the machine spindle.

Step 2: Fix the gage holder and displacement sensors to the turret or tool holder and align them to the axes.

Step 3: Place the air temperature sensor near the center of the machine work volume.

Step 4: Place the surface temperature sensor in a location to assess an estimate of the average temperature of the machine near the working area.

Step 5: Adjust the machine axes and displacement sensors so that all displacement sensors are near the centers of their ranges and positive reading occurs for relative motion of the displacement sensor toward the artifact.

Step 6: Check for setup hysteresis in each direction, as discussed in para. 7.1.4.2.

Step 7: Ensure that electronic test equipment, computers, etc., do not touch the machine. These shall be located as far as possible from the machine tool for the duration of the test.

Step 8: Place the machine in the "feed-hold" condition and zero the indicators electronically (if applicable).

Step 9: Ensure the setup has thermally stabilized from the effects of handling before recording data.

Step 10: Record data from the displacement sensors and two temperature sensors at intervals of 60 s or less. The test period should be at least 4 h. However, the minimum recommended test time is 24 h. See Fig. 6.2.1.4-3

Normal activities surrounding the machine shall continue during the test.

6.2.1.5 Data Analysis

(a) The thermal drift in the X direction, $ETVE_X$, shall be taken as the maximum range of readings from either displacement sensor in this direction for any 4-h period over the duration of the test.

(b) The thermal drift in the Z direction, $ETVE_z$, shall be taken as the maximum range of readings from either displacement sensor in this direction for any 4-h period over the duration of the test.

(c) Tilt about the Y direction (relative to the starting position) shall be calculated and recorded for each measurement interval. It is obtained by taking the difference between the two X-direction displacement sensors and dividing by the distance between them.

(d) The thermal drift of tilt about the Y direction, $ETVE_{YY}$, shall be taken as the maximum range of recorded tilts for any 4-h period over the duration of the test.

The standard uncertainty due to the environmental temperature variation error is given by

$$u_{ETVE} = \sqrt{\frac{ETVE^2}{12}}$$

The *ETVE* used in the equation above shall be the largest of the *ETVE*s measured by any displacement sensor for any spindle-and-turret combination and any axis direction on the machine.

See Fig. 6.2.1.4-3 for a graph of *ETVE* data.

6.2.1.6 *ETVE* Test, Five Displacement Sensors. It is also possible to measure the *ETVE* using a setup that has five displacement sensors reading against an appropriate test artifact. This test is appropriate for rotating-sensitive-direction tool spindles and also can be useful for observing angular tilts of a work spindle. Such five-sensor systems are also used in this Standard for the measurement of spindle errors. A setup showing five displacement sensors on the lathe is given in Fig. 6.2.1.6-1. Specifics of the test setup and analysis for the five-sensor *ETVE* test may be found in ANSI B5.54.

6.2.2 Thermal Computations. On all tests that measure machine accuracy, corrections shall be applied for the nominal differential expansion of machine scales, mechanical masters, and, if applicable, changes in the wavelength of the laser interferometer. These computations are described in the sections on the specific tests. Besides these corrections, it is a requirement of this Standard that the User also compute the expanded thermal uncertainty (with the *ETVE* equal to zero, if that test has been deferred). This expanded uncertainty shall be used to determine the suitability of the test environment. The test environment shall be considered acceptable if the expanded thermal uncertainty, as defined below, does not exceed 25% of the specification zone for any of the performance tests listed in Form 4. If the expanded thermal uncertainty exceeds 25% of the specification zone for a particular test in the table, the machine environment does not conform to the Supplier's guidelines, and the User chooses not to upgrade the environment, permissible specification zone limits for those tests shall be increased. The increase shall be equal to the amount by which the expanded thermal uncertainty exceeds 25% of the specification zone. The following equation shall apply:

$$\text{Permissible specification zone} = \text{specification zone} + [U_T(L) - 0.25 \text{ specification zone}]$$

If the expanded thermal uncertainty exceeds 25% and the machine environment conforms to the Supplier's guidelines, no derating of the permissible specification zones for the tests given in Form 4 shall be allowed. Methods for testing compliance of the thermal environment to the Supplier's guidelines are given in Nonmandatory Appendix C. The expanded thermal uncertainty shall be calculated for each performance test from the equation

$$\pm U_T(L) = \pm k u_{cT} = \pm 2 u_{cT}(L)$$

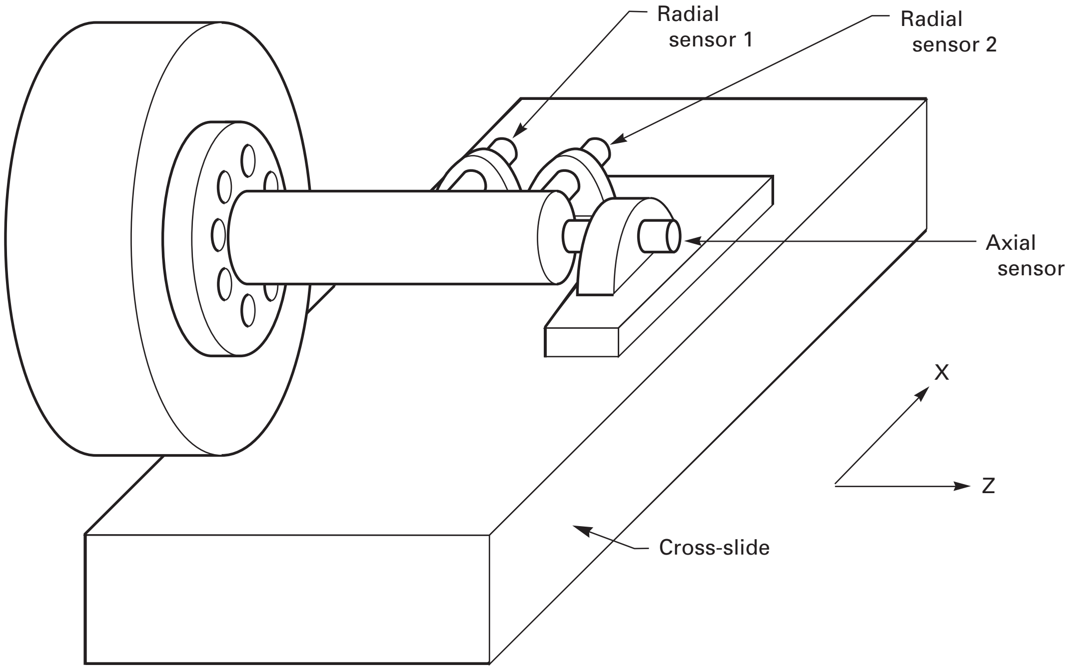
where u_{cT} is the combined standard thermal uncertainty for a given measurement and k is the coverage factor (which, for this computation, will be assumed to be 2).

Values in the equation are absolute values and should be taken as positive.

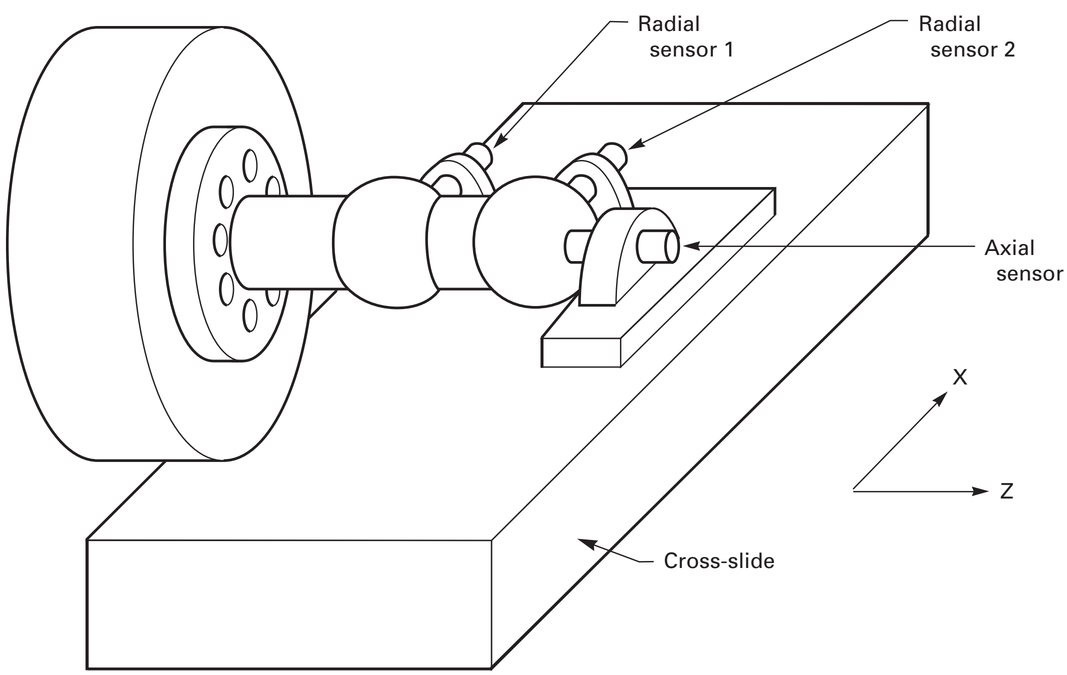
6.2.2.1 Combined Standard Thermal Uncertainty, u_{cT}. The combined standard thermal uncertainty is defined in section 4, Definitions, for the general case of a length measurement. For this Standard, it requires interpretation. The general form is given by

$$u_{cT}(L) = \sqrt{u_{ETVE}^2 + L_s^2(T_s - 20)^2 u^2(\alpha_s) + L^2(T - 20)^2 u^2(\alpha) + L_s^2 \alpha_s^2 u^2(T_s) + L^2 \alpha^2 u^2(T)}$$

Fig. 6.2.1.4-2 Setup Showing Three Displacement Sensors Used to Measure the Environmental Temperature Variation Error (*ETVE*) Between a Nominal Tool Location and a Work Spindle



(a)



(b)

Fig. 6.2.1.4-3 Graph of Environmental Temperature Variation Error (*ETVE*) Data

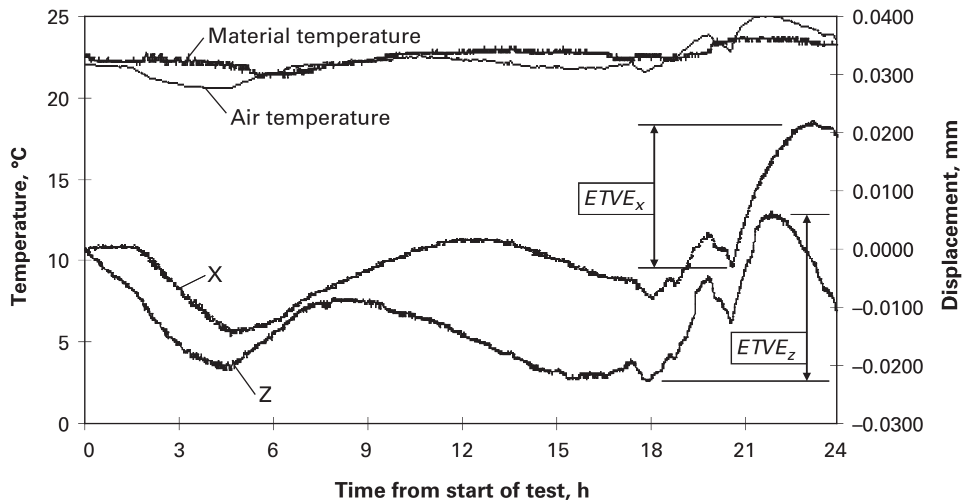


Fig. 6.2.1.6-1 Setup Showing Five Displacement Sensors Used to Measure the Environmental Temperature Variation Error (*ETVE*)

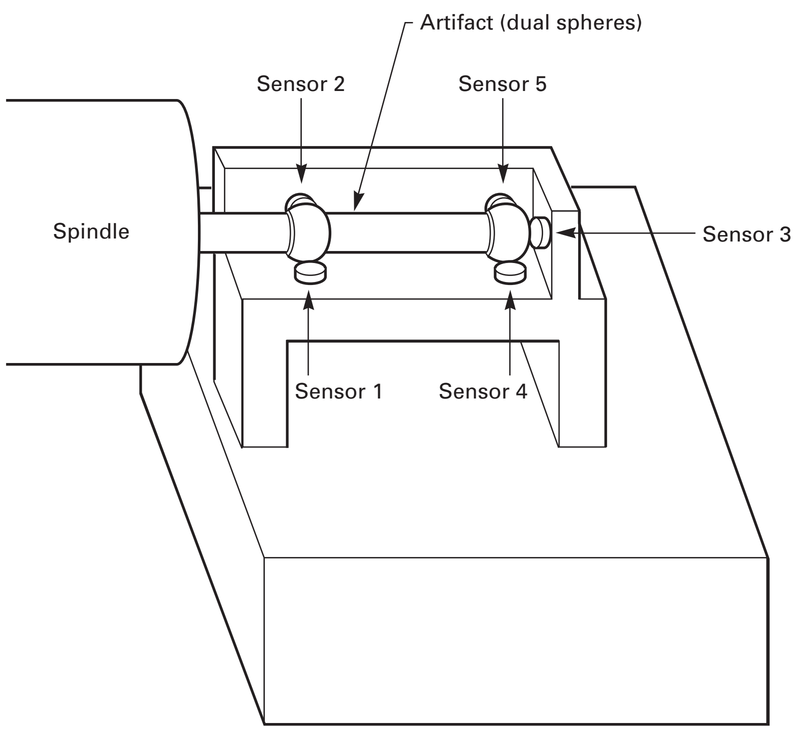


Table 6.2.2.1-1 Specification Zones Derated Due to an Excessive Expanded Thermal Uncertainty

Parameter	Lengths Used for Uncertainty Calculation	Paragraph
Linear positioning (per axis)	...	7.2
Bidirectional systematic deviation of positioning	$L = L_s$ = axis length	7.2.7.1
Bidirectional accuracy of positioning	$L = L_s$ = axis length	7.2.7.3
Unidirectional systematic deviations of positioning	$L = L_s$ = axis length	7.2.7.2
Unidirectional accuracies of positioning	$L = L_s$ = axis length	7.2.7.4
Thermal tests	...	7.7
Spindle thermal stability test	$L = L_s = 0$	7.7.2
Thermal drift of axis drives	$L = L_s$ = axis length	7.7.3
Composite thermal error	$L = L_s$ = ½ longest axis length	7.7.4
Circular tests	...	7.9
Circular deviations	Ball bar length or circular contour radius	7.9.5
Tool-setting system drift	$L = L_s = 0$	8.4
Linear measurement accuracy	$L = L_s$ = axis length	8.6.4

GENERAL NOTE: See Nonmandatory Appendix L.

where

L = the length being measured (usually, in machine tool applications, this is nominally the same as the length of the standard)

L_s = the length of the standard (calibrated gage or laser displacement)

T = the temperature of the machine scales, °C

T_s = the temperature of the standard, °C

$u(T)$ = the uncertainty in the measurement of the temperature of the machine scale

$u(T_s)$ = the uncertainty in the measurement of the temperature of the standard (air temperature in the case of the laser)

$u(\alpha_s)$ = the uncertainty of the nominal coefficient of expansion of the master [$u(\alpha_s) = 0$ for laser interferometers]

u_{ETVE} = the standard uncertainty due to the environmental temperature variation error. Tilt *ETVE* used for yaw specification zone (see Table 6.2.2.1-1)

α = the thermal expansion coefficient of the machine scale

α_s = the thermal expansion coefficient of the standard ($\alpha_s = 0.93 \times 10^{-6}$/°C for lasers)

6.2.2.2 Uncertainty of Coefficients of Expansion, $u(\alpha)$. The uncertainty in the nominal thermal expansion coefficient of a body shall be denoted $u(\alpha)$ for the part and $u(\alpha_s)$ for the standard. This value, like that of α itself, must be an estimate. Various methods such as the following can be used to make this estimate:

(a) The estimate may be based on the distribution found among results of actual experiments conducted on a number of like objects.

(b) The estimate may be based on the distribution found among published data.

(c) In the absence of other information, for the purposes of this Standard, the uncertainty in the nominal coefficient of expansion should be represented by a rectangular distribution with bounds of $\pm 0.1\alpha$. The standard uncertainty then becomes

$$u(\alpha) = 0.1\alpha/\sqrt{3}$$

$$u(\alpha_s) = 0.1\alpha_s/\sqrt{3}$$

Of the three possibilities given above, (a) is the recommended method.

Because the effects of inaccuracy of the estimate of the uncertainty are of second order, it is considered sufficient that good judgment be used.

Clearly the concept of thermal expansion coefficient of the standard does not directly apply to lasers. However, the wavelength of a laser is dependent upon the refractive index of air, and that refractive index is a function of temperature, as is the length of a material body. It can be shown that without loss of generality, the coefficient used to correct laser readings or changes in ambient temperature (0.93×10^{-6}/°C) can be used in the place of the coefficient of expansion when using lasers. To the level of accuracy currently required for machine tool calibrations, it is assumed that the uncertainty in this value is equal to zero.

6.2.2.3 Uncertainty of Temperature Measurement. When the temperature of a body is measured and there is an uncertainty associated with this measurement, this uncertainty comes from the thermometer calibration, thermometer mounting procedures, and instrumental variations. This uncertainty can be estimated by various methods, such as the following:

(a) The estimate may be based on the distribution found among results of actual measurements conducted on a number of like objects, using the same thermometers and the same procedures.

(b) The estimate may be based on the distribution found in published data regarding the use of such thermometers and specific procedures.

(c) The estimate may be made from prior judgment regarding the range of possible error. For the purposes of this Standard, in the absence of other information, temperature measurement uncertainty should be estimated as being represented by a rectangular distribution with bounds of ±1°C when using thermocouples and ±0.5°C when using thermistors or platinum resistance thermometers (RTDs).

For method(c), where the error is estimated by a rectangular (uniform) distribution, the standard uncertainty in temperature measurement is given by

$$u(T) = \sqrt{\frac{(a^{+} - a^{-})^2}{12}}$$

where

a^{+} = the upper range of the rectangular distribution
a^{-} = the lower range of the rectangular distribution

Note that when estimating the uncertainty in temperature measurement when using a laser as a standard, the uncertainty is in the measurement of air temperature. For the purposes of this Standard, it can be obtained from any of the three options above. If method (c) is chosen, the estimated ranges of temperature uncertainties are the same.

6.2.2.4 Other Temperature Effects. It is possible for errors caused by differential expansion to be induced in machines when they are operated at mean temperatures significantly different from the temperature at which they were aligned and calibrated. It is not within the current state of the art to develop simple tests for these effects. Therefore, if a machine is to be accepted at a mean temperature that is significantly different from that used during alignment and calibration, the positioning accuracy and repeatability, and the circular performance tests described in para. 7.9 shall be repeated for each temperature. The Supplier shall specify quantitatively the magnitude of temperature change that is significant, i.e., the significant mean temperature change (SMTC), for a given machine with given specification zones. Furthermore, the Supplier shall specify a safe operating temperature range (SOTR) within which the machine should be kept to prevent physical damage to the machine.

6.3 Relative Vibration Tests

The relative vibration tests shall be performed under conditions equivalent to those pertaining during the performance tests (see section 7). The test environment shall be considered acceptable if the vibration amplitude measured between the machine spindle and the work table is less than 25% of the machine specification zone for bidirectional repeatability for the appropriate axis. For the purposes of this Standard, this amplitude shall be assessed by the following simple functional tests. Care should be taken that such tests include both the steady state vibrations and any transients that might occur during normal use. In principle, such tests would last for a complete daily cycle, but this is not practical. The minimum recommended duration is 10 min. These tests are specified with the full knowledge that they do not constitute a well-defined measurement of the forced vibration amplitude, but rather some complicated function that relates only in a very general way to that amplitude. If the machine does not pass the functional test, Nonmandatory Appendix D provides recommended procedures for accurate measurement of the vibration spectra at the User–Supplier interface for the purposes of determining conformance to the Supplier's specifications.

Should the vibration amplitude as measured in this test exceed the requirements and the cause of the vibration be traced to sources that are the User's responsibility, and if the User does not desire to upgrade the machine interface, then the machine specification shall be derated, as specified in para. 6.3.1.

It bears repeating that the vibration tests described above do not assess the classical dynamic performance of the machine tool when subjected to cutting conditions that lead to regenerative chatter.

6.3.1 Methodology for Functional Relative Vibration Tests. As with the *ETVE* test (para. 6.2.1), this test may be conducted a single axis at a time or for all axes simultaneously. In either event, high-resolution, high-bandwidth displacement sensors, conforming to the requirements of section 9, shall be attached to the tool post of the machine and set to read against a test ball or other artifact mounted in the machine spindle. (This test can also be performed in reverse, with the displacement sensor in the spindle and the artifact in the tool post position.) The artifact used for the *ETVE* test is the recommended fixture since this test will be performed at the same time (see Fig. 6.2.1.4-1). In the absence of other guidance, the position used for the *ETVE* test shall be the default position for this functional vibration test. Recommended displacement sensors are capacitance gages or other high-bandwidth sensors meeting the requirements of section 9. In the event that only two displacement sensors are used, the direction of each displacement sensor shall be aligned with the machine axis. The maximum spread of the displacement sensor(s) reading over a period of no longer than 5 s

Table 6.3.1-1 Performance Parameters Derated Due to Excessive Environmental Vibration

Parameter	Paragraph
Linear positioning (per axis)	7.2
Unidirectional accuracies of positioning	7.2.7.4
Bidirectional accuracy of positioning	7.2.7.3
Bidirectional repeatability	7.2.7.5
Unidirectional repeatabilities	7.2.7.6
Spindle axis of rotation (per spindle)	7.6
Asynchronous radial error motion	7.6.3.1
Asynchronous axial motion	7.6.3.2
Circular tests	7.9
Circular hysteresis	7.9.5
Radial deviations	7.9.5
Subsystems repeatability	8.3
Tool-change repeatability	8.3.1
Turret repeatability	8.3.2
Repeatability, location, and drift of tool-setting system(s)	8.4
Repeatability of tool-setting system	8.4.1
Machine performance as a measuring tool	8.6
Measurement repeatability	8.6.1
Linear measurement accuracy	8.6.4

shall be judged to be the machine vibration amplitude for that axis. The displacement sensors shall be read as rapidly as possible, and therefore, high-bandwidth capacitance gages, as described in section 9, should be used. In the event that a single displacement sensor is used, the direction of displacement indication shall be aligned with each machine axis in succession and a similar analysis performed on the data. The purpose of this test is to assess vibration caused by the environment, not vibration caused by the machine. The test is therefore carried out with the machine turned off, that is, the main machine power off. In some cases, high-precision machines are supplied with vibration isolation (pneumatic isolators, for example). In these cases, the isolation system shall be turned on or a separate agreement shall be made between the Supplier and the User. In the case where the relative vibration amplitude, measured with the machine off, exceeds 25% of the specification zone of the machine for a particular test, the machine vibration environment does not conform to the Supplier's guidelines, and the User chooses not to upgrade the environment, permissible specification zone limits for specific tests in this Standard, given in Table 6.3.1-1, shall be automatically increased such that the measured vibration amplitude is 25% of the new specification zone.

NOTE: This test does not measure vibrations caused by machine electronics, hydraulics, axis drives, etc. Further tests given in this Standard provide this information (see para. 7.6.2).

6.4 Electrical Tests

Well-defined procedures and highly developed instruments exist that enable the measurement of the parameters characterizing the electrical power supplied to a machine. It is, however, the position of this Standard that such tests are, in the general case, not required and should be undertaken only in the event that the machine does not meet performance specifications and there is reason to suspect the electrical power. Failures due to electrical power usually show up as intermittent control or readout failures, which are difficult to link to mechanical causes. In the case that the power is suspect, this Standard provides Nonmandatory Appendix E, which describes the recommended procedure for determining the conformance of the electrical environment to the Supplier's guidelines. The User should pay particular attention to the proper grounding of the machine in accordance with the Supplier's guidelines, as this is one of the most common causes of improper electrical performance.

6.5 Utility Air and Other Tests

As with electrical power tests, there exist many complicated procedures for determining the quality of the utility air, hydraulics, or other services to the machine when such services are required. It is the position of this Standard that exhaustive tests should not be required for checking conformance to specification unless a problem traced to the air or other supply is evident. As stated previously, variations in the mean value of the supplied air pressure can, on certain machines, cause changes in machine squareness and positional drifts, so that if such changes occur, air pressure is a possible suspect. It shall therefore be the responsibility of the Supplier to examine, using the gages supplied with the machine, the mean pressure and pressure variations of air or other services at the input to the machine. If, in the Supplier's judgment, such fluctuations are excessive, then further tests shall be performed for determining conformance of User-supplied air or other services to the Supplier's specification. If, however, the Supplier judges such fluctuations to be insignificant, then the utility air and/or other services shall be judged as conforming to specification, without further testing.

7 MACHINE PERFORMANCE

7.1 General

The Supplier shall be responsible for providing a machine that meets all performance specifications agreed upon between the Supplier and the User, when installed according to the Supplier's recommendations in any environment meeting the requirements of section 5. If required, derating of the acceptable specification zones shall be applied as described in section 6. Note that the specification zone for any given test is the value given in para. 1.1. If a machine meets the performance specifications and other conditions agreed upon between the Supplier and the User, the User should accept the machine.

7.1.1 Test Conditions

7.1.1.1 Environment. Where the temperature of the environment can be controlled, it shall be set to 20°C (68°F). Otherwise, the measuring instrument output and the machine nominal readings shall be adjusted to yield results corrected to 20°C (68°F), where applicable. This means that for material standards, a nominal differential expansion (*NDE*) correction shall be applied (see section 4) and other instruments, such as laser interferometers, shall be compensated for environmental conditions. Those tests where environmental compensation and *NDE* correction shall be used are listed in Table 6.2.2.1-1 (see para. 6.2.2.1).

The machine and, if relevant, the measuring instrument or artifact standard shall have been in the test environment long enough (preferably overnight) to have reached a thermally stable condition before testing. They shall be protected from drafts and external radiation such as sunlight, overhead heaters, and machine lights. All tests should be run under the lighting conditions that will be used during normal machine operation; that is, if the machine is to be run with its internal lights on, it should be tested with the lights on. For a thorough discussion of thermal time constants, see ANSI B89.6.2.

7.1.1.2 Sign Conventions. In addition to magnitude, the signs of machine performance parameters can be important when communicating and analyzing measurement results and when making compensations and adjustments. Recommendations are given in Nonmandatory Appendix N.

7.1.1.3 Machine to Be Tested. The machine shall be completely assembled and fully operational. All the necessary leveling operations, geometric alignment, and Supplier functional checks shall be completed before starting performance testing. A minimal set of functional checks is given in Nonmandatory Appendix F. All performance tests in section 7 shall be carried out with the machine in an unloaded condition (i.e., without a workpiece, unless specified otherwise).

Users should be aware that changing machine parameters or adjustments of any kind may affect the results of various performance tests. When using this Standard for machine acceptance, these parameter changes and adjustments should be made prior to the commencement of acceptance testing.

7.1.1.4 Compensation Systems. Some machines are equipped with computer-controlled compensation systems for geometric or thermal errors, or both. If the machine is so equipped, tests should be run with the compensation system on. Users desiring to see uncompensated errors may request, as part of the original specification, that these tests also be performed with the compensation system off.

7.1.1.5 Machine Warm-Up. The tests shall be preceded by an appropriate warm-up procedure. If the procedure is not specified in this Standard for a particular test, it may be specified by the Supplier of the machine or agreed upon between the Supplier and the User. If no conditions are specified, the preliminary machine movements shall be restricted to only those necessary to set up the measurement instrument.

7.1.2 Foundation Checks and Machine Alignment. In some cases, Users will be applying this Standard to machines that have been installed for some time. Before performing any measurements, the User should realign the machine following the Supplier's recommended procedures. If the machine has more than three supports, the User should pay particular attention to checking that the foundation is properly cured and meets the Supplier's specifications. If the machine is not correctly aligned and supported, poor performance test results are very likely. For a further discussion of these issues, see Nonmandatory Appendix G.

7.1.3 Chucks and Other Part-Holding Devices. Several of the performance tests described in this Standard require the use of a chuck or other part-holding device to attach instrumentation to the machine. Unless otherwise agreed upon between the Supplier and the User, the part-holding device to be used for these tests shall be that which is supplied with the machine and to be used during normal machine operation. If the machine has been supplied without such a part-holding device, then a part-holding device specified by the machine Supplier shall be used for the purposes of performance testing.

7.1.4 Test Setup and Instrumentation

7.1.4.1 General. Most measurements prescribed in this Standard are carried out to measure motion between the component of the machine that holds the workpiece and the component that holds the cutting tool. All test setups normally involve two fixtures: one that establishes the reference point or surface, and a second that holds some type of indicator to read against this reference point or surface. The specific setups and instrumentation are provided for suggestions only. Other instrumentation and setups providing comparable results can be used. However, before starting any of the measurements, the User of this Standard shall ensure that the particular setup and instrumentation function properly within the machine tool environment. Two main tests should be used for such checks: setup hysteresis and stability.

The machine hysteresis is measured, in this Standard, as part of the compliance and hysteresis check in Nonmandatory Appendix H.

7.1.4.2 Setup Hysteresis Tests. The goal of this test is to discover any hysteresis effects, which may be caused by loose bolts in test setups, insufficient structural strength in the brackets, etc. Any hysteresis is normally revealed as a lack of repeatability in machine performance testing.

Setup hysteresis is measured by applying a suitable force in the direction of the intended measurement, between these two fixtures and observing the resulting deflection.

The procedure is as follows:

Step 1: Set up and zero an indicator between the two fixtures in the direction and location of the intended axis performance test.

Step 2: Apply the force by hand to the fixture holding the datum reference.

Step 3: After the force is applied, gradually decrease this force to zero and read the indicator.

Step 4: Apply a force by hand in the opposite direction, gradually decrease the force to zero, and read the indicator. The difference in readings is the datum hysteresis.

Step 5: Apply the force to the fixture holding the indicator

Step 6: Gradually decrease this force to zero and read the indicator.

Step 7: Apply a force by hand in the opposite direction, gradually decrease the force to zero, and read the indicator. The difference in readings is the indicator fixture hysteresis. The arithmetic sum of the hysteresis values for the datum fixture and indicator fixture is the total test setup hysteresis.

The sensitivity of the result to the magnitude of the force is, in general, insignificant. If significant hysteresis[5] is measured, and if this hysteresis cannot be reduced by increasing the stiffness of the test setup, it may be caused by the machine itself. In such cases, further testing shall be discontinued until this condition is corrected.

7.1.4.3 Setup Stability Tests. Machine tools are subject to a wide variety of vibrations from both internal and external sources. These vibrations vary in both frequency and amplitude depending on time, location within the machine, and machine axis positions. The stiffness and damping characteristics of machines may exclude these vibrations from having an effect on the actual performance of the machine. However, improper mounting of test equipment may also make the instrument or the test sensitive to these vibrations. The setup stability test is designed to assure that the mounting of instruments does not significantly affect the uncertainty of measurements.

The procedure is as follows:

Step 1: Mount the measuring instrument in the manner used for the performance test.

Step 2: Position the machine in the middle of travel for the performance test.

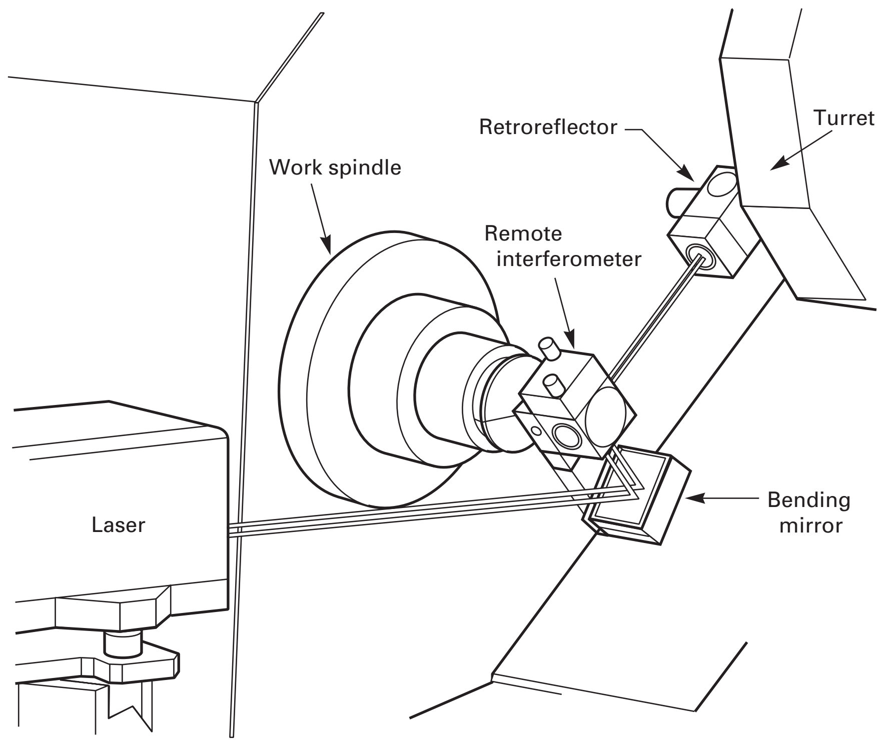
Step 3: Set the instrument to zero and sample the output at a rate and time equal to those used in the test,[6] without moving the machine.

The mounting of instruments can be altered to reduce the range of sampled data. Mountings preferably should be stiffened; however, softening of mounts can also reduce the sensitivity to certain vibrations. If changes to the mounting do not reduce the range, the machine itself may be responsible. Check seismic vibration, and continue testing.

[5] Conventional practice is that the hysteresis be less than one-tenth of the desired measurement repeatability.

[6] The range of the data sampled should not exceed 10% of the specification zone for the performance test.

Fig. 7.2.3-1 Typical Setup for a Laser Interferometer



7.2. Positioning Accuracy and Repeatability, Linear Axes

7.2.1 General. The tests described in paras. 7.2.2 through 7.2.8 are meant to represent a minimum requirement to ensure conformance to accuracy and repeatability specifications. They are not comprehensive. A laser interferometer is the preferred measuring instrument.

WARNING: These tests should not be performed until after the thermal test outlined in para. 6.2, as, if the thermal environment is inadequate, these tests will yield incorrect results and will have to be redone.

7.2.2 Lines of Measurements. The default lines of measurement for laser interferometer tests shall be along two (or more) lines in the work zone parallel to the machine linear axis directions. For a simple Group 1 turning machine, the cross-slide (X) should be measured close to the work spindle face and the in-feed (Z) axis along the work spindle centerline. Other options may be specified according to machine group, usage, and configuration. If so, such lines shall be made part of the original machine specification and described in equivalent detail. Note that this Standard requires the measurement of angular error for each linear axis (see para. 7.4). For efficiency, these measurements can be made at the same time and in essentially the same locations as the positioning accuracy and repeatability, linear axes.

7.2.3 Alignment. The laser interferometer shall be aligned as recommended by the laser interferometer Supplier. Particular attention should be paid to cosine error, and alignment should be such that cosine error is less than 1% of the specification zone of the axis under test. A typical laser setup for testing a slide way is shown in Fig. 7.2.3-1. In the figure, the interferometer is shown mounted in the spindle; however, on some machines the spindle cannot be locked, and thus the setup as shown would lead to instabilities. On machines where the spindle cannot be locked, a bracket should be made to position the interferometer (or retroreflector) near the point where a part would be, with the bracket attached to the spindle housing. This is very important. An easy check is to set up the interferometer, lock the spindle, and try to rotate the spindle by hand, observing the interferometer readout. No change greater than one-tenth of the specification zone required for the test should be observable.

7.2.4 Compensation for Environmental Conditions. This test requires that the interferometer be corrected for air temperature, air pressure, and air humidity, and the machine scale be corrected for thermal expansion. To perform these corrections, the environmental compensation unit supplied with the laser interferometer shall be used. Further, the part temperature sensor shall be placed in a position where the temperature corresponds, as closely as possible, to the temperature of the machine scale or its equivalent. The correct effective coefficient of expansion of the machine scales shall be used (see Form 4), and the instrument manufacturer's instructions for the compensation shall be followed. Note that it is a requirement of this Standard that the nominal differential expansion (*NDE*) correction be performed. If the laser system does not provide for environmental correction, both laser readings and scale readings shall be corrected manually. The procedure for making these corrections is given in Nonmandatory Appendix I.

7.2.5 Measuring Intervals. Measuring intervals shall be no larger than 25 mm (1 in.) for axes of 250 mm (10 in.) length or less. For longer axes, the interval shall be no more than one-tenth of the axis length. The points chosen for measurement should not be those points used by the Supplier to acquire data used for ball screw or lead screw compensation. Furthermore, these points should be chosen at intervals that are not even fractions of the machine scale intervals. A simple way to accomplish this is to use metric intervals on a machine with English scales or screws, and vice versa. For machines that use ball or lead screws for displacement readout, the User should make these closer-spaced measurements an integral part of the specification. The procedure for measuring periodic error is described in para. 7.2.8.

7.2.6 Measurements. Before commencing measurements, the machine shall be run through an exercise sequence of two complete back-and-forth cycles for each linear axis, using the same program or manual time sequence that will be used during data acquisition. The default traverse speed for these measurements shall be the machine's maximum programmable feed rate. Other traverse speeds may be negotiated between the User and the Supplier. Next, five sets of bidirectional measurements shall be taken for each axis sequentially along the line specified in para. 7.2.2 and at the points specified in para. 7.2.5, stopping the machine for a short duration, 1 s to 5 s, at each of the data points. The laser readings should be averaged for about 0.25 s, and at least 120 points should be taken to compute this average. (On some large machines, longer settling times may be required. In that case, the settling time should be negotiated between the User and the Supplier.) These data shall be acquired without rezeroing the laser system. A set of measurements shall consist of the machine axis readings and the corresponding laser readings. Note that for each point there will be 10 measurements, 5 in each direction. These data shall be treated as described in the para. 7.2.7.

7.2.7 Data Analysis and Reported Parameters. For each measurement, the respective deviation of position ($x_i\uparrow$ or $x_i\downarrow$) shall be calculated as the measured actual position minus the target position. For each axis, the deviation data shall be plotted in a graph such as that illustrated in Fig. 7.2.7-1. Figure 7.2.7-1 shows the complete set of data. For clarity, the forward data are shown separately in Fig. 7.2.7-2. On both figures, the data averages are shown as dark lines. From these data, the following parameters shall be computed and reported for each axis, and the resulting quantities shall be compared to the appropriate specification zones:

(*a*) bidirectional systematic deviation of positioning, E

(*b*) unidirectional systematic deviations of positioning, $E\uparrow$ and $E\downarrow$

(*c*) bidirectional repeatability, R

(*d*) unidirectional repeatabilities, $R\uparrow$ and $R\downarrow$

The equations for computing these parameters are given in the paras. 7.2.7.1 through 7.2.7.8. These computations should be calculated using a computer program. For those who wish to perform the computations graphically, an approximate method is given in para. 7.2.7.9. A report for a typical axis is summarized in Table 7.2.7-1.

7.2.7.1 Bidirectional Systematic Deviation of Positioning of an Axis, *E*. To determine the bidirectional systematic deviation of positioning, first average the computed deviations from the target position in the forward and reverse directions. The difference between the algebraic maximum and minimum of the mean (average) unidirectional positional deviations for both approach directions (i.e., $\bar{x}\uparrow$ and $\bar{x}\uparrow$) at any position along or around the axis is the reported value, that is, the range of the average or mean values as shown in Fig. 7.2.7-1. The equation is

$$E = \max.(\bar{x}\uparrow, \bar{x}\downarrow) - \min.(\bar{x}\uparrow, \bar{x}\downarrow)$$

7.2.7.2 Unidirectional Systematic Deviations of Positioning, *E*↑ and *E*↓. The unidirectional systematic deviations of positioning are just the ranges of the average plots in the forward and reverse directions. Mathematically they are the differences between the algebraic maximum and minimum of the mean unidirectional positional deviations for both approach directions (i.e., $\bar{x}_i\uparrow$ or $\bar{x}_i\downarrow$) at any position along or around the axis; that is

$$E\uparrow = \max.(\bar{x}_i\uparrow) - \min.(\bar{x}_i\uparrow)$$

and

$$E\downarrow = \max.(\bar{x}_i\downarrow) - \min.(\bar{x}_i\downarrow)$$

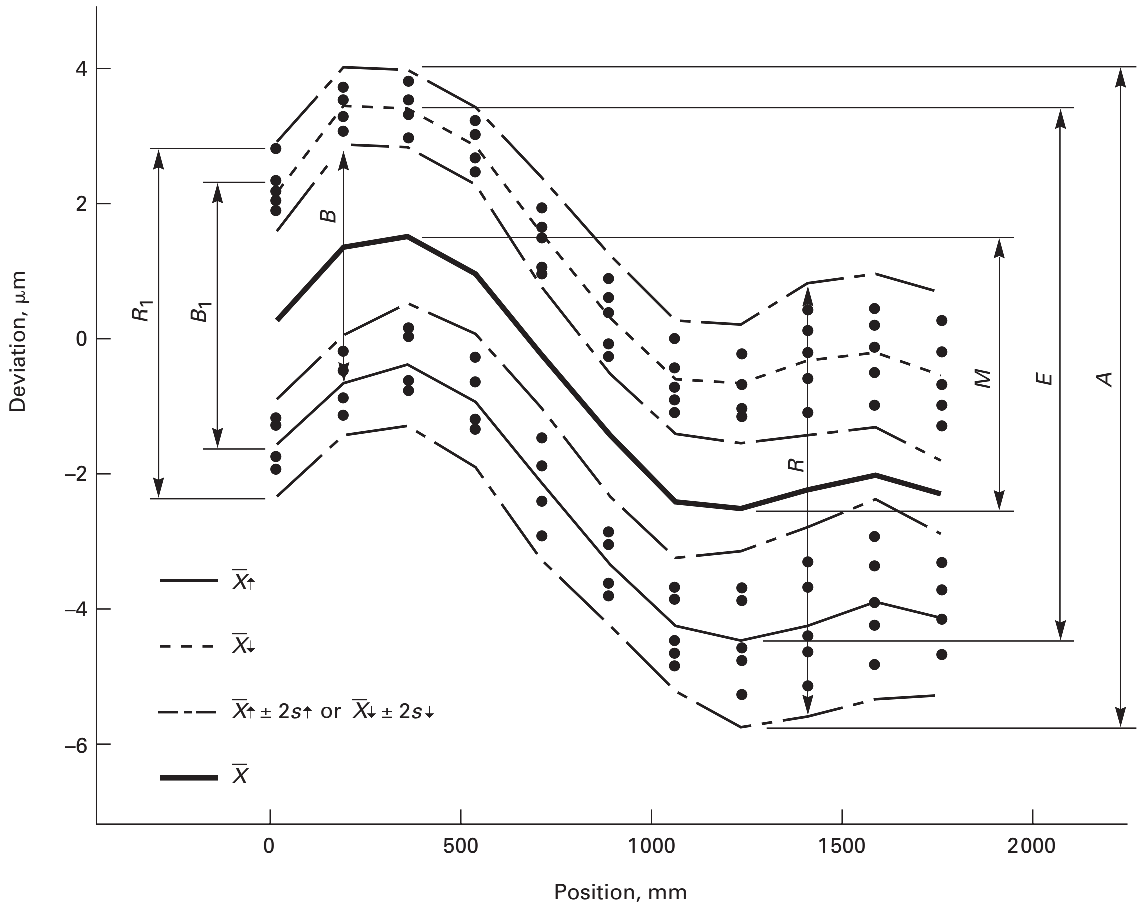
7.2.7.3 Bidirectional Accuracy of Positioning of an Axis, *A*. The bidirectional accuracy of positioning is the range derived from the combination of the bidirectional systematic deviations and the estimator of the standard uncertainty of bidirectional positioning obtained using a coverage factor, k, of 2. The estimates of the uncertainty are computed for each average value according to

Table 7.2.7-1 Typical Test Results (Test for Linear Axis up to 2 m)

i	1		2		3		4		5		6		7		8		9		10		11	
Target position, P_i, mm	6 711		175 077		353 834		525 668		704 175		881 868		1055 890		1234 304		1408 462		1580 269		1750 920	
Approach direction	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑
Positional deviations, µm																						
$j = 1$	2,3	−1,2	3,6	−0,5	3,5	0,2	3,0	−0,6	1,7	−1,9	0,4	−3,0	−0,4	−3,7	−0,2	−3,7	0,2	−3,5	0,3	−3,2	−0,1	−3,6
2	2,1	−1,7	3,5	−0,9	3,3	−0,6	2,7	−1,2	1,5	−2,3	0,2	−3,5	−0,7	−4,3	−0,6	−4,4	−0,2	−4,3	−0,1	−3,8	−0,6	−4,0
3	1,9	−1,9	3,1	−1,1	3,0	−0,7	2,4	−1,3	1,0	−2,9	−0,2	−3,7	−1,0	−4,6	−1,0	−5,1	−1,0	−5,0	−0,9	−4,7	−1,2	−4,5
4	2,8	−1,3	3,7	−0,2	3,8	0,1	3,6	−0,7	1,9	−1,4	0,9	−2,8	0,0	−3,6	−0,2	−3,6	0,5	−3,2	0,5	−2,8	0,4	−3,2
5	2,2	−1,9	3,2	−0,8	3,5	−0,7	2,6	−1,3	1,1	−2,3	−0,1	−3,7	−0,9	−4,5	−1,1	−4,6	−0,5	−4,5	−0,4	−4,1	−0,9	−4,5
Mean unidirectional positional deviation, $\bar{x}_i$	2,3	−1,6	3,4	−0,7	3,4	−0,4	2,8	−0,9	1,4	−2,2	0,2	−3,3	−0,6	−4,1	−0,6	−4,3	−0,2	−4,1	−0,1	−3,7	−0,5	−4,0
Estimator of standard uncertainty, s_j	0,3	0,4	0,3	0,4	0,3	0,5	0,3	0,5	0,4	0,5	0,4	0,4	0,4	0,5	0,4	0,6	0,6	0,7	0,6	0,7	0,6	0,6
$2s_j$	0,7	0,7	0,6	0,7	0,6	0,9	0,6	0,9	0,8	1,1	0,9	0,8	0,9	1,0	0,9	1,3	1,2	1,4	1,1	1,5	1,2	1,2
$\bar{x}_i - 2s_j$	1,6	−2,3	2,8	−1,4	2,8	−1,3	2,2	−1,9	0,6	−3,2	−0,6	−4,2	−1,4	−5,1	−1,5	−5,5	−1,4	−5,5	−1,3	−5,2	−1,7	−5,1
$\bar{x}_i + 2s_j$	2,9	−0,9	4,0	0,0	4,0	0,5	3,4	0,0	2,2	−1,1	1,1	−2,5	0,3	−3,2	0,3	−3,0	1,0	−2,7	1,0	−2,3	0,8	−2,8
Unidirectional repeatability, $R_j = 4s_j$	1,3	1,4	1,2	1,5	1,2	1,8	1,2	1,9	1,6	2,2	1,7	1,7	1,7	1,9	1,8	2,5	2,3	2,9	2,3	2,9	2,5	2,3
Reversal value, B_i	−3,9		−4,1		−3,8		−3,7		−3,6		−3,6		−3,6		−3,7		−3,9		−3,6		−3,5	
Bidirectional repeatability, R_i	5,2		5,4		5,3		5,2		5,5		5,3		5,4		5,8		6,5		6,2		5,9	
Mean bidirectional positional deviation, $\bar{x}_i$	0,3		1,4		1,5		0,9		−0,4		−1,5		−2,4		−2,5		−2,2		−1,9		−2,2	

Axis Deviation, mm	Unidirectional ↓		Unidirectional ↑		Bidirectional	
Reversal value, B	Not applicable		Not applicable		0.0041	(at $i = 2$)
Mean reversal value, $\bar{B}$	Not applicable		Not applicable		–0.0037	
Range mean bidirectional positional deviation, M	Not applicable		Not applicable		0.0040	[0.0015 – (–0.0025)]
Systematic deviation of positioning, E	0.0040	[0.0034 – (–0.0006)]	0.0039	[–0.0004 – (–0.0043)]	0.0077	[0.0034 – (–0.0043)]
Repeatability of positioning, R	0.0025	(at $i = 11$)	0.0029	(at $i = 10$)	0.0065	(at $i = 9$)
Accuracy, A	0.0057	[0.0040 – (–0.0017)]	0.0061	[0.0005 – (–0.0055)]	0.0096	[0.0040 – (–0.0055)]

Fig. 7.2.7-1 The Full Data Set for the Positioning Deviations of an Axis



$$s_i\uparrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(x_{ij} - \bar{x}_i\uparrow)^2}$$

and

$$s_i\downarrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(x_{ij} - \bar{x}_i\downarrow)^2}$$

Then A is given by

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

7.2.7.4 Unidirectional Accuracies of Positioning, *A*↑ and *A*↓. The unidirectional accuracies of positioning are computed analogously to the computation of A, described in para. 7.2.7.2. They are the ranges representing the combination of the unidirectional systematic deviations and the estimator of the standard uncertainty of unidirectional positioning obtained using a coverage factor of 2.

$$A\uparrow = \max.(\bar{x}_i\uparrow + 2s_i\uparrow) - \min.(\bar{x}_i\uparrow - 2s_i\uparrow)$$

and

$$A\downarrow = \max.(\bar{x}_i\downarrow + 2s_i\downarrow) - \min.(\bar{x}_i\downarrow - 2s_i\downarrow)$$

7.2.7.5 Bidirectional Repeatability for an Axis, *R*. Bidirectional repeatability for an axis is defined as the maximum value of the bidirectional repeatability of positioning for an axis; that is

$R = \max.(R_i)$

where

$R_i = \max.(2s_i\uparrow + 2s_i\downarrow + |B_i|;\ R_i\uparrow;\ R_i\downarrow)$

$R_i\uparrow = 4s_i\uparrow$

$R_i\downarrow = 4s_i\downarrow$

7.2.7.6 Unidirectional Repeatabilities, *R*↑ and *R*↓. Unidirectional repeatabilities are defined as the maximum value of the repeat abilities at any position; that is

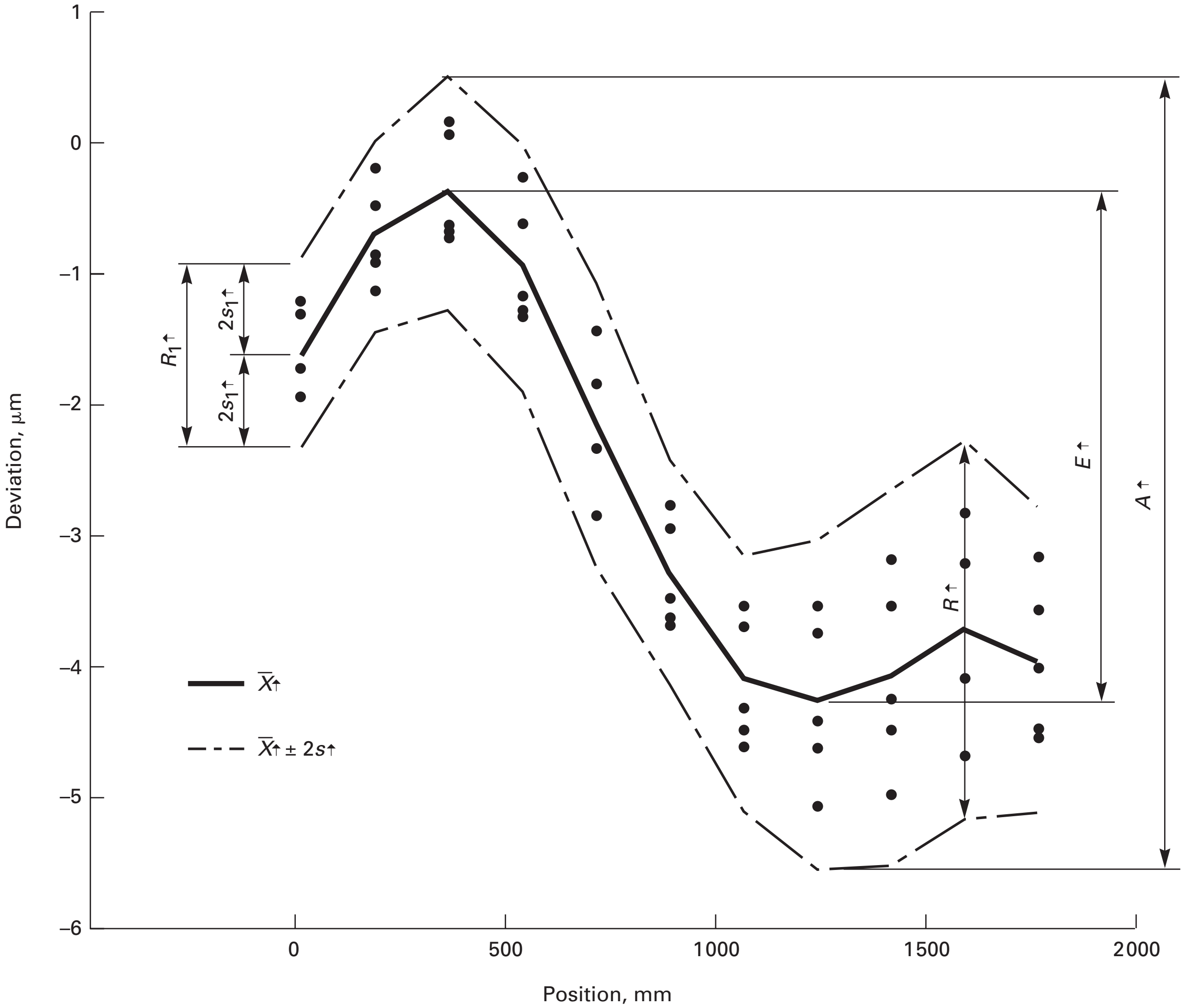
$$R\uparrow = \max.(R_i\uparrow) = \max.(4s_i\uparrow)$$

and

$$R\downarrow = \max.(R_i\downarrow) = \max.(4s_i\downarrow)$$

7.2.7.7 The Reversal Deviation, *B*. The reversal deviation is the algebraic maximum of the absolute mean reversal deviations, $|B_i|$, at any position along or

Fig. 7.2.7-2 Positioning Deviations of an Axis, Forward Direction Only



around the axis, determined using the procedure and under the conditions specified in this Standard.

$$B = \max.\ (|B_i|)$$

7.2.7.8 The Mean Reversal Value, $\overline{B}$. The mean reversal value is the algebraic mean of the absolute reversal values, $|B_i|$, at all target positions along or around the axis.

$$\overline{B} = \frac{1}{m}\sum_{i=1}^{m} B_i$$

7.2.7.9 Approximate Calculations. If a computer program is not available to calculate the standard uncertainties of the positioning data, then it is possible to estimate them from the range. This can be done graphically. The procedure is as follows. At each of the target points, measure the range graphically. Convert the range into a standard uncertainty using the factors shown in Table 7.2.7.9-1. For a given sample size, n, and range, Rn_i, the appropriate standard uncertainty, s_i, is estimated by

$$s_i = Rn_i/d_2(n)$$

In the table, the entry for a sample size of 5 is highlighted, as the recommended number of repeated measurements for each target position is 5. The table, however, may also be used for other sample sizes. Note that the sample size of 20 is also highlighted, as that is the sample size used for the analysis of uncertainty in spindle error motion (see para. 7.6).

7.2.8 Periodic Error. Nearly all scales used on turning centers contain either classical periodic error (caused by pitch error in lead screws or ball screws, mismounted nuts, etc.) or some form of interpolation error, which occurs during electronic interpolation between scale

Fig. 7.2.8-1 Periodic Error of a Linear Axis (Unidirectional)

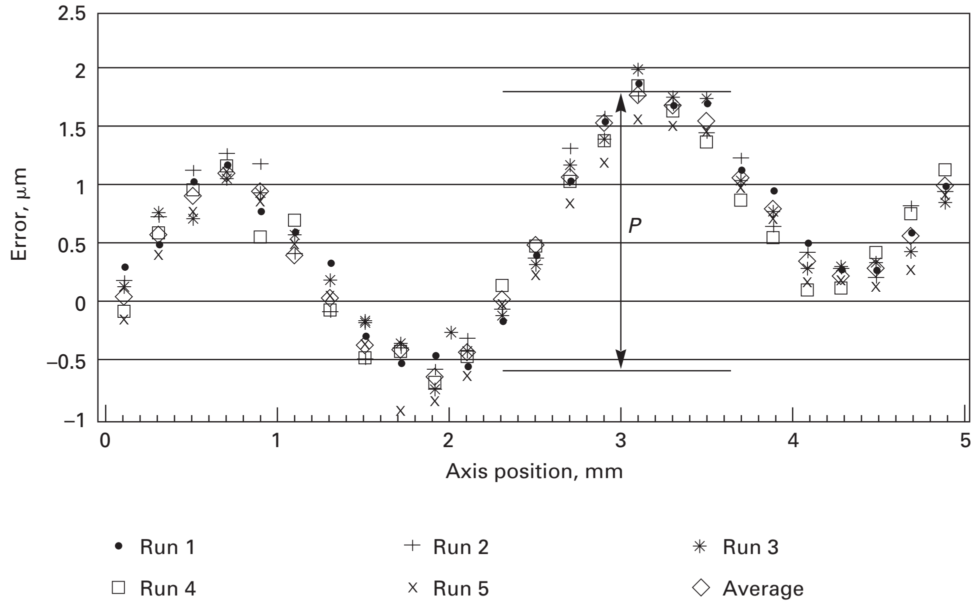


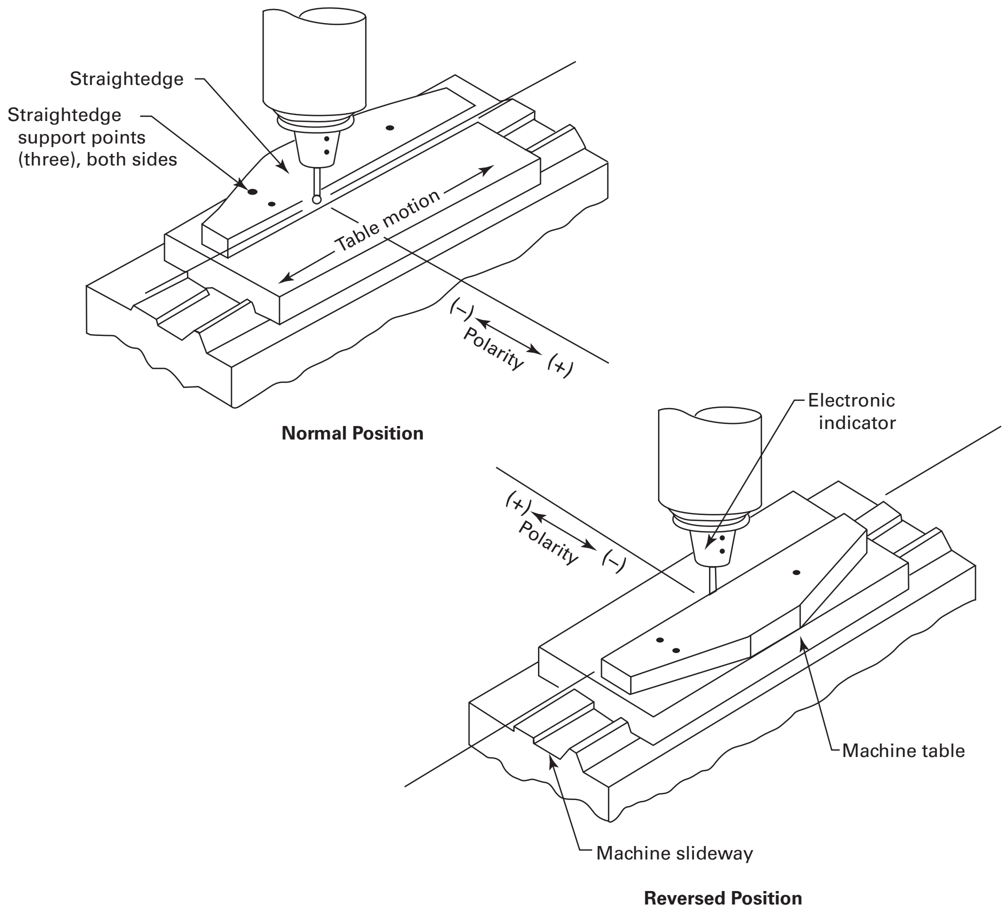
Table 7.2.7.9-1 Conversion Factors for Graphically Estimating Standard Uncertainty

Sample Size, *n*	Conversion Factor, $d_2(n)$
5	2.33
6	2.53
7	2.70
8	2.85
9	2.97
10	3.08
12	3.26
15	3.47
20	3.74

divisions on line scales, moiré scales, inductive scales, and the like. Even laser interferometer scales have periodic error with a periodicity that is the wavelength of light or a fraction thereof, depending upon the exact optical configuration of the system (although periodic error in laser systems is generally small, it can be important on very high-precision machines). Users of this Standard with machines whose bidirectional systematic deviation of positioning is expected to be less than 300 nm (approximately 8 μin.) should consult with a laser manufacturer regarding this effect.

With a laser interferometer on all turning machines except those noted above, it is particularly easy to check for periodic error by measuring a large number of closely spaced displacements over an interval equal to the periodicity of the machine scale. For the purposes of this Standard, the positioning error should be measured for 20 points unidirectionally, evenly spaced, over two periods of the pitch of the expected periodic error. For a screw, this would be the screw pitch; for a line scale, the line spacing; for an inductive scale, the coil spacing, etc. If the pitch of the scale is quite small, as on a line scale, fewer points can be taken. These measurements shall be repeated five times. These data shall be plotted as shown in Fig. 7.2.8-1. The periodic error, P, is the total range of the average of the deviations, as shown in the figure. It

Fig. 7.3.1.1-1 Setup for Measuring Straightness Using an Electronic Indicator and a Mechanical Straightedge



is computed precisely the same as $E\uparrow$, as described in para. 7.2.7.1; that is, for this test

$$P = \text{max.}\ (\bar{x}_i\uparrow) - \text{min.}\ (\bar{x}_i\uparrow)$$

7.3 Straightness Error

The straightness of a linear axis is measured by positioning a straightedge in the workpiece position, aligned to the motion axis, and measuring the lateral motion in the two directions orthogonal to the traverse direction, using an indicator in the tool position. The best positions for performing the straightness measurement in the machine work zone are those that most commonly reflect the normal position of the workpiece in the work zone.

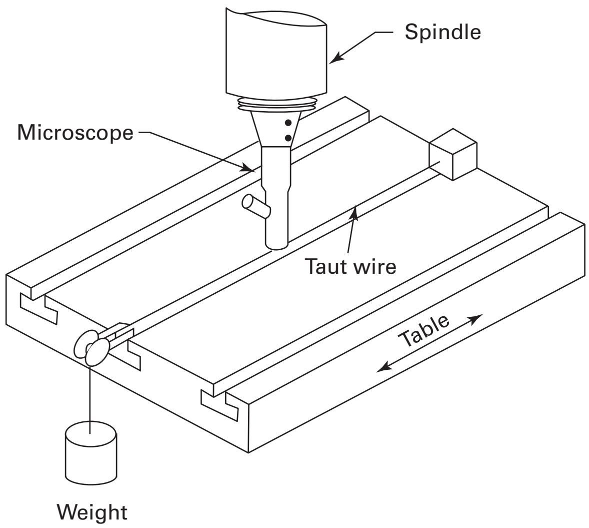
7.3.1 Test Procedure. Common methods of straightness measurement use mechanical straightedges, optical straightedges, taut wires, geometry lasers, and laser straightness interferometers.

7.3.1.1 Mechanical Straightedges. The straightedge is fixtured in the work-holding spindle and is aligned approximately parallel to an axis motion.[7] The straightness error is measured with a mechanical or electronic indicator or a plane mirror interferometer (if the straightedge has an optical-quality reflective surface) mounted in the machine's tool position. This setup is depicted in Fig. 7.3.1.1-1.

WARNING: The calibration chart of the straightedge should be used to determine if its accuracy is adequate compared to the straightness specification of the slide under test (see section 9). If the straightedge is not accurate enough, the calibration chart or a technique called *straightedge reversal* 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 straight-

[7] For large machines, either a very long straightedge is required or the straightedge must be staged. To improve relative alignment between stages, larger overlap of gage positions is required, but this increases the number of gage positions. It is thus difficult and time-consuming to make accurate straightness measurements on a large machine using a short straightedge [cases exist where mechanical straightedges have been used successfully for distances up to 2 m (approximately 80 in.)].

Fig. 7.3.1.2-1 Test Setup for Measuring Straightness Using a Taut Wire



ness of a horizontal axis when the sag of the straightedge due to gravity is important.

WARNING: 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 air turbulence. Since the measurement is differential and the air gap is small, it is usually not necessary to make corrections for errors in laser wavelength due to atmospheric conditions such as temperature and pressure. For the highest measurement accuracy, however, these corrections should be made.

7.3.1.2 Taut Wire. Taut wires are often used for measuring the horizontal straightness on large machines. The wire is stretched along the axis direction, and measurements of wire position are made with a sensor (proximity sensor or microscope) mounted in the machine's tool position (see Fig. 7.3.1.2-1).

7.3.1.3 Geometry Laser. A laser head is mounted in the work-holding spindle and the laser beam aligned along the axis of motion, as shown in Fig. 7.3.1.3-1. A sensor[8] (either a lateral effect photodiode or a quadrant photodiode) capable of measuring the lateral motion of the spindle from the laser beam is attached in the nominal tool position.

WARNING: When using this method, care must be taken due to "wandering" of the laser beam and to intensity variations over the beam cross-section as a function of distance, which are caused by interference, diffraction, and thermal effects. For best results, averaging should be performed at every point, the air in the laser path should be vigorously mixed using fans, and an adequate number of repetitions should be performed.

7.3.1.4 Laser Straightness Interferometers. The most commonly used laser straightness interferometers consist of a Wollaston prism and a straightness reflector. The straightness reflector should be mounted in the work-holding spindle, and the Wollaston prism should be mounted in the tool position (see Fig. 7.3.1.4-1).

WARNING: The centerline of the straightness reflector is analogous to the mechanical straightedge. Thus, extreme care must be taken in the fixturing of this reflector, particularly in situations where bending is suspected. Any local bending will cause the centerline of the reflector to change its position (see Fig. 7.3.1.4-1), and the result obtained will not reflect the straightness one would obtain on a part fixtured at multiple points over the table surface. This situation can be partially rectified by mounting the reflector to a secondary surface that is kinematically supported over the table.

Laser straightness interferometers, like alignment and geometry lasers, are sensitive to changes in the properties of the air. Mixing and averaging should be used to minimize the effects of these changes.

Flatness errors of the mirrors of the straightness reflector are also sources of measurement errors. Reversing the straightness reflector as shown in Fig. 7.3.1.4-1, and averaging the results from the two positions, is conceptually similar to straightedge reversal and can cancel this error.

7.3.1.5 Measurement Procedure. Before commencing measurements, the machine shall be run through an exercise sequence of two back-and-forth movements between the first and last target points.

[8] Interference filters are often used at the sensor to reduce the effects of changes in ambient illumination.

Fig. 7.3.1.3-1 Test Setup for Measuring Straightness Using an Alignment Laser

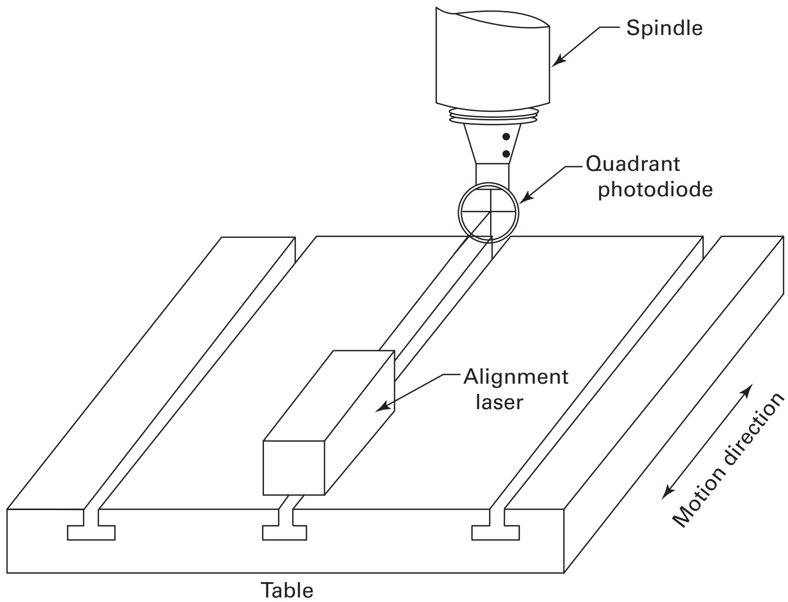
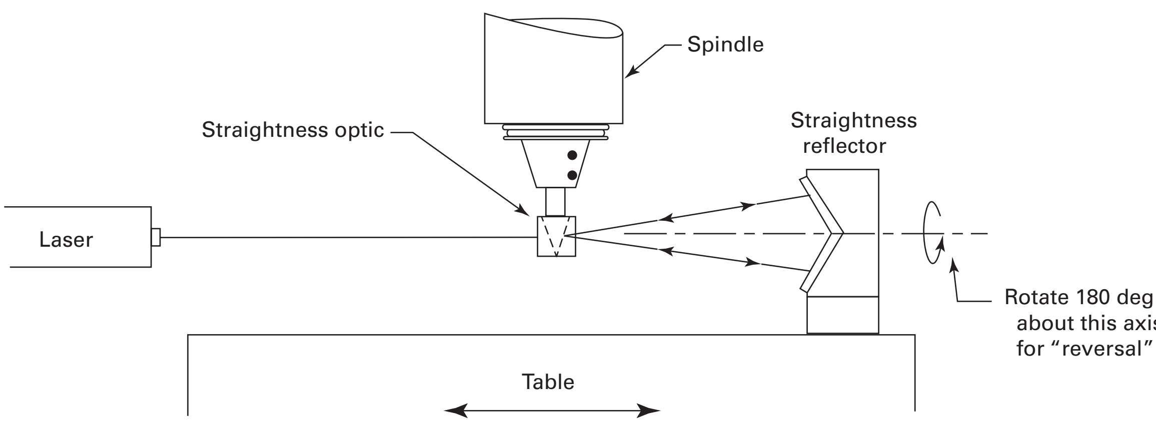


Fig. 7.3.1.4-1 Typical Straightness Interferometer



The machine shall be programmed to move the axis under test and to position it at a series of target positions.

At a target position, the data can be recorded with the machine stationary or during continuous motion. The target positions are required over the full travel range of the axis. The measuring intervals shall be no larger than 25 mm (1 in.) for axes of 250 mm (10 in.) or less. For longer axes, the interval shall be no more than one-tenth of the axis length.

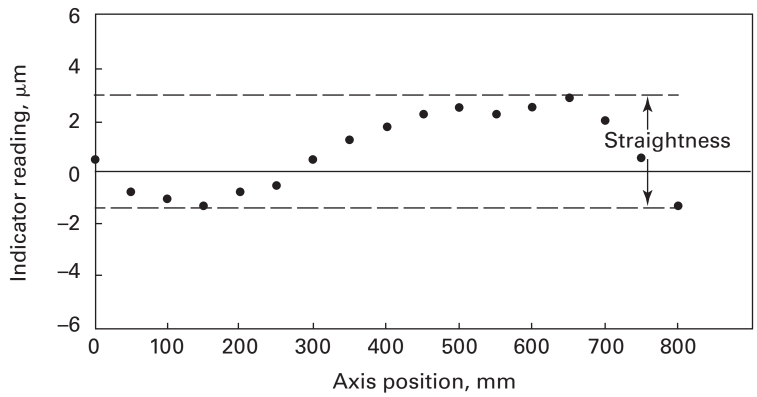
Five sets of bidirectional measurements shall be made at all the target positions. The default traverse speed shall be the machine's maximum programmable feed rate. Other feed rates may be negotiated between the User and the Supplier. A set of measurements shall consist of the target positions and the corresponding instrument readings.

7.3.2 Data Analysis. For each set of bidirectional measurements, two parallel lines are created such that all measured values are between the two lines, and the separation of the two lines is a minimum.

Although common algorithms can establish these two lines, other line "fitting" methods may be more readily available to the User and are therefore acceptable as approximations. For example, the two enveloping lines may be established as parallel to a simple regression line fit (least-squared error) or end point fit.

The straightness for each measurement is the range of residual values from the applicable fit. Graphically it is

Fig. 7.3.2-1 Typical Plot Showing Straightness Data With the Straightness for a Particular Axis Clearly Labeled



the distance between the enveloping lines as measured against the deviation (vertical) graph scale (i.e., slope due to alignment removed). The average and the standard uncertainty of the five straightness values calculated as such are reported as the straightness error of the axis. Straightness errors should also be plotted in a manner similar to that shown in Fig. 7.3.2-1, where the least-squared error line has been applied and the slope has been subtracted such that the straightness value for the axis may be obtained directly as the distance between the two enveloping lines.

7.4 Angular Error (Yaw) Motions, Linear Axes

7.4.1 General. Because of significant Abbe offsets when machining, errors in tool point location can occur due to angular errors in the machine linear slides. On a simple Group 1 machine, these errors consist of small rotations about the Y-axis and are called yaw errors. This Standard requires that these angular error motions be measured for all linear machine axes. For machines where rotations about other than the Y-axis are important, measurements of these angular error motions should be made part of the original machine specification. The lines of measurement shall be those lines used for the positioning accuracy and repeatability test for linear axes as specified in para. 7.2.2. A typical setup for making these measurements is shown in Fig. 7.4.1-1 for the cross-slide of a Group 1 machine. The measuring intervals, averaging times and number of points, and measurement sequence, including the exercise cycle, shall be those used for the linear tests as specified in paras. 7.2.5 and 7.2.6. The data shall be reported as given in para. 7.2.7, except that the names of the parameters shall be different. They shall be computed for each axis as follows:

(a) bidirectional systematic angular error, E_{ae}
(b) bidirectional total angular error, A_{ae}
(c) unidirectional systematic angular error, $E_{ae}\uparrow$ and $E_{ae}\downarrow$
(d) unidirectional total(s) angular error, $A_{ae}\uparrow$ and $A_{ae}\downarrow$
(e) bidirectional repeatability of angular error, R_{ae}
(f) unidirectional repeatabilities of angular error, $R_{ae}\uparrow$ and $R_{ae}\downarrow$
(g) reversal deviation of angular error, B_{ae}

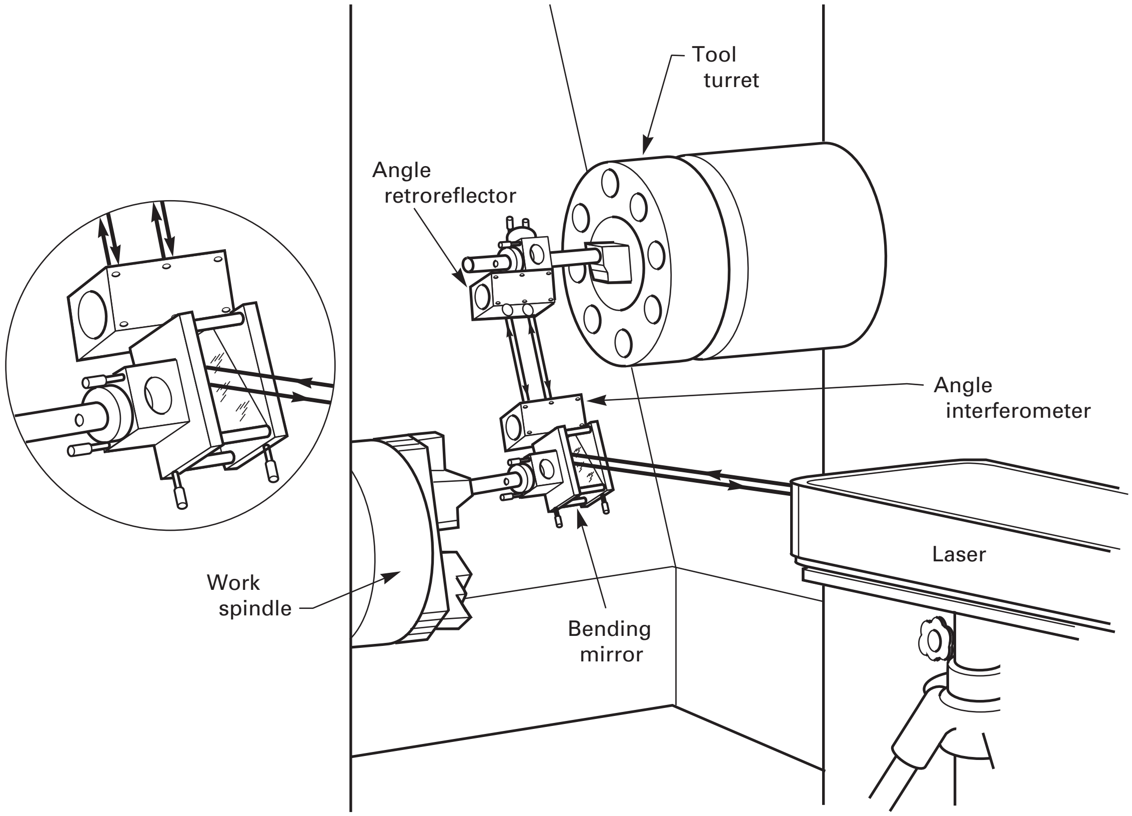
7.4.2 Estimating the Effect of Angular Error. Angular error leads to positioning error for positions not on the lines measured in the linear positioning accuracy and repeatability test (see para. 7.2). The magnitude of this error depends upon the perpendicular distance to the axis measurement lines and the point under consideration (the functional point). This perpendicular distance is called the Abbe offset (see section 4). To obtain the estimated error at any point, the value of the angular error for that position, in radians, need only be multiplied by the Abbe offset.

7.4.3 Angular Error Measurement Methods. Angular error is usually measured with electronic levels, a laser angular interferometer, or an autocollimator. The data can be recorded with the machine stationary or during continuous motion. However, for measurement during continuous motion, the use of electronic levels should be avoided in favor of the angular interferometer or autocollimator.

7.5 Positioning Accuracy and Repeatability, Rotary Axes

7.5.1 General. As with the measurement of linear positioning, complete verification of a rotary axis designed for positioning can be a time-consuming task. In paras. 7.5.2 through 7.5.8, a practical set of tests is defined that represents a good compromise between the cost of testing and the cost of inaccuracy. The tests are divided into two types. The first is for full-circle angular positioning (paras. 7.5.2 through 7.5.7), and the second is for interpolation errors on a much finer scale (para. 7.5.8). These tests are analogous to the tests performed for linear axes, and the same parameters are reported, except in angular units. A similar exercise procedure should be

Fig. 7.4.1-1 Typical Setup for Measuring the Angular Error Motion (Yaw) of the Cross-Slide on a Group 1 Machine



followed, i.e., twice through the bidirectional test before acquiring data. The angular positioning test can be used for any servoed rotary axis. The angular positioning accuracy and repeatability are measured in a minimum of nine positions.

7.5.2 Setup With an Indexing Table and an Interferometer. The preferred method for testing the positioning accuracy of a rotary axis is to use a calibrated indexing table in combination with a laser angular interferometer. Using this combination provides continuous angular displacements and automatic operation. A calibrated index table is fixtured to the face of the rotary axis to be tested. The angular attachment to a commercial laser interferometer is attached to the indexing table with a double retroreflector mounted on the center. Figure 7.5.2-1 illustrates a typical setup for angular positioning measurement using a calibrated index table and a laser interferometer on the spindle, C-axis, of a lathe. Laser-based, angular interferometers can have large errors if not properly aligned and need to be corrected for nonlinearity if the measurement angle exceeds a few degrees. In such cases, the laser interferometer Supplier's recommendations should be followed.

The axis of rotation of the calibrated indexing table shall be aligned parallel to the rotary axis being tested. In addition, the centerline of the double retroreflector shall be square with the rotary axis being tested. Figure 7.5.2-2 illustrates the method for adjusting and verifying this alignment. An indicator is bracketed to the cross-slide and adjusted so that the stylus contacts the outer edge of the double corner cube reflector. The indicator is zeroed at this point. The cross-slide is moved so that the indicator is clear of the corner cube. The rotary table is lifted,[9] and the rotary axis being tested is rotated 180 deg, with the antirotation bar in place on the rotary table of the indexing table. The indexing table is then reclamped and the cross-slide returned to its original position. The procedure is repeated for a 90-deg and a 270-deg rotation. For each pair of rotations, the reading of the indicator should be within 50 µm (0.002 in.) to ensure an error less than 1 part in 1,000 of the measured angle.

NOTE: Such a procedure assumes that the side faces of the angular retroreflector assembly are parallel to the plane defined by the centerline of the two cube corners to within 5 µm (0.0002 in.).

[9] When measuring turrets, which also "rise" when indexed, the combination height change of indexing table and turret may cause loss of laser signal. In this case, it is acceptable to index the turret and indexing table independently, provided the optics can accommodate the angular increment. If this cannot be accommodated, the autocollimator method (para. 7.5.3) or the polygon method (para. 7.5.4) may be substituted.

Fig. 7.5.2-1 Schematic for the Measurement of Angular Positioning Using an Indexing Table and a Laser Interferometer

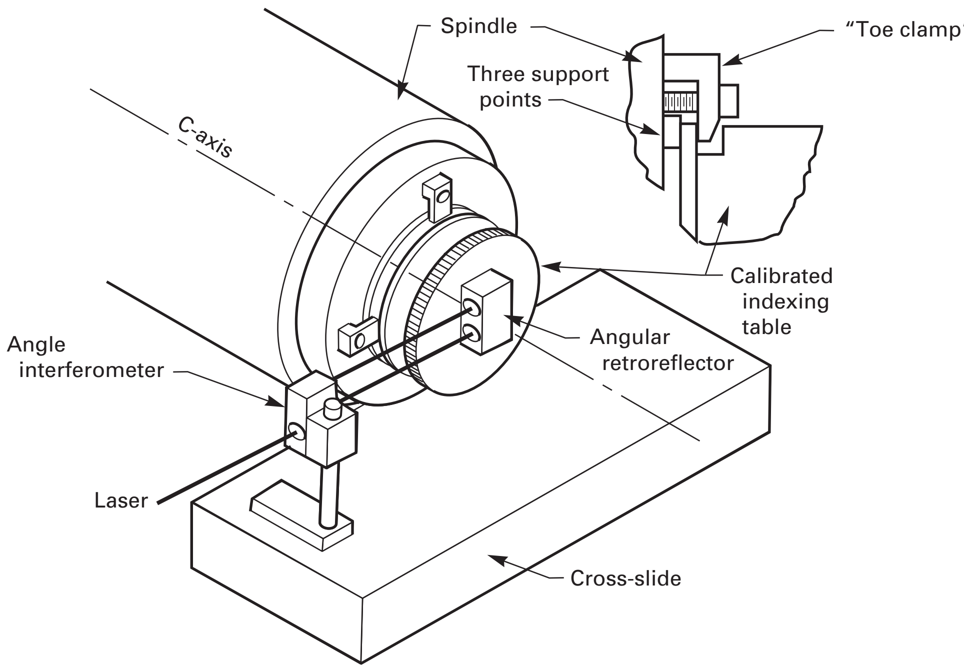
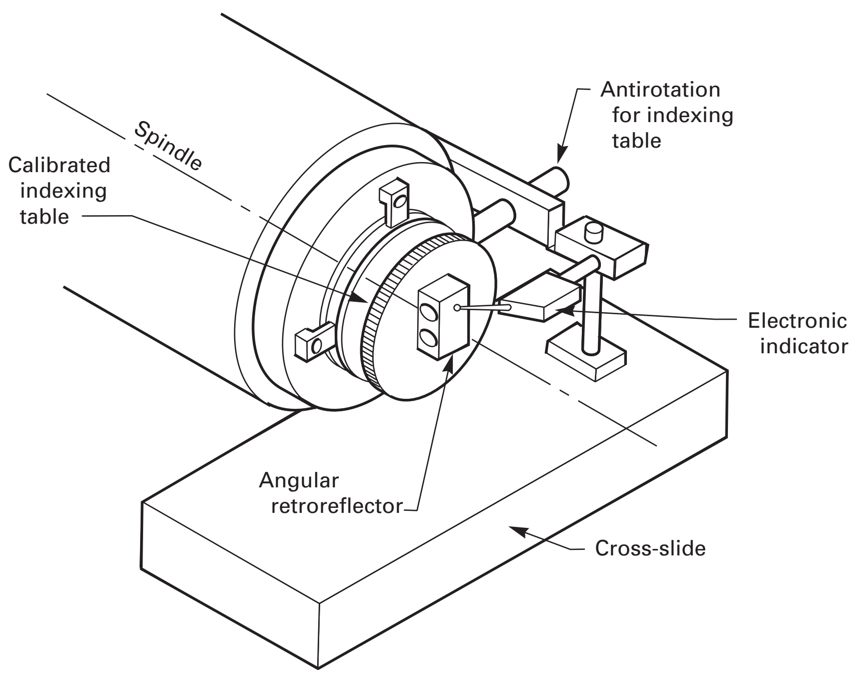


Fig. 7.5.2-2 Setup for Adjusting the Alignment of an Indexing Table and a Laser Angle Interferometer



Before commencing measurements, the machine shall be run through an exercise cycle of two complete clockwise and counterclockwise cycles for each rotary axis, using the same program or manual time sequence that will be used during data acquisition. The testing procedure is to command the machine under computer control to step known angular intervals and either manually or under computer control rotate the calibrated indexing table in the reverse direction to maintain a condition of perpendicularity between the retroreflectors and the interferometer. Data shall be taken and analyzed as described in para. 7.5.7.

7.5.3 Setup With an Indexing Table and an Autocollimator. The procedure for testing angular positioning using an indexing table and autocollimator is conceptually similar to that using an indexing table and an interferometer, as described in para. 7.5.2. As before, a calibrated indexing table is fixtured to the face of the rotary axis to be measured. Again, attention should be paid to fixture-induced stresses and table alignment, which can alter the calibration accuracy. A flat mirror, with its face parallel to the axis of rotation, is mounted to the surface of the indexing table facing a manual or electronic autocollimator with the appropriate resolution and accuracy (see section 9).

NOTE: The autocollimator has a smaller range than the laser interferometer and is therefore not preferred, except in the case when the combination of turret "rise" and indexing table "rise" is excessive for a laser interferometer.

The procedure is to first exercise the machine by running the calibration program twice (see para. 7.5.2) and then to command the machine under computer control to step known angular intervals and either manually or under computer control rotate the calibrated indexing table in the reverse direction to maintain a condition of near perpendicularity between the mirror surface and the autocollimator. After exercise, measurements shall be taken and the data analyzed as described in para. 7.5.7.

7.5.4 Setup With a Polygon. This test is performed using a calibrated optical polygon with a minimum of nine faces for a positioning axis, or with a number of faces equal to the number of turret positions for an indexing axis. The polygon is appropriately fixtured to the face of the rotary axis to be measured. Special attention should be given to the attachment of the polygon to minimize any fixture-induced stresses that might distort the polygon mechanically and alter the calibration accuracy. Calibration shall be to at least the level required for the application. A manual or electronic autocollimator should then be placed so that an image is obtained from one of the polygon faces. A sample setup is shown in Fig. 7.5.4-1 for a servoed spindle axis. The autocollimator shall also have been calibrated to the required accuracy. Details on the polygon and autocollimator are given in section 9.

After checking for on-scale behavior of the system by commanding the machine under computer control to step the appropriate faces of the polygon to a condition of perpendicularity with respect to the autocollimator, the axis should be exercised (two complete cycles, see para. 7.5.2) and a series of readings shall be taken in an incremental fashion on the angular position of each of the polygon faces.[10] After exercise (see para. 7.5.2), measurements shall be taken and the data analyzed as described in para. 7.5.7.

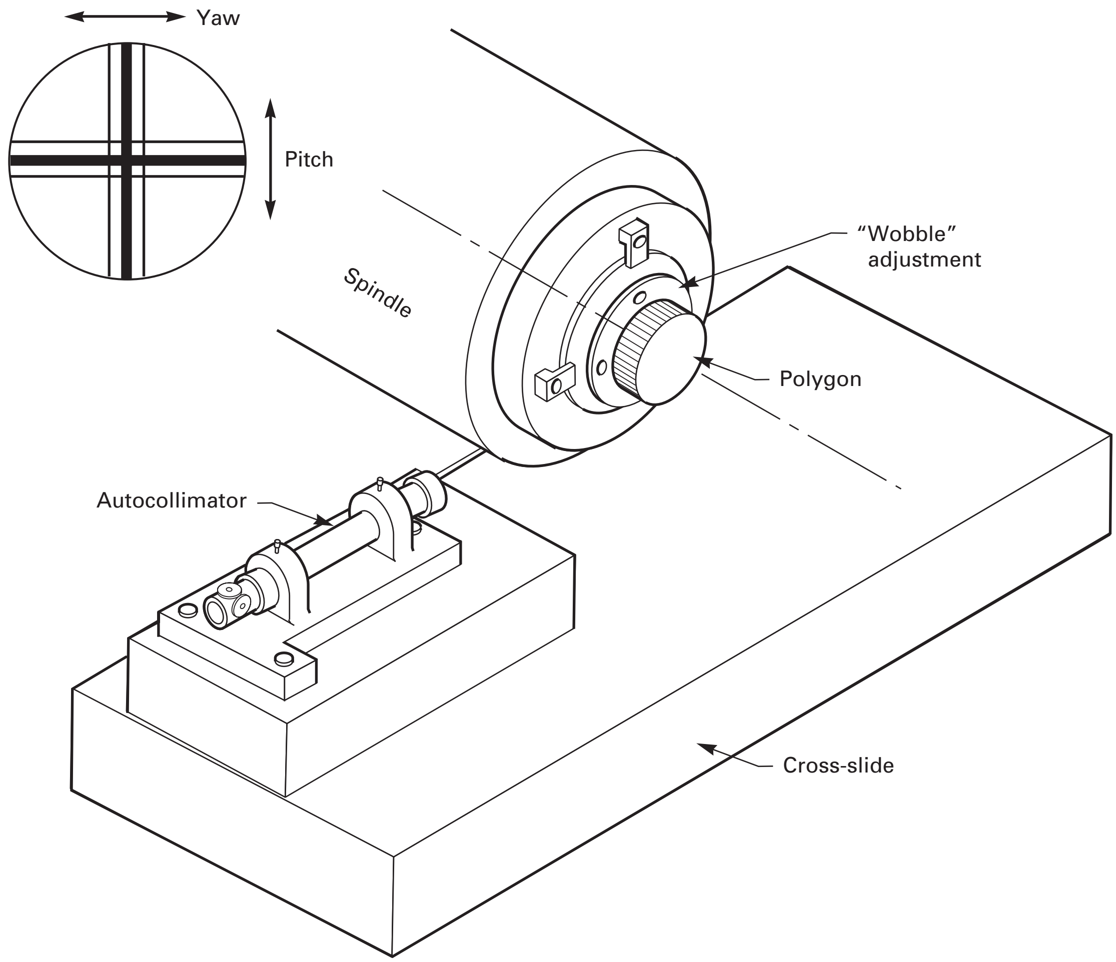
7.5.5 Setup With a Rotary Encoder. A third method for checking angular positioning, and perhaps periodic angular positioning, involves using a calibrated rotary encoder. If such a system is used, the instrument manufacturer's recommendations for system mounting and alignment shall be followed, and the calibration of the device shall meet the minimum requirements as specified in section 9. A typical setup is shown in Fig. 7.5.5-1. Following exercise (see para. 7.5.1), measurements shall be taken and the data analyzed as described in para. 7.5.7.

7.5.6 Setup With a Level. On some machines it is possible to measure the angular positioning of the turret or other rotary axis using an indexing table and an appropriate level as a small-angle indicator. In this case, the level should be bracketed in a position equivalent to that shown for the laser angular retroreflector in Fig. 7.5.2-2. If a level is used, the procedure outlined in para. 7.5.2 should be followed, including machine exercise cycle. Measurements shall be made and the data analyzed as described in para. 7.5.7.

7.5.7 Angular Position Measurements and Data Analysis. Independent of the measurement instrumentation selected, a series of bidirectional measurements shall be taken in this fashion over the full-circle angular position of the spindle, rotary axis, or turret at the predetermined number of locations, repeating this procedure 5 times as described in para. 7.5.1. Five sets of bidirectional measurements shall be taken. When using the laser interferometer, the readings at each location shall be averaged for 0.25 s, taking a minimum of 120 points. The angular deviation at each angular position shall be measured 10 times, 5 times in one rotation direction and 5 times in the reverse rotation direction. The data shall be plotted as shown in Fig. 7.2.8-1 and analyzed following

[10] Particular attention must be paid to obtain the correct sign (+ or −) for the autocollimator deviation when performing this calibration. On a machine with a servoed rotary axis, this sign may easily be obtained by jogging the machine in a direction of increasing angle and ensuring that the autocollimator reading also indicates an increasing angle. On an indexing machine, hand pressure on the rotary table, in the correct direction for a positive angle, is usually sufficient to create an autocollimator reading for obtaining the correct sign.

Fig. 7.5.4-1 A Polygon Mounted to a Spindle Axis



the prescription for linear axes as given in para. 7.2.7, except that the units are in arcseconds or decimal degrees and only nine target angular positions are required. Although only nine positions are required by this Standard, if the instrumentation allows, taking a larger number of points is highly recommended. Note also that, in many cases, the periodic angular positioning (see para. 7.5.8) can be assessed simultaneously with performing this test.

The data obtained from the angular positioning tests shall be analyzed using the same procedures as are used to analyze a linear axis (see para. 7.2.7). The parameters reported shall be the same except that the units shall be in arcseconds or decimal degrees rather than millimeters.

7.5.8 Periodic Angular Positioning. After obtaining the large angular positioning parameters, it is necessary on a servoed angular axis to check the angular interpolation of the scale devices. Since many different types of angular scales are used, it is difficult to define, in general, an interval of small angle measurement that will be sufficient for all applications. This test is necessary because angular encoders are often built in such a fashion that the error between integral angles can be extremely small, but the error in interpolation between these angles can greatly exceed the error at integral angles. The interval for periodic angular positioning measurement should be chosen such that it encompasses at least the interpolation interval on an angular axis using optical encoders, moiré gratings, or inductive scales. On rotary tables whose angular position is measured by the position of a worm gear drive, the interval shall correspond to at least two rotations of the worm gear. Once the interval has been established, this Standard provides for three methods of measuring the periodic angle positioning. One uses the angular attachment to a commercial laser interferometer system, the second uses a mechanical setup consisting of an electronic or mechanical indicator and a micrometer, and the third uses a rotary encoder.

7.5.8.1 Periodic Angular Positioning Using a Laser Interferometer. The setup for this measurement is similar to that shown in Fig. 7.5.2-1, without the indexing

Fig. 7.5.5-1 Typical Setup for Measuring the Angular Positioning Accuracy of a Rotary Axis Using an Angular Encoder

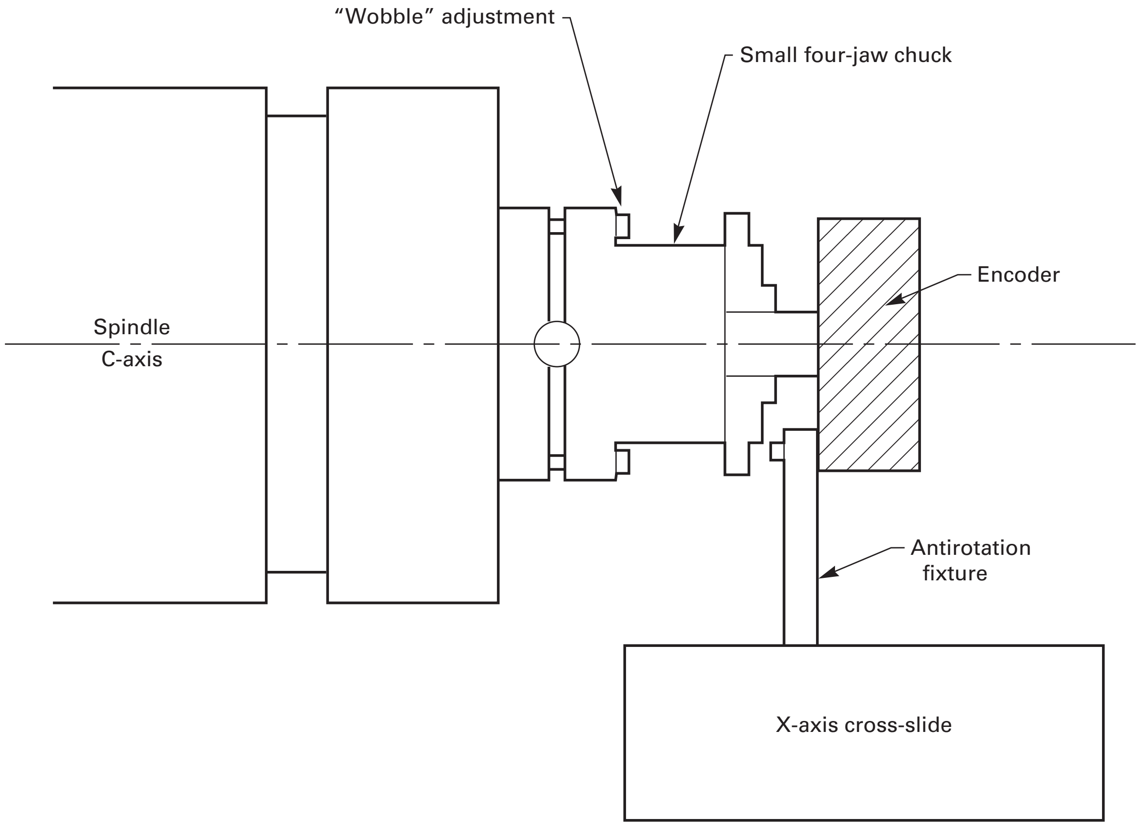
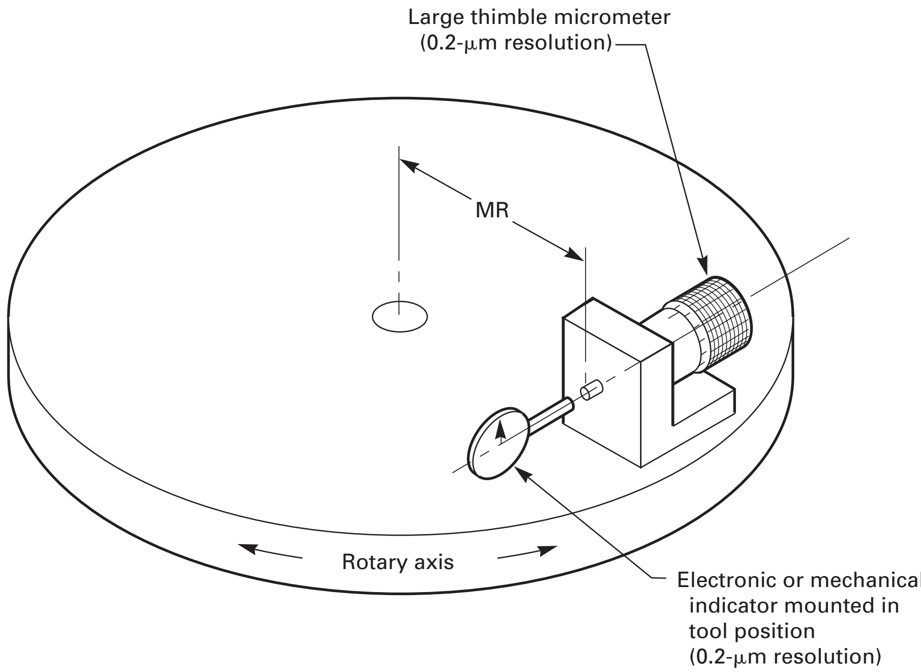


table. Here, the angular attachment to a commercial laser interferometer is used with the double retroreflector mounted in the position of the polygon of para. 7.5.4. Note that this measurement may be made with the indexing table in place as part of the angular positioning test if the option in para. 7.5.2 is used. The servoed axis of the machine is then commanded to move in intervals one-twentieth of the period of the expected periodic error cycle and the laser angle reading recorded. This procedure shall be performed unidirectionally and repeated five times over the same range, without rezeroing the laser interferometer, to ensure consistency and assess instrumental and environmental drifts. The differences between the laser angle reading and the incremental angle command shall be plotted as shown in Fig. 7.2.8-1 for a linear axis (except the deviation units are in arc-seconds). The periodic angular positioning is the range of the average angular deviations as shown in the figure. The analysis is analogous to that for unidirectional systematic deviation of positioning (see para. 7.2.7.2). Note that this procedure often reveals periodic components of interpolation that can be used for analysis purposes outside the scope of this specification. Note also that laser-based angular interferometers can have large errors if not properly aligned and need to be corrected for nonlinearity if the measured angle exceeds a few degrees. The interferometer manufacturer's recommendation shall be followed regarding the angle range of the angle interferometer.

7.5.8.2 Periodic Angular Positioning Using Displacement Measurements. Periodic angular positioning can also be readily measured using displacement-measurement apparatus. A mechanical setup using a micrometer and an appropriate electronic or mechanical indicator with a spherical stylus is shown in Fig. 7.5.8.2-1. A laser displacement-measuring interferometer, or other long-range displacement indicator, can also be substituted for the micrometer and indicator shown. The machine is commanded to move in intervals of one-twentieth of the interval determined, and at each point the electronic or mechanical indicator is rezeroed using the micrometer. The angular motion, θ (in radians), is approximately the ratio of the measured displacement divided by the radius, as shown in the figure. With either the laser interferometer or the mechanical setup, this approximation is valid only for small angles, and corrections shall be applied if the measured angle exceeds a few degrees.

Differences between the angle calculated from the displacement measurement and the incremental angle

Fig. 7.5.8.2-1 Typical Setup for Periodic Angular Error Measurement Using Mechanical Means



command shall be plotted as shown in Fig. 7.2.8-1 for a linear axis (except the units are angular), and the periodic angular positioning shall be computed as in para. 7.2.8. The angle may be calculated from the displacement measurements by dividing the displacement measurement by the measurement radius, MR (Fig. 7.7.4.1-2), and then computing the answer, which is in radians, to either arcseconds or decimal degrees.

7.5.8.3 Periodic Angular Positioning Using a Rotary Encoder. The periodic angular positioning may also be measured using an appropriate rotary encoder. The setup shall be performed as described in para. 7.5.5 and as shown in Fig. 7.5.5-1, and, in fact, the periodic angular positioning shall be assessed as part of the angular positioning if such instrumentation is available. The measurement intervals and the data reduction shall be as described in para. 7.5.8. Note that the rotary encoder often has periodic errors of the same magnitude of the rotary measurement device used in the table or spindle to be tested. This should be thoroughly assessed before using such a device for this measurement, and in no case should a rotary encoder be used that has the same interpolation interval as the encoder used on the table or spindle to be tested.

7.6 Spindle Axis of Rotation

Traditionally, a simple lathe or turning machine is equipped with a spindle for fixturing a part (work spindle), and a cross-slide, mounted on a saddle, for fixturing tools. Modern machines can be equipped with multiple spindles, multiple turrets, and even rotating (“live”) tooling (tool spindles). It is impossible, in this Standard, to cover all conceivable configurations. For the purposes of this Standard, tests are defined for all work spindles and all part spindles that are supplied as part of a machine purchase. If spindles are to be excluded from these tests because they are “auxiliary” spindles (see section 4), this exclusion shall be agreed upon between the User and the Supplier as part of the original machine specification. Otherwise, such spindles shall be tested following the procedures described in paras. 7.6.1 through 7.6.4 and 7.7.

7.6.1 General. The general problem of the specifying and testing of axes of rotation is thoroughly treated in ANSI B89.3.4M. The details of that Standard will not be repeated here. Rather, minimum tests are defined that are necessary for ensuring spindle performance for the average User; others should refer to ANSI B89.3.4M for further background material. Measurements for both rotating sensitive direction and fixed sensitive direction (see section 4) are discussed.

For axes of rotation, the general term “error motion” is used herein to refer to the relative displacement in the sensitive direction between the tool (or gage head) and the workpiece. Error motions in the sensitive direction cause one-for-one form errors to be cut into the workpiece and thus are most significant for machine tool performance characterization. Error motions perpendicular to the sensitive direction are considered to be in the nonsensitive direction and are not evaluated in this Standard. For the purposes of this Standard, two types of sensitive direction are recognized. The first, fixed sensitive direction, occurs in turning, i.e., lathes, where the part is rotating in the spindle of interest and the tool is fixed. The second, called rotating sensitive direction, occurs where the tool is rotating and the workpiece fixed. In the case of turning centers, this Standard is applicable only where such machines are equipped with "live" tooling. This Standard provides procedures for the evaluation of the ranges of some of the relevant spindle error parameters. The error parameters used in this Standard are limited to subsets of average and uncertainty in radial, axial, and tilt motions.

All the measurements in this section require rotating a test ball, mandrel, or other artifact in a fixture at high speeds. Users are therefore warned to use appropriate cautions to ensure operator safety.

7.6.2 Structural Motion. Before commencing with spindle error testing, the structural motions of the machine shall be assessed with the spindle off. These tests are similar in setup to those tests for relative vibration given in para. 6.3.1. They are, however, conducted in conditions designed to point out relative motion between the spindle and the tool, which is caused by the machine itself rather than the environment or actual spindle rotation. The tests shall be run two times for each axis

(a) first with the machine's power and auxiliary systems on but with the machine drives off, that is, the emergency stop position

(b) second with the machine's power and auxiliary systems, such as hydraulics, turned on, and with the machine drives on, that is, with the machine in the feedhold mode

The setup is shown in Fig. 6.2.1.4-1. The values obtained from these tests should be compared to those obtained in the functional relative vibration tests (para. 6.3.1). If the vibration amplitude in either of these conditions exceeds 25% of the specification zone for unidirectional repeatability and the User has met the Supplier's guidelines regarding vibration and environment, the Supplier shall be responsible for rectifying the situation.

7.6.3 Spindle Tests, Fixed Sensitive Direction. Figure 7.6.3-1 shows some test setups suitable for the measurement of the spindle error motions for the case of fixed sensitive direction, that is, for a work spindle. (In the following tests, it is assumed that a signal, proportional to the angular orientation of the spindle, is generated so that polar plots of the error motion as a function of spindle angle can be generated either in a computer or on an oscilloscope.) A precision test ball, or other suitable artifact, is mounted in the machine spindle, and the displacement indicator is mounted to the tool post or to a fixture rigidly attached to the tool post. The ball or artifact should be centered around the axis of rotation so as to minimize eccentricity. (It is assumed in the later text that the spindle analysis system is capable of removing small residual eccentricities.) The displacement indicator[11] and test artifact should meet the specifications outlined in section 9. (In the case of ultrahigh precision machines, such as diamond turning machines, residual errors due to artifact out-of-roundness should be removed. See ANSI B89.3.4M for this procedure.)

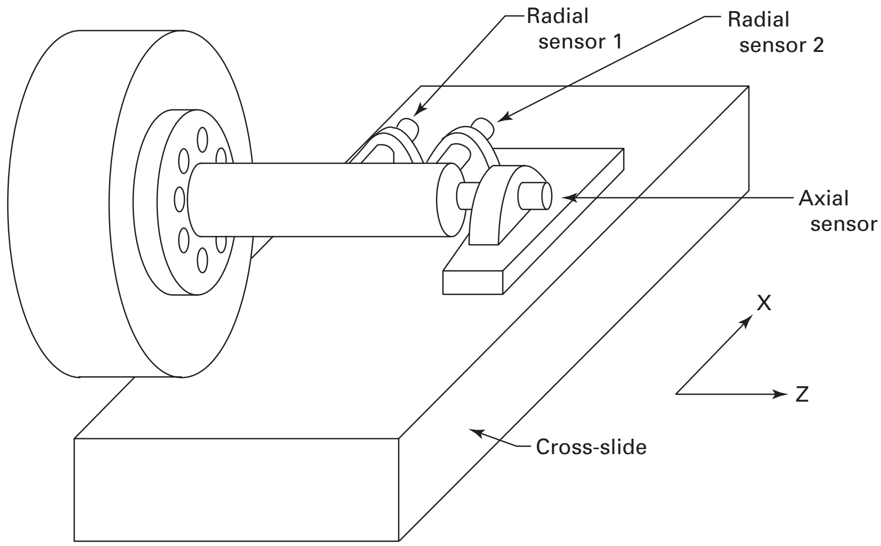
7.6.3.1 Radial Error Motion, Fixed Sensitive Direction. The radial error motion shall be measured by positioning the displacement indicator in the radial direction, as shown in Fig. 7.6.3-1. Radial error motion measurements shall be made at three spindle speeds after the spindle has been allowed a warm-up period at half the maximum revolutions per minute for a period of 10 min. The spindle speeds chosen for this test shall be approximately 10%, 50%, and 100% of the machine's recommended maximum spindle speed. At each speed, a polar plot of the spindle error motion shall be made for a minimum of 20 revolutions. The machine User should also simply observe the output of the error-indicating system while changing the spindle speed slowly throughout its total speed range. There may be speeds at which excessive error motion results due to structural motion. If such speeds exist, they should be reported and avoided when machining. A typical plot for a single spindle speed is shown in Fig. 4-2. This plot should be evaluated as follows. First, the data shall be least-squares fit to a circle and any residual eccentricity removed. Then the average (mean) values of the radial error motion and the asynchronous error motion values shall be computed for a minimum number of 16 angles uniformly distributed around the circle. (Many commercial spindle error analyzers sample at a much larger number of angles; 16 is the minimum, but a larger number is preferred.) The maximum range of these averages shall be called the average radial error motion (it is precisely analogous to the unidirectional systematic deviation; see para. 7.2.7.2). Similarly, the maximum value of the asynchronous motion shall be called the asynchronous error motion.

Although the plot (see Fig. 4-2) looks the same for fixed sensitive direction and rotating sensitive direction, the plot represents the measure of a different quantity. The rotating-sensitive-direction setup(s) should never be used for fixed sensitive direction measurements.

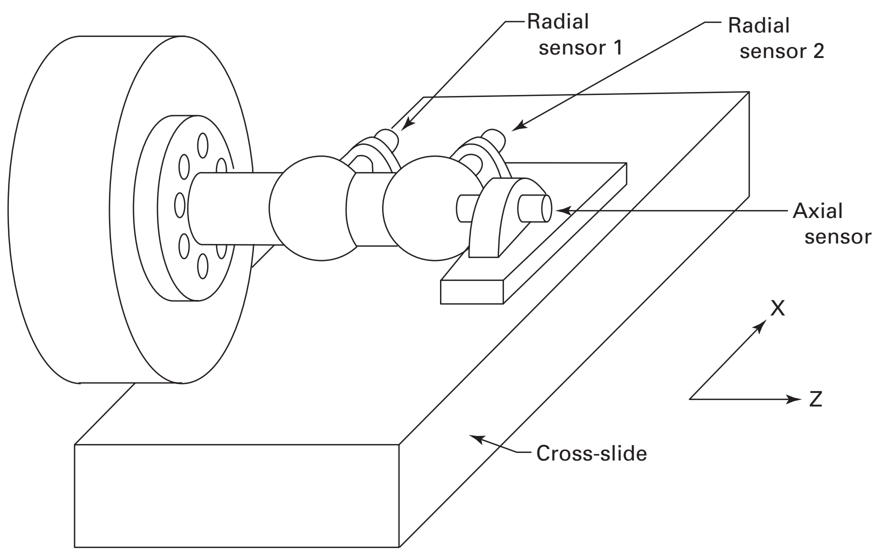
7.6.3.2 Axial Error Motion Test for Fixed Sensitive Direction. The axial error motion shall be measured by

[11] At the time of the writing of this Standard, displacement indicators that work on eddy current principles are, in general, unsuited for spindle measurements. This is because they sense changes in the metallurgy of the test artifact, as well as its geometry, and can give incorrect results. For all spindle measurements, a high-bandwidth indicator that senses only the geometry of the artifact shall be used.

Fig. 7.6.3-1 Test Setups for Measuring Spindle Error Motions in the Case of Fixed Sensitive Direction



(a)



(b)

positioning the displacement indicator in the axial direction, as shown in Fig. 7.6.3-1. Axial error motion shall be measured following the same procedure, including the warm-up cycle, and at the same spindle speeds as those specified for radial error motion. The analysis of the error motion polar plot for axial error motion is also conceptually identical to that for radial error motion, except that fundamental error motion should not be removed analytically. The asynchronous axial motion shall be the maximum value of the range at any angle on the error motion polar plot measured on a radial line through the polar chart center. The average axial error motion shall be the range of the average error motion values, defined with respect to the least-squares center.

7.6.3.3 Tilt Error Motion, Fixed Sensitive Direction. Traditionally, tilt error motion in the fixed sensitive direction has been measured by simultaneously sensing error motions at two spatially separated points, as is shown in Fig. 7.6.3-1. For the purposes of this Standard, the following alternative is offered. First, the test ball or other artifact and capacitance gage are fixtured as described in para. 6.2.1 and shown in Fig. 7.6.3-1, illustration (a), and the average radial error motion and the asynchronous radial error motion measured. Next, the ball or other artifact and indicator are refixtured a distance of at least 50 mm (approximately 2 in.) from the previous position and a second set of measurements of these parameters performed. The difference in the radial error/motion measurements divided by the distance between them [nominally 50 mm (approximately 2 in.)] is the average tilt motion error. The difference in the asynchronous radial error motion divided by the length is the asynchronous tilt motion error, in radians. The measurement of radial error motion may be used for the first measurement if the second measurement is taken shortly thereafter.

Accurate measurement of the tilt error motion requires simultaneous sensing of the radial error motion at two spatially separated points, as shown in Fig. 7.6.3-1, illustration (b), using radial sensors 1 and 2. A commercial spindle error analyzer can be used for this purpose, or a test fixture with two balls with their centers spaced some distance apart [50 mm (approximately 2 in.) is adequate], or a precision test mandrel or other artifact may be attached to the spindle and aligned with high precision to the axis of spindle rotation, to minimize eccentricity. As stated previously, the balls (or mandrel, or any master in the commercial system) shall have a roundness such that any errors in their form are less than the value of error expected in the machine (see section 9). Otherwise, procedures taken from ANSI B89.3.4M should be used to extract artifact out-of-roundness from the measurement. In either case, the analysis below assumes that the two capacitance gages are set upon the equators of the balls or along the test mandrel at a distance, L_d, from one another. The two displacement indicators should be adjusted such that their sensitivity (output voltage/displacement) is the same and their outputs differenced before input into a spindle analyzer, or their gains calibrated and the subtraction performed in software. In either event, the spindle shall be run for at least 20 revolutions at the three spindle speeds selected, as in para. 7.6.3.1, and the differences between the two readings (gage 1 and gage 2) plotted on a polar plot. The asynchronous tilt error motion value shall be the maximum range from the total error motion polar plot obtained from the difference between the two gage readings, measured along a radial line through the polar chart center and scaled by the length, L_d, between the two gages. That is

$$\beta(\theta) = [r_2(\theta) - r_1(\theta)]/L_d$$

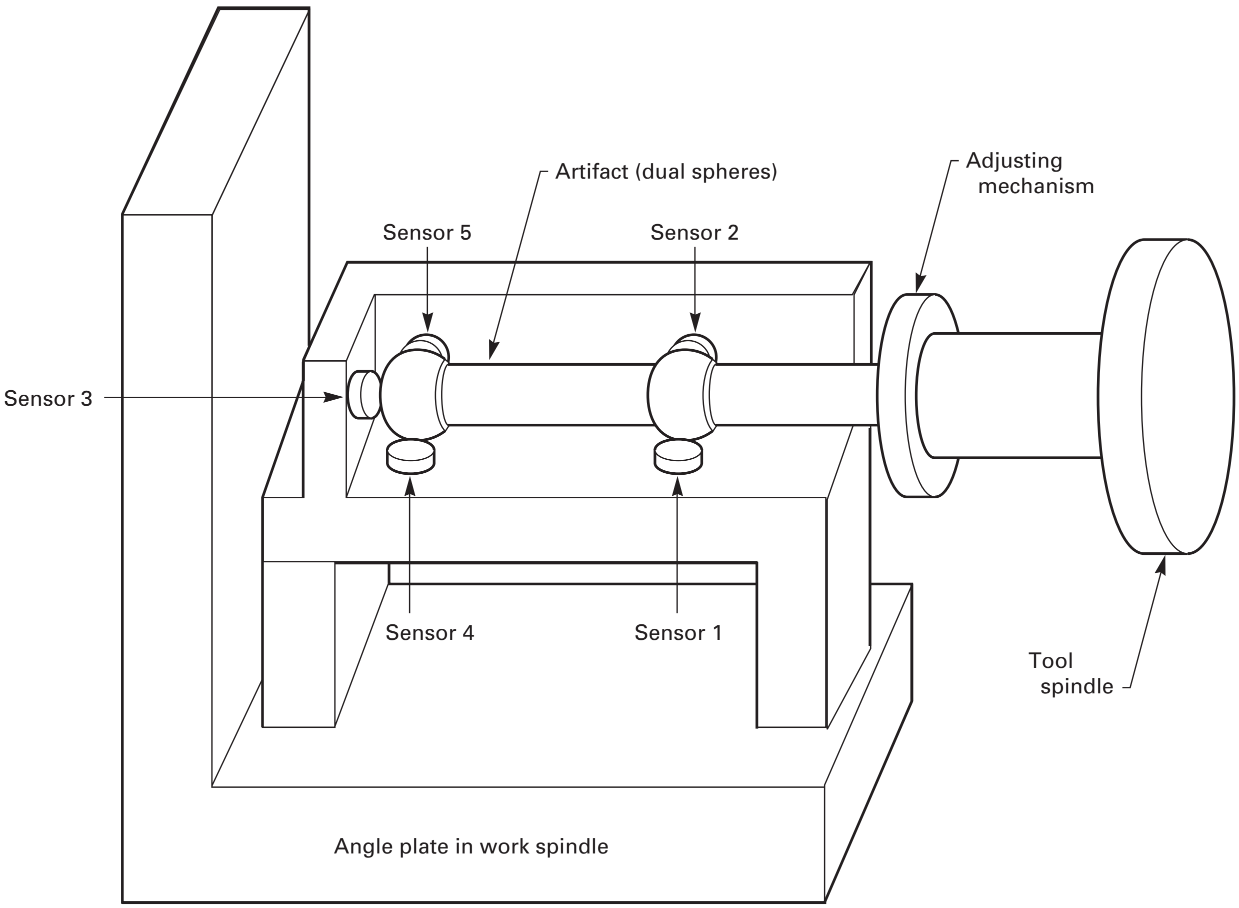
where

L_d = distance between the centers of the two gages
$r_1(\theta)$ = radial motion at gage 1
$r_2(\theta)$ = radial motion at gage 2
$\beta(\theta)$ = tilt motion, rad
θ = angular orientation of the spindle (angle on polar chart)

The average tilt error motion shall be the difference between the maximum and the minimum average error motion value, irrespective of radial direction, and defined with respect to the least-squares center, as in the equation above. For practicality, the computation of the averages and the asynchronous error motions at 16 positions shall be sufficient. For the purposes of this Standard, the maximum value of the asynchronous motion at the 16 positions shall be reported as the asynchronous tilt error motion. For the most accurate estimate, the average tilt motion shall be removed from the data and the maximum range on the resulting plot used for the asynchronous motion analysis procedure.

7.6.4 Spindle Tests, Rotating Sensitive Direction. This test is used only on machines that have auxiliary spindles for milling, i.e., "live tooling." Figure 7.6.4-1 shows a test setup for the measurement of the spindle error motions for the case of rotating sensitive direction. In this setup, a precision test ball or other artifact is mounted in the machine tool "live" spindle, which is the normal location for a tool. The precision test ball or artifact can be the ball or artifact used previously for the *ETVE* test, hysteresis test, and the like, and shall be of a precision greater than that desired for the spindle error motion test. (Various methods exist for removing the imprecision of the test ball or artifact from the spindle error motion measurement. These techniques should be used in ultraprecision equipment and are outlined in ANSI B89.3.4M. For the "live tooling" on most turning centers, however, a test ball or artifact of sufficient accuracy that imperfections in form may be neglected is readily procured.) Displacement indicators are generally mounted to the work spindle of the machine in orthogonal orientations. The displacement indicators should be

Fig. 7.6.4-1 Test Setup for Measuring Spindle Error Motions in the Case of Rotating Sensitive Direction



of the no ncontacting type, such as capacitance, with a bandwidth sufficient to cover the rpm range specified. The bandwidth required depends upon the number of undulations per revolution to be resolved and the rpm range of the spindle. For most turning centers with "live tooling," a bandwidth of 10 kHz is acceptable for speeds upto 6 000 rpm, and scaling of this value can be used for other spindle speeds. If capacitance gages were used for the *ETVE* and other tests and they have appropriate bandwidth, they can also be used for the spindle analysis tests. Figure 7.6.4-1 shows one type of commercial error analyzer, but other models that meet similar specifications are perfectly suitable.

The ball or artifact should be centered around the axis of tool rotation so as to minimize eccentricity, and a signal proportional to the spindle rotation angle, generated by some subsidiary means or the ball or artifact, should be mounted slightly eccentric and this eccentricity used to generate the signals necessary for a polar plot. The setup for this latter case is shown in Fig. 7.6.4-2, and both cases are described in detail in ANSI B89.3.4M. A third method, using a commercially available spindle analyzer, is also acceptable.

7.6.4.1 Radial Error Motion, Rotating Sensitive Direction. The radial error motion shall be measured by computing and displaying the error motion polar plot according to the following equation:

$$r(\theta) = r_0 + \Delta X(\theta) \cos \theta + \Delta Y(\theta) \sin \theta$$

where

r_0 = the value of the radius set by the alignment of the test ball or artifact

$\Delta X(\theta)$ = output of the gage oriented with the X-axis

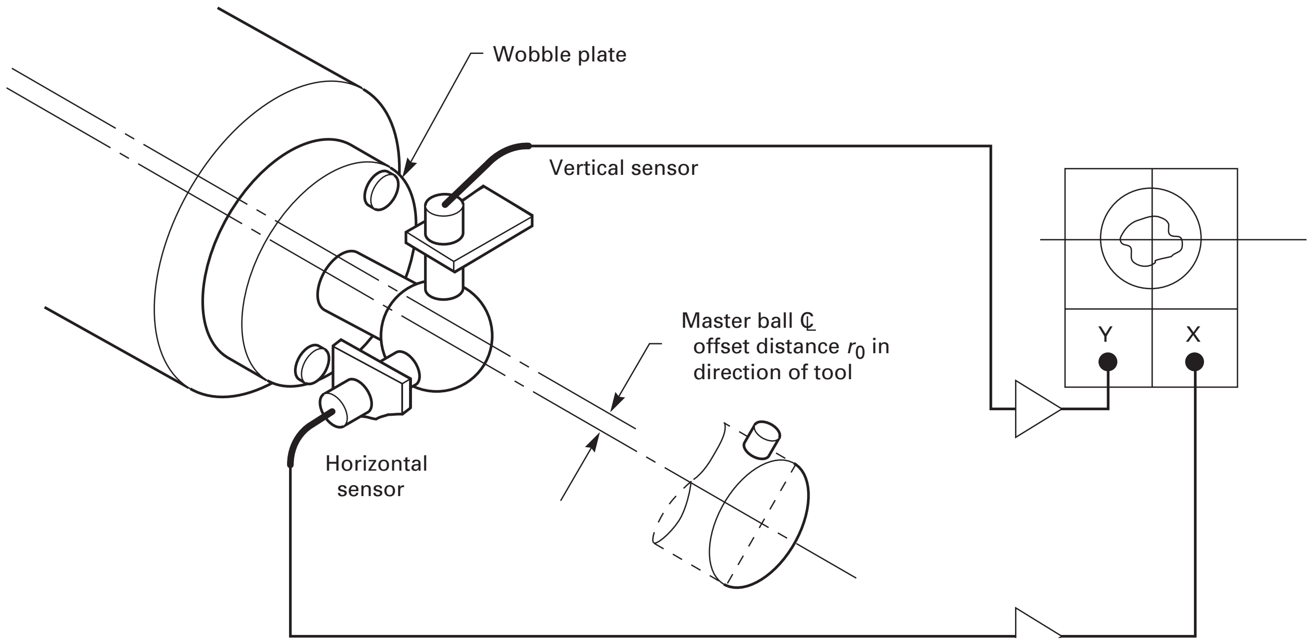
$\Delta Y(\theta)$ = output of the gage oriented with the Y-axis

θ = angle of rotation of the spindle

Radial error motion measurements shall be at three spindle speeds after the spindle has been allowed a warm-up period at half the maximum revolutions per minute for a period of 10 min. The spindle speeds chosen for this test shall be 10%, 50%, and 100% of the machine's recommended maximum spindle speed. At each speed, a polar plot of the spindle error motion shall be made for a minimum of 20 revolutions.[12] A typical plot for a single

[12] For maximum accuracy, a higher number of revolutions may be required for ball and roller-bearing spindles.

Fig. 7.6.4-2 Spindle Test Setup With an Eccentric Ball



spindle speed is shown in Fig. 4-2. The machine User should also simply observe the output of the error-indicating system while changing the spindle speed slowly throughout its total speed range. Speeds may be observed where excessive error motion results due to structural resonances. If such speeds exist, they should be avoided when machining. For the purposes of this Standard, only two error motion values shall be computed from the error motion plot. The asynchronous radial error motion value (per spindle) shall be the maximum range in the radial error motion as computed from the total error motion polar plot (before averaging), measured along a radial line through the least-squares center, as shown in Fig. 4-2. Next, the average (synchronous) radial error motion polar plot shall be computed by averaging the radial error motion polar plot results for the total number of revolutions. A typical average (synchronous) error motion polar plot is shown as the dark line in Fig. 4-2. The average (synchronous) radial error motion, for the purpose of this Standard, shall be the maximum value of the average (mean) radial error motion minus the minimum value of the average (mean) radial error motion, as measured with respect to the least-squares center of the polar plot.

7.6.4.2 Axial Error Motion Test for Rotating Sensitive Direction. The axial error motion shall be measured by positioning the displacement indicator (such as a capacitance gage) in the axial direction, as shown in Fig. 7.6.3-1, or by using a commercial spindle analyzer system. For the measurement of axial motion with a rotating sensitive direction, synchronization to the spindle angular orientation and sophisticated data analysis are not required. Here, the maximum range of the displacement over approximately 20 revolutions of the spindle shall be used as a measurement of axial error motion. The measurements can be done most simply with a commercially available spindle analyzer, but an oscilloscope can also be used. This test is sometimes not required, since for many applications, such as boring, axial motion is in the nonsensitive direction. For certain other applications, such as contour milling and fly cutting, however, it can contribute significantly to machining error and degradation of surface finish. For these applications, these tests should be performed.

7.6.4.3 Tilt Error Motion, Rotating Sensitive Direction. In the past, tilt motion has not been commonly measured for axes of rotation with a rotating sensitive direction. To measure this tilt motion, either a suitably equipped commercial spindle error analysis system or four capacitance sensors and electronics for differencing the data in a setup similar to that shown in Fig. 7.6.4-1 shall be used. In the first case, the spindle error analyzer shall be set up according to the Supplier's recommendations and the tilt motion computed in the software. In the second case, data shall be taken and analyzed as in para. 7.6.3.3 or para. 7.6.3.4, except that the differences between the outputs of sensors 1 and 4 and sensors 2 and 5 shall be used as the ΔX and ΔY in the equation and r_0 shall be set equal to zero (note that sensor 3 is not required). The average tilt motion, in radians, shall be obtained by dividing the average differences by the distance between the sensors in the test setup. The maximum value shall be reported. The maximum value of the differences in the asynchronous error motions (total range on the polar plot), divided by the distance between the sensors, shall be reported as the asynchronous tilt motion value.

7.7 Machine Thermal Tests

7.7.1 General. For the thermal tests described in this section, the machine shall be powered up with auxiliary services operating and axis in the feed-hold position, with no spindle rotation, for a period sufficient to stabilize the effects of internal sources. The machine and measuring instrument shall be protected from drafts and external radiation such as that from overhead heaters or sunlight. If the machine is equipped with an enclosure and the machine will be operated with this enclosure closed, then these thermal tests shall be done in this configuration.

All tests shall be carried out with the machine in the unloaded condition. Where the machine involves rotating both the workpiece and the tool on separate spindles, the tests shall be carried out for each spindle. In all cases, the tests shall be between a nominal workpiece location and a nominal tool location, or vice versa. If any compensation capability or facilities for minimizing thermal effects, such as air or oil showers, are available on the machine tool, they shall be used during the tests and their existence recorded.

All measuring instruments described in paras. 7.7.2 through 7.7.4 shall conform to instrumentation and test equipment requirements given in section 9 and also be "cap" tested according to the procedures outlined in Nonmandatory Appendix J. The results of the cap test on the instrument should be no greater than one-tenth of the expected test deviation, or the instrument should be modified or changed.

7.7.2 Spindle Thermal Stability Test. Movements of spindles caused by self-induced temperature changes yield significant errors in machining for both rotating and fixed sensitive direction. Before proceeding with this test, the machine should be in a quiescent state as described in para. 7.7.1, after a soak-out period of at least 12 h.

7.7.2.1 Spindle Warm-Up Test. This test should be performed for all lathe, tool, and work spindles. For this test, a test fixture, such as that used for the spindle error analysis tests (paras. 7.6.3 and 7.6.4), is fixtured in the machine spindle and set to read against a five-sensor "nest" as shown in Fig. 7.6.4-1 for a tool spindle and Fig. 7.6.3-1 for a work spindle. The sensor nest should be fixtured to the tool post or to the cross-slide in the location of the tool post when measuring work spindles.[13] The sensor nest should be fixtured to the work spindle when testing a tool spindle. The sensors should be of similar sensitivity to those used in the *ETVE* and spindle error tests and be of the noncontacting type (see section 9). If desired, a test mandrel and a sensor-mounting bracket, made of a low-expansion alloy material, may be substituted for the test balls and fixturing used previously.[14] In either event, the mandrel or balls shall be adjusted to minimize radial runout and the sensors set to read positive for deflections of the balls or mandrels toward them. The spindle shall then be turned on to 75% of maximum speed. Data from the five sensors shall be taken at intervals of 5 min max. During the first 30 min of the test, the range of the data at all sensor locations shall be noted. The test shall proceed until the maximum change in any sensor reading over any 30-min period, at all of the sensor locations, has reduced to 15% of the maximum of that sensor change over the first 30 min of the test, or for a maximum of 4 h, whichever is smaller. The data shall be plotted as shown in Fig. 7.7.2.1-1. Angular drifts of the axis average line are plotted in Fig. 7.7.2.1-2. The data recorded at each interval should be an average of measured displacements over a 5-s period. If a digital measurement system is used, a minimum of four samples per revolution for 20 revolutions, at any time during the 5-min period, shall be sufficient. The zero for this figure shall be established by reading the sensors immediately after spindle rotation has commenced. To facilitate comparison between machines, this Standard requires reporting the offsets of the spindle axis average line, as close as possible to the chuck, part-holding device, or, in the case of tool spindles, the tool-holding device (see para. 7.1.3). First, compute the thermal tilts of the spindle axis average line (refer to Fig. 7.6.4-1 for gage designations). The tilts are

$$D_{x,z} = \frac{D_5 - D_2}{L_d}$$

and

$$D_{y,z} = \frac{D_4 - D_1}{L_d}$$

where subscripts x, y, and z designate the plane of tilt, and

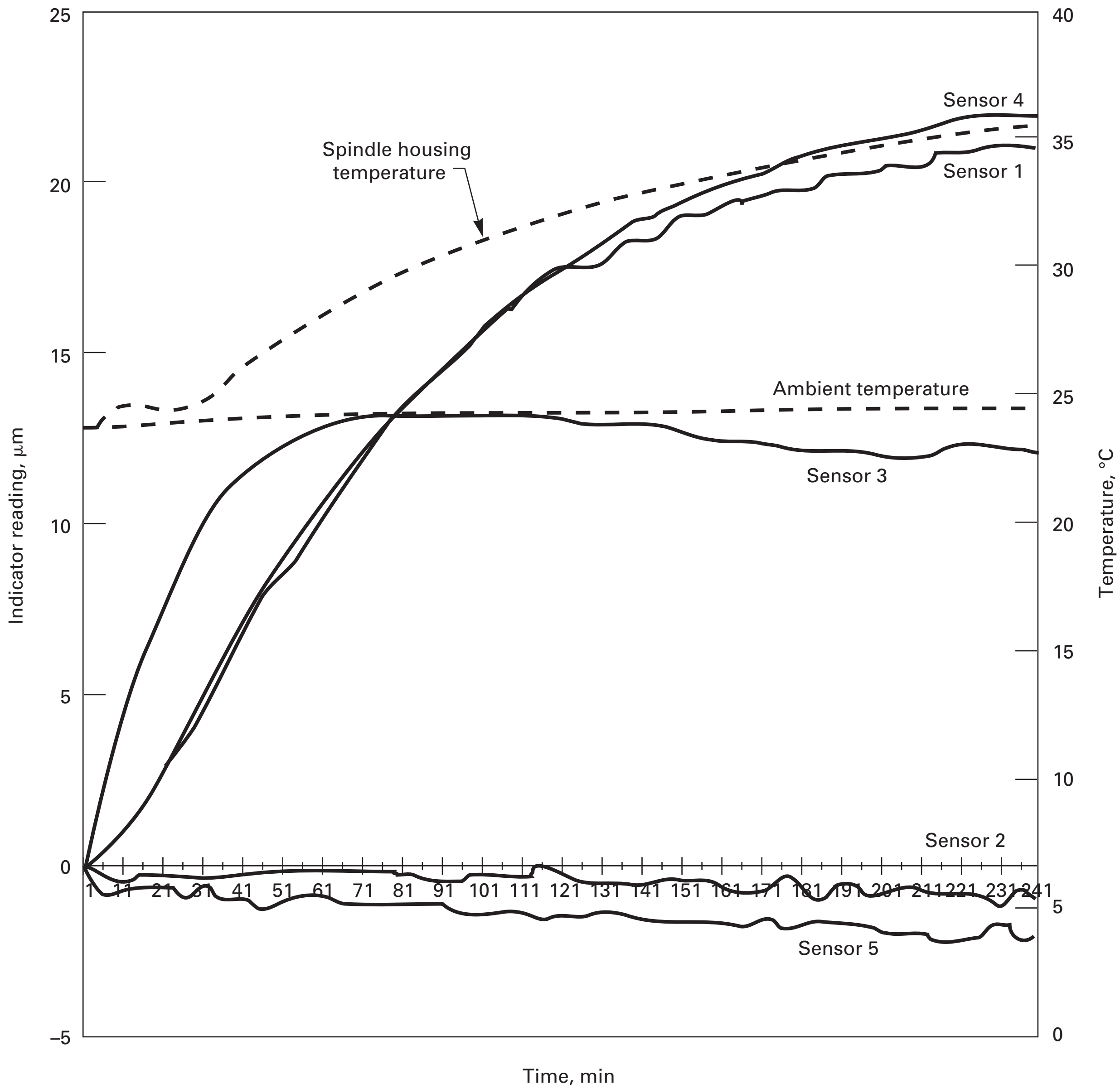
D_1 = reading of gage 1
D_2 = reading of gage 2
D_4 = reading of gage 4
D_5 = reading of gage 5
$D_{x,z}$ = tilt about the x direction
$D_{y,z}$ = tilt about the y direction
L_d = distance between gages 2 and 5 or 1 and 4

Note that the tilt angles are in radians, defined with respect to the gages and not to the machine's axes. Positive tilts indicate tilting toward the gage pair used in the computation.

[13] For work spindles, two sensors in a five-sensor nest will be in the nonsensitive direction and need not be used.

[14] If desired, the fixturing for the gage nest and for the test ball may also be made of low-expansion material. The concept here is, in so far as possible, to check the thermal stability of the spindle and not the thermal stability of the test fixture(s).

Fig. 7.7.2.1-1 Sensor Data From a Typical Spindle Thermal Warm-Up Test



To determine the offset drifts, measure the distance, $L_{1,2}$, between the centerlines of sensor 1 or sensor 2 and the face of the chuck, other part-holding device, or tool-holding device. The offsets of the axis average line at the face of the chuck, etc., are given by

$$D_x = D_2 - L_{1,2} \times D_{x,z}$$
$$D_y = D_1 - L_{1,2} \times D_{y,z}$$
$$D_z = D_3$$

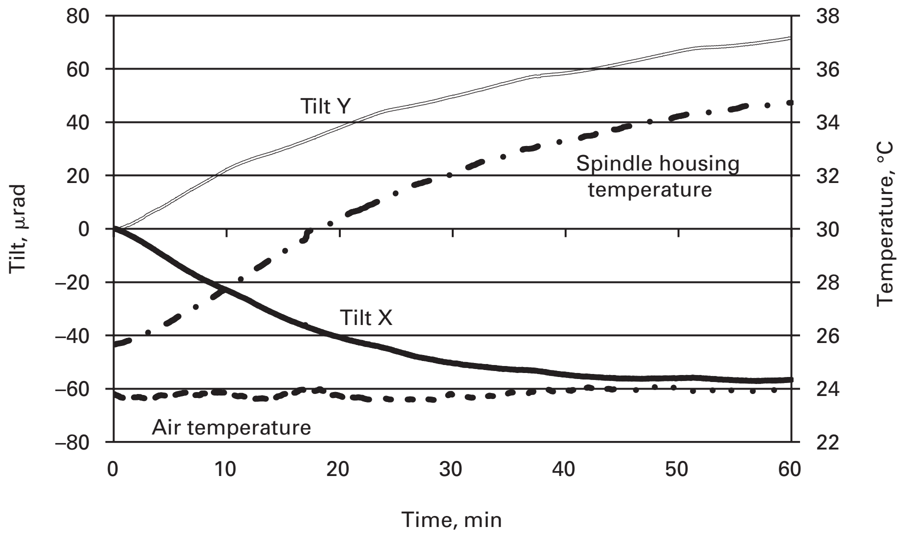
where

D_3 = the reading of gage 3
D_x = the X offset in the selected plane
D_y = the Y offset in the selected plane
D_z = the Z offset

Like the angles, the offsets are positive in the direction of the gages and not necessarily in machine coordinates. For this test, the numbers reported shall be a range of the average in precise analogy to the systematic deviations of positioning discussed in para. 7.2. As with the *ETVE* test, this test should be performed in a configuration suggested by the Supplier; that is, if the machine has spindle thermal control, this facility should be on. If thermal control involves fluids on external spindle components, appropriate instruments should be used.[15]

[15] When tests are performed using cutting lubricant, capacitance sensors should not be used.

Fig. 7.7.2.1-2 Tilts of the Axis Average Line, Spindle Warm-Up Test



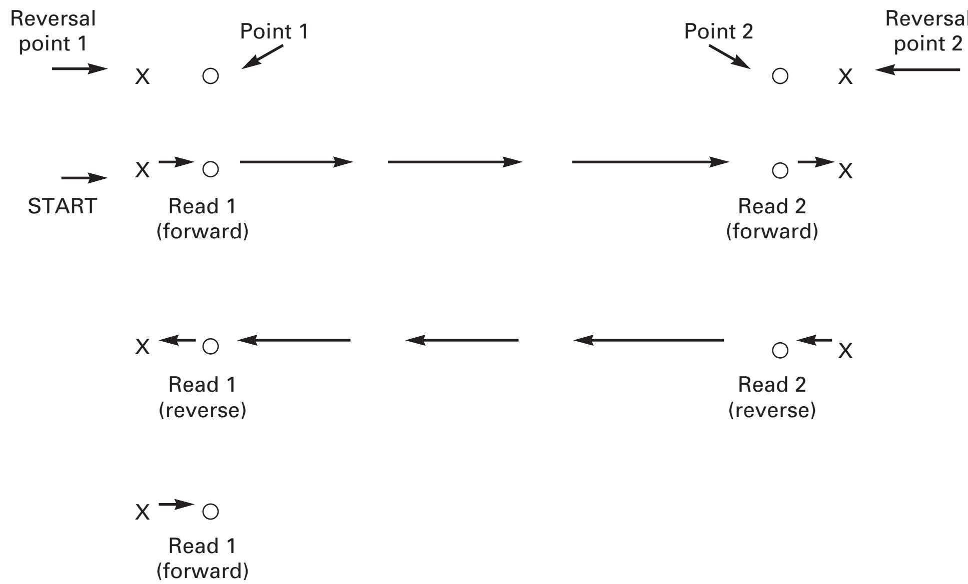
7.7.2.2 Transient Shutoff Test. The behavior of a spindle during warm-up is often dramatically different than the behavior of a spindle during cool-down. This can lead to significant problems when using machines in intermittent duty cycles. It is therefore recommended that a transient shutoff thermal stability be measured. This is performed with either of the two setups, fixed sensitive direction or rotating sensitive direction, and for each of the machine work or tool spindles. For the purpose of this Standard, this test should last for the length of time required for the preceding test on that spindle (see para. 7.7.2.1) or 4 h, whichever is shorter. For either rotating or fixed sensitive direction, this test is performed in the same way. At the end of the warm-up test, the spindle is turned off and the sensors read for a period equal to that of the warm-up test. The data are analyzed as described in para. 7.7.2.1. The transient shutoff thermal stability is defined as the total range of the linear (and angular) readings for a period of 1 h after spindle shut-down. Again, the data are taken at intervals of 5 min max., with each data point being an average of all the readings obtained for a minimum of 5 s within the 5-min interval. For a more detailed discussion of the sampling required, see para. 7.7.2.1.

7.7.3 Thermal Distortion Caused by Moving Linear Axes. This test is carried out to identify the effects of internal heat generated by the machine positioning system (linear axes only) on the machine structure observed as displacements between a nominal workpiece and a nominal tool. The test indicates the amount of drift in the machine axis "home" position as well as the amount of the elongation of machine scales during the warm-up period.

7.7.3.1 Test Procedure. A displacement-measuring instrument, usually a laser interferometer, shall be set so as to measure the distance traversed by the axis under test (corresponding to the relative motion between the nominal tool and the nominal workpiece of the machine) between two target positions. Note that prior to the test, the laser interferometer should be "cap" tested as specified in Nonmandatory Appendix J. An example of a typical test setup is shown in Fig. 7.2.3-1. Note that the setup is the same as that used for the positioning accuracy and repeatability test. The two target positions should be selected close to the end points of travel, where applicable. Two additional reversal positions should be selected outside this test range to allow for bidirectional measurement. Measuring instrumentation shall be located so as to allow for minimum opening in the machine enclosure (if supplied) during the measurements.

Starting from one of the reversal positions, the machine shall be programmed to move the axis to target position 1, where it shall remain at rest long enough for the actual position reached to be measured and recorded. The axis shall then move in the same direction to target position 2, where the second reading shall be taken. The motion should then continue to reach the second reversal point where the direction will be reversed. The readings at target positions 2 and 1 shall then be measured and recorded during this motion in the reverse direction. A diagram showing this procedure is given in Fig. 7.7.3.1-1. The programmed traverse rate shall be 0.5 times the rapid traverse rate, and the dwell time shall be the settling time used for the positioning accuracy and repeatability tests (see para. 7.2). Different dwell times and traverse rates produce different heat inputs; therefore, they cause different axis drifts. If other dwell times and traverse

Fig. 7.7.3.1-1 Path for Measuring Thermal Distortion Caused by Moving Linear Axes



rates are to be specified, they shall be the subject of prior agreement between the User and the Supplier.

The test sequence described above shall then be repeated, recording data bidirectionally at the two target positions. During the first 30 min of the test, the range of the data for each axis shall be noted. The test shall proceed until the maximum change in any axis reading over any 30-min period at both endpoints has reduced to 15% of the maximum of either endpoint change over the first 30 min of the test, or for a maximum of 4 h, whichever is smaller. Before commencing the test on another axis, sufficient time should be allocated to allow for the machine to cool down. The ambient temperature shall be continuously monitored during these tests.[16] Note that on a machine of normal size, a very large number of data will be produced by this test, which may last as long as 4 h. It is recommended that the average value over 10-min intervals be retained, rather than the full data set. The average position values should then be used to compute the thermal drift. Note that this test does not fully assess the machine's thermal behavior but rather indicates thermal problems and can be effective for machine comparison.

If the measuring instrument incorporates compensation for environmental factors, such as air temperature and pressure, then these shall be used. If the measuring instrument incorporates facilities by which the measured data can be modified for the part temperature, then the part sensor shall not be used. For machines using lasers for positioning feedback, environmental compensation for air temperature, pressure, and humidity should be used, if available as part of the normal machine configuration as supplied by the Supplier.

[16] It is useful to measure the drift during the cool-down period. To do this, at the end of the test period, the machine should be at the target position that indicated the largest drift and this position periodically recorded as the machine cools down.

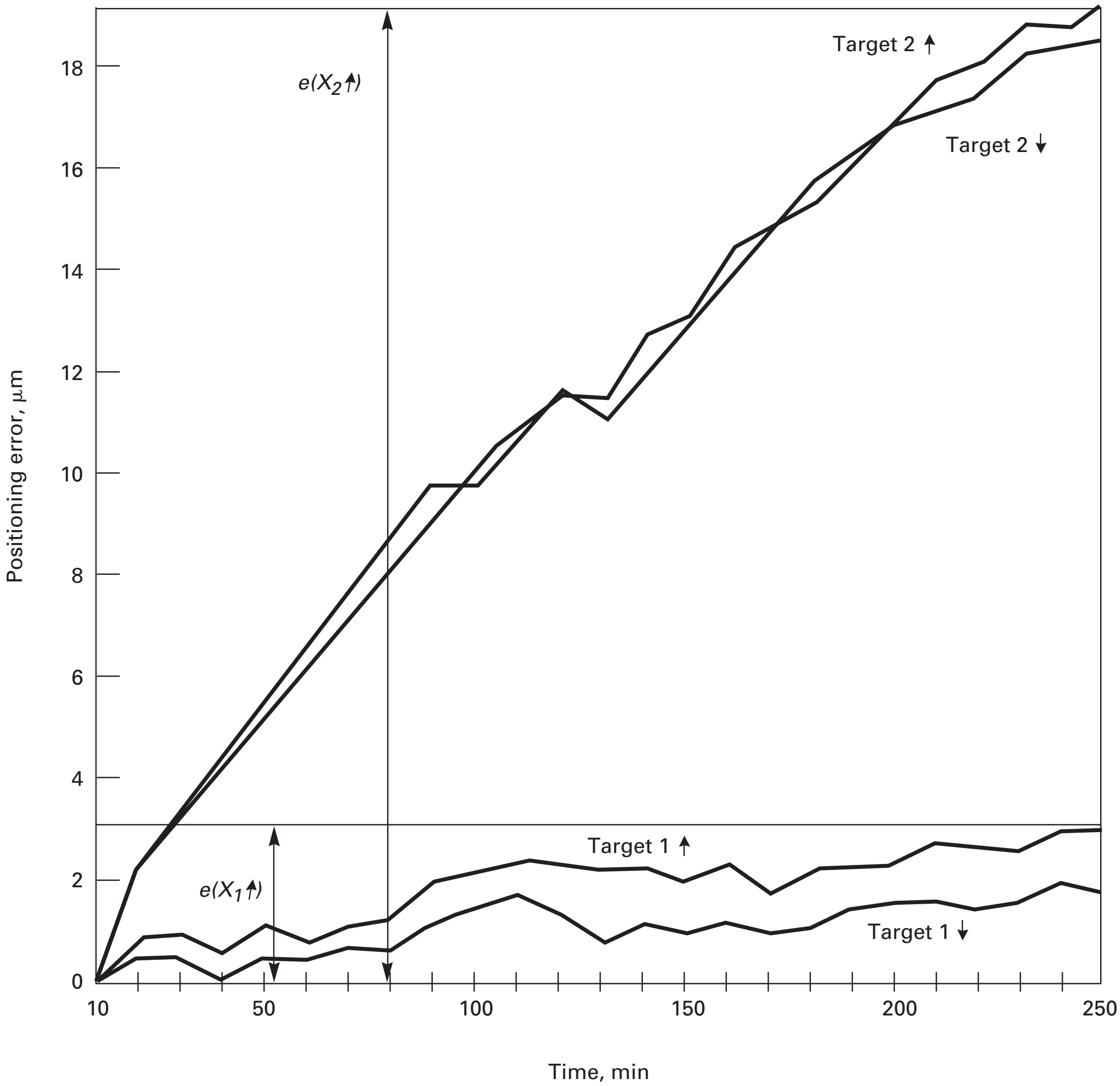
7.7.3.2 Interpretation of Results. At the end of the test period, the error at the two target positions for each direction shall be calculated at 10-min intervals. This shall be done by subtracting the first average position reading from all subsequent readings. The data sets shall be plotted in the form of position error versus time graphs, an example of which is shown in Fig. 7.7.3.2-1. With reference to this figure, error $e(x_1\uparrow)$ is the total range of thermal drift of target position 1 in the X direction for the forward direction, and error $e(x_2\uparrow)$ is the total range of thermal drift of target position 2 in the X direction for the forward direction. The drifts in the reverse direction will be noted similarly, using the down arrow ($\downarrow$).

The dwell (settling) times, traverse rates, setup positions, position of the air temperature sensor, type of test equipment, and target positions shall be recorded with the test results.

7.7.4 Composite Thermal Error. This test is carried out to identify the combined effects of the internal heat generated by the main spindle(s) and the positioning systems on the relative position between the workpiece and the tool. Note that the results of this test cannot be derived from the results of the two types of tests described in paras. 7.7.2 and 7.7.3.

7.7.4.1 Test Procedure. Figure 7.6.3-1 shows a typical measurement setup for a lathe or a turning center

Fig. 7.7.3.2-1 Position Error Versus Time for a Typical Test for Thermal Distortion Caused by a Moving Linear Axis



with a single work spindle and a single tool position or turret. Three displacement indicators shall be rigidly mounted to the tool-holding zone of the machine, so as to be able to monitor

(a) the relative displacements occurring between the structure that holds the tool and the structure that holds the workpiece along the two orthogonal axes parallel to the axes of travel of the machine

(b) tilt or rotation around one axis[17] normal to the spindle axis

If the machine has more than one spindle or turret, the test(s) should be performed as follows. On multiple-turret, single-spindle machines, the sensor should be placed in the most commonly used turret and the artifact in the spindle. Where possible, all axes should be exercised. On machines with two spindles and one turret, use one spindle with the gage and sensor nest and the turret, but exercise both spindles and the turret. On machines with two spindles and two or three turrets, one commonly used spindle and one commonly used turret should be selected, but all spindles and all turrets should be exercised. For machines with a milling spindle head, the test should be performed twice: first with the sensor nest in a turret, measuring with respect to a work spindle; and second with the

[17] If desired, this test may also be performed on a turning center with "live tooling" for each of the tool spindles. In that case, the test for each spindle should be specified in equivalent detail. Also, the five-gage nest (Fig. 7.6.4-1) may be used.

sensor nest in a work spindle, reading with respect to the milling spindle. Wherever possible, all the other axes and spindles should be exercised during the test. If desired, the User may also select other combinations if these combinations are made part of the specification and described in equivalent detail.

The temperature of the machine structure, as close as possible to the front spindle-bearing housing, along with the ambient temperature, shall be continuously monitored. Although these temperatures do not exactly correlate to the measured displacements, they are indications of the thermal changes on the machine structure.

The spindle(s) shall be run continuously at half the maximum speed throughout the test. The axes shall be moved from the test position to the far end of travel and immediately returned to the test position, where they should dwell for a sufficient time for the next reading to be recorded. Axis movements shall be at half the rapid traverse rate except for the final 5-mm (approximately 0.2 in.) approach to the test position, which should be carried out at a low feed rate, and the dwell time shall be the settling time as specified in the positioning accuracy and repeatability test (see para. 7.2).

NOTE: The sequence of axis and other movements, including turret indexing, should be such as to avoid collisions with the measuring equipment and to keep the direction of approach to the test position constant. Other test conditions, including variable spindle speed spectra, may be specified by prior agreement between the User and the Supplier. The dwell time, spindle speed spectrum, traverse rate, sequence of axis movements, and travel ranges change heat input and therefore can cause different drift rates.

The test shall proceed in this manner until the change in the position over any 30-min period, at all the measurement locations, has reduced to less than 15% of the maximum position change over the first 30 min of the test, with a maximum test time of 4 h. The results should be plotted in graphs of deflection and temperature versus time, as shown in the example given in Fig. 7.7.4.1-1. Note that, as in the preceding test, a large number of data points may be generated by this test. Again, only the average value over a reasonable period of time, for example, 5 min to 10 min, should be retained for the purposes of analysis.

7.7.4.2 Interpretation of Results. The effect of warming up the machine structure on the ability of the machine to maintain the position of the tool relative to the workpiece can be assessed from the deflection-versus-time graphs. The results are influenced by the positional repeatability of the machine axis.

7.7.4.3 Presentation of Results. The range of displacements along each machine axis within the first 30 min [$c(X_1,30)$, $c(X_2,30)$, $c(Z,30)$] and during the total test period [$c(X_1,t)$, $c(X_2,t)$, $c(Z,t)$, where t is the time at the end of the spindle-running period] shall be recorded along with the distance, L_{cte}, between the two X displacement indicators and the total time of the test, t. These values, as shown in Table 7.7.4.3-1, shall be presented with the deflection-versus-time graphs. The test procedure, traverse rate, dwell time, sequence of axes movements, location of target positions, and the location of the measurement setup, including the locations of the temperature sensors, should also be reported with the results of the tests.

Thermal drift for each direction shall be reported as the range of displacements for the indicator reading in the respective direction. For X and Y directions, the greater range of either displacement indicator shall be the value reported. Thermal tilts shall be calculated as the range of tilts about X and Y directions. The thermal tilt at any time is the difference in the two indicated readings in the same direction divided by the separation distance.

7.8 Critical Alignments

7.8.1 General. In a lathe or turning center, some alignments reflect themselves one-to-one into errors in the finished part. For a simple two-axis machine, these alignments are the parallelism of the in-feed (Z slide) with the spindle axis of rotation and the perpendicularity of the cross-slide (X-axis) to the spindle axis. These critical alignment parameters shall be measured using metrology instrumentation or by cutting test parts and performing part-trace tests for all X–Z axis pairs. The procedure for performing a part-trace test is outlined in Nonmandatory Appendix K. If the machine is equipped with on-machine probing, the probing system could possibly be used to perform these tests. In such cases, the Supplier shall provide appropriate brackets and electrical connections. Both procedures are allowed in this Standard. Note, however, that the measurements performed by cutting test parts contain information regarding the thermal variations of the machine due to spindle growth and thus will yield different results than the measurements performed using metrology instruments. The choice of test(s), either measurement with a straightedge or test part measurement, or both, shall be clearly stated as part of the original machine specification.[18]

NOTE: Those Users desiring to assign an algebraic sign to squareness and parallelism measurements should follow the conventions given in Nonmandatory Appendix N. Most of the figures in the following sections show negative squareness errors.

[18] In the absence of specifications to the contrary, the general parameters of machine geometry are presumed to apply when the machine is "cold." The reason for this rule is that the "hot" conditions are too variable to have any meaning. If the squareness of X to C is measured when the machine is "cold" using the straightedge or log reversal, and then measured "hot" using the part-trace past center, the thermal errors can be identified. The machine User is, of course, concerned with the "bottom line" accuracy. If the User is aware of the sources of each error, special procedures can often be developed to improve the bottom-line accuracy. These are often called "procedural solutions."

Fig. 7.7.4.1-1 Typical Results From a Composite Thermal Error Test

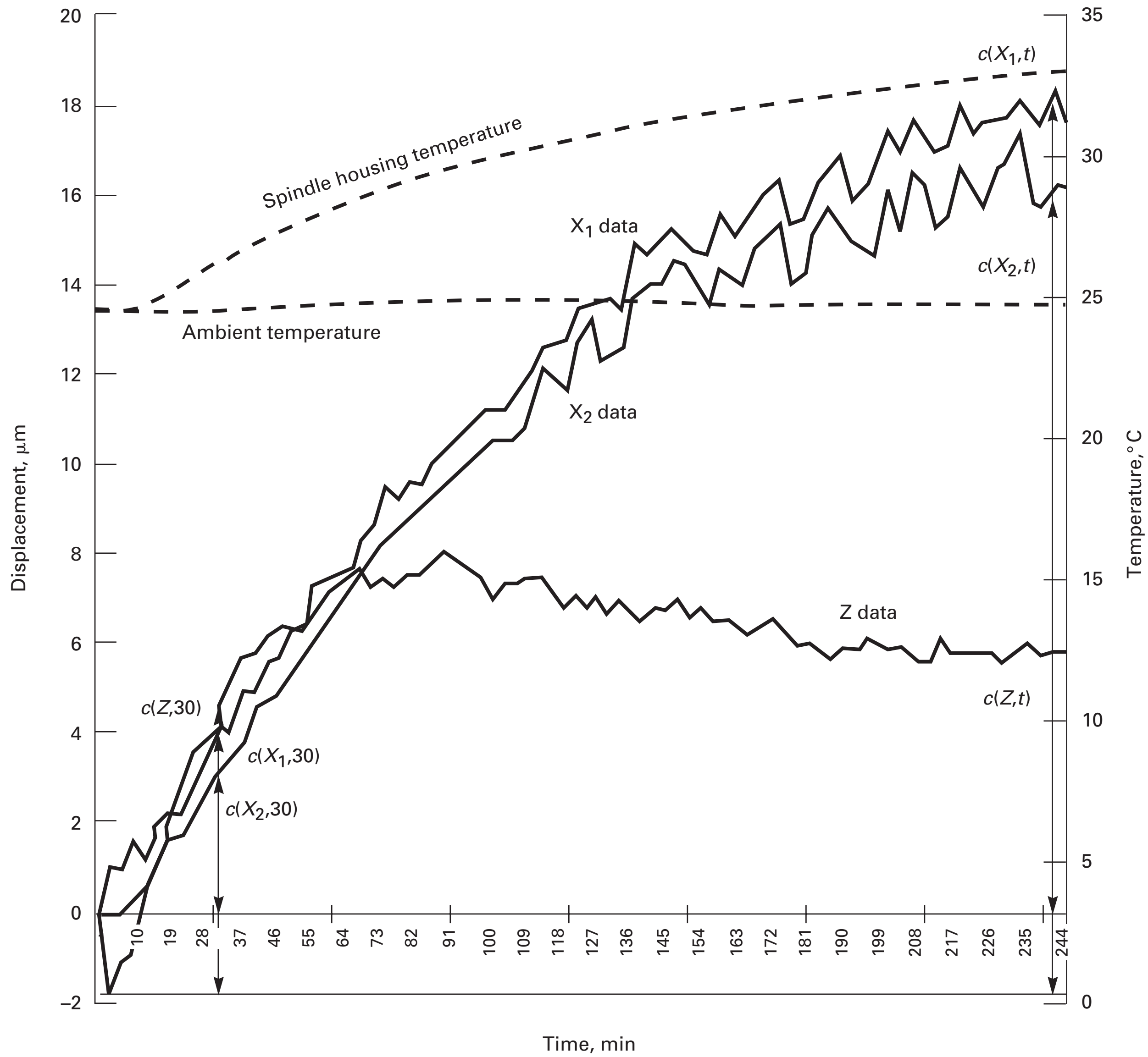


Table 7.7.4.3-1 Typical Presentation of Results From Composite Thermal Error Tests

Reported Data	X_1	X_2	Y_1 [Note (1)]	Y_2 [Note (1)]	Z
After 30 min	$c(X_1,30)$	$c(X_2,30)$	N/A	N/A	$c(Z,30)$
After end of spindle running period, *t*	$c(X_1,t)$	$c(X_2,t)$	N/A	N/A	$c(Z,t)$
Time, *t*					
Distance, L_{cte}					

NOTE:
(1) Values for Y_1 and Y_2 are obtained only when the optional five-gage nest is used. They are in the nonsensitive direction for work spindles on lathes.

7.8.2 Squareness of the Cross-Slide (X-Axis) With the Work Spindle Axis (Often a C-Axis)[19]

7.8.2.1 Measurement Using a Mechanical Straightedge. A typical setup for measuring the squareness of the cross-slide to the spindle axis using a mechanical straightedge and a displacement indicator (or an optical straightedge substituting for a mechanical straightedge and a plane mirror interferometer as the indicator) is shown in Fig. 7.8.2.1-1, which shows a horizontal spindle turning center. (A straightedge can be manufactured rather than purchased; see para. 7.8.2.2.) With the spindle at position $\theta = 0$, the straightedge is mounted so as to straddle the rotary axis center and aligned using the indicator with the machine axis. The change in separation between the gaging surface of the straightedge and the appropriate machine axis, which in Fig. 7.8.2.1-2 is the X-axis, is measured either optically or mechanically. A least-squares fit to the data yields a line whose slope is equal to the angle, *ANGF*, between the X-axis and the straightedge gaging surface. Next, the rotary axis is rotated to $\theta = 180$ deg and a similar measurement performed yielding an angle, *ANGR*. Note that the straightedge must be of the right length and properly clamped for this 180-deg reversal to be possible without damaging the machine or the straightedge, or both. The angles involved are shown in Fig. 7.8.2.1-2. In Fig. 7.8.2.1-2, an arbitrary "forward direction" with the angular axis at zero angle is depicted and the "reverse direction" with the angular axis rotated 180 deg. The angle *F* in the figure is the squareness error between the straightedge and the spindle axis resulting from initial alignment, while the angle *W* is the desired squareness error. The measured angles and the respective orientations are denoted by *ANGF* and *ANGR*. The out-of-squareness is the bisector of these two angles, algebraically $W = ½ \times (ANGF + ANGR)$. If the straightedge is supplied with a correction table, corrections should be made prior to the creation of the graph shown in Fig. 7.8.2.1-3.[20] In the cases of highest accuracy, the straightedge should be precalibrated using straightedge reversal (see ANSI B5.54 for the mathematics of this technique). If it is desired to measure the out-of-squareness of a Y-axis, this can be done using the same procedure, but with the spindle at positions $\theta = 90$ deg and $\theta = 270$ deg.

7.8.2.2 Measurement by Part Tracing Past Center. Measurement by part tracing past center is illustrated by Figs. 7.8.2.2-1 and 7.8.2.2-2. The procedure consists of facing an aluminum cylinder to center with an appropriate tool.[21] Since this test is performed after the spindle has been on the machine, the Supplier shall recommend an appropriate warm-up cycle, machining time, and soak-out time. The size of the cylinder depends on the size of the machine. The diameter, D_c, should be somewhat less than the swing of the lathe but need not be greater than 300 mm (approximately 12 in.) for small machines. The cylinder may also be used, if the User selects, to measure the Z-axis parallelism; thus, its length, L_c, should be at least 300 mm (approximately 12 in.) or the maximum *Z* capacity of the lathe, whichever is smaller. Figure 7.8.2.2-1 shows that the test cylinder is drilled and countersunk at six locations but is only mounted at three. Six holes are necessary only if the cylinder will be measured using straightedge reversal methods (see ANSI B5.54). The part should be "roughed" with one tool and then finished with a light cut using a new, sharp tool. After cutting, the spindle is stopped and the machine allowed to soak out. A displacement indicator is then bracketed on the X slide in the tool position and indicated against the part over the range of X travel used to machine the face. The data obtained from this are shown in Fig. 7.8.2.2-3, as the "before center" data. (Ideally, the indicator should always read zero when traversed along the cutting path, but thermal changes may cause the machine spindle axis to move.) Next, the indicator is rebracketed to the tool post, with the bracket that moves it the radius of the part in the X direction. This is illustrated in Fig. 7.8.2.2-2. This allows the indicator to travel beyond center. The data obtained from this measurement are shown in Fig. 7.8.2.2-3 as the "after center" data. The bisector of these two angles is the machine out-of-squareness, as is clearly indicated in Fig. 7.8.2.2-3. Calculations are equivalent to those given in para. 7.8.2.1.

NOTES:

(1) One-half the change in direction (angle) that is observed by the indicator as it travels across center is the "effective" nonsquareness of the X-axis (including spindle growth) at one particular interval of the spindle growth curve. The "effective" nonsquareness will depend on which direction the facing cut is made as well as the interval on the spindle growth curve. This test can be used as an educational experiment to reveal the sensitivities to these variables. The effect of using the constant cutting velocity feature (variable spindle speed) can also be measured. Since the test part is generated with the spindle running, this test will not, in general, give the same results as the test conducted with the mechanical straightedge.

(2) A diamond tool and aluminum cylinder is the preferred equipment because of minimum wear, lack of built-up edge, and sharpness. Elimination of the built-up edge means that there is minimum sensitivity to cutting velocity, rake angles, type of coolant, etc. Diamond tools have a sharpness that permits very light cuts [0.1 μm (approximately 4 μin.) or less] if the machine has that

[19] Note that many lathes use "diameter programming" and care should be taken when programming a machine with these setups to avoid possible damage to expensive instruments.

[20] The data shown in this figure contain a sinusoid straightness term that may not be typical of most machines.

[21] Depending upon the machine accuracy, this tool can be a single crystal diamond tool, or a polycrystalline diamond insert with a small nose radius [less than 0.75 mm (approximately 0.03 in.)], or another sharp tool of comparable nose radius.

Fig. 7.8.2.1-1 Setup for Measuring Squareness of the Cross-Slide to the Work Spindle Using a Mechanical Straightedge

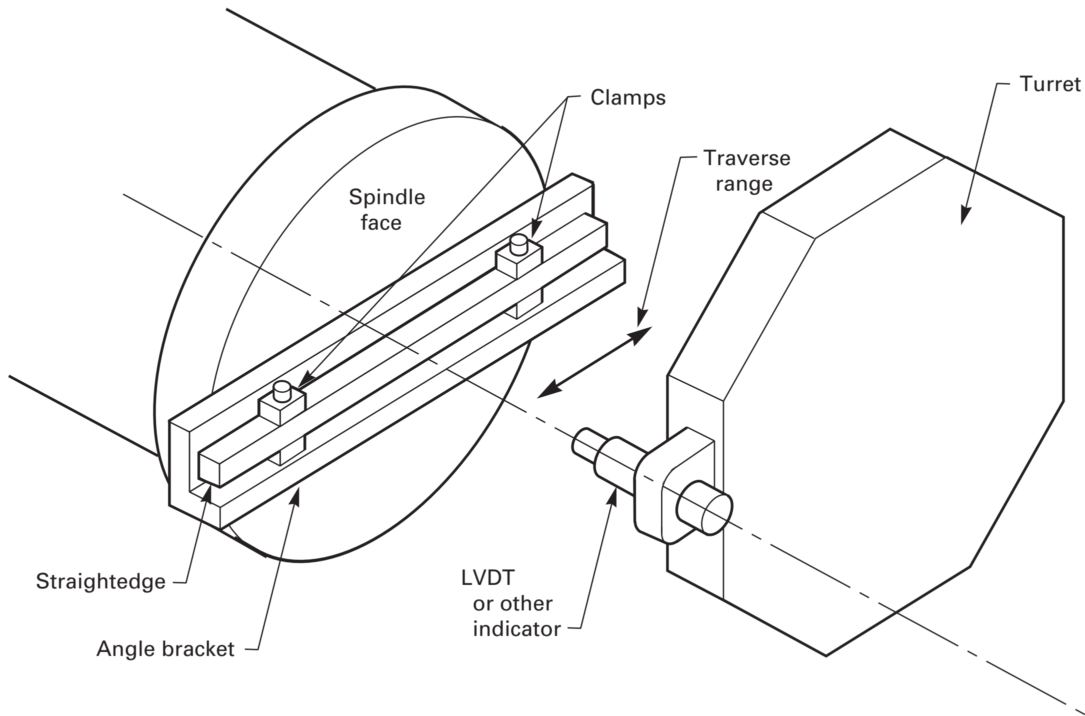


Fig. 7.8.2.1-2 Schematic Showing the Angles Involved When Measuring Cross-Slide Squareness to the Spindle Axis

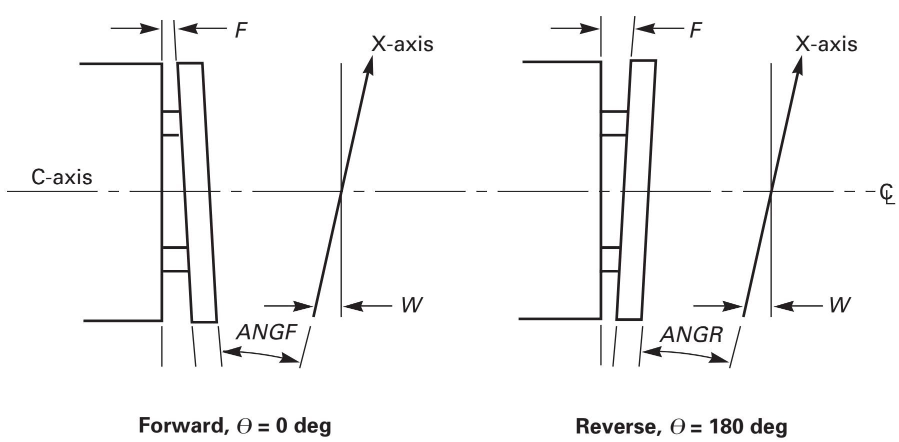
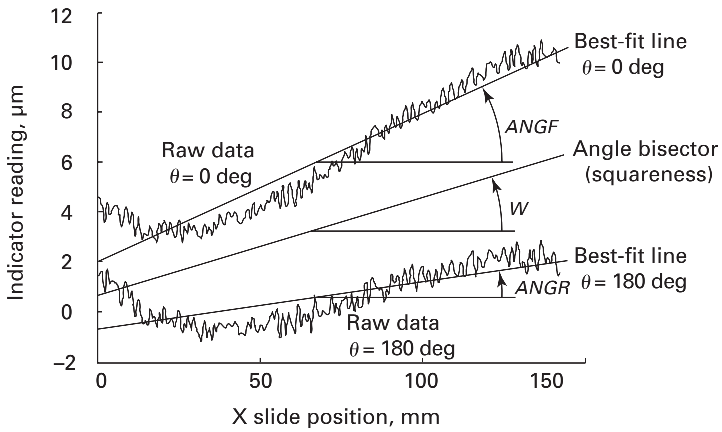


Fig. 7.8.2.1-3 Typical Data From a Cross-Slide Out-of-Squareness Measurement



GENERAL NOTE: The direction of axis travel and the corresponding indicator reading are important to determining the direction of squareness error.

positioning capability. Cutting-force deflection on light finishing cuts is usually negligible.

(3) Bracketing the indicator to a position different than the functional point of the tool causes an error in the calculated squareness if the X-axis has a yaw error. The error equals the change in yaw error per unit of X-axis motion times half the distance between the indicator positions. The yaw error per unit of axis motion can be estimated by plotting the measured yaw error as a function of the X-axis position. It equals the angle of the best-fit line through the data points over the range of the X-axis positions used to measure the face of the cylinder.

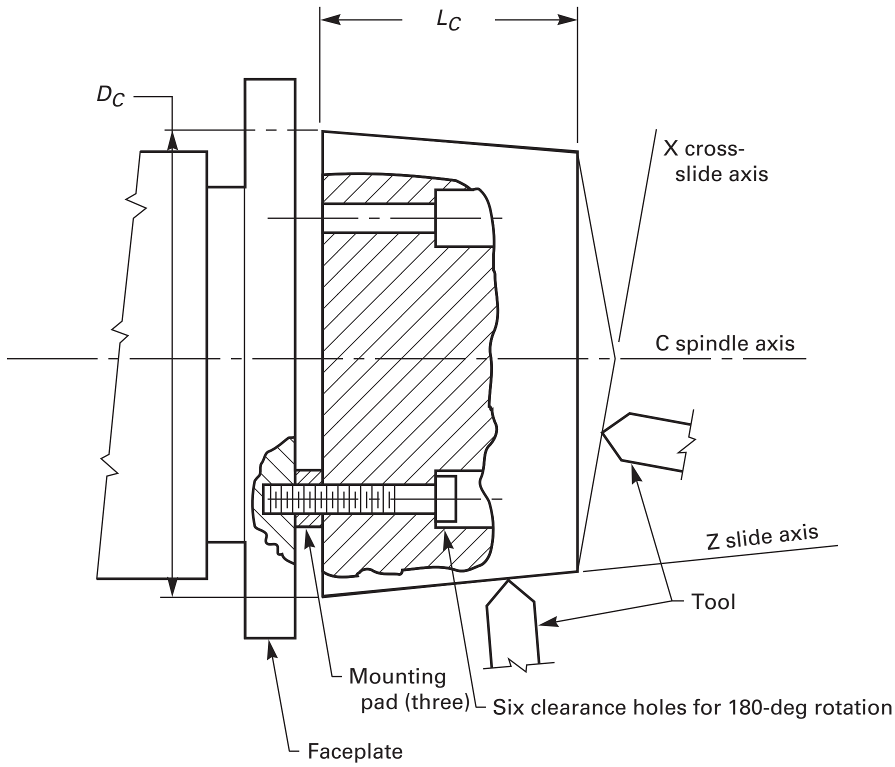
7.8.2.3 End-for-End Cylinder Reversal. The same cylinder faced in para. 7.8.2.2 may also be used for a straightedge, as described in para. 7.8.2.1. First, the cylinder is machined using the machine *Z*-axis to make a cylinder. While the turned cylinder is still in the machine, its straightness is measured using reversal principles, as described in ANSI B5.54. The diamond turned cylinder, which has a known straightness profile as a result of the straightedge reversal procedure, is removed and remounted on a bracket on the spindle approximately parallel with the X-axis in both horizontal and vertical planes. This is shown in Fig. 7.8.2.3-1. The cylinder serves as the mechanical straightedge described in para. 7.8.2.1. A displacement indicator is mounted on the X-axis at the functional-point tool location, and traversed in the X direction along the crest (diameter) of the cylinder until it reaches center. The spindle is then rotated 180 deg and the trace repeated in the outward direction. The data are fit to straight lines, as shown in Fig. 7.8.2.1-3. The bisector of the angle between the two best-fit straight lines to these data is the nonsquareness of the X-axis to the C-axis in the cold condition. (Straightness of the X-axis can also be assessed since the cylinder now has a known nonstraightness, but that is not a requirement of this Standard.)

7.8.3 Parallelism of the Longitudinal Slide (Z-Axis) With the Work Spindle (C-Axis) in the X–Z Plane[22]

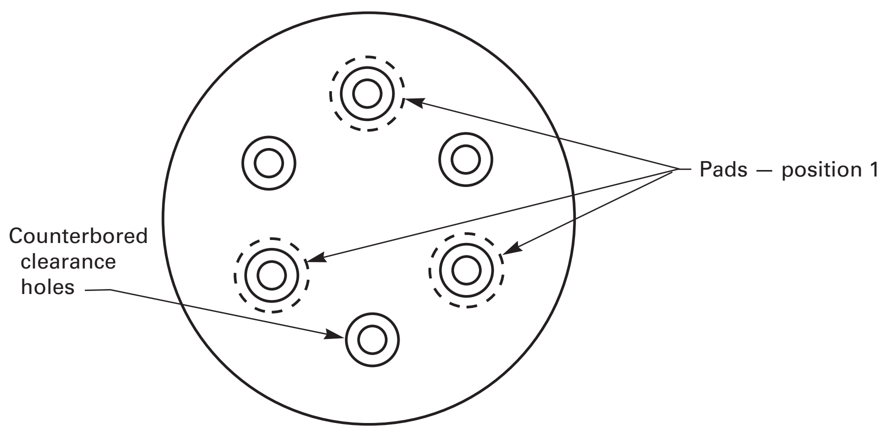
7.8.3.1 Straightedge Rotation Method. Figures 7.8.3.1-1 and 7.8.3.1-2 illustrate the straightedge rotation method. It consists of mounting a straightedge (either optical or mechanical), or precision mandrel, on the spindle and adjusting it approximately parallel to the *Z*-axis. Figure 7.8.3.1-1 shows the setup on a vertical spindle lathe, and Fig. 7.8.3.1-2, a horizontal spindle lathe. An indicator is bracketed in the tool position, facing in the X direction, and a trace is made along the front side of the straightedge. These data are plotted as shown in Fig. 7.8.2.1-3. The spindle is rotated 180 deg, the indicator is rebracketed using an extension bracket from the tool post, and a second trace is made from the back side along the same line element of the straightedge. These data are also plotted. The angle that bisects the best-fit straight line to these two sets of data is the “cold” out-of-parallelism of the *Z*-axis to the C-axis. The calculations are identical to those given in para. 7.8.2.1. (Analysis of these two traces also gives the straightness of the straightedge and the straightness of the *Z*-axis of the machine; see ANSI B5.54 for a full discussion of straightedge reversal).

[22] Some lathes are quite long. If either the mechanical straightedge or part-trace test option is chosen, the User should specify the length of the straightedge or cylinder as part of the original machine specification.

Fig. 7.8.2.2-1 Two Views of the Cylinder Used for Measuring Machine Out-of-Squareness and Parallelism



(a)



(b)

GENERAL NOTE: The taper and the cone angle on the test cylinder are highly exaggerated.

Fig. 7.8.2.2-2 Part-Trace Test Past Centers to Determine Cross-Slide Squareness With the Spindle Axis

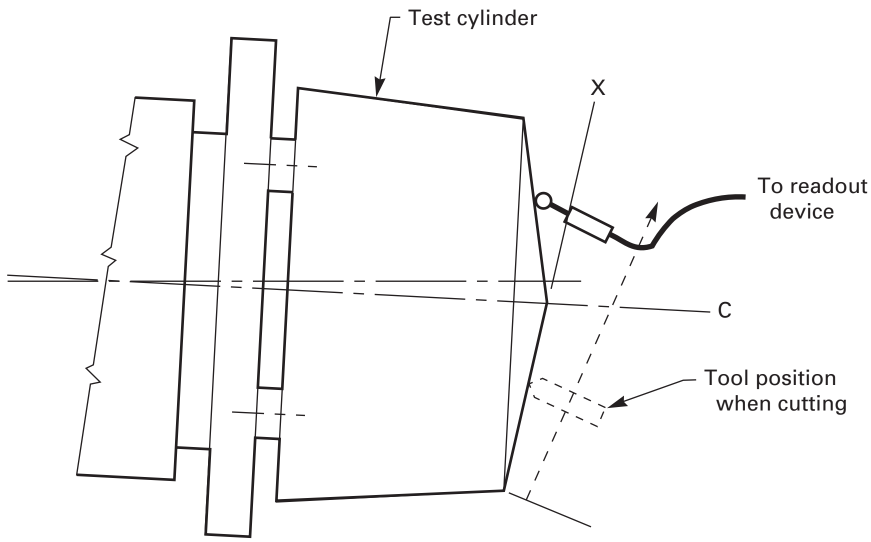
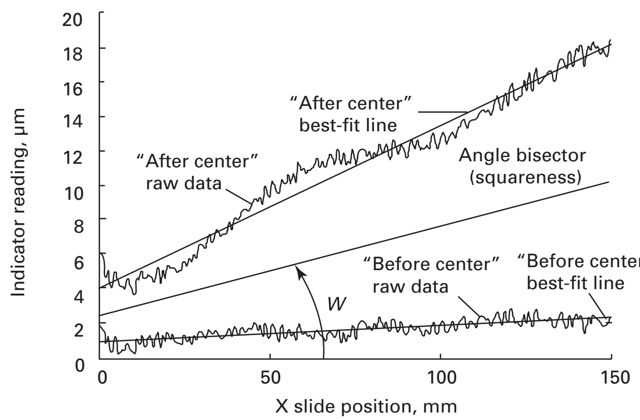


Fig. 7.8.2.2-3 Typical Data From a Cross-Slide Out-of-Squareness Measurement by Part Tracing Past Center



GENERAL NOTE: The direction of axis travel and the corresponding indicator reading are important to determining the direction of squareness error.

7.8.3.2 Turned Cylinder Method. Figure 7.8.3.2-1 illustrates the technique for part tracing on a cylinder. It consists of turning an aluminum cylinder (see Fig. 7.8.2.2-1), using tooling as described in para. 7.8.2.2, on the "front" side (normal machining side) of center, letting the machine soak out, and then making two part traces with an appropriate displacement indicator (see Nonmandatory Appendix K), one on the front side and the other on the back side of center. If this option is selected, the Supplier should specify a soak-out time, a machining time, and an appropriate warm-up cycle. Note that the second trace has to be made by rebracketing the indicator and not moving the machine in the X direction. This is particularly true for vertical turret lathes, where the Z slide is stacked on the X slide. Data from these traces are plotted as shown in Fig. 7.8.3.2-2. As in the previous test, the out-of-parallelism of the Z-axis to the C-axis is the line that bisects the best-fit straight lines to these data. Note that the indicator, when it is bracketed across centers, should be at the same Z position, with respect to the turret, as was the cutting tool and, when the cylinder is traversed, the same range is traversed as when the part was machined. (The straightness of the Z-axis as well as its parallelism to the C-axis in both the machine "hot" and "cold" condition can be determined from these traces.)

The part trace on the front side of center is conceptually zero since it has just been diamond turned. It may, however, show a slope if the heat generated in the spindle during machining is not symmetrically distributed or the drive motor is located next to the spindle. These

Fig. 7.8.2.3-1 Cylinder Reversal for Cross-Slide Squareness

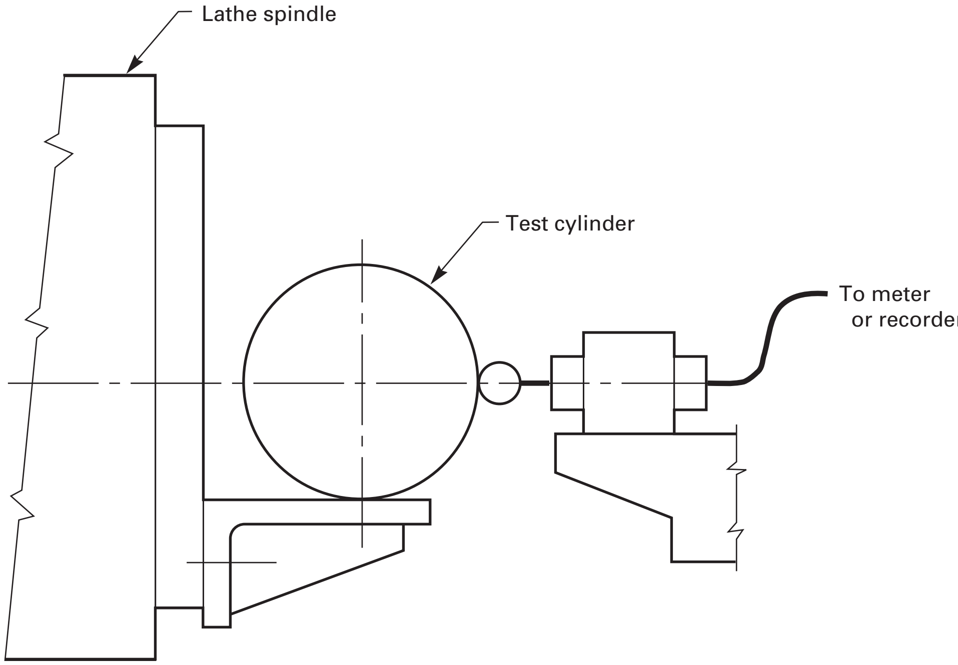


Fig. 7.8.3.1-1 Setup for Straightedge Rotation on a Vertical Spindle Lathe for Measuring Z-Axis Parallelism to the C-Axis

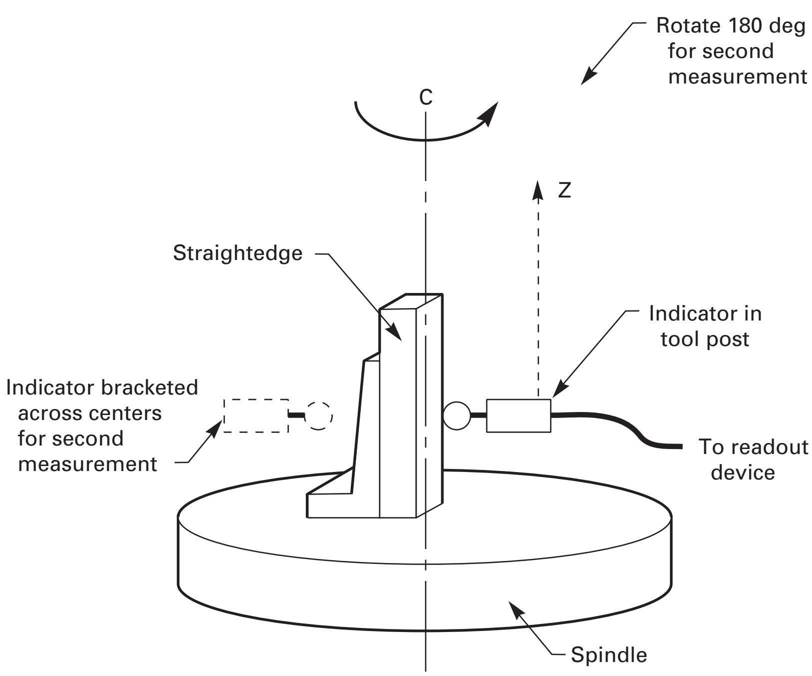


Fig. 7.8.3.1-2 Setup for Straightedge Rotation on a Horizontal Spindle Lathe for Measuring Z-Axis Parallelism to the C-Axis

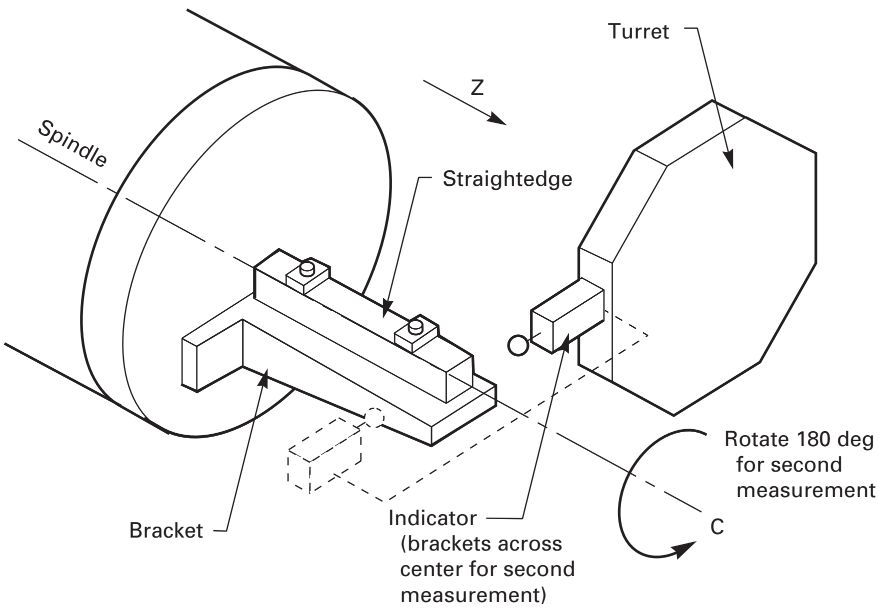


Fig. 7.8.3.2-1 Z-Slide Parallelism Schematic Showing the Test Cylinder

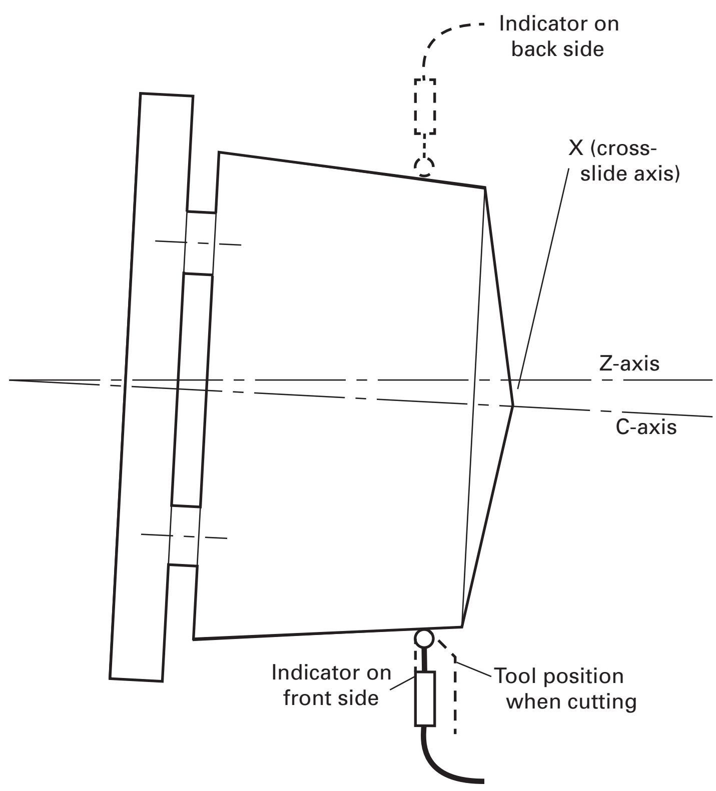
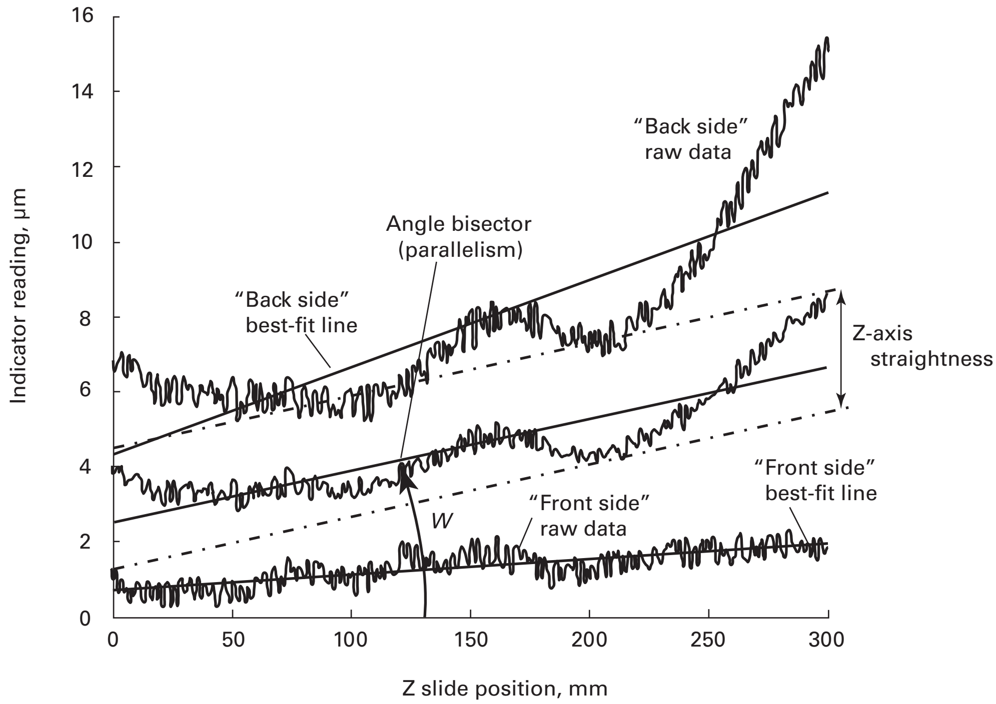


Fig. 7.8.3.2-2 Typical Data From a Parallelism Measurement Using the Turned Cylinder Method



GENERAL NOTE: The direction of axis travel and the corresponding indicator reading are important to determining the direction of squareness error.

heat sources can rotate the headstock of the machine so the average axis line tilts with respect to the Z-axis. The slope of the part trace on the front side of center represents this tilt. The "cold" parallelism is determined by the bisector of the angle between the best-fit straight lines on the front- and back-side traces.

7.8.4 Long-Range Parallelism of the Z-Axis (Longitudinal Slide) With the C-Axis (Work Spindle). When parallelism is required for the total length of a longitudinal axis, a dual straightness measurement can be made using the laser straightness interferometer and straightness reflector, as shown in Fig. 7.8.4-1. Conceptually, this is the same as cutting a cylinder and indicating the opposite side. Two straightness measurements are required. For the first measurement, the laser beam and path of the moving Wollaston prism (straightness interferometer) are aligned mechanically (i.e., no data fit is permitted). The spindle, with straightness reflector, is rotated 180 deg and the second straightness measurement recorded. The average straightness at each Z-axis position is plotted for each of the two measurements, as shown in Fig. 7.8.4-2. At each measurement point in both the forward and the reverse directions, the laser reading should be averaged for a minimum of 5 s and should include a minimum of 2 000 data points. Neither data curve is corrected for alignment of the optics, slide way, and laser beam.[23] The setup for a vertically traversing axis is more complicated. It is shown in Fig. 7.8.4-3. In this case, a retroreflector is used in the tool position, and the laser and bending mirror must be moved between the setups. In no case should the straightness reflector, shown in the insets 1 and 2 of the Fig. 7.8.4-3, be moved.

7.9 Contouring Performance Using Circular Tests

7.9.1 General. Circular tests provide a rapid and efficient way of measuring a machine tool's contouring accuracy along a circular contour.[24] Circular contours provide one of the best checks for contouring performance in that as a machine is traversing with multiple axes along a circular trajectory, each axis goes through sinusoidal acceleration, velocity, and position changes. The tests specified here are for machines with only two axes. More complex tests, if desired, should be devised

[23] In principle, the parallelism of the Z-axis to the spindle axis can be obtained without mechanical alignment for the first measurement. However, error can be significant when measuring large straightness values.

[24] When used statically in a point-to-point positioning mode, the ball bar can also provide valuable information about positioning performance and machine geometry.

Fig. 7.8.4-1 Dual Straightness Measurement for Parallelism

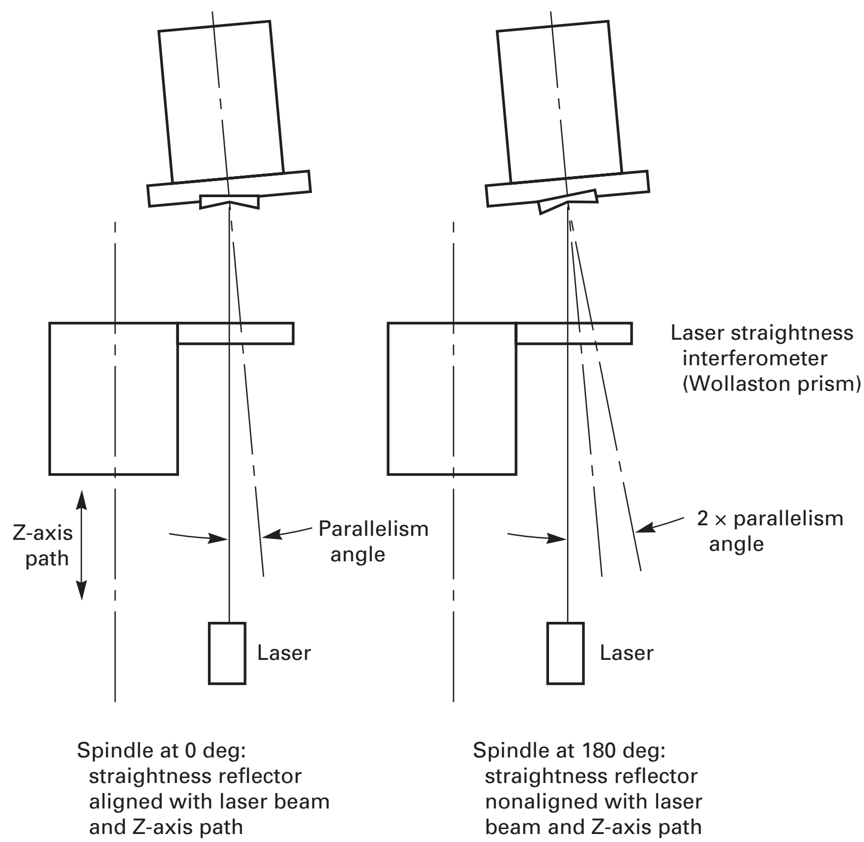


Fig. 7.8.4-2 Graphing of Both Straightness Measurements for Twice the Angle of Parallelism

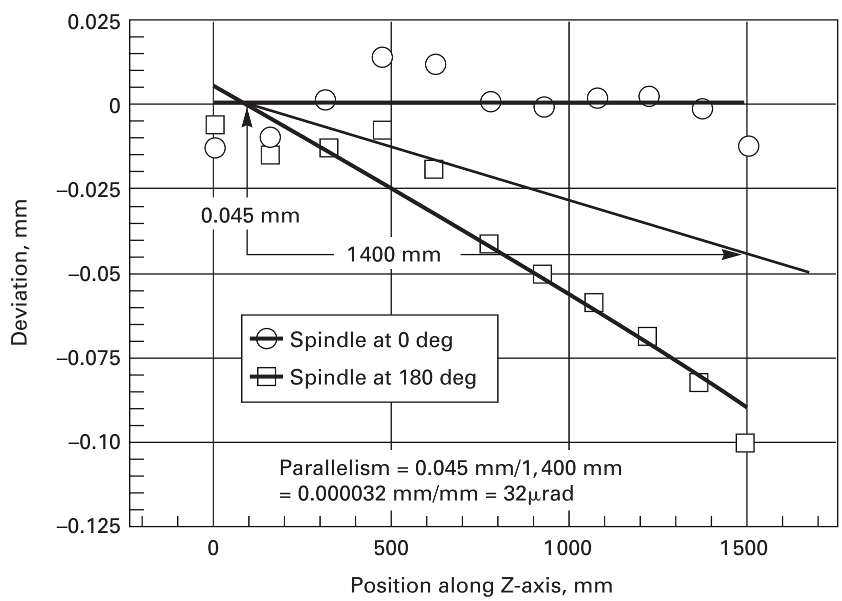
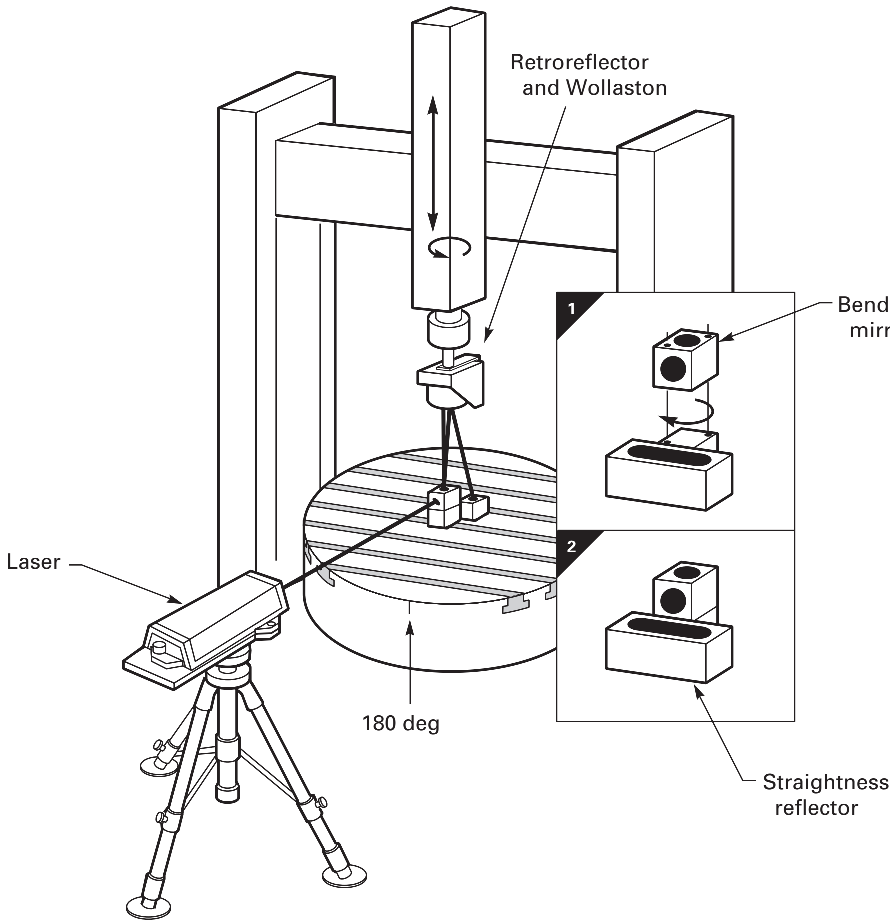


Fig. 7.8.4-3 Setup for Measuring Long-Range Parallelism of the Z-Axis in the Case of a Vertically Traversing Axis



for other machines and agreed on between the Supplier and the User as part of the machine purchase. Each test specified shall be run at two speeds: approximately 10% of the maximum feed rate and 80% of the maximum feed rate. On some machines, the controller will automatically slow the feed rate to compensate for errors. Therefore, the User shall measure the time required to perform the ball bar test and report the actual feed rate from the circle circumference and the time. Other feed rates may be specified by the User, if desired. For this test, the length of the telescoping ball bar should be slightly less than one-half the range of travel of the shortest axis under test or 250 mm (approximately 10 in.), whichever is smaller. For clarity of explanation, the tests described in paras. 7.9.2 through 7.9.4 are illustrated for a particular type of telescoping ball bar. Any ball bar system conforming to the requirements of this Standard shall state, as part of the output data, the angular interval used for ball bar length measurement during circular contouring. For these tests, the spindle shall be rigidly locked.[25] Other test conditions are given in para. 7.1.

7.9.2 Telescoping Ball Bar Performance —X–Z Plane, 360-deg Trace.[26] On some machines, there is enough axis travel in both X and Z to perform a 360-deg full-circle test. On such machines, the 360-deg ball bar test is required. A setup for such a test is shown in Fig. 7.9.2-1. Note that in this configuration the fixed socket is no

[25] Machines that incorporate angular positioning capability with spindle rotation may exhibit angular "hunting" of the spindle, leading to unwanted errors when making measurements. Angular motion may be reduced by turning the spindle off and disengaging the drive (if possible). A frictional antirotation device, such as a magnetic base, should be placed between the fixed and rotating positions of the spindle. Under no circumstances should a rigid connection be made between the fixed and rotating portions of the spindle. The friction connection protects both the operator and the spindle from damage due to inadvertent starts.

[26] Many lathes are programmed in diameter, rather than radius. Users should take care not to damage the instrumentation.

longer on the centerline of the spindle in the X direction. Before programming the machine, it shall be located using the procedure recommended by the ball bar manufacturer. After location of the fixed socket, the machine should be programmed to make a complete 360-deg trace in the X–Z plane, in both the clockwise and counterclockwise directions. Typical results of such a test are shown in Fig. 7.9.2-2. The data for the test shall be analyzed and reported as described in para. 7.9.5.

7.9.3 Telescoping Ball Bar Performance—X–Z Plane, 190-deg Trace. Where possible, a 190-deg test should also be performed. [The primary limitation is usually the minimum length of the ball bar and the traverse length of the X-axis. Many commercial ball bars have a minimum length of 100 mm (approximately 4 in.), thus requiring an X-axis of 200 mm (approximately 8 in.) before this test can be performed.] A setup for this test is shown in Fig. 7.9.3-1. For this test, the support arm may also be placed below the ball bar. The machine should be programmed to move along the arc shown in the figure, from 190 deg to 0 deg and back, at both of the preselected feed rates (see para. 7.9.1). Typical results of such tests are shown in Fig. 7.9.3-2. Data are analyzed and reported as described in para. 7.9.5.

7.9.4 Telescoping Ball Bar Performance—X–Z Plane, 100-deg Test. The 100-deg test should be used only on those machines where either the 360-deg test or the 190-deg test cannot be performed due to limitations in axis positioning or available ball bar lengths. The telescoping ball bar conforming to the requirements of section 9 shall be used for this test. One of the magnetic sockets, called the "fixed socket," is attached to the work spindle using a suitable fixture and the machine chuck. The other socket, called the "free socket," is attached at the nominal position of the tool in the turret. Such a setup is shown in Fig. 7.9.4.-1. The machine is commanded to move along a radius from the position labeled 0 deg to the position labeled 100 deg and back to position 0 deg at both of the preselected feed rates (see para. 7.9.1). The results are presented in a polar plot such as that shown in Fig. 7.9.4-2. Data are analyzed and reported as in para. 7.9.5.

7.9.5 Telescoping Ball Bar Data Analysis. For each ball bar test — the 100-deg, the 190-deg, or the 360-deg —the circular hysteresis,[27] H; the circular deviations for clockwise, $G\uparrow$, and counterclockwise, $G\downarrow$, contouring; and the radial deviations, F_{max} and F_{min}, for clockwise ($\uparrow$) and counterclockwise ($\downarrow$) contouring, corrected to 20°C (68°F), shall be reported, as well as the measured feed rates in the clockwise and counterclockwise directions. The circular hysteresis is the maximum radial difference between the two actual tool paths in the clockwise and counterclockwise directions at any given angle. The circular deviation is the minimum radial separation of two concentric circles that will envelope the actual path. Finally, the radial deviations are the maximum and minimum deviations from the true ball bar length, corrected to 20°C (68°F). For the purposes of this Standard, the manufacturer of the ball bar shall supply an effective coefficient of thermal expansion for the ball bar and recommendations as to appropriate ball bar calibration procedures, where applicable. Table 7.9.5-1 shows typical results of a ball bar test. The data are taken from the 190-deg trace shown in Fig. 7.9.3-2.

7.9.6 Contouring Performance Using Precision Disks or a Grid Encoder. This Standard allows the substitution of precision disks or grid encoders for the telescoping ball bars in the circular test. The circular test is a comparison of a circular path carried out by a machine tool to an accurate circle, a circular comparison standard. For disks, this comparison is carried out using a 2D probe reading against a precision disk. When grid encoders are used, the pattern on a special grid encoder is sensed using photo-optical sensors. On the machine tool, a circle is programmed; the diameter of the circle corresponds to the diameter of the circle comparison standard. The 2D probe or the photo sensor is moved on the circular path by the machine tool and either measures deviations of the program circle from the disk standard, or, in the case of the grid encoder, simply gives the X–Y coordinates of the programmed path. Commercial systems are available for both the precision disks and the grid encoders. The deviations from circularity so measured are analogous to those obtained with the circular test using the ball bar. The analysis shall be done in the same manner as that for the circular test; see para. 7.9.5.

7.9.7 Equivalent Test Procedures. At the time of the issuance of this Standard, several ball bar designs or other instruments are in the process of development and testing. The use of any of these ball bars or other instruments is suitable, as long as the instrument system is able to perform the tasks described in para. 7.9 with the required accuracy (see section 9).

7.10 Cutting Performance Tests

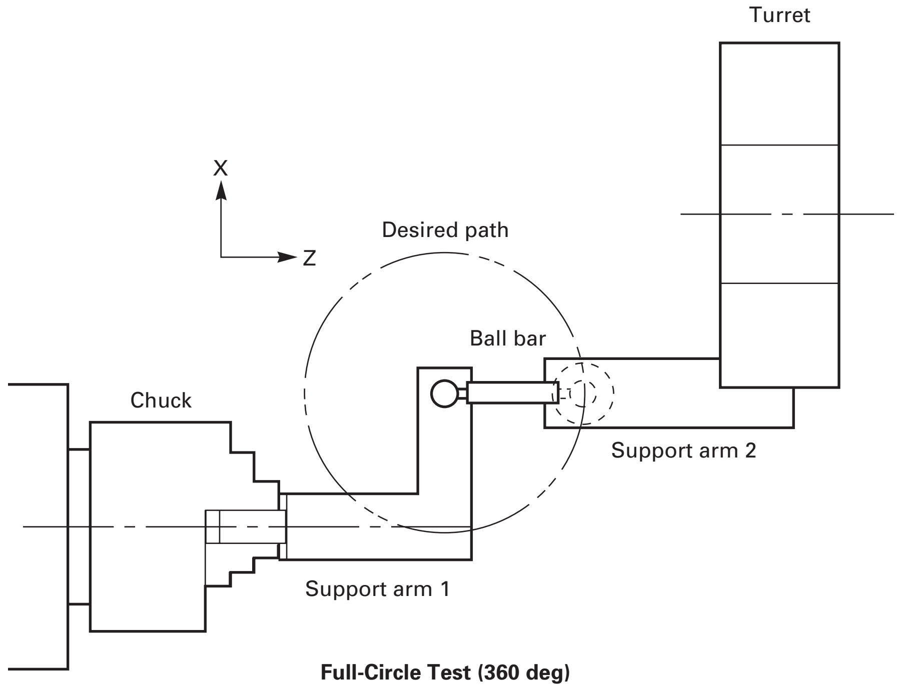
7.10.1 General. In the performance of a cutting operation, the following conditions or limitations may arise:

(a) The drive cannot deliver the necessary torque and it either stalls or the machine breaks. This leads to a test of the ability to utilize the rated torque. A preliminary to this test is the test of spindle idle run losses.

(b) Chatter occurs. In roughing cuts, this leads to excessive vibratory forces that may damage the tool and to chatter marks on the surface in finishing cuts.

[27] When performing this test, care should be taken that the machine is moving at the correct feed rate. If the feed rate is different in the counterclockwise and clockwise directions, the circular hysteresis will be measured erroneously.

Fig. 7.9.2-1 Typical Setup for a 360-deg Ball Bar Test



Full-Circle Test (360 deg)

Fig. 7.9.2-2 Typical Results From a 360-deg Ball Bar Test

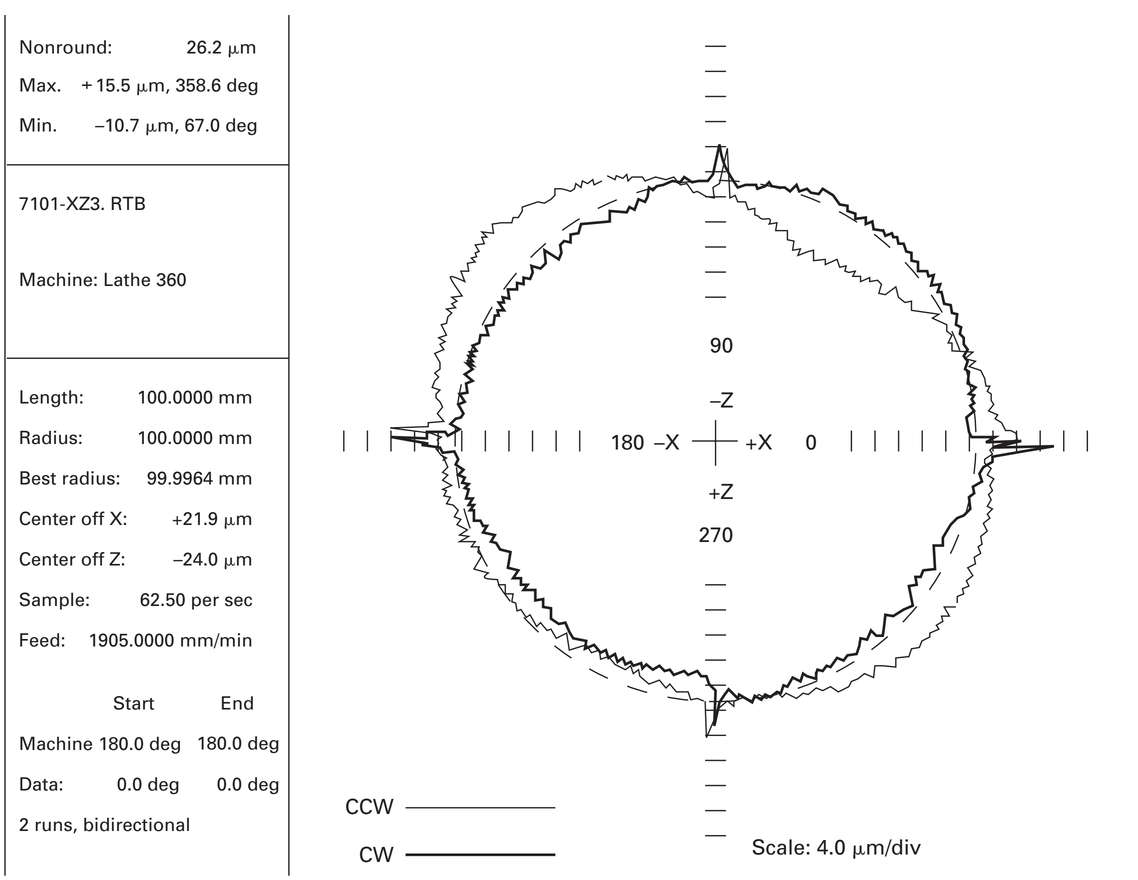


Fig. 7.9.3-1 Typical Ball Bar Setup for the 190-deg Test on a Lathe

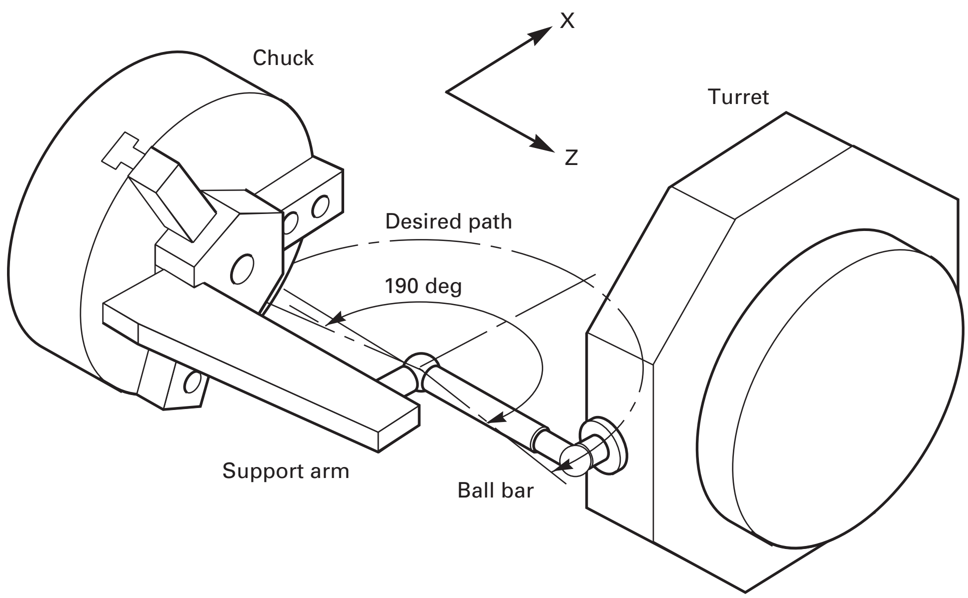


Fig. 7.9.3-2 Typical Results From a 190-deg Ball Bar Test on a Lathe

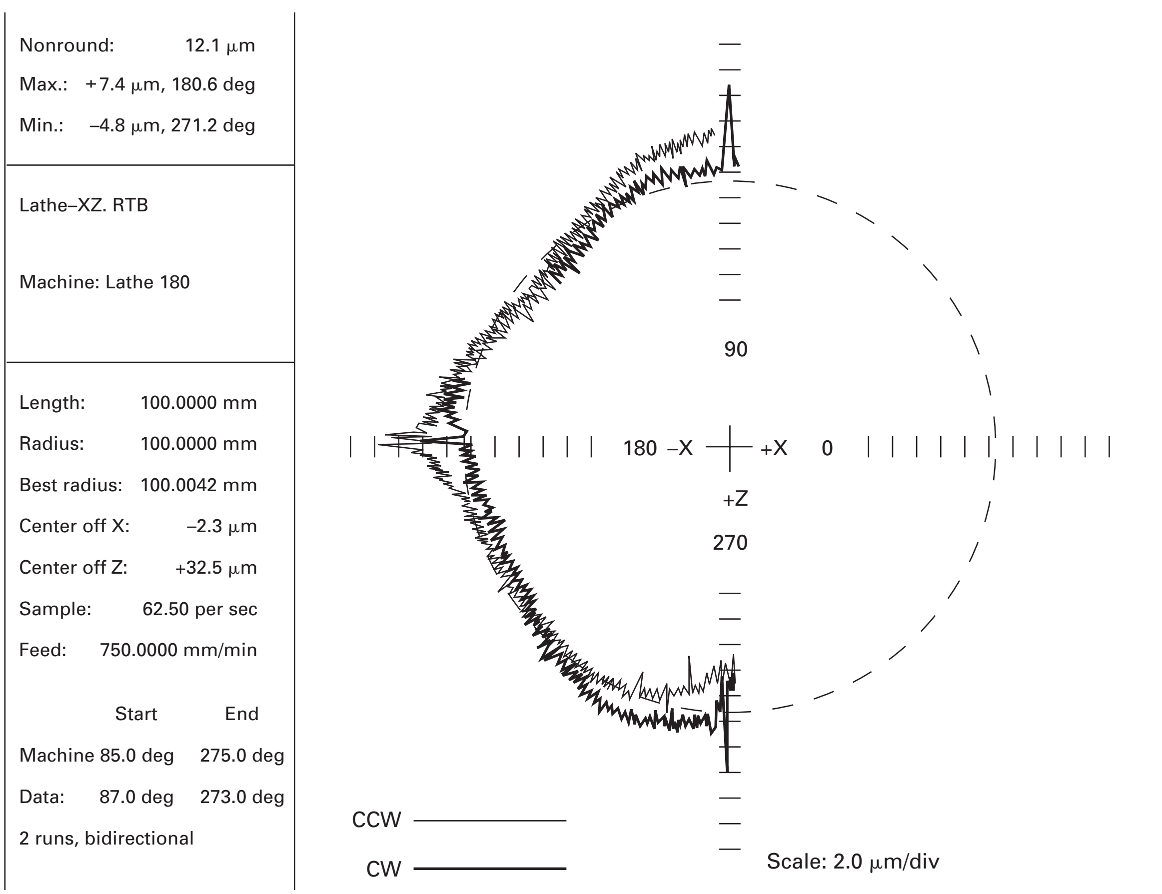
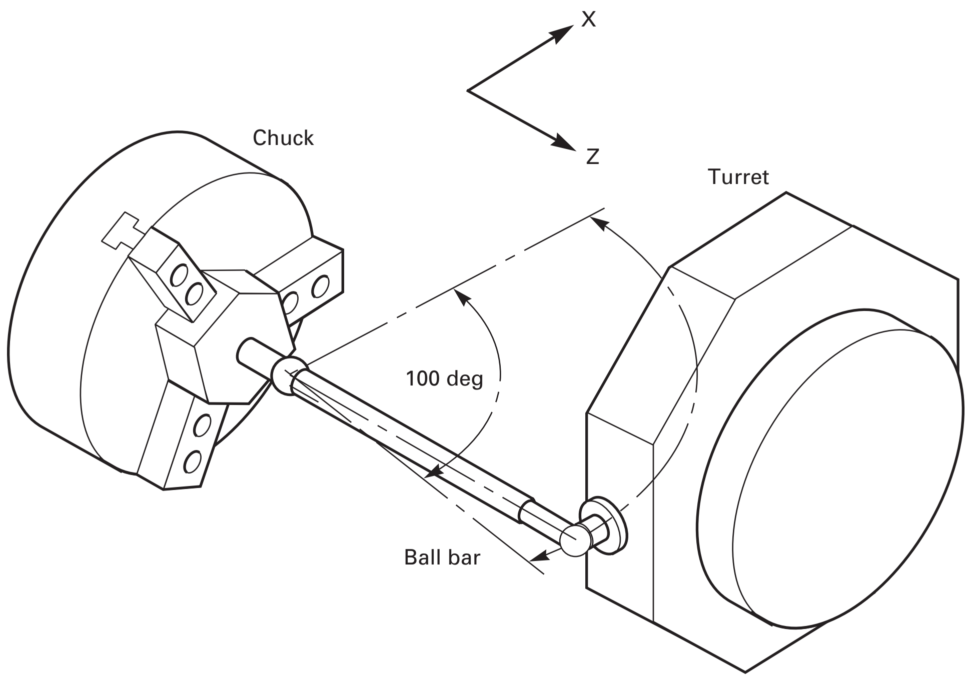


Fig. 7.9.4-1 Typical Ball Bar Setup for a 100-deg Test



(c) In stable cuts (without chatter), the deflections in the system (e.g., in the tool, spindle, structure, fixture, or workpiece) cause errors of position and profile of the machined surface.

(d) Other kinds of problems may arise, such as failures of the coolant delivery system, leakage of oil from the spindle-lubricating system, or clogging of chips in the chip-removal system. These are not discussed further in this Standard.

7.10.1.1 Limitations. The limitations specified in para. 7.10.1 (a) and (b) shall be determined in well-organized tests performed under carefully specified conditions. For practical reasons, the tests are organized in the following sequence:

(a) Spindle Idle Run Loss Test. This test is carried out first to measure the power available for the cutting tests.

(b) Chatter Limits and Full Torque Test. Measurements of these two limitations are combined in a test(s) agreed upon by the User and the Supplier, during which one or the other limitation prevails.

7.10.2 Spindle Idle Run Loss Test. This test measures the economy of the drive and potential heat sources. It is also useful, for the cutting tests, to know the actual power available on the spindle at the various speeds. This test should be performed for each work spindle and each tool spindle.

In this test, the spindle is run idle in five steps over its total speed range and, using a wattmeter, the power required is recorded and a graph like the one in Fig. 7.10.2-1 produced. The wattmeter is connected to the power feed of the spindle drive. The measured lost power includes losses in the electric drive as well as those in the transmissions and bearings. It has been sufficiently established that these losses are little affected by the useful load on the spindle. The net available power shall correspond to that provided in the specifications of the machine tool (see Form 1).

7.10.3 Chatter Limits Test and Full Torque Test. Because of the wide variety of turning centers currently available, the User and the Supplier should negotiate as part of the original specification a cutting performance test that will determine the capability of the machine to apply its full torque (horsepower) to a metal-removal operation, without the existence of chatter.

7.11 Multifunction Cycle Test

7.11.1 General. The machine shall be cycled through all basic machine functions for a specified time period (usually 24 h) to demonstrate its complexity, capability, and short-term reliability. Preceding this test, a subsidiary test should be performed to check the function of the machine limit switches, coolant cycling, etc.

7.11.2 Procedure. The machine and control shall cycle automatically under numerical control for a specified time period agreed upon between the Supplier and the User. The program used for the cycling test shall position the machine over its entire work zone and shall include all basic machine functions, tool changes,

Fig. 7.9.4-2 Typical Results of a 100-deg Ball Bar Test

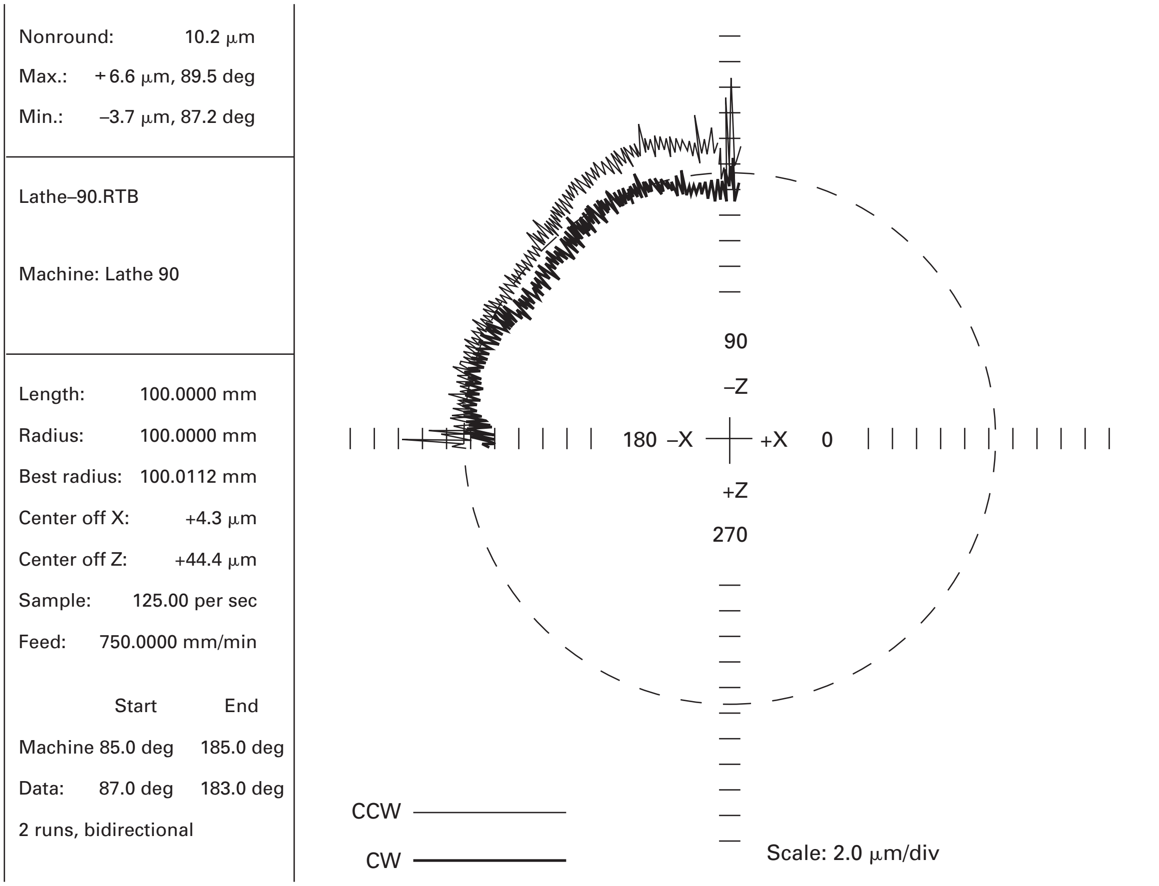
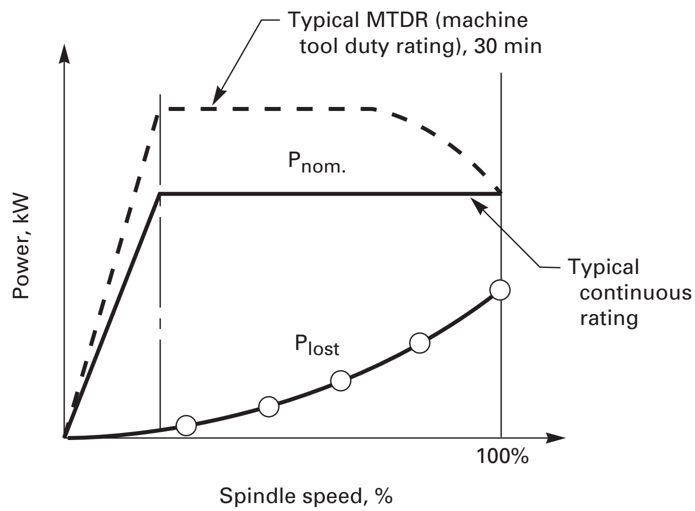


Table 7.9.5-1 Typical Results of a Ball Bar Test

Parameter Name	Symbol	Value, µm
Circular hysteresis	H	131.7
Circular deviation, clockwise	$G\uparrow$	130.0
Circular deviation, counterclockwise	$G\downarrow$	127.0
Minimum radial deviation, clockwise	$F_{min}\uparrow$	–70.0
Minimum radial deviation, counterclockwise	$F_{min}\downarrow$	–59.0
Maximum radial deviation, clockwise	$F_{max}\uparrow$	61.7
Maximum radial deviation, counterclockwise	$F_{max}\downarrow$	73.2

GENERAL NOTE: The results are dependent on the following conditions:
(a) machine: not applicable
(b) test angular range: 190 deg
(c) ball bar length: 77 mm
(d) angular measurement interval: manufacturer supplied
(e) contour speed: 1 335 mm/min

Fig. 7.10.2-1 A Typical Plot of the Power Loss in the Spindle Idle Run Loss Test



traverse and feed motions, contouring, G-code canned cycles, etc. The spindle shall operate through its entire speed range during the test. A complete program run time (cycle) shall not exceed 15 min, unless specifically negotiated between the Supplier and the User. The Supplier and the User shall also negotiate and make part of the original specification the number of failures, if any, and the type of failures that are to be allowed during the specified time period.

8 MACHINE PERFORMANCE (ADDITIONAL)

8.1 General

Many turning centers offer optional features. In this section, an attempt has been made to include tests for those most commonly supplied. If a machine is to be purchased with options that are not covered in these sections, the User and the Supplier should devise an appropriate functional test to be made part of the original machine specification.

8.2 Coaxiality of Axes of Rotation[28]

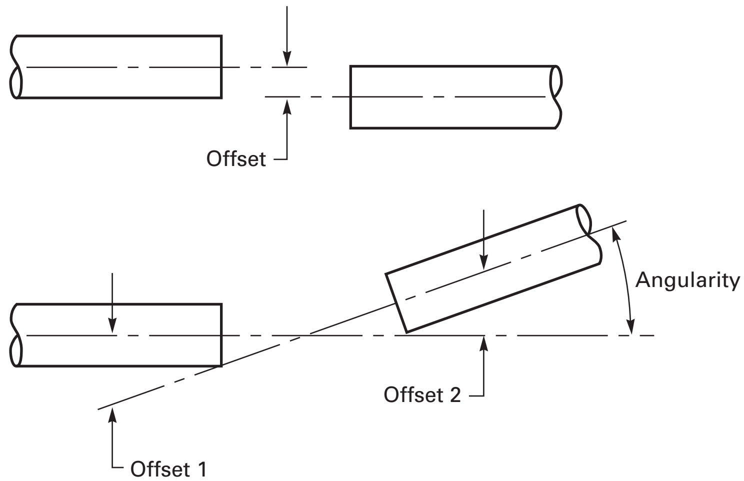
The alignment of axes of rotation is necessary on many machines. For example, it may be necessary when two spindle axes need to be aligned or when a tail stock needs to be aligned to a spindle axis. This alignment parameter is independent of the actual mechanical runout of the spindle nose(s) or tail stock itself. Such runout should be determined by traditional machine tool practices and corrected where necessary. Five methods of checking the alignment of axes of rotation are given below. The first two methods (paras. 8.2.1 and 8.2.2) have been traditionally used for the alignment of rotating machinery. The third method (para. 8.2.3) is more modern and requires the use of a laser alignment system. The fourth method (para. 8.2.4) relates to methods used for establishing rotary table axis alignment on machining centers. Finally, the fifth method (para. 8.2.5) is one that is traditionally used for aligning tail stocks on normal production machines. The choice of the method used is left to the User; however, the chosen method should be made part of the original specification and should have an accuracy sufficient for the intended use of the machine. Note that none of these methods can determine the coaxiality that may exist during operation with a workpiece loaded, tail stock pressure, etc.

Four parameters are required to specify the alignment of two axes of rotation.[29] Two of these parameters specify the angularity between the two axes, and the other two, the offset between the two axes in some specified plane. Note that in the presence of any angularity, the offset is a function of position. This situation is depicted in Fig. 8.2-1 in one plane. For historical reasons, as well as reasons relating to measurement procedures, angles are normally described with respect to vertical and horizontal planes, and offsets are defined similarly. We follow this convention in this Standard and, for each of the proposed measurement methods, clearly specify the plane where the offsets are to be reported. If not specified, these offsets should be reported in a plane nominally 50 mm (approximately 2 in.) from the face of the

[28] These measurements are often used to make machine adjustments. If the alignments are worse than the Supplier's specifications, then such adjustments should be made.

[29] The nomenclature in this section refers to horizontal spindle machines. Those using other configurations should specify the planes in which the offsets and angles are to be reported. Sag measurements should not be required for vertical spindle machines.

Fig. 8.2-1 Illustration of Angularity and Offset Between Two Axes of Rotation



machine main spindle. For the purpose of this section, the following nomenclature is defined:

HA = the horizontal angle between two axes of rotation
HO = the horizontal offset between two axes of rotation in a specified plane
VA = the vertical angle between two axes of rotation
VO = the vertical offset in a specified plane

Traditionally these measurements are performed with the machine cold, but the User is warned that the offsets and angles change with temperature. These changes are measured in para. 7.6.

8.2.1 Rim-and-Face Method. The rim-and-face measurement method requires the use of two displacement indicators conforming to the requirements of section 9. Depending upon machine accuracy levels, the displacement indicators could range from dial gages to air-bearing LVDTs. A typical setup, using dial gages attached with brackets to short stiff mandrels fixtured to the two axes of rotation, is shown in Fig. 8.2.1-1. In the figure, the indicators are set for positive reading for motions toward the indicator dials. For simplicity of notation, the rotary axis to the left in the figure is called the C-axis, and the axis to the right, the M-axis. The bracket holding the indicators and the mandrels should be as short and as stiff as possible. Before commencing the test, the sag (compliance) of the bracket shall be measured. This is done by attaching the bracket to a stiff mandrel supported between centers, as shown in Fig. 8.2.1-2. For spans up to 200 mm (approximately 8 in.), a steel mandrel 50 mm (approximately 2 in.) in diameter shall be considered adequate. (For very high-accuracy machines, a calculation of the requisite mandrel diameter should be calculated or a correction applied for mandrel sag.) The indicators are zeroed at the top position (12:00 in the figure) and the mandrel rotated until the indicators are at the bottom position (6:00 in the figure). The readings of both indicators are recorded. The sag of the rim indicator, RR_s, will generally be negative (pay attention to signs), while the sign of the sag of the face indicator, FR_s, will depend on details of the setup. This test shall be performed three times and the mean of the readings computed. The indicators are then fixtured to the two axes of rotation (see Fig. 8.2.1-1), the two axes rotated together, and indicator readings taken at the 12:00, 3:00, 6:00, and 9:00 positions. These measurements should be repeated three times, with care taken to avoid thermal effects (gloved hands and a temperature shield may be required on high-accuracy machines). The alignment parameters of the two axes in the plane of the rim indicator are given by

$$VO = \frac{RR0 - RR6 - RR_s}{2}$$

$$VA = \frac{FR6 - FR0 - FR_s}{DIA}$$

$$HO = \frac{RR3 - RR9}{2}$$

$$HA = \frac{FR9 - FR3}{DIA}$$

where

DIA = the diameter of the circle traveled by the face indicator centerline
FR_s = the mean sag of the face indicator
$FR0$ = the mean face reading at 12:00
$FR3$ = the mean face reading at 3:00
$FR6$ = the mean face reading at 6:00
$FR9$ = the mean face reading at 9:00
HA = the horizontal angle
HO = the horizontal offset

Fig. 8.2.1-1 Typical Setup for the Rim-and-Face Test

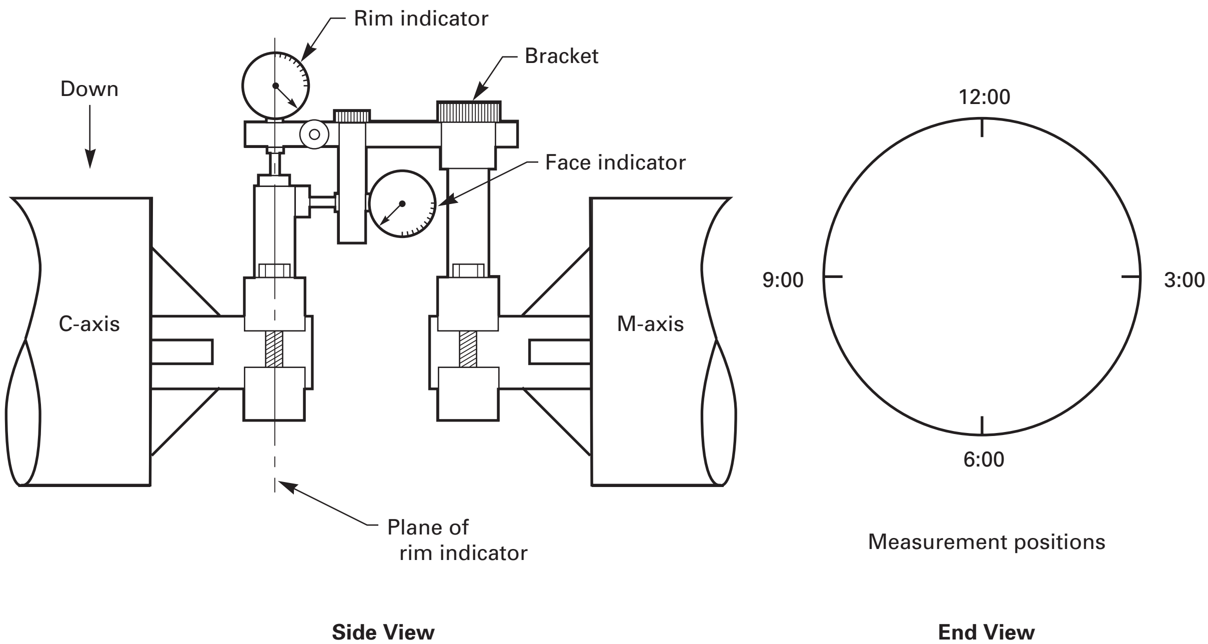


Fig. 8.2.1-2 Setup for Measuring the Sag of a Pair of Indicators

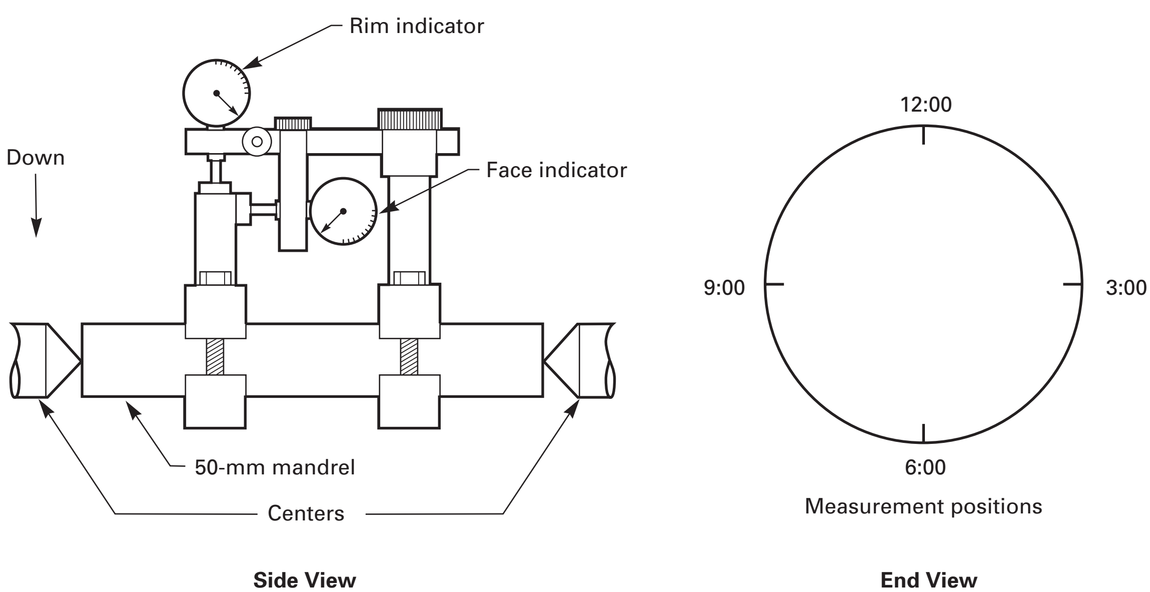
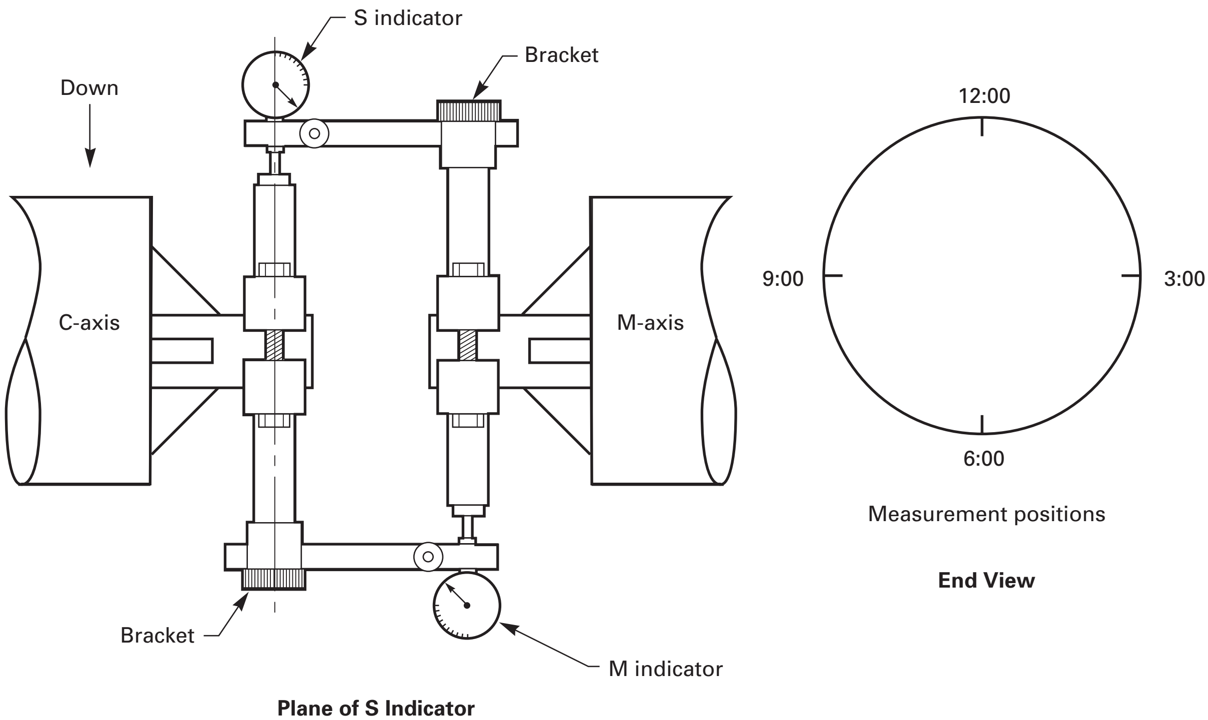


Fig. 8.2.2-1 Typical Setup for the Reverse Indicator Method



RR_s = mean sag of the rim indicator
$RR0$ = mean rim reading at 12:00
$RR3$ = mean rim reading at 3:00
$RR6$ = mean rim reading at 6:00
$RR9$ = mean rim reading at 9:00
VA = vertical angle
VO = vertical offset

If desired, standard uncertainties in these quantities may be computed (see Nonmandatory Appendix M).

8.2.2 Reverse Indicator Method. The setup for the reverse indicator method is shown in Fig. 8.2.2-1. As in the rim-and-face method, two appropriate indicators shall be used, with the choice depending upon machine accuracy. The indicators shall be set to read positive for motions toward the dials, as shown in the figure. Before commencing measurements, the sag of the indicator setup shall be measured. The procedure is as outlined in para. 8.2.1, with the reverse indicator brackets (Fig. 8.2.2-1) being substituted for the rim-and-face brackets in Fig. 8.2.1-1. The indicators shall be zeroed at the 12:00 position, the mandrel rotated to the 6:00 position, and the readings from the S and the M indicators recorded. This measurement shall be performed three times and the mean sags computed. The indicators shall then be fixtured to the two axes of rotation, using mandrels as described in para. 8.2.1. Once mounted, the two axes shall be rotated and indicator readings taken at the 12:00, 3:00, 6:00, and 9:00 positions. These measurements should be repeated three times and the means computed. The misalignment of the two axes in the plane of indicator S is given by

$$VO = \frac{-(SR0 - SR6 - SR_s)}{2}$$

$$VA = \frac{-(SR0 - SR6 - SR_s + MR0 - MR6 - MR_s)}{2D_g}$$

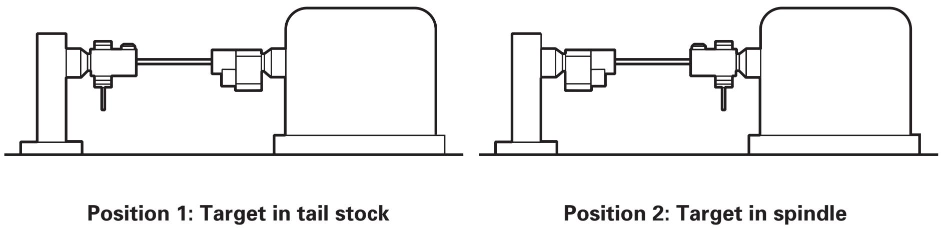
$$HO = \frac{-(SR3 - SR9)}{2}$$

$$HA = \frac{-(SR3 - SR9 + MR3 - MR9)}{2D_g}$$

where

D_g = the distance between the S and M gages
$MR0$ = the mean M gage reading at 12:00
$MR3$ = the mean M gage reading at 3:00
$MR9$ = the mean M gage reading at 9:00
MR_s = the mean sag of the M gage
$R6$ = the mean M gage reading at 6:00
$SR0$ = the mean S gage reading at 12:00
$SR3$ = the mean S gage reading at 3:00
$SR6$ = the mean S gage reading at 6:00
$SR9$ = the mean S gage reading at 9:00
SR_s = the mean sag of the S gage

Fig. 8.2.3-1 Rotation Axes Alignment Using an Optical Alignment Laser



For the definitions of *HA*, *HO*, *VA*, and *VO*, see nomenclature in para 8.2.1.

8.2.3 Optical Tail Stock Alignment. Several alignment laser systems are available that may also be used for axes of rotation alignment. A basic system is shown in Fig. 8.2.3-1. In such a system, a laser is attached to either of the axes of rotation and a photodetector attached to the other of the two. Procedures vary. Some systems require rotating one axis by hand, taking readings of the laser position, and then rotating the other axis by hand and again recording the results. Other systems require rotating the axes together as described in paras. 8.2.1 and 8.2.2. The out-of-alignment of the two axes of rotation is calculated by the system software. In all cases, the Supplier's recommendations for the laser instrument system usage should be followed. The measurements shall be repeated three times, and mean values for the four out-of-alignment parameters shall be calculated.

8.2.4 Two-Sphere Axis Alignment. To perform the two-sphere axis alignment test, a set of test balls is fixtured to one spindle and adjusted to have minimum runout (each ball is separately adjusted). Such a situation is shown in Fig. 8.2.4-1, illustration (a), where the fixture is in the machine main spindle. Here, the fixture used for the spindle error analysis may be readily used. Next, an indicator bracket is attached rigidly to the second rotary axis [shown as a tail stock in Fig. 8.4.2-1, illustration (a)]. The bracket should be stiff and light and needs to be stable only for the duration of the test. The bracket should also be checked for sag using a procedure similar to that described in paras. 8.2.1 and 8.2.2. If the sag is excessive, a stiffer bracket should be used or the sag measured, as described in para. 8.2. The mean sag at gage 1, SR_1, and the mean sag at gage 2, SR_2, as well as their standard uncertainties, shall be recorded. Also, if a high-thermal-expansion material is used, the thermal effects may bias the result and the bracket should be insulated. An indicator shall be positioned on the bracket to read against the artifact at position 1, and three full-circle traces shall be taken as the tail stock is rotated. Data from these circle tests are least-squares fit to a circle, and the mean circle center, CX_1, CY_1, determined. Next, the indicator is rebracketed to make three traces around the artifact at position 2. Again, the data are least-squares fit to a circle to obtain a CX_2, CY_2 center. (Two indicators can also be used at the same time, which requires less stability but introduces the problem of matching gage calibrations.) For this Standard, the offsets are reported at position 1, which is nominally 50 mm (approximately 2 in.) from the main spindle face. The equations are

$$HO = HO_1 = CX_1$$

$$VO = VO_1 = CY_1 - \frac{SR_1}{2}$$

$$HO_2 = CX_2$$

$$HA = \frac{HO_2 - HO_1}{D_g}$$

$$VO_2 = CY_2 - \frac{SR_2}{2}$$

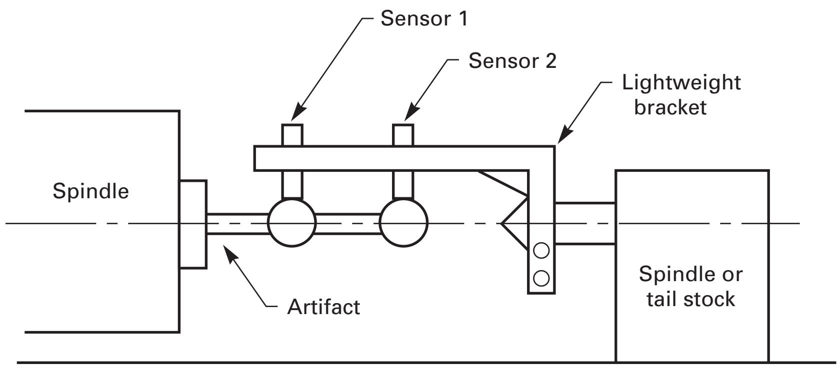
$$VA = \frac{VO_2 - VO_1}{D_g}$$

where D_g is the distance between the two gages.

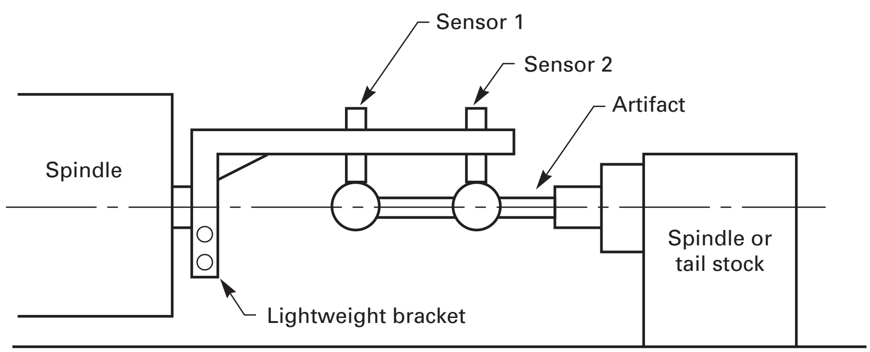
As shown in Fig. 8.2.4-1, illustration (b), the setup may be reversed and the measurement repeated. Similar procedures should be followed. Note that the gage numbering is the same to make the previous equations apply.

8.2.5 Parallelism of the Z-Axis With Other Linear Axes, *W*. For machines equipped with auxiliary axes that move in the Z direction, such as a tail stock, it is important to measure the parallelism of the auxiliary axis motion with the machine Z-axis. This situation is illustrated in Fig. 8.2.5-1 for a machine with a movable tail stock. The simplest method for measuring this parallelism is to indicate against the tail stock center using indicators in the X–Z and Y–Z plane. At some initial position, the indicators are zeroed. Then the tail stock is moved in increments. After each motion increment, the indicators are again moved to read against the tail stock,

Fig. 8.2.4-1 Two-Sphere Setup for the Alignment of Two Rotation Axes

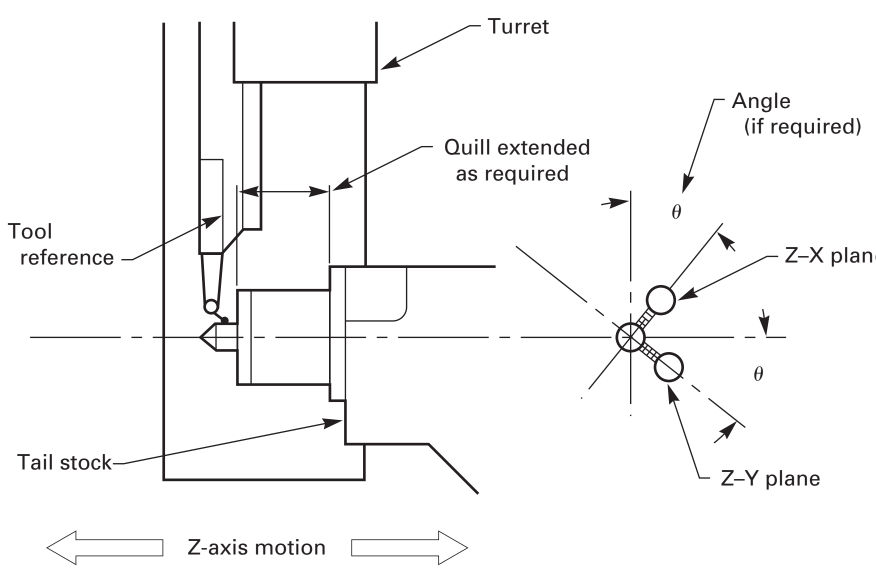


(a)



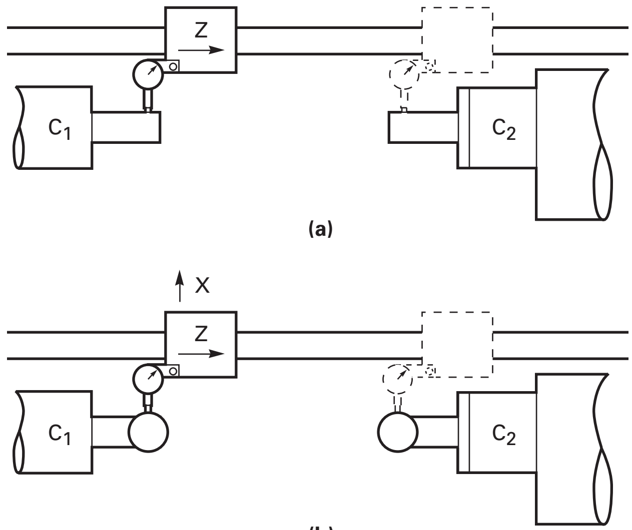
(b)

Fig. 8.2.5-1 Schematic of the Measurement of Parallelism of the Z-Axis to the Axis of a Movable Tail Stock



GENERAL NOTE: Move the tail stock in increments along the entire stroke, and clamp during measurement.

Fig. 8.2.5.1-1 Setup for Measuring Tail Stock Alignment Using the In-Feed (Z) Axis



at the same point on the tail stock, using the machine Z-axis. The indicator data are plotted for both planes, and the slopes of the lines obtained by least-squares fitting are the out-of-alignment in the respective planes. At least 10 positions along the Z-axis should be used for each plane and the standard uncertainty obtained from the least-squares fit to the slopes reported.

8.2.5.1 Mechanical Tail Stock Alignment. Many machines are equipped with a tail stock. In these cases, it is often sufficient to indicate the tail stock centerline location with respect to the spindle centerline, using the machine in-feed.[30] This situation is depicted in Fig. 8.2.5.1-1, illustrations (a) and (b), where the two axes of rotation are called C_1 and C_2. First the parallelism of the C_1-axis to the Z-axis is measured in both the X and Y planes, using the procedures described in para. 7.7.3.1. (Values obtained previously may be used.) Next, the Z-axis is traversed and the parallelism of C_2 measured by the same procedure. Note that this procedure does not require that the mandrels be precisely aligned to the spindle axis. The offset is measured using precision spheres. These precision spheres, of the same diameter (see section 9), are mounted at a fixed distance from the face of the spindle and the face of the tail stock. The recommended distance is 50 mm (approximately 2 in.), as discussed previously, though other distances may be chosen. They are adjusted to have minimum runout. First, the X deviation of the surface of the sphere in spindle C_1 is measured; then, the Z-axis is traversed to position 2, without rezeroing the indicator, and the X deviation of the second sphere and C_2 determined. The measurement is performed similarly in the Y direction. Offsets and angles are then calculated.

8.2.6 Parallelism of the Z-Axis (Longitudinal Slide) With the C-Axis (Work Spindle) in the Y–Z Plane.[31] Parallelism of the Z-axis to the C-axis in the Y–Z (vertical) plane is important on some machines that require facing a workpiece to center without a defect, at different positions along the Z-axis. Stated in a different way, if the tool is set to centerline height at one position of the Z-axis, it will not be at centerline in other positions unless the Z-axis motion is parallel to the C-axis in this plane. This parallelism may be measured by one of the three methods mentioned previously for measuring the parallelism in the Y–Z plane. That is, it may be measured using a mechanical straightedge positioned in the correct direction (para. 7.8.3.1), by part traces on a machined cylinder (para. 7.8.3.2), or by using a straightness interferometer (para. 7.8.4). When using the first two methods, appropriate attention should be paid to gravitational sag on a horizontal spindle machine.

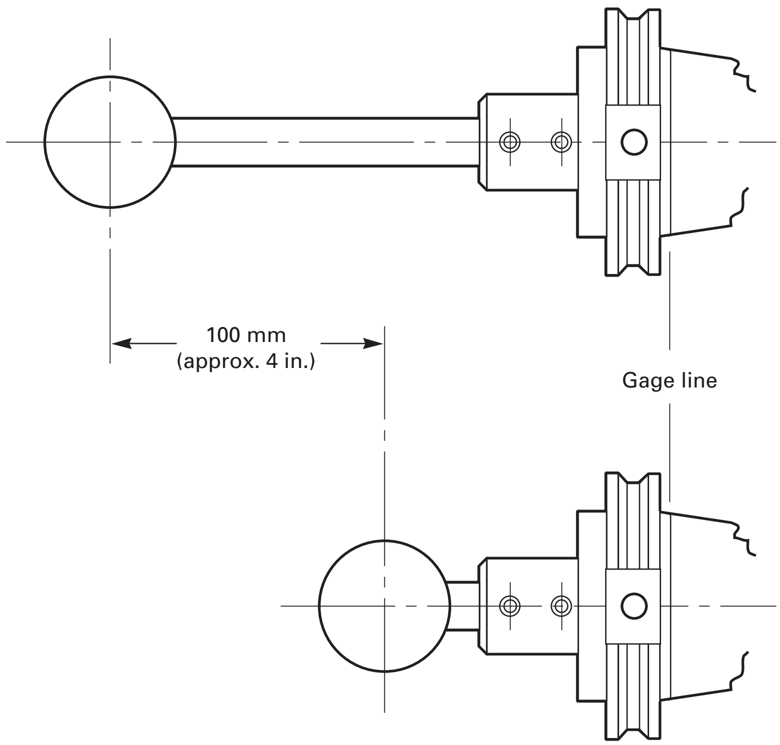
8.3 Subsystems Repeatability

Turning centers are complex systems and contain many subsystems that also contribute to the accuracy and performance of the machine. Subsystems that contribute

[30] Note that the results of this procedure are biased by angular and straightness errors of the in-feed axis.

[31] Parallelism of the Z-axis to the C-axis in the X–Y (vertical) plane is important on some machines that require facing a workpiece to center without a defect ("blip") at different positions along the Z-axis. Stated in a different way, if the tool is set to centerline height at one position of the Z-axis, it will not be at centerline at other positions.

Fig. 8.3.1-1 Tool Holders Used for Tool-Change Repeatability



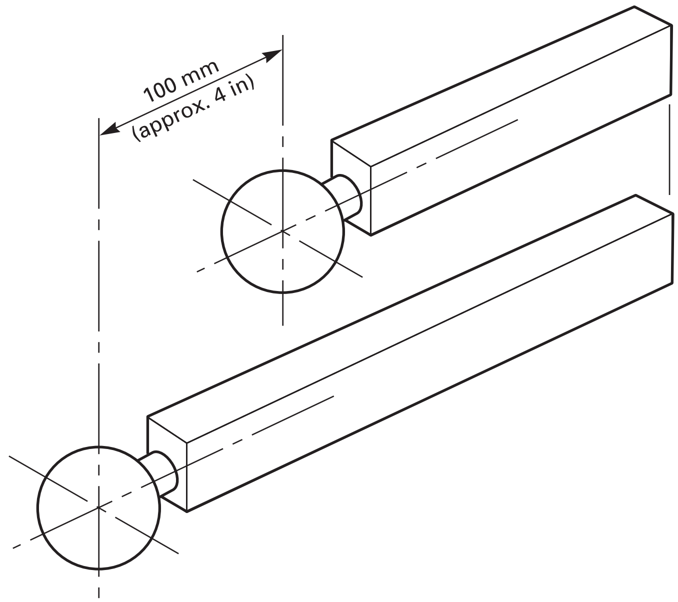
to the accuracy are the tool-change repeatability; turret repeatability; and tool-setting-system repeatability, location, and drift. Tests for these important subsystems are addressed in paras. 8.3.1 through 8.4.

8.3.1 Tool-Change Repeatability. For the purposes of this Standard, tool change repeatability is checked using two tool holders selected by the User from a Supplier's specified tooling package. Precision test spheres are to be mounted in these tool holders in a manner similar to that shown in Fig. 8.3.1-1. One of the test spheres is to be at the minimum possible distance from the turret or tool holder, and the second test sphere is to be mounted on a rigid column at a distance of 100 mm (approximately 4 in.) from the first sphere. (These lengths are default options, and the User is free to select other lengths appropriate to the application, if required.) The tool holders with their test spheres are to be inserted in User-selectable positions in the tool magazine for the machine, and a displacement indicator nest is to be rigidly attached to the machine chuck in the nominal position of the part.[32] The test then proceeds as follows. The first sphere is loaded into the turret and the machine jogged into position such that the two displacement indicators are nulled. This position is recorded. This procedure is repeated on the second sphere. An automatic cycle is established to place sphere 1 into the turret and position it to its established null in the displacement indicator nest, withdraw it safely from the nest, interchange it with sphere 2, position sphere 2 to its null position in the nest, and then withdraw and return sphere 2 safely to the tool magazine. This program is executed 10 times in rapid succession, and the X and Z offsets of each ball are recorded for each trial. Four tool-change repeatabilities are defined: they are the difference between four standard uncertainties of the X and Z readings for the short setup, minus the machine unidirectional repeatability for the direction(s) of approach to the sensor nest (para. 7.2.7.6); and the difference in 4 times the standard uncertainty of the X and Z readings, minus the machine unidirectional repeatability for the direction of approach to the sensor nest for the long setup.[33] For example, the tool-change repeatability for one tool length in the X direction is given by

[32] This test can, if required, be performed on an axis-by-axis basis using a single sensor.

[33] Note that on most lathes the Y is the nonsensitive direction; however, improper Y positioning will lead to a dimple at the center of a faced part and thus is included here as an important parameter.

Fig. 8.3.2-1 Example Tool Holders to Be Used for Turret Repeatability



$$u_x = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_{ti} - \bar{x}_t)^2}$$

and

$$R_{xts} = 4u_x - R\uparrow$$

or

$$R_{xts} = 4u_x - R\downarrow$$

where

n = 10, the default value for this test
$R\uparrow$ or $R\downarrow$ = the appropriate repeatability for the X-axis
R_{xts} = the tool-change repeatability for that direction and tool length
u_x = the estimate of the standard uncertainty
x_{ti} = the i^{th} reading in the X direction
$\bar{x}_t$ = the average of the 10 readings in the X direction

Note that this test includes changes in tool position caused by rotating the tool magazine and any thermal errors induced by traversing to and from the tool-change location. To obtain the most realistic estimate of tool-change effects, the User should have the two spheres with their tool holders placed in magazine locations that require extensive motion of this mechanism.

8.3.2 Turret Repeatability. Turret repeatability is checked using a method analogous to that described in para. 8.3.1 for tool-change repeatability. For this test, the short and the long precision test spheres are mounted in two User-selectable turret positions. The tool holders should be those normally supplied with the machine. If the machine has straight-shank tooling, tool holders such as those shown in Fig. 8.3.2-1 are appropriate. As described in para. 8.3.1, a two-indicator sensor nest is rigidly attached to the machine chuck in the nominal position of the part. After establishing the null locations for both tools, an automatic cycle is established to place sphere 1 into the indicator nest, withdraw it, index the turret, and place sphere 2 into the indicator nest. This program is executed 10 times in rapid succession and the X–Z deviations for both tool and turret positions are recorded. Four turret repeatabilities are defined. They are the difference between 4 times the standard uncertainty of the X and Z readings for the short setup, minus the machine unidirectional repeatability for the direction(s) of approach to the sensor nest (para. 7.2.7.6); and the difference in 4 times the standard uncertainty of the X–Z readings, minus the machine unidirectional repeatability for the direction(s) of approach to the sensor nest for the long setup in the second turret position. The calculation and notation are identical to those outlined in para. 8.3.1.

8.3.3 Optional Tool-Change and Turret Repeatability Using a Tool Probe. When a machine is equipped with a tool probe, there may be significant advantages to using it to assess tool-change repeatability and turret repeatability. In addition to reduced setup, the test parameters may be more accurately isolated from the positioning repeatabilities of the machine and the measurement sensors.

The required hardware is the same as that for the primary tests except that the gage nest is replaced by the tool probe measuring in X and Z directions.

8.3.3.1 Test Procedure for the First Sphere. Measure the X and Z location 10 times. Between each measurement, return the machine to the location where a tool change would take place, but do not exchange tools. Exchange spheres. Repeat the 10 measurements for the second sphere.

Alternate measurements of first and second sphere for a total of 10 additional cycles in which the tool changer is used.

8.3.3.2 Analysis. The analysis is the same as that for the primary test procedure (see para. 8.3.1) except that the unidirectional machine positioning repeatability values are not used. For the 20 sets of X and Z measurements for each sphere, the first 10 do not include a tool change and the second 10 do include the tool change.

$$u_x = \sqrt{\frac{1}{9}\sum_{i=11}^{20}(x_{ti} - \bar{x}_t)^2}$$

$$u'_x = \sqrt{\frac{1}{9}\sum_{i=1}^{10}(x_{ti} - \bar{x}_{t'})^2}$$

and

$$R_{xts} = 4u_x - u'_x$$

This calculation is performed for each direction, and each sphere (i.e., four times)

8.3.4 Gage Line Repeatability. The purpose of this test is to determine the gage line repeatability for all of the pockets on a turret with tool-changing capabilities. For this test, the short tool (see Fig. 8.3.2-1) is used. First the tool is put in one pocket and its X–Z offsets measured three times using the tool-setting system. The tool is then inserted in all the other pockets, in turn, measuring its offsets three times for each pocket. The total range of the X offsets is reported as the X gage line repeatability, and the total range of the Z offsets is reported as the Z gage line repeatability. If desired, the standard uncertainty in the offsets may be calculated on a pocket-by-pocket basis (see Nonmandatory Appendix M).

8.4 Repeatability, Location, and Drift of Tool-Setting System(s)

Turning centers are now supplied with tool-setting systems that allow for the automatic setting of tool offsets in the X and Z directions. (Other names, such as tool-setters, tool-gaging, and tool-setting probes, are also used.) On most turning machines, the Z direction location is set with respect to some feature on the machine part-holding device. The X direction, on the other hand, is set with respect to a more stable machine parameter, that is, the spindle axis of rotation. Tests here are designed with this in mind. If the machine has more than one work spindle or turret, tests should be performed for each possible spindle–turret combination. Further, if the tool-setting system is on a movable arm, the arm should be moved between each tool set when checking repeatability. Only one such combination is discussed here, namely, the single spindle–single turret. If other options are desired, they should be negotiated between the User and the Supplier and be made part of the original machine specification.

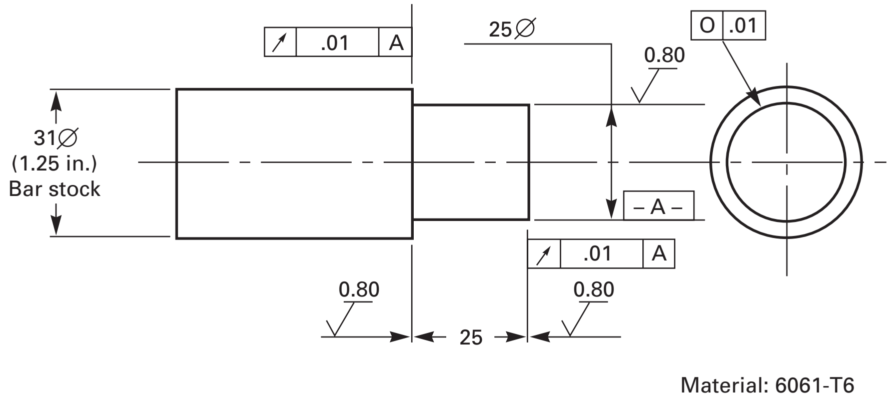
8.4.1 Repeatability of the Tool-Setting System. Before establishing the position of the tool-setting system with respect to the spindle centerline, it is necessary to check its repeatability. To do this, a new insert or a small precision ball should be mounted in the location of an insert in the tool holder. Whichever option is chosen, the tool holder should be short and as stiff as possible. Before proceeding, the machine should be exercised following an exercise procedure to be specified by the machine Supplier. Next, the machine should be jogged to allow the tool or ball to contact the tool-setting system in both the X and Z (if applicable) directions and an original X–Z position established. A cycle should be established, following the Supplier's recommendations, to quickly reset the tool 10 times. This procedure should be representative of how the tools will be set during normal machine operation. If the machine is equipped with an arm that moves in and out of the work zone, that arm should be introduced during each cycle; that is, the tool-setting cycle should be that normally used to set tools when machining. For each of these 10 repeats, the X and Z locations of the tool (ball) should be recorded. From these numbers, a standard uncertainty should be computed for each axis, following the procedures outlined in para. 8.3.1. The repeatability should be reported for both the X and Z (if applicable) directions as 4 times the standard uncertainty obtained from these measurements.[34]

For some specific purposes, it might be desirable to test the tool-setting sensor independent of the complete system performance. In that case, the procedures described above should be followed but the tool-setting arm left in position. The repeatability of the sensor in both the X and Z directions should be computed as above.

8.4.2 Original Location of the Tool-Setting System. To initially establish the position of the tool-setting system, this Standard requires cutting a test part. This proposed

[34] The results obtained from this test will vary, depending upon the withdrawal distance from the tool-setting station and the machine traverse speeds used. It is recommended, for this repeatability test, that the withdrawal distance be only 5 mm (approximately 0.2 in.) and the traverse speed be kept at less than one-tenth maximum traverse.

Fig. 8.4.2-1 Test Part for Determining the Location of a Tool-Setting System and Tool-Setting-System Drift



test part is shown in Fig. 8.4.2-1. It consists of a small cylinder, the cut portion of which is 25 mm (approximately 1 in.) in diameter and 25 mm (approximately 1 in.) long. These dimensions do not need to be precise. The material for this test part is 6061-T6 aluminum, like that used for the previous tests for machine critical alignments (see para. 7.8). A part program is established to face the part, turn the diameter, and face the small ledge near the spindle base. For the finish cut, a sharp single-crystal diamond tool, polycrystalline diamond tool, or other appropriate insert with a small nose radius of approximately 0.5 mm (approximately 0.020 in.) and low-tool-wear characteristics when machining aluminum shall be used. Before the finish cut is made, the tool position shall be sensed using the tool-setting system in both the X and the Z directions. The locations in machine coordinates of the tool as reported by the tool-setting system should be recorded. The final cut should then be made on the part to a specified nominal diameter. Before the part is removed from the spindle, the Z offset between the step on the part and an appropriate feature on the chuck face, spindle nose, or spindle faceplate should be measured in the Z direction. This distance should be compared to the Z reading of the tool-setting system to establish the correct offset.

The diameter of the test part should then be measured. Depending upon the application, this diameter may be measured on the machine with an appropriate micrometer or taken off the machine and measured using suitable metrology instrumentation of the requisite accuracy for the application. The difference between the actual diameter and the programmed diameter should then be used to establish the correction to the X location of the tool-setting system. For high-accuracy applications, nominal differential expansion corrections should be made (see section 4, Definitions). This should be entered into the machine controller, taking care to get the appropriate sign (the sign of the correction can be checked by remachining the same part to a smaller diameter and repeating the test).

8.4.3 Combination Test for Tool-Setting-System Drift.[35] The location of the tool-setting system with respect to the spindle centerline and an appropriate spindle surface will vary with the machine's thermal state. Exhaustive tests could be conducted analogous to those given in para. 7.7. This Standard defines a single test that combines several of these effects. This test requires the machining of four test parts of 6061-T6 aluminum using two tools. A drawing of the test part is given in Fig. 8.4.2-1. The duration of the test shall be the duration established in previous spindle thermal stability tests (para. 7.7.2) or 4 h, whichever is shorter. The tools used for this test are the same type as the tool used for the original location of the tool-setting-system tests described in para. 8.4.2.

The test normally proceeds as follows.[36] The first part is mounted following the procedure that will normally be used in machining. The spindle is then set to run at 50% of maximum speed (revolutions per minute). The first part is faced. Then the tool is set following the normal procedures used when machining. Then the diameter and face "A" of the part are cut. At the end of this machining cycle, the spindle is kept running at the same speed and the X and Z axes of the machine are exercised over most of their travel (the part should not be contacted), at 80% of rapid traverse, for a period of one-fourth the duration of the test, or 1h, whichever is shorter. At the end of this period, the spindle is stopped, a new blank mounted, and the process of facing, tool-setting, and part diameter and step cutting repeated. After the second part is cut, a new tool is inserted into the tool holder (or the turret indexed to a new tool) and the process repeated for two more parts. At the completion of this test, all four test parts are measured for both

[35] This test may include spindle thermal stability (see para. 7.6.2).

[36] For machines that cannot follow this procedure, a conceptually equivalent procedure shall be agreed upon between the User and the Supplier and made part of the original machine specification.

step height (Z direction) and diameters (X direction). The instrumentation chosen for the measurement is application and machine-accuracy dependent. For example, on many turning centers, micrometers and height gages might be sufficiently adequate. On diamond turning centers, other instrumentation is required.

The data are analyzed as follows. The differences between the programmed diameters and the measured diameters are computed. The step height data are computed similarly. The total range of the difference between the programmed and actual diameters is reported as the X-axis tool system drift, and the total range of the difference in programmed step heights versus actual step heights is reported as the Z-axis tool system drift. If desired, more than four test parts may be used to establish the statistical validity of the results. In this case, groups of parts should be machined in rapid succession at each of the time intervals previously defined and the average diameter step height and standard uncertainties computed for each interval.

8.5 CNC Performance Tests

8.5.1 Test for Minimum Block Execution Time. A part program shall be prepared to run the machine tool in one axis only, using the maximum practical traverse length and linear interpolation. This is normally the Z-axis on turning centers. The length of line segments shall be set to a value one-fourth the "desired increment length," which should be the chordal length normally used when contour cutting. For example, if the machine will be used to make parts with a normal chordal length of 1 mm (approximately 0.04 in.), the test line segment length shall be 0.25 mm (approximately 0.01 in.). The part program shall have the feed rate programmed in the first block, where it can be easily modified. The number of program blocks shall not exceed the "block look-ahead" limit of the control.

The program shall be run and the feed rate set at the maximum feed rate specified by the Supplier for this test. The feed rate shall be measured by a time-recording device or by a laser interferometer set in the feed rate measurement mode. The measured feed rate and the programmed feed rate shall be compared. If the measured feed rate matches the programmed feed rate within 5%, the controller passes this test and the minimum block execution time, *MBET*, is computed as below. If the measured feed rate is less than 95% of the programmed feed rate, the programmed feed rate shall be reduced, in reasonable increments, and the test repeated until a match (within 5%) between the measured feed rate and the programmed feed rate occurs. The feed rate where the measured and programmed feed rates agree, V_{max}, shall be used to calculate the minimum block execution time, *MBET*. It is given by

$$MBET = INCR/V_{max}$$

In no case shall the machine be run at an unsafe speed.

8.6 Machine Performance as a Measuring Tool[37]

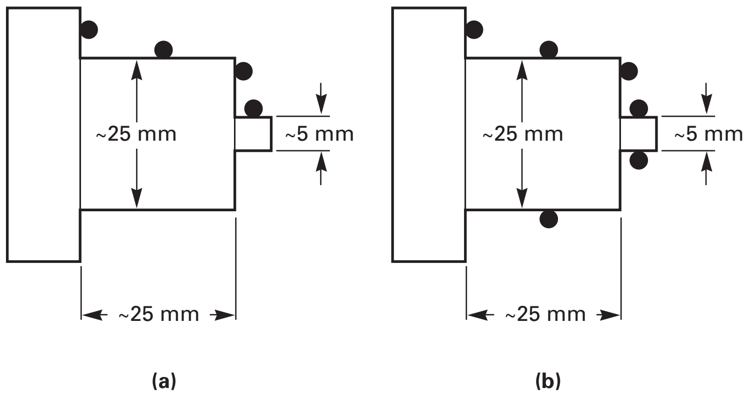
The following procedures have been designed to evaluate the performance of a turning center, equipped with a suitable probing system, as a measuring machine. The tests described in paras. 8.6.1 through 8.6.4 are meant to apply to machines equipped to measure in the point-to-point mode. Although machines equipped for part scanning are not currently commercially available, these tests could also be used on such machines, provided their data were acquired in the point-to-point measuring mode. The results of these tests do not reflect on the performance of the machine tool in a metal-cutting mode. The following tests address the issue of measuring performance in discrete stages that depend on the level of software capability provided by the Supplier and the intended use of the measuring system. Testing shall be performed in a manner that most closely represents the way in which the machine's measurement system will be used after acceptance. The tests described in paras. 8.6.1 through 8.6.4 are in conceptual agreement with similar tests for coordinate measuring machines, as outlined in ASME B89.4.1, and machining centers, as outlined in ANSI B5.54. For three-axis applications, ANSI B5.54 should be used. Prior to commencing these tests, the machine probe shall be calibrated according to the Supplier's recommendations for normal operation of the machine when measuring parts, using an artifact of a different size than the part that will be machined and measured. Qualification on the test artifact to be used for this test is specifically excluded. It is also assumed that prior to performing these tests the machine performance has been assessed as described in section 7 of this Standard.

8.6.1 General. Unless otherwise specified by the User, the measurement repeatability and feature measurement accuracy tests shall be performed along the spindle centerline and in the center of the work zone. The probe orientation and configuration shall represent the configuration to be used after acceptance, with a default stylus length of 50 mm (approximately 2 in.). Note that the value for measurement repeatability and feature measurement accuracy is dependent on position, probe configuration, and stylus length; therefore, the User may specify other locations and configurations or several locations and configurations, if required, as part of the original specification.

In these measurement repeatability and feature measurement accuracy tests, the requirement in the definition of repeatability to sense the same quantity is satisfied by measuring the center coordinates of the precision artifact rigidly mounted in the spindle near the center of the work zone. Ten determinations of the reference artifact's center shall be made as rapidly as practical to determine measurement repeatability. For each axis, 4 times the stand-

[37] The tests described in para. 8.6 do not cover cases in which the machine is used as a comparator.

Fig. 8.6.2-1 Approximate Location of Probed Points, Depending on Probe Configuration, When Measuring a Machined Test Part



ard uncertainty of the artifact's center coordinates shall be reported as the measurement repeatability for that axis. Machine measurement repeatability shall be reported on a per-axis basis. To determine the feature measurement accuracy, the same data shall be used; however, these data shall be evaluated by the software to determine the size of the artifact being measured. If a data point(s) obtained during this test appears to be an outlier (see section 4, Definitions), this point may not be simply discarded when either defining the standard uncertainty or the dimensions of the artifact. Rather, the complete test shall be repeated and the data from a complete test evaluated.

For machines that have the option of operating in a radius mode or a diameter mode, all tests shall be performed and reported in the radius mode. For machines that operate only in a diameter mode, all results computed as diameters shall be divided by 2 and reported as radii.[38]

The User is cautioned that it is extremely important that the measuring stylus be on center in the Y direction for the measurement of diameters or radii. The error made when the stylus is off center while measuring a diameter is given by

$$error = \frac{2(offset)}{DIA^2}$$

where

DIA = the part diameter
$offset$ = the distance above or below center

8.6.2 Measurement Accuracy Where Software Allows for Only 1D Measurements. For this test, a test part shall be machined in the spindle. The part is User-selectable, with two diameters not greater than 80% and 40%, respectively, of the maximum swing. The default size for the part is given in Fig. 8.6.2-1. The material is not specified but should be a dimensionally stable metal capable of holding an accurate surface finish. A thermometer conforming to the requirements of section 9 shall be appropriately thermally contacted with the test part in a position that does not interfere with probing, and a second thermometer placed in a position designated by the Supplier as being representative of the mean scale temperature. The two diameters of the test part shall be measured 10 times each using at least 10 points along each profile of the test part.[39] In the case of machines capable of measuring past the spindle centerline, the diameters of the test part shall be measured 10 times each using at least 5 points along each profile of the test part. The step height of the test part, indicated in the figure, shall be measured 10 times using at least 5 points on each face. Contact points for each set shall be as widely spaced as possible. From these data, two average measured radii, R_{p1} and R_{p2}, corrected for temperature, and the average step height, Z_{p0}, corrected for temperature, shall be computed. The equations are as follows:

$$R_{p1} = R_{M1}[1 - \alpha_s(T_s - 20) + \alpha(T - 20)]$$

$$R_{p2} = R_{M2}[1 - \alpha_s(T_s - 20) + \alpha(T - 20)]$$

and

$$Z_{p0} = Z_{M0}[(1 - \alpha_s(T_s - 20) + \alpha(T - 20)]$$

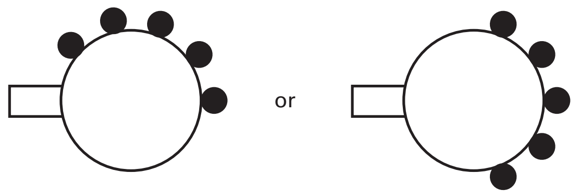
where

R_{Mi} = the measured radii
T = the average temperature of the point selected as representative of the mean scale temperature
T_s = the average temperature of the test part during measurement
Z_{M0} = the measured step height
α = the nominal thermal expansion coefficient of the machine scales
α_s = the thermal expansion coefficient of the test part

[38] Diametrical measurements are preferred. Radial measurements are susceptible to thermal drift of the spindle centerline with respect to the probe location.

[39] This test part will be measured in a metrology laboratory and thus serves as the calibration gage for checking machine accuracy.

Fig. 8.6.3-1 Approximate Location of Probed Points, Depending on Probe Configuration, When Measuring a Test Sphere



The mean values and their standard uncertainties are computed following standard procedures (see section 4).

Measurement repeatability shall be computed as

- X measurement repeatability, *MR*(*X*): 4 times the largest standard uncertainty of either radius
- Z measurement repeatability, *MR*(*Z*): 4 times the standard uncertainty of the step height

The test part shall be measured using dimensional-measuring equipment at 20°C (68°F) in a metrology lab. The measuring equipment should be suitable for the machine accuracy specification. The feature measurement accuracy shall be computed as follows:

(a) The feature measurement accuracy in the X direction, *FM*(*X*), shall be reported as the largest of the differences between either of the average radii measured on the machine, corrected for temperature, and the radii measured in the metrology lab.

(b) The feature measurement accuracy in the Z direction, *FM*(*Z*), shall be reported as the difference between the average step measured on the machine, corrected for temperature, and the step height measured in the metrology lab.

There is no test for probe lobing for a machine of this configuration.

8.6.3 Measurement Accuracy Where Software Allows for 2D or 3D Measurements. A 25-mm (approximately 1-in.) calibrated reference sphere, conforming to the requirements of section 9, shall be mounted in the main spindle such that it is readily accessible for machine probing. A thermometer conforming to the requirements of section 9 shall be appropriately thermally contacted with the test sphere in a position that does not interfere with probing, and a second thermometer placed in a position designated by the Supplier as being representative of the mean scale temperature. Ten sets of at least 10 readings shall be made on the reference sphere. Contact points for each set shall be as widely spaced as possible, as shown in Fig. 8.6.3-1. X and Z coordinates of the center of the ball and the radius of the ball shall be computed for each set of readings, using the software supplied with the machine. From these computed results, an average measured radius, corrected for temperature, R_{p0}, and the average X and Z center coordinates, X_{p0} and Z_{p0}, and their standard uncertainties shall be computed.

Measurement repeatability shall be reported as

- measurement repeatability, *MR*(*X*): 4 times the standard uncertainty of the mean X coordinate
- measurement repeatability, *MR*(*Z*): 4 times the standard uncertainty of the Z mean coordinate
- measurement repeatability, *MR*(*R*): 4 times the standard uncertainty of the mean radius

Note that these repeatabilities are defined as the uncertainties obtained from the calculated values for 10 sets of readings.

The spindle shall be rotated approximately 180 deg with the reference sphere remaining rigidly attached. Ten more sets of at least 10 readings shall be made on the opposite side of the reference sphere in a similar manner. The X and Z coordinates of the center of the ball and the radius of the ball shall be computed for each set of readings. From these computed results, the average measured radius, corrected for temperature, R_{p180}, and the average X and Z coordinates, X_{p180} and Z_{p180}, and their standard uncertainties shall be computed.

The feature measurement accuracy, *FMA*, in both directions shall be computed as

$$FMA(X) = \max.(|R_{p0} - R_{\text{sphere}}|, |R_{p180} - R_{\text{sphere}}|) + |X_{p0} - X_{p180}|$$

$$FMA(Z) = \max.(|R_{p0} - R_{\text{sphere}}|, |R_{p180} - R_{\text{sphere}}|)$$

where

R_{sphere} = calibrated radius of the gage at 20°C (68°F)

For each reading in each of the 10 sets of data, a radius is calculated using the average computed center location. For each set of data, the minimum point radius is subtracted from the maximum point radius. The largest value among these is the specification zone for circular profile measurement accuracy, *CPMA*.[40]

8.6.4 Linear Measurement Accuracy. The procedure described in this paragraph represents a minimum requirement to ensure conformance to linear measurement accuracy specifications. Linear measurement accuracy can be considered a combination of the

[40] A number of error sources contribute to circular profile measurement accuracy, such as probe lobing, thermal errors, geometric errors, and the CNC's ability to repeatably latch the probe's interrupt signal.

positioning accuracy of the machine, the ability of the measurement system to repeat a measurement, and any offsets introduced by probe performance. Since the bidirectional systematic deviation of positioning of an axis (para. 7.2.7.1) and the feature measurement accuracy (para. 8.6.2 or 8.6.3) have been previously measured, the values obtained for these measurements shall be used in the computation of the linear measurement accuracy.

The linear measurement accuracy for each linear axis, $LMA(X)$ and $LMA(Z)$, shall be reported. It is the sum of the measurement repeatability, MR, for an axis (para. 8.6.2 or 8.6.3); the feature measurement accuracy, FMA, for that axis (para. 8.6.2 and 8.6.3); the spindle thermal stability, D_x or D_z (para. 7.7.2); and the bidirectional systematic deviation of positioning of an axis, E (para. 7.2.7.1), minus the bidirectional systematic deviation of positioning of an axis multiplied by the radius of the artifact, R_A, used in the feature measurement accuracy test and divided by the axis length, L, of the axis of interest.[41] That is

$$LMA(X) = MR(X) + FMA(X) + D_x + E(X) - E(X) \times (R_A/L_X)$$

$$LMA(Z) = MR(Z) + FMA(Z) + D_z + E(Z) - E(Z) \times (R_A/L_Z)$$

8.7 Machining Test Parts

8.7.1 General. Machining test parts have an important role in the acceptance of machine tools. However, using such test parts alone to determine machine accuracy and acceptance is not recommended. There are many variables that can affect the test part in machining tests that have no direct relation to the machine tool. Examples include material properties, tool wear, coolant flow and selection, temperature fluctuations in the workpiece, programming errors, and fixture-induced distortions. Thus, machine positioning accuracies and alignment are best tested by the procedures outlined in this Standard. Two types of tests are discussed in paras. 8.7.2 and 8.7.3, respectively.

8.7.2 Standard Test Parts. A large number of standard test parts have been generated as the result of decades of work by other standards committees. If a test part is required, an appropriate standard part should be chosen and made part of the original machine specification. This part should contain tests for contouring accuracy, threading, and boring, as well as any other machining operations that are of importance to the machine user.

[41] The number reported is highly approximate and is intended only to give a worst-case estimate.

8.7.3 Production Parts. Where the machine is to be used in producing a single part or a family of parts, the best machine test to determine machine capability would be a run of production parts that are as close to the production part as possible. In this case, the machine shall be started and allowed 1 h for warm-up. The first part shall be cut and checked and any corrections to the tooling or programming made at that time. An additional 6 to 10 parts shall also be cut over a 2-day period, allowing the machine to settle into thermal stability. The machine shall be kept running between the various test cuts, in a dry cycle, to increase thermal stability of the machine, without requiring an excessive amount of material to be cut and inspected. Further tests shall be negotiated between the User and the Supplier and be part of the original machine specification.

8.8 Parametric Tests

To obtain more complete information regarding the machine, some Users may desire to perform complete parametric testing, measuring angular error terms other than yaw (para. 7.4), and also measuring straightness errors. If these error measurements are performed, the User should follow the instrumentation guidelines for these tests given in ANSI B5.54. The measurement procedure and data analysis should, however, follow the procedure given for positioning accuracy and repeatability of linear axes as specified in para. 7.2. This includes lines of measurement, measuring intervals, and measurement procedures, including data analysis. The data should be reported with the correct titles, as has been done for the measurement of angular error motion (yaw) in para. 7.4. Note that for straightness measurements, a straight line alignment term must be removed before data analysis, as is described in ANSI B5.54.

9 TEST EQUIPMENT AND INSTRUMENTATION

9.1 General

The instruments specified in this Standard are for recommendation only. Other instruments with similar capabilities and accuracy are acceptable for use with this Standard. It is recommended that the contributions to measurement uncertainty of instruments and artifacts being used be sufficiently small such that the resulting expanded ($k = 2$) measurement uncertainty, U, is less than an appropriate fraction of the specified value for the performance parameter being measured. Unless otherwise specified, one-eighth is the appropriate fraction for performance parameters that are derived from a range or envelope of values (e.g., positioning accuracy and repeatability, straightness, and circular deviations), and one-fourth is the appropriate fraction for performance parameters specified as a maximum deviation from nominal (e.g., squareness and parallelism). In paras. 9.2 through

9.11, simplified guidelines are given to approximate this condition for individual cases. All instrument and artifact calibrations shall be traceable to a national metrology institute such as the National Institute of Standards and Technology (NIST). Calibration frequency shall conform to standards related to the instrument or artifact used.

9.2 Temperature

The time constant of thermometers shall be no more than one-tenth of the cycle time of the highest frequency component of the temperature variation of interest in a test. The time constant is the time required for the thermometer to indicate 63.2% of its final change due to a step change in temperature (see ANSI B89.6.2 for further clarification). The resolution of thermometers shall be no greater than one-tenth of the amplitude of the lowest-amplitude component of temperature variation of interest in a test.

Thermometers used for nominal differential expansion correction or laser wavelength correction shall be calibrated by suitable means to an accuracy of ±0.1°C over the temperature range of use.

9.3 Relative Vibration

Relative vibration shall be measured using a high-resolution, undamped displacement indicator. Resolution of 0.1m (approximately 0.000004 in.) or better is recommended. Such indicators should also have a bandwidth of at least 1 kHz.

9.4 Displacement

9.4.1 Laser Interferometers. Laser interferometers shall have a frequency stability of such that this long-term stability represents an error less than one-fourth of the unidirectional repeatability, linear axes, of the machine (in meters), divided by the length (in meters) of the longest machine axis. The resolution of such a system shall be better than one-fourth of the unidirectional repeatability, linear axes.[42]

9.4.2 Grid Encoders. Grid encoders used for contouring performance testing shall be calibrated with an error of less than one-fourth of the unidirectional repeatability, linear axes, of the machine.

9.4.3 Precision Reference Ball(s). The precision reference ball(s) in the tests for *ETVE*, tool-change and turret repeatability, and machine performance as a measuring tool shall be spherical to within one-fourth of the unidirectional repeatability, linear axes, of the machine tool. Reference balls used for the feature measurement accuracy test shall be calibrated for their diameter to within one-fourth of the unidirectional repeatability, linear axes, of the machine.

9.4.4 Precision Disks. The precision disk(s) used for the contouring test shall be calibrated to an accuracy of one-fourth of the unidirectional repeatability, linear axes.

9.4.5 Telescoping Ball Bars. The balls on the end of the telescoping ball bar shall be spherical to within one-fourth of the unidirectional repeatability, linear axes, of the machine tool and equal in diameter to within one-fourth of the unidirectional repeatability, linear axes, of the machine. The length variation due to sag of the telescoping ball bar in any position shall be less than the resolution of the machine being tested, and the resolution of the ball bar indicator shall be equal to or better than the machine resolution. Any ball bar system conforming to the requirements of this Standard shall state, as part of the output data, the angular interval used for ball bar length measurement during circular contouring. The ball bar shall be calibrated to an accuracy of one-fourth of the unidirectional repeatability, linear axes.

9.4.6 Displacement Indicators. Displacement indicators used for the *ETVE* test, machine thermal tests, critical alignment, rotary axis alignments, tool-change repeatability, and repeatability in drift of tool-setting systems, as specified in this Standard, shall be calibrated to within one-fourth of the unidirectional repeatability, linear axes, of the machine. Capacitance probes, laser interferometers, linear variable differential transformers (including air-bearing types[43]), fiber-optic proximity sensors, dial gages, or other developed instrumentation that accurately measures displacement throughout the range of machine displacement variation are acceptable. The bandwidth of the probe(s) to be used for these tests is unspecified, as these tests are sufficiently slow that a bandwidth of a few hertz is sufficient. Users are cautioned to ensure that the bandwidth of the indicator being used is sufficient for the intended purpose.

9.5 Angle

9.5.1 Autocollimators. Autocollimators used for the positioning accuracy and repeatability, rotary axes, and the periodic angle positioning accuracy shall be calibrated to within one-fourth of the unidirectional repeatability, rotary axes, of the axis to be measured. Calibration shall be performed on a regular basis or after any suspected instrumental damage.

[42] Users concerned with the suitability and accuracy of a laser system for their application should contact the Precision Engineering Division, NIST, 100 Bureau Drive, M/S 8200, Gaithersburg, MD 20899-8200, http://www.nist.gov.

[43] Air-bearing LVDTs are preferred for the part-trace tests on high-precision machines.

9.5.2 Polygons. Polygons used for the positioning accuracy and repeatability, rotary axes, shall be calibrated to within one-fourth of the unidirectional repeatability, rotary axes, of the axis to be measured.

9.5.3 Indexing Tables. Indexing tables used for testing shall be calibrated to within one-fourth of the unidirectional repeatability, rotary axes. Self-calibration is an acceptable method for traceability.

9.5.4 Rotary Encoders. Rotary encoders shall be calibrated to within one-fourth of the unidirectional repeatability, rotary axes. Self-calibration is an acceptable method for traceability.

9.5.5 Angle-Measuring Interferometers. Several manufacturers offer differential interferometers for the measurement of small angles. For the use of these interferometers, the instrument manufacturer's recommendations and constants regarding the conversion of differential displacement to angle shall be followed, with particular attention paid to the nonlinear corrections required for large angles. Special attention should also be paid to the alignment of the optical elements when such alignment is performed by the User.

9.5.6 Differential Levels. Differential levels shall be calibrated to within one-fourth of the unidirectional repeatability, angular positioning.

9.6 Pressure

The accuracy and repeatability of the pressure sensor used for correction of the laser interferometer shall be at least ±1 mm Hg (approximately 0.019 psi).

9.7 Humidity

Humidity measurement for correction of the laser interferometer wavelength shall be sufficiently accurate that it contributes no more than one-fourth of the unidirectional repeatability, linear axes, to laser measurement error.

9.8 Utility Air

The utility air pressure shall be measured using the gages supplied with the machine, unless otherwise specified as part of the original machine specification.

9.9 Spindle Error Measurement

At the time of this writing, the only suitable indicators for spindle error measurement are high-bandwidth capacitance gages. Such gages shall be calibrated to within one-fourth of the unidirectional repeatability, linear axes, and shall have a bandwidth of at least 10 kHz. The User shall specify for particular applications if a higher bandwidth is required. Other indicators of equivalent bandwidth may be substituted, with the warning that some such indicators may be sensitive to parameters other than displacement, and this condition must be investigated.[44]

9.9.1 Commercial Instruments. Commercial instruments that measure spindle error motion shall have sensors that conform to the requirements for spindle error measurement given in para. 7.6. Furthermore, such instruments shall provide documentation to ensure that any internal algorithms conform to the measurement procedures as described in this Standard.

9.10 Straightness Measurements

9.10.1 Indicators. Displacement indicators for straightness measurements shall conform to the requirements of para. 9.4.6.

9.10.2 Straightedges. Staightedges used for the straightness measurements shall be calibrated to within one-fourth of the straightness requirement of the axis to be measured. Self-calibration (reversal) is an acceptable method for traceability.

9.11 Test Part Measurement

If a coordinate measuring machine is used for a test part measurement, it shall conform to the requirements of ASME B89.4.1 and have a working tolerance for volumetric performance less than one-fourth of the specification zone for the specific machining test(s). If other inspection methods are used, all instruments, gages, and procedures required for these measurements shall have calibrations to ensure that individually the error component that they introduce shall be at least one-tenth of the specified measurement accuracy for the test part.

[44] In particular, inductive sensors are also sensitive to the metallurgy of the mandrel or ball used as a reference artifact when testing spindles.

NONMANDATORY APPENDIX A
GUIDE FOR USING THE DRAFT TURNING CENTER STANDARD

A-1 GENERAL

The primary purpose of this Standard is to aid in purchasing of machines to specification. When purchasing a new machine, the User should clearly specify the desired machine classification (Form 1 in section 1) and the machine performance (Forms 4 and 5 in section 1). The entries in Forms 4 and 5 shall be considered the specification zones for the purchased machine. If desired, the User may also describe the proposed machine environment on Form 2; however, it is the responsibility of the Supplier to provide these environmental guidelines with the machine quote. When the machine is received, it should be tested, and, subject to environmental derating, the measured values for the tests described should be less than or equal to the specification zones in the original machine specification. Note that the machine should be tested in the environment in which it will be used. Testing at the Supplier's plant can be useful but is not a substitute for testing after machine installation.

The tests described in this Standard are in logical sequence but not necessarily the most rapid sequence in machine testing. The most rapid sequence groups tests in terms of similar instrumentation. The following is a suggested procedure for testing that the Committee currently believes would minimize the testing time. Only the testing of a simple two-axis lathe, with a single work spindle, is covered. Further, it is assumed that programs and all necessary fixtures have been prepared in advance.

A-1.1 Recommended Tests: Day 1

Tests should be performed in the order given below. The recommended Day 1 tests use a displacement indicator nest as shown in Fig. 6.2.1.4-2.

- relative vibration test (para. 6.3)
- *ETVE* test (para. 6.2.1)
- structural motion test (para. 7.6.2)
- spindle thermal stability test (para. 7.7.2)
- spindle error motions, fixed sensitive direction (para. 7.6.3)
- composite thermal error (para. 7.7.4)

Note that the composite thermal error test requires 4 h to perform. After this test, the machine must be allowed to come to equilibrium before other testing can proceed.

A-1.2 Recommended Tests: Day 2

The recommended Day 2 tests require the use of a laser interferometer.

- positioning accuracy and repeatability, X-axis (para. 7.2)
- angular error motion, X-axis (para. 7.4)
- positioning accuracy and repeatability, Z-axis (para. 7.2)
- angular error motion, Z-axis (para. 7.4)
- thermal distortion caused by moving linear axes (para. 7.7.3)

Again, after completion of these tests, the machine will be in a warmed-up thermal state and needs to be allowed to come to equilibrium.

A-1.3 Recommended Tests: Day 3

The recommended Day 3 tests require a calibrated telescoping ball bar, a test part, and tooling or appropriate straightedges and indicators, and a power meter.

- contouring performance using circular tests (para. 7.9)
- critical alignments (para. 7.8)
- spindle idle run loss test (para. 7.10.2)
- multifunction cycle test (para. 7.11)

A-1.4 Recommended Tests: Day 4

The Day 4 tests require at least material and tooling. If other test parts are specified, a metrology laboratory for part measurement is required.

- chatter limits test and full torque test (para. 7.10.3)
- other test parts, as specified

NONMANDATORY APPENDIX B
1-DAY TEST FOR MACHINE PERFORMANCE

B-1 PURPOSE

When it is desired to estimate machine performance within 1 day, the following tests, taken from the body of the Standard, are recommended. These tests are for a machine with only two linear axes and a single work spindle. Machines with more than two axes require more testing. To perform these tests in 1 day requires advance preparation of test equipment and machine programming.

B-2 POSITIONING ACCURACY AND REPEATABILITY, LINEAR AXES; AND ANGULAR ERROR MOTIONS, LINEAR AXES

The positioning accuracy and repeatability and the angular error motion of both machine axes should be measured following the procedures outlined in paras. 7.2 and 7.4. The data shall be analyzed as described in paras. 7.2.7 and 7.4.1.

B-3 CONTOURING PERFORMANCE USING CIRCULAR TESTS

The machine's contouring performance shall be measured using a telescoping ball bar, using the procedure described in para. 7.9.2, 7.9.3, or 7.9.4, whichever is applicable. The data shall be analyzed as described in para. 7.9.5.

B-3.1 Critical Alignments

The squareness of the cross-slide (X-axis) with the work spindle axis (often a C-axis) shall be measured as described in para. 7.8.2. The parallelism of the longitudinal slide (Z-axis) with the work spindle (C-axis) in the X–Z plane shall be measured as described in para. 7.8.3.

B-3.2 Structural Motion

The structural motion of the main spindle shall be measured in accordance with the procedures given in para. 7.6.2.

B-3.3 Spindle Thermal Stability Test

The thermal stability of the main spindle shall be measured in accordance with the procedures given in para. 7.7.2.

NONMANDATORY APPENDIX C THERMAL ENVIRONMENT VERIFICATION TESTS

C-1 PURPOSE

The performance of machine tools is strongly affected by the detailed characteristics of the thermal environment that surrounds them. Parameters of importance include cooling medium (usually, but not always, air), velocity of cooling medium, frequency and amplitude of temperature variations of the cooling medium, mean temperature of that medium, and temperature gradients within that medium. The effects of these parameters and others are discussed in detail in ANSI B89.6.2. It is the thesis of ANSI B89.6.2 and of this Standard that currently it is not possible to specify a thermal environment that will ensure a specific value for the expanded thermal uncertainty, $U_T(L)$, para. 6.2.2. For a thorough discussion of the technical situation, the reader is referred to ANSI B89.6.2. The purpose of this Nonmandatory Appendix is, however, to specify procedures and responsibilities for testing the thermal environment in the event the *ETVE*, as measured in para. 6.2.1, is excessive. That is, the expanded thermal uncertainty exceeds that required for the machine, and the machine User contends that his environment meets the Supplier's parameters. For the purpose of this Standard, these parameters include cooling medium velocity, nominal mean temperature, frequency and amplitude range of temperature variation, and horizontal and vertical temperature gradients. The following tests are designed to measure these parameters for the purposes of assuring conformance to the Supplier's parameters.[1]

C-2 METHOD OF TEST

To ensure that the environment itself is tested rather than any characteristic of the machine tool supplied, these tests should be conducted with the machine tool, support computers (if supplied), and any other auxiliary equipment related to the machine tool, turned off for a period of 24 h preceding the test, to allow adequate soak out of any thermal gradients induced by the machine tool. Normal activity, however, should be continued about the machine as this constitutes part of the User-supplied environment. With these constraints, the tests specified in paras. C-2.1 through C-2.4 should be performed.

C-2.1 Velocity

Since air is the most widely used cooling medium in dimensional metrology laboratories, the following tests are structured for measuring air velocity. If some other medium is to be used for heat transfer, then methods for testing its properties should be part of the machine specifications.

For the measurement of velocity, several types of instruments are suitable. These instruments and a discussion of the measurement problems are given in Tables B-1 and B-2 of ANSI B89.6.2. The instruments used should be properly calibrated, and the test personnel should be aware of both the limitations of their instruments and their operation.

Using appropriate instruments, the velocity of the cooling medium around the machine shall be measured. Measurements shall be made at the corners of a cubic volume that completely encompasses the machine, and the velocity shall be computed as the average of these eight measurements.

C-2.2 Mean Ambient Temperature

The mean ambient temperature shall be measured using a thermometer with characteristics as specified in section 9. The mean ambient temperature shall be the time average temperature of five readings taken at the center of the machine work zone over a period of time spanning the longest test. (The use of five readings, rather than two, for the measurement of the mean ambient temperature is justified here for diagnostic purposes.)

C-2.3 Frequency and Amplitude of Temperature Variation

The range of frequencies of temperature variation and the amplitude of those variations shall be determined by measuring and continuously recording the temperature at the center of the work zone over a period of time that should, at a minimum, be representative of a daily cycle (i.e., 24 h). The maximum peak-to-valley temperature variation shall be determined from the recorded data. The data shall be analyzed to determine the range

[1] This Nonmandatory Appendix discusses only measurements of air temperature, and the User is warned that sometimes thermal effects are caused by coupling of infrared and visible radiation to the machine. If the environment appears to conform to the Supplier's parameters after performing the tests in these appendices and the *ETVE* of the machine is still not within specification, radiation coupling should be seriously examined.

of temperature variation for a daily cycle and an hourly cycle, subject to the condition that isolated disturbances that are shorter in duration than the minimum period (maximum frequency) specified by the Supplier shall be ignored. The daily variation shall be defined as the maximum range of temperature readings in 24 h, subject to the condition on transients mentioned above. The amplitude of the superimposed hourly cycle shall be defined as the maximum range of temperature variation in any 1-h interval, subject to the same condition.

C-2.4 Thermal Gradients

Thermal gradients shall be determined by measuring the temperature at the extreme corners of the machine in a horizontal plane and also at the highest and lowest locations of the machine. These temperatures shall be defined as the average value of no less than five readings over an interval of 10 min. The vertical gradient shall be determined to be the difference between the maximum and the minimum temperatures anywhere along a vertical line through the machine divided by the distance between the measurement point of these extreme temperatures. The horizontal gradient is defined as the difference between the maximum and the minimum temperatures along any horizontal line through the machine divided by the distance between the measurement points of these extreme temperatures. These readings shall be taken over a period of at least as long as the longest acceptance test (or 24 h) and the greatest value of the gradient reported.

C-3 ANALYSIS

If any of the parameters measured in section C-2 exceed the Supplier's specified parameters, it shall be the responsibility of the User to correct the problem to conform with those specified parameters, or else to be willing to accept the performance derating described in section 6 of this Standard. If the parameters so measured meet the Supplier's specified parameters, it shall be the Supplier's responsibility to correct the performance of the machine tool to meet the specified working tolerances.

NONMANDATORY APPENDIX D
SEISMIC VIBRATION VERIFICATION TESTS

D-1 SCOPE

The purpose of this Nonmandatory Appendix is to recommend vibration measurement instrumentation and procedures for measuring vibration at machine installation sites. Vibration levels shall be measured at the proposed machine site(s) to compare to allowable site vibration limits established by the machine Supplier. This document also defines the instrumentation and measurement procedures to establish vibration on the machine for additional analysis. This Nonmandatory Appendix does not address the determination of vibration sources or reduction of vibration levels. This task is usually involved and requires the knowledge of vibration specialists.

D-2 DEFINITIONS

To the extent possible, this document is intended to be self-defining. It is written for individuals with an engineering background. Definitions for specific vibration terminology may be found in the Institute of Environmental Sciences and Technology Document IEST-RP-CC024.1, "Measuring and Reporting Vibration in Microelectronics Facilities."

D-3 VIBRATION ACCEPTANCE CRITERIA

The machine Supplier shall provide site vibration criteria of acceptability. Below these levels the machine can operate successfully, and above these levels problems may occur. Each machine Supplier has different formats and levels of acceptance. The type of vibration measurements to be taken depends on format and vibration units specified by the machine Supplier. Based on the type of criteria, the vibration specialist should determine the necessary measurement units, frequency range, measurement locations, and instrumentation.

D-3.1 Criteria Units

Vibration is characterized by amplitude versus time or frequency. The amplitude can be defined in displacement, velocity, acceleration, or power spectral density. Depending on the type of criteria, the amplitude ordinate can be defined in either the time domain or frequency domain.

D-3.1.1 Amplitude Units. Since the machine is a cutting tool, units of displacement are most useful in relation to machine performance. However, velocity and acceleration are more appropriate parameters for measuring machine site vibration. Displacement may be suitable for specific situations, but it is not recommended for general vibration measurements.

D-3.1.2 Ordinate Units. The use of time or frequency for the ordinate depends on the acceptance criteria format of the machine Supplier. Time-based criteria are referred to as a "time history," which provides measurement of transient or very low-frequency vibratory events, such as beat signals. The frequency domain allows measurement over a very short time range, which provides the ability to diagnose many dynamic events.

D-3.2 Criteria Format

As defined in para. 5.3, the Supplier shall provide, as part of the machine specification, a statement of acceptable vibration. The criteria should be provided by the Supplier or listed as part of the machine specification form (Form 2; see section 1), if used. At least two criteria format options are presented: frequency response function and time history. The supplied acceptance criteria shall define the format to present the vibration data for ease of comparison.

D-3.2.1 Frequency Response Function Criteria. Frequency response function criteria are specified as a vibration amplitude as a function at specific frequencies. The criteria are usually presented as allowable vibration amplitude versus frequency, in hertz. The frequency range may vary from Supplier to Supplier. In general, seismic vibrations are applicable over a range of 0 Hz (DC) to 100 Hz. Vibration levels have a large dynamic range, and it is sometimes helpful to present amplitude data in logarithmic scale. If decibels are used, the standard reference values shall be used.

D-3.2.2 Time History. Time history measurements represent the vibration during the time period of interest. The Supplier should specify a maximum peak-to-peak acceptable vibration level and a time period over which it applies. The vibration amplitude is typically specified in units of velocity or acceleration.

D-4 INSTRUMENTATION

This section describes various instruments required to perform on-site vibration measurements. Various types of sensors, signal conditioners, recorders, computer programs, and signal analyzers are available for acquiring these data. This section is not intended to single out any particular equipment manufacturer; its purpose is to recommend types of equipment that meet the requirements of this Standard.

D-4.1 Transducers

Many types of transducers exist for various types of vibration measurements. The measurements specified in this Standard require a seismic accelerometer or a specific type of velocity transducer.

D-4.1.1 Seismic Accelerometers. The two most important requirements for the accelerometer are frequency response and sensitivity. Site vibration measurements generally require low frequency and high sensitivity. The minimum frequency response linearity should be less than 1 Hz, preferably 0.5 Hz. The frequency response should be greater than 100 Hz. The sensitivity of the accelerometer should be 10 V/g or greater, where g is equal to 9.8 m/s^2 (386 in./sec^2).

D-4.1.2 Velocity Transducers. These sensors are also referred to as geophones. The sensitivity of the geophone should be 4 V/cm/s (approximately 10 V/in./sec) or greater. The frequency response linearity requirement of the velocity transducer is the same as for the accelerometer, 0.5 Hz to 100 Hz.

D-4.2 Amplifiers and Signal Conditioners

The transducers require amplifiers and signal conditioners. Most seismic accelerometers require an amplifier, but some models may have built-in electronics that do not require signal conditioning. Velocity transducers may require amplification and signal conditioning, depending upon the sensitivity and signal-to-noise ratio. It is the responsibility of the vibration specialist to use the proper signal conditioners.

D-4.3 Signal Recording and Analysis Instruments

The type of instrumentation required for signal recording and analysis depends on the type of criteria and format that have been provided by the machine Supplier. The frequency response criteria require a fast fourier transform (FFT) dynamic signal analyzer or a digital recorder. Time history data can be acquired with an oscilloscope, a digital recorder, or an FFT analyzer.

D-4.3.1 FFT Signal Analyzers. This type of analyzer is the most sophisticated means of measuring vibration because it provides the greatest amount of information about the vibration signal. In most cases, this additional information is necessary to understand the vibration environment. Many types of FFT analyzers exist, from many different manufacturers. One- and two-channel units, handheld devices, and PC-based formats are readily available. Note that using a data recorder, as specified in para. D-4.3.2, requires the use of an FFT analyzer after the data are acquired. It is the User's responsibility to understand the instrument, its capabilities, and its limitations.

The following are guidelines for FFT analysis configuration and specifications:

(a) Noise Floor. 100 dB/√Hz.

(b) A/D Resolution. The resolution of the analog-to-digital (A/D) converter should be at least 12 bits. The better analyzers have a 16-bit A/D resolution.

(c) Dynamic Range. The dynamic range should be at least 70 dB. The better spectrum analyzers have higher dynamic range.

(d) Frequency Resolution. This parameter, as it applies to the analyzer, is denoted in number of lines over which the analysis range is divided. Most analyzers have selectable resolution from 100 lines to 1 600 lines. The resolution, in hertz, is calculated by dividing the frequency range by the number of lines. For example, a frequency range of 0 Hz to 100 Hz acquired with a 400-line analysis has a 0.25-Hz (100/400) resolution. The frequency resolution used must be compatible with the resolution of the frequency response criteria. If the criteria are defined at every 1 Hz, the data must be acquired with a 1-Hz resolution. For example, 0 Hz to 100 Hz criteria defined every 1/2 Hz would need to be acquired with 200 lines of resolution. This Standard recommends that data from 0 Hz to 100 Hz be acquired with 400 lines of resolution, producing 0.25-Hz resolution data. The overall frequency resolution is also dependent on the transducer frequency response. The procedure above should be followed, and modified only when the machine Supplier's specification requests otherwise.

(e) Antialiasing Filter. This filter prevents incorrect reporting of frequency components due to undersampling of higher-frequency signals. This filter is found on most (if not all) FFT analyzers. It should always be used.

(f) Averaging. Most analyzers have an averaging feature. It is used to reduce the effects of transient events such as personnel or vehicular activity. Ten averages should be taken for all measurements. Some spectrum analyzers have various types of averaging functions, such as linear, root mean square, peak hold, or exponential. Linear or summation averaging should be used.

(g) Window Functions. This feature is used to force a generalized vibration signal into discrete time-domain periods. When window functions are not used, the frequency response of the vibratory signal is incorrectly distributed throughout the frequency range. There are many types of window functions. The most popular are Hanning, flat top, and uniform. Other windows provide excellent amplitude accuracy and poor frequency accuracy, and vice versa. The Hanning should be used for all measurements specified in this Nonmandatory Appendix.

D-4.3.2 Data Recorders. For ease of gathering vibration data in the field, the use of a multichannel data recorder is useful and convenient. Such an instrument allows for three or more channels of data to be recorded simultaneously, while providing a permanent record for archives and verbal data annotation during specific events. Additionally, the recorder allows a record of the real-time response, which can be most useful. The data can then be processed at a later date using in-house data reduction techniques such as the FFT analyzers specified in para. D-4.3.1. The recorder format shall be digital and shall use digital audio tape (DAT) because of its excellent signal-to-noise ratio and dynamic range, as compared to analog tape.

D-4.3.3 Oscilloscopes. Most facilities have an oscilloscope and personnel who can operate it, which allows a User to take baseline time history readings. The oscilloscope is also useful for viewing beat signals, transient events, and hourly and daily vibratory changes. The oscilloscope should be set to AC-coupled and free-run triggering. The vibration amplitude is determined by viewing the signal and determining the peak-to-peak voltage amplitude, and using the transducer sensitivity for converting to appropriate amplitude units.

D-5 TEST PROCEDURE

The procedures for making vibration measurements are fairly simple once the appropriate analysis equipment is selected and configured as required.

D-5.1 Calibration

At a minimum, the vibration measurement equipment should have been calibrated by a qualified lab, traceable to NIST, in the past 12 months. Site calibration of the transducers at the start of the testing is required.

D-5.2 Transducer Mounting

For all measurements, the transducers should be mounted directly and firmly to the floor or a common interface for measuring three mutually orthogonal axes. Such mounting arrangements are referred to as “triaxial.” Some accelerometers incorporate three triaxial transducers in one device. When this mounting arrangement is used, all three channels should be acquired simultaneously. Time-independent triaxial measurements should not be performed.

D-5.3 Measurement Location

In general, the transducers should be mounted in the general area where the machine will rest. This area should encompass the outer envelope of the machine plus 3 m (approximately 10 ft.) beyond this footprint.

D-5.4 Acquiring and Recording Data

Vibration measurements should be made during normal operations of the facility. Nearby equipment that will be operating when the machine is expected to be used should be running during the vibration testing. A written test log or voice channel on a data recorder should be maintained by the individual performing the test so that any abnormal events during the test can be recorded. A test should be repeated if abnormal events occur. Normal vehicular traffic should not be excluded. When the environmental conditions are satisfactory, the data should be recorded on tape, saved to memory, and printed or manually recorded.

D-5.4.1 Time History. For time history criteria, the measured peak-to-peak vibration levels should simply be compared to the permissible level. The machine Supplier may provide vertical and horizontal criteria. The User should take care to compare the acquired data to the criteria in the appropriate direction.

D-5.4.2 Frequency Response Function. Comparison of frequency response function criteria to frequency domain vibration data can be more effort than taking the data. If the criteria have the same level at all frequencies (straight line) or little changes in amplitude, it will be easy enough to draw the criteria over the printed vibration levels. If the criteria are not constant or uniform, it may be easier to use software to compare data and criteria. This involves digitizing the criteria, which in some cases requires entering levels at 1-Hz increments. The vibration data stored on the FFT analyzer must be downloaded onto a PC. This requires different steps, depending on the analyzer manufacturer. Using a spreadsheet, math, graphing, or special program, the vibration data and criteria are combined into a single graph. Once the data are in a software format, they can be manipulated, graphed, and analyzed in a usable format.

D-6 CRITERIA ASSESSMENT

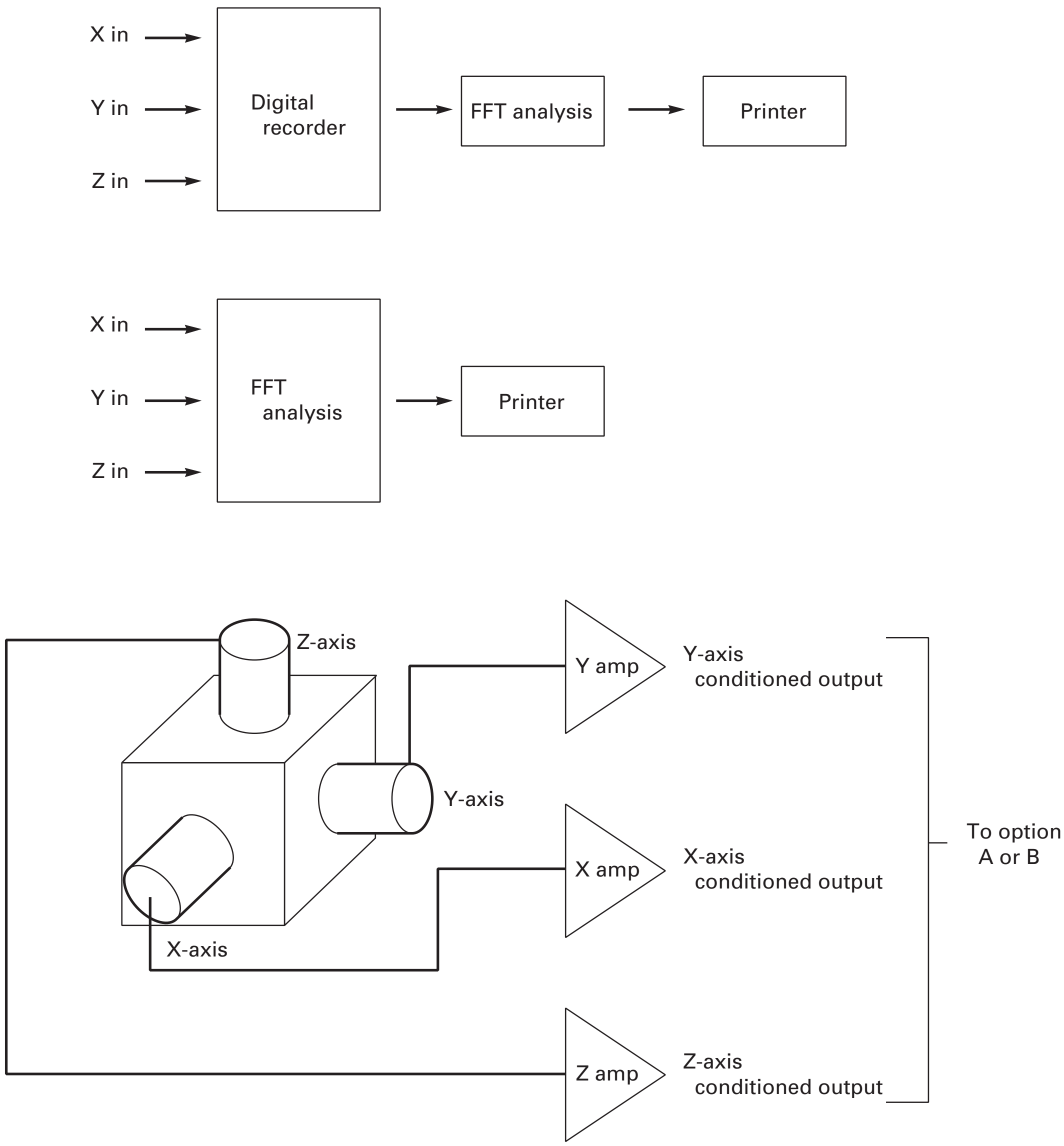
D-6.1 Measured Vibration Below Criteria

If the vibration levels measured by the procedure in section D-5 are within the Supplier’s criteria, no additional work is required. It is the sole responsibility of the Supplier to maintain the performance of the machine to meet specifications.

D-6.2 Measured Vibration Above Criteria

If the vibration levels exceed the Supplier’s specifications, it is the responsibility of the User to isolate the vibration to conform to the specification, or else accept a performance derating as described in para. 6.3. Again, this Nonmandatory Appendix does not provide information on how to reduce excessive vibration

Fig. D-8-1 Diagram of Sensor Arrangement and Instrumentation Configuration



levels, but vibration isolation will reduce the levels. Before the vibration levels can be reduced, the source of the vibration must be determined. It may be easy to do this with the equipment described in section D-4. Shock and vibration isolator suppliers, who specialize in low-frequency vibration attenuation, should be contacted if vibration isolation or a vibration survey is required.

D-7 REPORT

A report shall be issued by the vibration specialist within approximately 3 weeks. The report shall include all backup information and analyzed data with a comparison to the machine specification. The report shall include the following as a minimum:

(a) title
(b) dates (of data collection and of the report's issuance)
(c) calibration information
(d) description and diagram of test setup
(e) procedure
(f) analysis
(f) summary

Note that the report should serve to archive the baseline vibration data for later review, if problems arise after machine installation.

D-8 FIELD INSTRUMENTATION DIAGRAM

A diagram of the instrumentation is given in Fig. D-8-1.

NONMANDATORY APPENDIX E
ELECTRICAL POWER VERIFICATION TESTS

E-1 PURPOSE

The purpose of this Nonmandatory Appendix is to specify test procedures for analyzing the electrical power supplied to a machine tool and its support equipment in the event that the electrical power is suspected of causing inadequate machine performance.

E-2 TEST EQUIPMENT

Although the parameters describing the electrical power supplied to a machine can be measured by a variety of instruments (voltmeters, oscilloscopes, etc.), it is the recommendation of this Standard that a power-line disturbance analyzer be used for these tests because of the excessive labor required when individual instruments are used. (The Dranetz-BMI series 2400 and the Dranetz Model 626-PA-600X are examples of acceptable power-line disturbance analyzers.) These units are designed to monitor a wide range of power-line disturbances and are capable of continuous, unattended operation. Typical measured parameters include sags, surges, impulses, and line frequency.

Sags are sudden voltage drops, which are detected by comparing the root mean square of each cycle to the steady state voltage. When the cycle-to-cycle level deviates by more than the preselected threshold, a sag is detected.

Surges are sudden voltage increases, which are normally detected using the same techniques as are used to detect sags. Again, a standard power-line monitor will note and record both the values of the surge and the time at which it occurred.

Impulses, in the technical language of power-line monitoring, refer to short-duration (approximately 1 μs to 1,000 μs) spikes superimposed upon the AC sine wave. Typically such impulses are measured as the amplitude of the spike alone with respect to the voltage level at the time the spike occurred, i.e., no subtraction or addition is made for the sinusoidal component.

Frequency changes in the line are also normally recorded by disturbance analyzers. Changes in frequency are self-explanatory.

E-3 METHOD

To ensure proper monitoring, the power supply to the machine should be monitored for a period that includes the normal cycle of machine tool operation. In the one-shift plant, this should include a complete shift. In the three-shift plant, complete 24-h monitoring is required. Additionally, care should be taken that the power-line monitoring occurs over a representative period that includes all normal or even intermittent electrical activity within the plant that could affect the machine. (As an obvious example, consider the case when arc welding is done only a few days a week at a location that uses the same feeder as the machine tool. In this case, the power-line monitoring should include a typical arc-welding sequence.)

For making these measurements, an approved, calibrated power-line monitor of the type discussed in section E-2 should be used. Appropriate thresholds (sag, surge, and impulse) should be set at the values corresponding to those levels set by the Supplier in the machine tool specification. Monitoring should continue for a sufficient period to ensure that all of the effects mentioned are included.

E-4 ANALYSIS

Typical power-line monitors provide printouts of both the levels and times at which deviations from the accepted thresholds occur. If the monitor is set with the thresholds described in section E-3, any such deviations recorded shall constitute nonconformance with the Supplier's specifications, and it shall be the responsibility of the User to correct such power-line defects. If no deviations from specifications occur, then it is the responsibility of the machine Supplier to correct the performance of the machine tool so that machine specifications are met.

NONMANDATORY APPENDIX F
MACHINE FUNCTIONAL TESTS

F-1 GENERAL

The tests described in this Nonmandatory Appendix are to verify machine functional specifications that are important but do not directly influence machine accuracy. Tests are given for feed rate, spindle speed (revolutions per minute), tool-change time, tool-setting-system measuring time, pallet-changing time, and axis- and turret-indexing time.

F-2 FEED RATE MEASUREMENTS

This test is intended to verify whether the machine tool axis moves at the commanded feed rate. Variations of actual feed rate from the commanded feed rate affect the quality of parts produced. Velocity profiles, which give an indication of the time required for the axis to reach the commanded feed rate (settling time), can be used to check the acceleration–deceleration settings and are useful for servo tuning and troubleshooting. Also, reduced settling time increases machine throughput. Dynamic measurements using a laser interferometer (used for measuring linear displacement accuracy) shall be used to measure the feed rate of machine tool motion.

F-2.1 Measurement Procedure

The lines of measurement for feed rate measurement should be the same as those for the positioning accuracy and repeatability, linear axes (para. 7.2). The laser shall be aligned as specified in para. 7.2. Two sets of bidirectional measurements shall be made for each axis, with the laser interferometer in the velocity mode. If the machine has ranges of feeds, measurements shall be taken at the center of the feed range for all feed ranges of the machine tool and at the specified rapid traverse rates. Otherwise, the measurements shall be performed at five steps over the total range of feed rates and at the specified rapid traverse rates. At each rate, for each axis, the average feed rate in the forward and reverse direction shall be recorded. The differences between the nominal feed rates and the measured feed rates, in both the forward and reverse directions, shall be within acceptable tolerance, as specified between the User and the Supplier.

F-3 SPINDLE RPM MEASUREMENT

This test is intended to verify that the spindle is running at the commanded (targeted) revolutions per minute. The spindle shall be run with no load at five different speeds equally spaced over its total speed range, and the number of revolutions per minute recorded using a strobe or other rpm indicator. (A spindle error analyzer can be used for this task; see para. 7.6.3.3). At each speed, a minimum of 100 revolutions shall be used to obtain the average revolutions per minute. The percent differences between the target revolutions per minute and the measured revolutions per minute shall then be reported for each of the five speeds. Differences as calculated using the following equation should be within the range specified in the original machine specification:

$$\text{spindle error speed (\%)} = \left(\frac{\text{measured spindle speed} - \text{target spindle speed}}{\text{target spindle speed}} \right) \times 100$$

F-4 TOOL-CHANGE TIME

This test is intended to measure the time it takes the machine tool to perform a tool-change operation.

F-4.1 Test Procedure

F-4.1.1 Equipment. A suitable timing device shall be used to measure the time it takes the machine tool to perform tool-change operations.

F-4.1.2 Test Location. The machine shall be positioned at the center of the work zone with the spindle stopped.

F-4.1.3 Measurement Procedure

Step 1. The machine shall be commanded to perform a tool change to pick up the nearest tool in the magazine and then return to the center of the work zone with that tool.

Step 2. This process shall be repeated 10 times.

Step 3. The average time period between the start of the machine motion from the center of the work zone and the return of the machine (after picking up the nearest tool) to the center of the work zone shall be reported as the minimum tool-change time.

Step 4. A similar procedure shall be repeated 10 times, with the machine moving from the center of the work zone to pick up the farthest tool and then returning back to the center of the work zone.

Step 5. The average time period between the start of the machine motion from the center of the work zone and the return of the machine (after picking up the farthest tool) to the center of the work zone shall be reported as the maximum tool-change time.

F-4.2 Data Analysis

Step 1 .The minimum tool-change time error shall be reported as the difference between the nominal minimum tool-change time and the measured minimum tool-change time.

Step 2. The maximum tool-change time error shall be reported as the difference between the nominal maximum tool-change time and the measured maximum tool-change time.

F-5 TOOL-SETTING-SYSTEM MEASUREMENT TIME

This test is applicable for machine tools with tool probes that are used to measure tool position (tool offsets). The machine shall be positioned at the center of the work zone. A program shall be written that will require the machine to perform a tool change, pick up the nearest tool in the tool magazine, and then perform a tool offset measurement using a tool-setting system and return back to the center of the work zone. This process shall be repeated 10 times. The average time period between the start of machine motion from the center of the work zone and the end of machine motion at the center of the work zone shall be reported as the tool-setting-system measurement time. The difference between the specified tool-setting-system measurement time and the measured tool-setting-system measurement time shall be within the specification agreed upon between the User and the Supplier.

F-6 PALLET-CHANGE TIME

The machine shall be positioned so that the tool is at the center of the work zone. A program shall be written to command the machine to perform a pallet change, loading the nearest pallet in the pallet-loading station into the machine and then returning the tool to the center of the work zone. This process shall be repeated 10 times. The average time period between the start of machine motion in the center of the work zone and the end of machine motion in the center of the work zone shall be reported as the pallet-change time. The difference between the specified pallet-change time and the measured pallet-change time shall be within the specification agreed upon between the User and the Supplier.

F-7 TURRET-INDEXING TIME

This test is applicable only for machines that have indexing turrets. The turret shall be positioned to the first tool position. The turret shall then be commanded to move to 10 additional, adjacent turret positions. The average time period taken by the turret to move to the 10 positions shall be reported as the turret-indexing time (total time for 10 indexes divided by 10). The differences between the actual turret-indexing time and the specified turret-indexing time shall be within the specification agreed upon between the User and the Supplier. This test should be performed for all turrets.

NONMANDATORY APPENDIX G MACHINE LEVELING AND ALIGNMENT

G-1 MACHINE LEVELING

Most machine tools do not have to be leveled. Absolute leveling is one method, and often a convenient method, for achieving straightness of travel. It is rarely a requirement, however. Many methods are now available for measuring straightness, squareness, and parallelism that are faster and better. The use of electronic levels for measuring the change in level, such as the pitch or roll, is, on the other hand, an important technique in modern machine tool metrology. Installation procedures that require absolute leveling should be questioned.

G-2 DISTRIBUTION OF LOADING ON MULTIPOINT-SUPPORTED MACHINES

Uniform distribution of loading on multipoint-supported machines is rarely a requirement. Such machines are generally mounted on a thick foundation block with adjustable wedges at each point of support. These wedges normally have a hole in their center to accommodate a grouted-in hold-down bolt to hold the machine down to the block. These wedges and hold-down bolts are adjusted "push-pull" to achieve the correct machine geometry. In so doing, the forces between the blocks and the machine may vary from point to point. Optimizing machine geometry should always be the goal. For machines of this type, the User should work closely with the machine Supplier to ensure the foundation is adequate for the machine. The Supplier's recommendations regarding machine alignment should be followed. If such procedures are followed, then the Supplier has sole responsibility for meeting the functional specifications of the machine, derated as appropriate for thermal effects and excessive relative vibration (see section 6).

NONMANDATORY APPENDIX H
COMPLIANCE AND HYSTERESIS CHECKS

H-1 GENERAL

The compliance and hysteresis test is designed to estimate machine compliance and hysteresis when a static load is applied between the tool and the workpiece. It provides a simplified indication of what more rigorous compliance testing would measure. Compliance values vary as functions of the position of the machine tool axes. The linear compliance is measured near the center of the work zone at a point defined by the Supplier and is measured for each linear positioning axis.[1] In general, the Supplier should specify the maximum load and provide appropriate fixturing.[2]

If a load is not specified, suggested values are given in Table H-1-1.

Two test procedures are included in this Nonmandatory Appendix for measurement of compliance and machine hysteresis. The first method (see section H-2,) is the preferred method. The situations in which the alternate method (see section H-3) may be appropriate are described in para. H-3.1. It must be emphasized that the alternate method should be considered only for machines with scale feedback.

WARNING: The suggested loads given in Table H-1-1 do not apply to spindles with a maximum speed of more than 10 000 rpm. In the case where such spindles are supplied, the User shall negotiate appropriate compliance and machine hysteresis tests with the Supplier.

H-2 MACHINE COMPLIANCE AND HYSTERESIS TEST

H-2.1 Test Setup

A typical setup for horizontal-lathe Z direction is shown in Fig. H-2.1-1. A displacement sensor such as an electronic indicator, dial gage, or laser interferometer is set to read the relative motion between the tool holder and the table along the linear axis. A load cell is aligned with the machine axis to be tested and rigidly fixtured between the machine table and the spindle. The setup should be such that the load cell will function under tension and compression. If the machine has backlash compensation, this test is conducted with the backlash compensation on.

H-2.2 Test Procedure

H-2.2.1 Equipment. The following equipment shall be used:

(a) displacement indicator
(b) force gage (load cell)

H-2.2.2 Machine Warm-Up. No warm-up condition is required.

H-2.2.3 Test Location. The machine axes shall be positioned in the center of their respective ranges.

H-2.2.4 Measurement Procedure[3]

Step 1. Zero the indicator at the beginning of each test.

Step 2. Move the machine axis under test in small increments until the maximum force specified or a maximum deflection[4] of 250 μm (approximately 0.01 in.) has been reached. Call this the positive direction.

Step 3. Record the command position, actual position, and force.

Step 4. Jog the axis in the opposite (negative) direction until the force drops to 1% of the maximum force (positive preload).

Step 5. Record the command position, actual position, and force.

Step 6. Continue jogging in the same (negative) direction until the force (or deflection) reaches its maximum value.

Step 7. Record the command position, actual position, and force.

Step 8. Jog the axis back in the plus direction until the force drops to 1% of the maximum force (negative preload).

Step 9. Record the command position, actual position, and force.

Step 10. Recording at additional points is recommended but not required.

[1] Users desiring to measure compliance and hysteresis for rotary positioning axes are referred to ANSI B5.54.

[2] Since the loads applied are large, appropriately tested and Supplier-approved fixturing is essential for the safety of personnel and the machine.

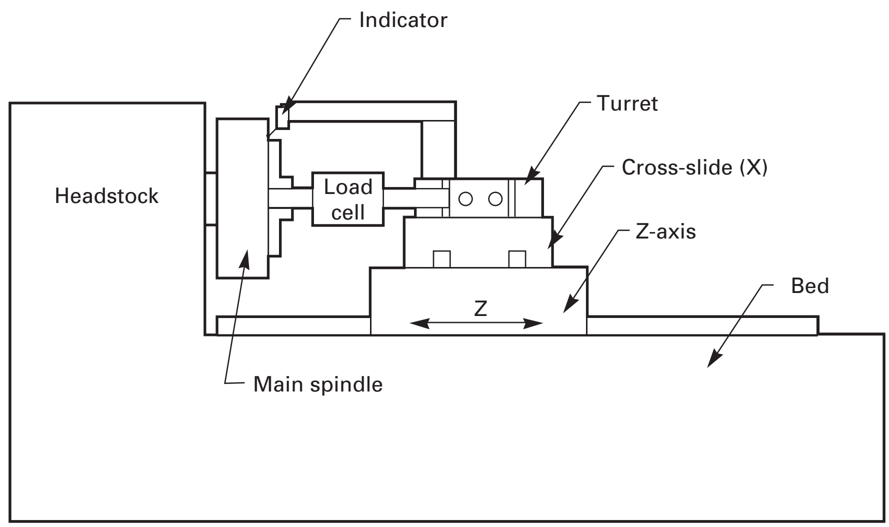
[3] Performing the test in this fashion removes any effects due to clearance in the test fixtures or deflections of the load cell.

[4] The deflection is defined as the difference between the actual position and the command position.

Table H-1-1 Suggested Maximum Loads for the Compliance and Machine Hysteresis Test

Spindle Torque, N·m	Force, N
20	1 100 (approximately 250 lb)
50	2 200 (approximately 500 lb)
100	4 500 (approximately 1,000 lb)
150	6 650 (approximately 1,500 lb)
200	8 900 (approximately 2,000 lb)
250 (and greater, at 600 rpm)	8 900 (approximately 2,000 lb)

Fig. H-2.1-1 Setup for Measuring the Compliance and Machine Hysteresis in the Z Direction



H-2.3 Data Analysis

To evaluate machine compliance and hysteresis, the deflection (actual position minus command position) at each of the measurement points is computed. The compliance in the direction of the axis is computed as the total range of the deflections divided by the total range of force (expressed as newton millimeters or inch-pounds). The machine hysteresis for the axis is computed as the range of deflection between the positive preload and negative preload points (expressed as millimeters or inches). The values to be used for these computations are indicated in Fig. H-2.3-1.

H-3 ALTERNATE MACHINE COMPLIANCE AND HYSTERESIS TEST: LINEAR AXES

H-3.1 Scope

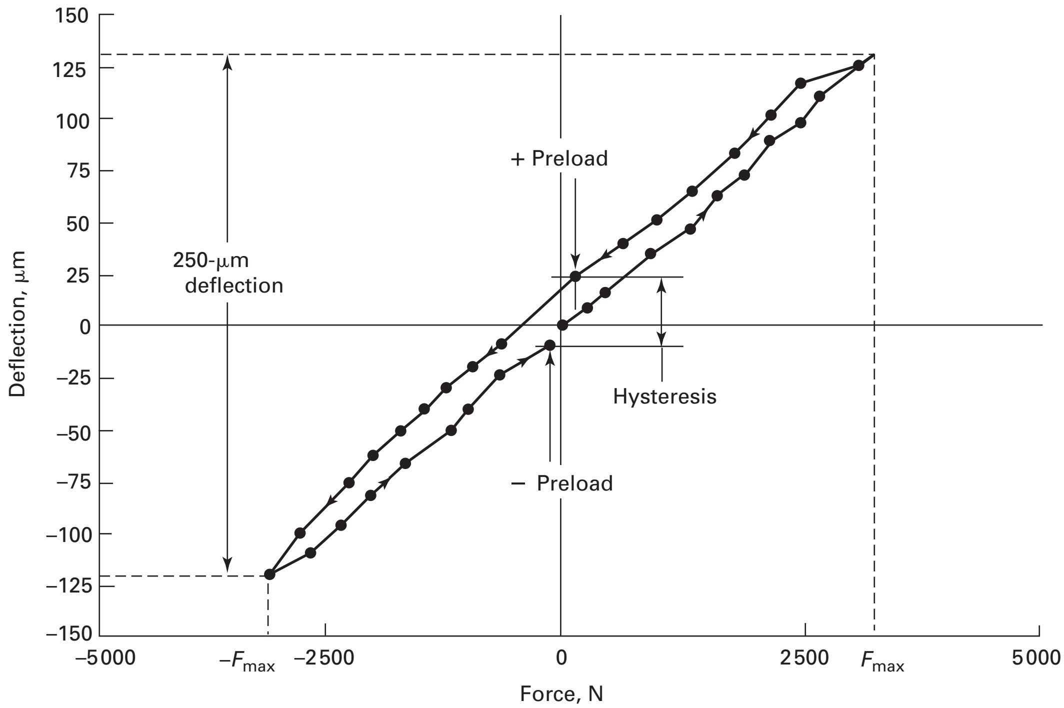
The alternate compliance and machine hysteresis test procedure may produce different results compared to those obtained following the primary procedure. For machine axes with rotary encoder feedback, the compliance and hysteresis values computed will probably be less. Thus, the machine performance will be overestimated using the alternate method. For machine axes with scale feedback, the alternate test procedure will likely produce similar results compared with the primary method for both compliance and hysteresis. In this case, the alternate method may be preferred as it generally requires less range on the displacement indicator. Therefore, it allows the use of a higher-resolution displacement indicator. In addition, the resolution of the machine display does not affect the resolution of the measurement.

H-3.2 Test Procedure

H-3.2.1 Equipment. The following equipment shall be used:

(a) displacement indicator
(b) force gage (load cell)
(c) linear actuator (e.g., differential screw, hydraulic jack)

Fig. H-2.3-1 Typical Plot Showing Results of a Compliance and Axis Hysteresis Test



H-3.2.2 Machine Warm-Up. No warm-up condition is required.

H-3.2.3 Test Location. The machine axes shall be positioned in the center of their respective ranges for this test.

H-3.2.4 Measurement Procedure

Step 1. Connect the linear actuator and the force gage in series between the spindle and the worktable.

Step 2. Set up the displacement indicator to record relative displacement between the spindle and the worktable.

CAUTION: Place the displacement indicator as near as possible to the point of force to minimize the effects of tilt errors.

Step 3. Create a zero-force condition with the linear actuator.

Step 4. Set zero on the displacement indicator.

Step 5. Operate the actuator to achieve the maximum test load [or a maximum deflection of 250 μm (approximately 0.01 in.)]. Call this the positive direction.

Step 6. Record the force and displacement.

Step 7. Operate the actuator in the opposite direction until the force drops to 1% of the maximum force (positive preload).

Step 8. Record the force and displacement.

Step 9. Continue operating the actuator in the same (negative) direction until the force (or deflection) reaches its maximum value.

Step 10. Record the force and displacement.

Step 11. Operate the actuator in the opposite (positive) direction until the force drops to 1% of the maximum force (negative preload).

Step 12. Record the force and displacement.

Step 13. Repeat the measurement procedure for each axis direction.

H-3.3 Data Analysis

The compliance for each axis shall be reported as the total range of recorded displacements divided by the total range of recorded forces. The machine hysteresis for each axis shall be computed as the range of measured displacements between the positive preload and negative preload points [expressed as micrometers (μm) or micro inches (μin.)].

NONMANDATORY APPENDIX I
LASER AND SCALE CORRECTIONS

I-1 LASER AND SCALE CORRECTIONS

If the laser interferometer used has environmental compensation features, the instrument manufacturer's recommendations regarding the use of these accessories shall be followed, with the material sensor placed on the appropriate machine scale or at some other position known to yield a measurement of the average scale temperature. Here the scale can be a lead screw, a ball screw, a linear scale, or an inductive scale. It is a requirement of this Standard that independent calibration of the temperature and pressure sensors of such compensation devices be performed on a regular basis (see section 9).

If the corrections are to be performed manually, they shall be computed according to the following equation for an uncorrected laser display reading:[1]

$$CLR = LDR\,\{1 + [7.86 \times 10^{-4}\,P_s/(T_s + 273)] - 1.5 \times 10^{-11}\,RH\,(T_s^2 + 160)\}$$

where

CLR = corrected laser reading
LDR = laser display reading
P_s = air pressure, kPa
RH = relative humidity of air, %
T_s = mean air temperature, °C

NOTE: The partial pressure of water vapor can be calculated from the relative humidity by multiplying the saturated vapor pressure at a particular temperature by the relative humidity expressed as a fraction. The saturated vapor pressure at 20°C (68°F) is 17.6 mm Hg (approximately 0.34 psi). Thus, for example, 50% relative humidity at 20°C would yield a partial pressure of 0.5 × 17.6 = 8.8 mm Hg (approximately 0.17 psi).

To compare the corrected laser reading to the machine readings, the machine readings must also be corrected for temperature. The corrected machine readings are given by

$$CMR = MDR[1 + \alpha(T - 20)]$$

where

CMR = corrected machine reading
MDR = machine display reading
T = scale temperature, °C, during measurements, in the case where the machine was set up at 20°C (68°F)
α = effective thermal expansion coefficient of machine scales

[1] This form of equation also assumes atmospheric air with the normal mixture of gases. Atmospheres that deviate significantly, particularly in regard to carbon dioxide and aromatic hydrocarbon concentration, have been observed and can lead to measurable errors. If this situation is suspected, appropriate corrections should be applied.

NONMANDATORY APPENDIX J
DRIFT CHECKS FOR SENSORS, INCLUDING LASERS

J-1 GENERAL

Many tests in this Standard involve the use of displacement sensors over long periods of time. These include the *ETVE* test (para. 6.2.1), the spindle thermal stability test (para. 7.7.2), thermal distortion caused by moving linear axes (para. 7.7.3), and the composite thermal error test (para. 7.7.4). Three of these tests require the use of short-range indicators, and one of these tests (thermal distortion caused by moving linear axes) requires the use of a laser interferometer. For the results of these tests to be most meaningful, the User should perform a stability test on the sensor before using it for the measurement. Such stability tests have traditionally been called "cap" tests. Two such tests are described in paras. J-1.1 and J-1.2.

J-1.1 Drift Check for Short-Range Electronic or Short-Range Displacement Indicators

Aside from the usual calibration checks, short-range displacement indicators should be checked for possible sensitivity to a thermal environment in which the test is to be performed. A drift check should be conducted by blocking the transducer and recording the output for at least the same period of time as the test to be performed using the indicator. "Blocking" a transducer is used to make it effectively indicate on its own frame base or cartridge. Figure J-1.1-1 shows a cartridge-type linear variable differential transformer (LVDT) blocked by means of a cap or capture device that holds the indicator armature in a fixed position relative to the cartridge. The figure also shows a similar clamp on a finger-type electronic indicator and on a capacitance gage.

During the electronics drift check, the entire displacement recording system should be located as close as possible to where it will be used during machine testing. Electronic drift tests have been useful in proving that in many cases where electronic indicators have been a suspected source of drift, the real cause was thermal drift.

J-1.2 Drift Check for Laser Interferometer Optics

Some optical systems have excessive drift apparently caused by thermal instabilities in the optic mounts and mismatched glass paths. The exact cause of these effects is not known, but experiments have shown that, for precision applications, the drifts inherent in the laser interferometer optics should be measured. To perform this drift check, the two retroreflectors are rigidly mounted to the remote interferometer as shown in Fig. J-1.2-1. The laser is then aligned with this interferometer and adjusted for maximum signal strength. The laser is zeroed and the drift of the system recorded over periods of time similar to those used for the *ETVE* test (para. 6.2.1). If the drift is excessive for the application, then the laser interferometer Supplier should be contacted and the situation rectified.

J-1.3 Drift Check for Laser Interferometer Systems

When used for displacement measurement, a laser interferometer can have several sources of drift: first, drift in the laser frequency; second, thermal drifts in the interferometer optics and mounting; and finally, drifts caused by incorrect calibration of the laser system temperature and pressure sensors. In this Nonmandatory Appendix, two simple tests are proposed to check the drift of most system components. In the first test, the laser is set up to read with a remote interferometer, as shown in Fig. J-1.3-1. The spacer between the interferometer and the retroreflector is made of steel, and the laser system temperature and pressure sensors placed as close as possible to the steel path. The steel spacer should contain holes to allow the free flow of ambient air and be at least 200 mm (approximately 8 in.) long. The temperature and pressure compensation of the laser is set, the part temperature sensor attached to the steel spacer, and the laser interferometer preset to the nominal length of the spacer. The appropriate expansion coefficient for the spacer shall be entered into the laser interferometer system.[1] The drift of the system is then measured over a period of time corresponding to the time of the proposed test (4 h for the thermal distortion caused by the moving linear axes test). The drift of the system should be less than one-fourth of the repeatability for unidirectional positioning, linear axes. If the drift is larger, then the laser system or its supporting sensors, or both, should be repaired.

The second test is to be used for those laser systems where the interferometer is an inseparable part of the laser head. In these cases, the laser and the retroreflector or sensor assembly are set up on, and rigidly attached to, a steel plate. The steel plate should be at least 25-mm

[1] The Supplier of the steel spacer shall provide an accurate measurement of its nominal length and its thermal expansion coefficient.

Fig. J-1.1-1 Capture Devices for Several Types of Displacement Indicators

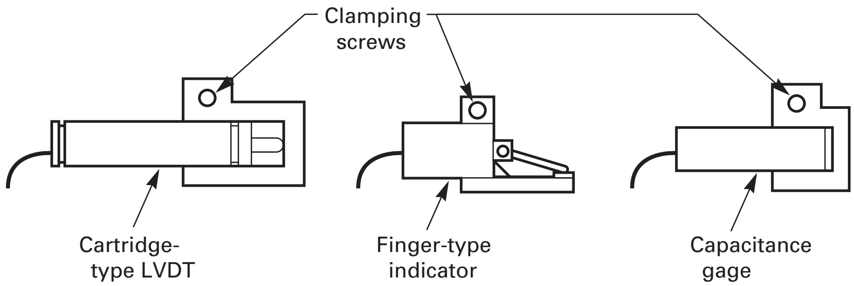
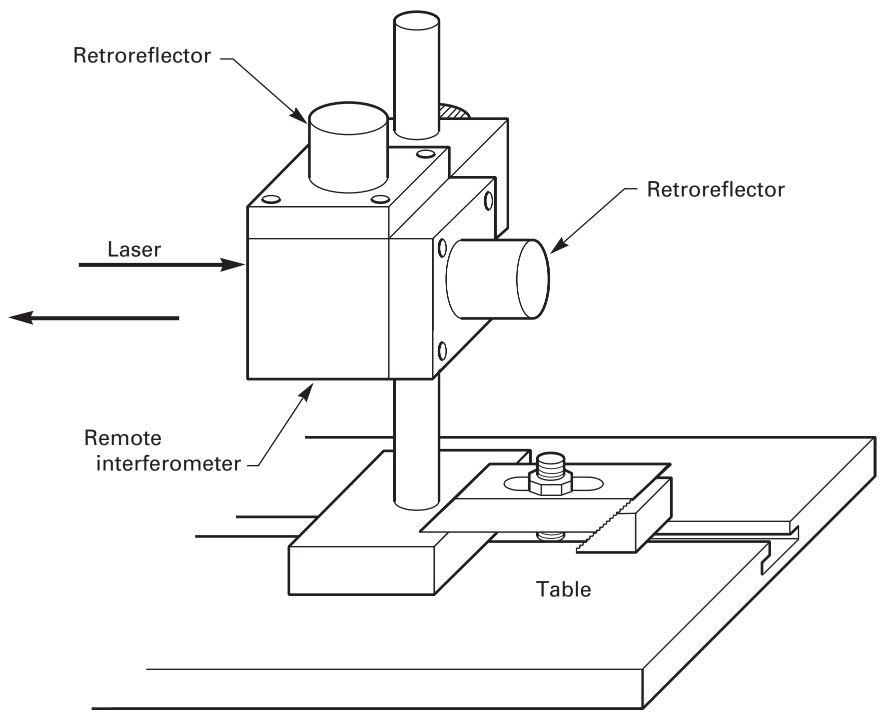
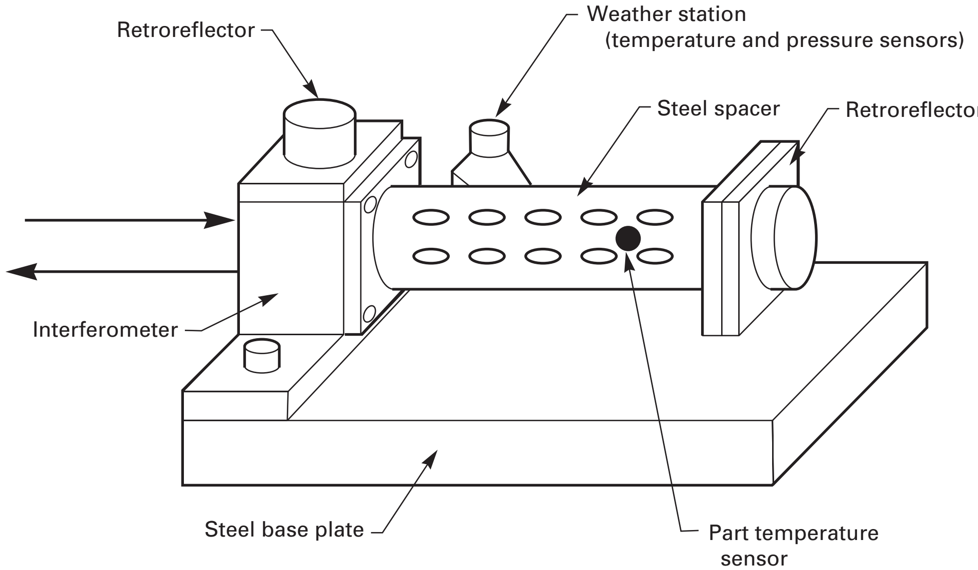


Fig. J-1.2-1 Proposed Setup for Measuring the Drift of the Laser Interferometer Optics



(approximately 1-in.) thick and mounted at three points. The face of the laser should be at least 200 mm (approximately 8 in.) from the retroreflector or sensor assembly. The environmental sensors should be placed as close as is possible to the laser beam path and the test conducted as described in the preceding paragraph. The drift of the system should be less than one-fourth of the repeatability for unidirectional positioning, linear axes. If the drift is larger, then the laser system or its supporting sensors, or both, should be repaired.

Fig. J-1.3-1 Proposed Setup for Measuring the Stability of the Laser Measurement System



NONMANDATORY APPENDIX K
THE PART-TRACE TEST

K-1 GENERAL

The part-trace test procedure consists of cutting a part and then replacing the tool with an appropriate displacement transducer[1] and repeating the original tool path, but with the spindle off. Readings from the transducer are recorded as the part is "traced." The part-trace test is a simple method for separating the errors introduced by machine geometry from those introduced by process variables such as tool wear, tool roundness and size errors, cutting-force deflection, hard spots in the material, thermal errors such as spindle growth, angular thermal drift of the C-axis average line, expansion of the tool holder toward the work, expansion of the work toward the tool, runout of the workpiece caused by radiation from the room lights when the spindle is stopped, and control system dynamic errors. If two-axis contour cuts are to be measured, it is necessary to use a round stylus having the same radius as the tool.

[1] LVDTs are preferred over optical and capacitance indicators for part-trace test purposes because LVDT transducers are not affected by coolant. They work equally well wet or dry. Air-bearing LVDTs are preferred over plain bearing LVDTs because their low stylus forces and absence of sliding friction avoid scratching of the work surface.

NONMANDATORY APPENDIX L
DISCUSSION OF THE *UNDE* AND THERMAL UNCERTAINTY

L-1 GENERAL

When calibration or measurement is performed at temperatures other than 20°C (68°F), nominal differential expansion (*NDE*) corrections must be made if the object to be calibrated or measured and the standard have different coefficients of thermal expansion. As defined in section 4, Definitions

$$NDE = \alpha L(T - 20) - \alpha_s L_s(T_s - 20) \qquad \text{(L-1)}$$

The variables are defined in section 3. The first term applies to the object being calibrated or measured. The second term applies to the standard. For laser calibration of a machine axis, the first term applies to the machine scale, while the second term applies to the laser. For on-machine part measurement using a probe, the first term applies to the part and the machine scale is the standard.

To estimate the uncertainty in making *NDE* correction, the ISO/IEC Guide to the Expression of Uncertainty in Measurement (1995) is used. The uncertainty depends on the uncertainty in each of the variables of eq. (L-1). It also depends on the sensitivity of the *NDE* result to variation in each variable. For the purposes of this Nonmandatory Appendix, it is assumed that no correlation exists between variations in individual variables. Therefore, four terms come directly from the uncertainty analysis.

$L\alpha u(T)_{\text{eff}}$ = length uncertainty due to uncertainty in temperature of the object being calibrated or measured

$L_s\alpha_s u(T_s)_{\text{eff}}$ = length uncertainty due to uncertainty in temperature of the standard

$L_s(T_s - 20)u(\alpha_s)$ = uncertainty of nominal expansion of the standard (L-2)

$L(T - 20)u(\alpha)$ = uncertainty of nominal expansion of the object being calibrated or measured (L-3)

The subscript "eff" is used to indicate that this term contains not only the uncertainty in temperature measurement but also the range of temperatures that probably occurred during a test or measurement. One component of this uncertainty is related to the accuracy of temperature measurement. This is the length uncertainty due to temperature measurement (see section 4, Definitions). The second component is related to the effective scale temperature due to time and positioning-varying temperature gradients and their effect on the machine geometry and scales. For the purposes of this Nonmandatory Appendix, this second component is represented as a rectangular distribution with bounds $\pm(ETVE/2)/(L\alpha)$ for machine calibration, or $\pm(ETVE/2)/(L_s\alpha_s)$ when the machine is used as the measurement standard. Therefore, for calibration of a machine axis

$$u^2(T)_{\text{eff}} = \left[\frac{ETVE/2}{L\alpha\sqrt{3}}\right]^2 + u^2(T)$$

and

$$u^2(T_s)_{\text{eff}} = u^2(T_s)$$

For use of the machine as the measurement standard

$$u^2(T)_{\text{eff}} = u^2(T)$$

and

$$u^2(T_s)_{\text{eff}} = \left[\frac{ETVE/2}{L_s\alpha_s\sqrt{3}}\right]^2 + u^2(T_s)$$

In either case, the combined standard thermal uncertainty is written as

$$u^2_{cT}(L) = L^2(T - 20)^2u^2(\alpha) + L_s^2(T_s - 20)^2u^2(\alpha_s) + L^2\alpha^2u^2(T) + L_s^2\alpha_s^2u^2(T_s) + u^2_{ETVE}$$

where $u^2_{ETVE} = ETVE^2/12$ arises from either eq. (L-2) or (L-3).

The combined standard thermal uncertainty is used to derate performance specifications (section 6) or to calculate a thermal error index (TEI) for any situation where *NDE* correction applies. The examples in sections L-2 and L-3 demonstrate the calculation procedure.

L-2 CALCULATION OF EXPANDED THERMAL UNCERTAINTY FOR PURPOSES OF DERATING PERFORMANCE SPECIFICATIONS

The following calculations are meant to be representative of a measurement of positioning accuracy and repeatability, linear axes (para. 7.2). The specification zone is for the bidirectional accuracy of positioning, *A*.

Performance parameter: bidirectional accuracy of positioning

Specified accuracy: 33 μm/m (FIR)

Axis length: 1 016 mm

Measurement devices:

- laser interferometer (displacement)
- thermocouples (temperature of air and material)

Mean temperature: 26°C

ETVE: 33 μm

Coefficient of thermal expansion of the machine scale, α:

$$11.7 \times 10^{-6}/°C$$

Coefficient of thermal expansion of the laser, α_s:

$$0.93 \times 10^{-6}/°C$$

Specification zone

$$\begin{aligned} SZ &= 33\ \mu m/m\ (1.016\ m) \\ &= 33.5\ \mu m \end{aligned}$$

Standard uncertainty due to *ETVE* (para. 6.2.1)

$$\begin{aligned} u^2_{ETVE} &= ETVE^2/12 \\ &= 90.75\ \mu m^2 \end{aligned}$$

Uncertainty of nominal expansion of the machine scale [para. 6.2.2.2, method (c)]

$$\begin{aligned} u(\alpha) &= 0.1\ \alpha\sqrt{1/3} \\ &= 6.75 \times 10^{-7}/°C \end{aligned}$$

$$u^2(\alpha) = 4.56 \times 10^{-13}/°C^2$$

$$\begin{aligned} (UNE)^2 &= L^2(T - 20)^2u^2(\alpha) \\ &= (1\,016\ mm)^2(26°C - 20°C)^2 \\ &\quad (4.56 \times 10^{-13}/°C^2)(10^3 \mu m/mm)^2 \end{aligned}$$

Uncertainty of nominal expansion of the standard (para. 6.2.2.2; i.e., laser)

$$u(\alpha_s) = 0$$

$$(UNE)^2_s = L_s^2(T_s - 20)^2u^2(\alpha_s) = 0$$

Length uncertainty due to temperature measurement (para. 6.2.2.3)

$$\begin{aligned} u^2(T) &= [1 - (-1)]^2/12°C^2 \\ &= ⅓\ °C^2 \end{aligned}$$

$$\begin{aligned} u^2(T_s) &= [1 - (-1)]^2/12°C^2 \\ &= ⅓\ °C^2 \end{aligned}$$

$$\begin{aligned} LUTM^2 &= L^2\alpha^2u^2(T) + L_s^2\alpha_s^2u^2(T_s) \\ &= (1\,016\ mm)^2(11.7 \times 10^{-6}/°C)^2 \\ &\quad ⅓\ °C^2(10^3 \mu m/mm)^2 \\ &\quad + (1\,016\ mm)^2(0.93 \times 10^{-6}/°C)^2 \\ &\quad ⅓\ °C^2(10^3 \mu m/mm)^2 \\ &= 47.1\ \mu m^2 + 0.30\ \mu m^2 \\ &= 47.4\ \mu m^2 \end{aligned}$$

Combined standard thermal uncertainty (para. 6.2.2.1)

$$\begin{aligned} u^2_{cT}(L) &= u^2_{ETVE} + (UNE)^2 + (UNE_s)^2 + LUTM^2 \\ &= 90.8\ \mu m^2 + 16.9\ \mu m^2 + 0.00 + 47.4\ \mu m^2 \\ &= 155\ \mu m^2 \end{aligned}$$

$$u_{cT}(L) = 12.5\ \mu m$$

Expanded thermal uncertainty (para. 6.2.2)

$$\begin{aligned} U_T(L) &= 2u_{cT}(L) \\ &= 24.9\ \mu m \end{aligned}$$

Derating of specified parameter (para. 6.2.2)

$$U_T(L)/SZ = 24.9\ \mu m/33.5\ \mu m > 0.25$$

Because this ratio is greater than 0.25, a new acceptable limit must be specified.

$$\begin{aligned} SZ^* &= U_T(L)/0.25 \\ &= 100\ \mu m\ (FIR) \\ &= 100\ \mu m/1.016\ m \\ &= 98\ \mu m/m \end{aligned}$$

L-3 EXAMPLE CALCULATIONS WHEN A MACHINE IS BEING USED FOR PART MEASUREMENT

Two examples that apply to the use of a machine tool for measurement of parts are given in this section. The first is in metric units, and the second is in U.S. Customary units, for those who prefer that system. While many other errors may affect the measurement results, the TEI is calculated to estimate the expected measurement error due to thermal effects alone. In both these cases, a part tolerance, *TOL*, is substituted for the specification zone, *SZ*.

L-3.1 Example Calculation With *NDE* Correction

In this example, an aluminum part is measured on a machine with steel scales. The measurement conditions are summarized in Table L-3.1-1.

Standard uncertainty due to *ETVE* (para. 6.2.1)

$$\begin{aligned} u^2_{ETVE} &= ETVE^2/12 \\ &= (3.8 \times 10^{-5}\ m)^2/12 \\ &= 1.20 \times 10^{-10}\ m^2 \end{aligned}$$

Uncertainty of nominal expansion of the part [para. 6.2.2.2, method (b)]

Table L-3.1-1 Calculation of *TEI* for the Case When *NDE* Correction Is Made

Dimension = 4.0 m	*NDE* Correction [Note (1)]	T_{min} = 21.1°C
TOL = 0.25 mm	Material: aluminum 6061-T6	T_{max} = 23.3°C
α = 24.3 μm/m °C [Note (2)]	Temperature measurement accuracy = ±0.5°C	T_m = 22°C
α_s = 11.7 μm/m °C [Note (2)]		*ETVE* = 38 μm

NOTES:
(1) Standard and part temperatures are both measured as 22°C.
(2) These values are obtained from published data and may be in error by ±5%.

Table L-3.2-1 Calculation of *TEI* for the Case When *NDE* Correction Is Not Made

Dimension = 20 in.	No *NDE* correction	T_{min} = 70°F (measured)
Tolerance = 0.002 in.	Material: Ti 6-4	T_{max} = 78°F (measured)
α = 4.8 μin./in. °F [Note (1)]	Temperature measurement accuracy = ±1°F	T_m = 74°F (measured)
α_s = 6.5 μin./in. °F [Note (1)]		*ETVE* = 0.0003 in.

NOTE:
(1) These values are obtained from published data and may be in error by ±5%.

$$u(\alpha) = 0.05\,\alpha\sqrt{1/3}$$

$$u^2(\alpha) = (0.05)^2(24.3 \times 10^{-6})/°\text{C})^2\,(1/3)$$

$$\begin{aligned}(UNE)^2 &= L^2(T-20)^2u^2(\alpha)\\ &= (4\text{ m})^2(22°\text{C} - 20°\text{C})^2(0.05)^2\\ &\quad (24.3 \times 10^{-6}/°\text{C})^2\,(1/3)\\ &= 3.15 \times 10^{-11}\text{ m}^2\end{aligned}$$

Uncertainty of nominal expansion of the standard [para. 6.2.2.2, method (b); i.e., machine]

$$u(\alpha_s) = 0.05\,\alpha_s\sqrt{1/3}$$

$$u^2(\alpha_s) = (0.05)^2(11.7 \times 10^{-6}/°\text{C})^2\,(1/3)$$

$$\begin{aligned}(UNE_s)^2 &= L_s^{\,2}(T_s - 20)^2u^2(\alpha_s)\\ &= (4\text{ m})^2(22°\text{C} - 20°\text{C})^2(0.05)^2\\ &\quad (11.7 \times 10^{-6}/°\text{C})^2\,(1/3)\\ &= 7.30 \times 10^{-12}\text{ m}^2\end{aligned}$$

Note that the mean air temperature is used for both T and T_s in the equations used to calculate uncertainty of nominal expansion of part and of machine scale, respectively.

Length uncertainty due to temperature measurement (para. 6.2.2.3)

$$\begin{aligned}u^2(T) &= [1 - (-1)]^2/12°\text{C}^2\\ &= 1/3\,°\text{C}^2\end{aligned}$$

$$\begin{aligned}u^2(T_s) &= [1 - (-1)]^2/12°\text{C}^2\\ &= 1/3\,°\text{C}^2\end{aligned}$$

$$\begin{aligned}LUTM^2 &= L^2\alpha^2u^2(T) + L_s^{\,2}\alpha_s^{\,2}u^2(T_s)\\ &= (4\text{ m})^2(24.3 \times 10^{-6}/°\text{C})^2\,1/3\,°\text{C}^2\\ &\quad + (4\text{ m})^2(11.7 \times 10^{-6}/°\text{C})^2\,1/3°\text{C}^2\\ &= 3.87 \times 10^{-9}\text{ m}^2\end{aligned}$$

Combined standard thermal uncertainty (para. 6.2.2.1)

$$u_{cT}^2(L) = u_{ETVE}^2 + (UNE)^2 + (UNE)_s^2 + LUTM^2$$

$$\begin{aligned}u_{cT}(L) &= \sqrt{\begin{array}{l}1.20 \times 10^{-10}\text{m}^2 + 3.15\times10^{-11}\text{m}^2 + 7.30\times10^{-12}\text{m}^2\\ + 3.87 \times 10^{-9}\text{m}^2\end{array}}\\ &= 0.063\text{ mm}\end{aligned}$$

Expanded thermal uncertainty (para. 6.2.2)

$$\begin{aligned}U_T(L) &= 2u_{cT}(L)\\ &= 0.127\text{ mm}\end{aligned}$$

For the purposes of calculating the *TEI*, *NDE* is taken as zero when *NDE* corrections are made. There is no contribution to the estimated thermal error.

$$NDE = 0.00$$

Thermal error index

$$\begin{aligned}TEI &= \{[|NDE| + U_T(L)]/TOL\}(100\%)\\ &= (0.00 + 0.127\text{ mm}/0.25\text{ mm})(100\%)\\ &= 51\%\end{aligned}$$

L-3.2 Example Calculation Without *NDE* Correction

The second example of part measurement deals with measurement of a titanium part on a machine with steel scales, where the nominal differential expansion correction is not made. Measurement conditions are summarized in Table L-3.2-1. U.S. Customary units are used throughout.

Standard uncertainty due to *ETVE* (para. 6.2.1)

$$u^2_{ETVE} = ETVE^2/12$$
$$= (0.0003\ \text{in})^2/12$$
$$= 7.50 \times 10^{-9}\ \text{in.}^2$$

Uncertainty of nominal expansion of the part [para. 6.2.2.2, method (b)]

$$u(\alpha) = 0.05\ \alpha\sqrt{1/3}$$

$$u^2(\alpha) = (0.05)^2(4.8 \times 10^{-6}\ \text{in./in.°F})^2(1/3)$$

$$(UNE)^2 = L^2(T - 68)^2\ u^2(\alpha)$$
$$= (20\ \text{in.})^2(75°\text{F} - 68°\text{F})^2(0.05)^2$$
$$(4.8 \times 10^{-6}\ \text{in./in.°F})^2\ (1/3)$$
$$= 2.76 \times 10^{-10}\ \text{in.}^2$$

Uncertainty of nominal expansion of the standard [para. 6.2.2.2, method (b); i.e., machine]

$$u(\alpha_s) = 0.05\ \alpha_s\sqrt{1/3}$$

$$u^2(\alpha_s) = (0.05)^2(6.5 \times 10^{-6}\ \text{in./in.°F})^2(1/3)$$

$$(UNE)_s^{\ 2} = L_s^{\ 2}(T_s - 68)^2 u^2(\alpha_s)$$
$$= (20\ \text{in.})^2(74°\text{F} - 68°\text{F})^2(0.05)^2$$
$$(6.5 \times 10^{-6}\ \text{in./in.°F})^2(1/3)$$
$$= 5.07 \times 10^{-10}\ \text{in.}^2$$

Length uncertainty due to temperature measurement (para. 6.2.2.3)

LUTM cannot be calculated directly (see below).

When *NDE* correction is not made, the uncertainty related to temperature in eq. (L-1) depends on variations in the air temperature. Temperature measurement accuracies of part and machine are not relevant because these measurements are not made. The uncertainty of environmental temperature is introduced.

$$u(T_e) = ½(T_{\max} - T_{\min} + 2a)\sqrt{1/3}$$

where it is assumed that the machine and part temperatures at any time can be expected to have rectangular probability distributions with bounds ≥ ($T_{\max} - T_{\min} + 2a$). Variables are defined as

a = accuracy of air-temperature measurement
$T_{\max}$ = maximum air temperature measured over specified period of time
$T_{\min}$ = minimum air temperature measured over specified period of time

The variations in temperatures, T and T_s, are expected to be correlated under these assumptions, leading to the equation for *LUTM*, which includes the difference between scale and part expansion coefficients.

$$LUTM^2 = (1/12)(T_{\max} - T_{\min} + 2a)^2(L)^2(\alpha_s - \alpha)^2$$
$$= (1/12)(78 - 70 + 2)^2(°\text{F})^2(20\ \text{in.})^2(4.8$$
$$- 6.5)^2(\mu\text{in./in.°F})^2$$
$$= 9.63 \times 10^{-9}\ \text{in.}^2$$

Combined standard thermal uncertainty (para. 6.2.2.1)

$$u^2_{cT}(L) = u^2_{ETVE} + (UNE)^2 + (UNE)_s^{\ 2} + LUTM^2$$

$$u_{cT}(L) = \sqrt{7.50 \times 10^{-9}\text{in.}^2 + 2.76 \times 10^{-10}\text{in.}^2 + 5.07 \times 10^{-10}\text{in.}^2 + 9.63 \times 10^{-9}\text{in.}^2}$$
$$= 0.00013\ \text{in.}$$

Expanded thermal uncertainty (para. 6.2.2)

$$U_T(L) = 2u_{cT}(L)$$
$$= 2(0.00013\ \text{in.})$$
$$= 0.00026\ \text{in.}$$

Nominal differential expansion

$$NDE = |4.8 \times 10^{-6}\ \text{in./in.°F} - 6.5 \times 10^{-6}\ \text{in./in.°F}|$$
$$(20\ \text{in.})\ |74 - 68|°\text{F}$$
$$= 0.00020\ \text{in.}$$

Thermal error index

$$TEI = \{[|NDE| + U_T(L)]/TOL\}(100\%)$$
$$= (0.00020\ \text{in.} + 0.00026\ \text{in.}/0.002\ \text{in.})(100\%)$$
$$= 23.5\%$$

L-3.3 Summary

The different cases that can occur for temperature measurement are summarized in Table L-3.3-1

Table L-3.3-1 Summary of Equations for Thermal Uncertainty Calculations

Symbol	Definition	Equation
TEI	Thermal error index	$\{[NDE + U_T(L)]/TOL\}100\%$
NDE	Nominal differential expansion	
	The standard and the object are the same material	0
	NDE correction	0
	No NDE correction	$(NE) - (NE_s)$
NE	Nominal expansion of the object	$L\alpha(T_m - 20)$
L	Length of dimension	
α	Coefficient of thermal expansion of the object	Specified
T_m	Mean environmental temperature	Measured
(NE_s)	Nominal expansion of the standard	$L\alpha_s(T_m - 20)$
α_s	Coefficient of thermal expansion of the standard	Specified
$U_T(L)$	Expanded thermal uncertainty	$2u_{cT}(L)$
$u_{cT}(L)$	Combined standard thermal uncertainty	$\sqrt{(UNE)^2 + (UNE_s)^2 + (LUTM)^2 + u_{ETVE}^2}$
UNE	Uncertainty nominal expansion of the object	$u(\alpha)L(T_m - 20)$
$u(\alpha)$	Uncertainty of object thermal expansion coefficient	
	For method of para. 6.2.2.2(c)	$\sqrt{1/3}(0.1)\alpha$
(UNE_s)	Uncertainty nominal expansion of the standard	$u(\alpha_s)L(T_m - 20)$
$u(\alpha_s)$	Uncertainty of standard thermal expansion coefficient	
	For method of para. 6.2.2.2(c)	$\sqrt{1/3}(0.01)\alpha_s$
$LUTM$	Length uncertainty due to temperature measurement	
	For *NDE* correction	$\sqrt{\alpha^2 L^2 u(T)^2 + \alpha_s^2 L_s^2 u(T_s)^2}$.
	For no *NDE* correction	$u(T_e)L(\alpha - \alpha_s)$
$u(T)$	Uncertainty of object temperature measurement	$[(a^+ - a^-)/2](\sqrt{1/3})$
$u(T_s)$	Uncertainty of standard temperature measurement	$[(a^+ - a^-)/2](\sqrt{1/3})$
$u(T_e)$	Uncertainty of environment temperature	$(1/2)(T_{max} - T_{min} + 2a)\sqrt{1/3}$
a	Accuracy of temperature measurement ($\pm a$)	Specified
T_{max}	Maximum air temperature	Measured over specified time
T_{min}	Minimum air temperature	Measured over specified time
u_{ETVE}	Standard uncertainty due to the environmental temperature variation error	$(1/2)\ ETVE\sqrt{1/3}$
$ETVE$	Environmental temperature variation error	Measured over specified time
SZ	Specification zone (the zone specified for a parameter in a machine acceptance test)	Specified
TOL	Tolerance (used for specification zone, *SZ*, when measuring parts)	For ± 0.1 mm, $TOL = 0.1$ mm

GENERAL NOTE: "Object" refers to the object being calibrated or measured; "standard" refers to the calibrator or measuring device.

NONMANDATORY APPENDIX M CALCULATION OF UNCERTAINTIES

M-1 GENERAL

In many of the tests in this Standard, uncertainties have been assigned to the results of a measurement following widely accepted procedures [ISO/IEC Guide to the Expression of Uncertainty in Measurement, 1995(E)]. In a subtle deviation from these procedures, the uncertainties are being assigned to the machine tool, rather than the measurement system. That is, it is assumed that the measurand (for example, linear positioning) is uncertain when measured with a "perfect" measurement system because of "inherent" lack of repeatability in the machine itself. Since machine tools, at the current level of accuracy, obey the laws of classical physics, this assumption is probably incorrect. Machine tools are, in fact, much more repeatable than is commonly believed, as has been demonstrated on numerous occasions. In the case of machine tool measurements, the major uncertainties arise from a combination of

(a) incomplete definition of the measurand

(b) imperfect realization of the definition of the measurand

(c) nonrepresentative sampling — the sample measured may not represent the defined measurand

(d) inadequate knowledge of the effects of environmental conditions on the measurement or imperfect measurement of environmental conditions[1]

The fact is that the model normally used for the machine tool does not include all of the variables that are present when testing a machine. Thus, the observed dispersion of the measurement results is nearly universally of Type B. Because of the current accuracy level of the instrumentation (see section 9), this dispersion is correctly assigned to the machine tool rather than the instrument system. (Note that this is not the case for temperature-controlled, high-accuracy machines such as diamond turning machines, where errors in the measurement system begin to become the dominant sources of uncertainty. Users desiring to use this Standard on such machines should be prepared to address these issues as, though the procedures may appear to be identical, the assignment of lack of repeatability to the machine, rather than to the measurement system, may be erroneous.)

In the body of this Standard, uncertainties have not been computed for a number of tests due to one of the following four reasons:

(a) The test may be considered a functional test, and thus an assignment of uncertainty is not called for.

(b) The test was already in the process of standardization, or standardized, by the International Standards Organization (ISO) and uncertainties were not computed there.

(c) The test duration was such that making enough repeated measurements to have statistical significance was impractical.

(d) The tests were such that there existed a significant historical precedent that the test results should be treated as tolerances rather than measurements with associated uncertainties.

It is the purpose of this Nonmandatory Appendix to explain the reasoning behind the decisions and, for Users who so desire, provide the methodology for the assessment of uncertainties in cases where it is practical to do so. Again, we emphasize that these uncertainties should be assigned to the machine tool system (including the testing environment) and not to the measurement instrument. This can be correct only if the measurement instrument conforms to the requirements of section 9.

M-2 UNCERTAINTY CALCULATIONS CURRENTLY IN ASME B5.57

In this Standard, there are many tests where the uncertainties are calculated. Some of these tests, in fact, are designed primarily to estimate the uncertainties caused by various factors. In general, these types of tests are called "repeatability tests." The repeatability tests include the *ETVE* test (para. 6.2.1), the relative vibration test (para. 6.3), the structural motion test (para. 7.6.2), the subsystems repeatability tests (para. 8.3), and the repeatability of tool-setting systems test (para. 8.4.1).

Besides these general tests for repeatability, other tests where the uncertainty is estimated according to the standard methodology are positioning accuracy and repeatability, linear axes (para. 7.2); angular error (yaw) motions, linear axes (para. 7.4); positioning accuracy and repeatability, rotary axes (para. 7.5); original location of the tool-setting-system (para. 8.4.2); combination tests for tool-setting-system drift (para. 8.4.3); machine performance as a measuring tool (para. 8.7); and parametric tests (para. 8.8). These are not discussed further in this Nonmandatory Appendix.

M-3 FUNCTIONAL TESTS

After careful discussion, it was the opinion of the Committee that the following tests should be considered

[1] ISO Guide to the Expression of Uncertainty in Measurement, 1993(E).

functional tests where it is not appropriate to assign an uncertainty. These are setup hysteresis (para. 7.1.4.2), periodic linear and angular positioning (paras. 7.2.8 and 7.5.8), cutting performance (para. 7.10), multifunction cycle test (para. 7.11), mechanical tail stock alignment (para. 8.2.5.1), CNC performance test (para. 8.5), and machining test parts (para. 8.7). Uncertainties could, of course, be assigned to the final functional test, machining test parts, by machining a large number of parts and applying the procedures of statistical process control. Users desiring to do this should follow appropriate standardized methods.

M-4 UNCERTAINTY COMPUTATIONS NOT PRESENTLY IN ASME B5.57

Several of the tests presented in this Standard do not provide the User with the methodology for computing an appropriate uncertainty. These tests are

(a) spindle axes of rotation (para. 7.6)
(b) machine thermal test (para. 7.7)
(c) critical alignment (para. 7.8)
(d) contouring performance using circular tests (para. 7.9)
(e) coaxiality of axes of rotation (para. 8.2)

These are discussed, in turn, in paras. M-4.1 through M-4.5. In all cases, following previously established procedures, the repeatability for a given test should be reported as 4 times the standard uncertainty.

M-4.1 Uncertainty Calculation, Spindle Axes of Rotation

For spindle error motions, the Standard calls for performing the measurements at three spindle speeds. At each speed, the error motions are measured for a minimum of 20 revolutions and averaged to obtain the average error motion value. The maximum range of deviations from the average error motion value is reported as the asynchronous error motion, and not as an uncertainty in the error motion. This is because it has been demonstrated that asynchronous error motion, although it may appear to be random, is actually highly systematic, at least for the case of ball bearing and roller bearing spindles, which constitute a very large percentage of the spindles on turning centers. The systematic nature of the asynchronous motion is less well documented for aerostatic and hydrostatic spindles. Because of the very large number of revolutions required for assessing uncertainty on ball and roller bearing spindles, no procedure is recommended here.

If the User desires to obtain an uncertainty from these measurements on aerostatic and hydrostatic spindles, the complete test (20 revolutions) for each error motion should be repeated 10 times. For each of these repetitions, an average error motion and an asynchronous error motion should be computed. The estimate of the standard uncertainty for these quantities should then be calculated according to the following equation:

$$u_q = u(q) = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(q_j - \bar{q})^2}$$

where

q = the mean obtained from the 10 repeated trials
q_j = the outputs of the measurement procedure for each complete test (average or asynchronous error motion)

In the opinion of the authors of this Nonmandatory Appendix, following the above procedure would constitute unwarranted expense, as the information gained would not be particularly relevant to machine performance.

M-4.2 Machine Thermal Tests

All of the machine thermal tests, the spindle thermal stability test (para. 7.7.2), thermal distortion caused by moving linear axes (para. 7.7.3), and composite thermal error (para. 7.7.4), require a measurement to be performed over a period of 4 h or until "the maximum change in any sensor reading over any 30-min period, at all the sensor locations, has reduced to 15% of the maximum of that sensor change over the first 30 min of the test." These tests are clearly of long duration. If the User decides that it is necessary to obtain an uncertainty, then the tests should be performed many times (say, a minimum of five times) and standard uncertainties in the reported parameters computed as described in para. M-4.1. It is the recommendation of this Nonmandatory Appendix that this would constitute unwarranted expense.

M-4.3 Critical Alignments

All measurements for critical alignments in this Standard require measuring two straightnesses (using either an artifact standard, a straightness interferometer, or a test part) and taking the difference in slopes between two lines fit to the respective two sets of straightness data. To compute the uncertainty to be assigned to this final alignment value (call it *W*; see para. 7.8.2.1), the following approximate procedure should be followed.

Each straightness measurement should be performed five times. Data should be acquired at the same positions used for the positioning accuracy and repeatability, linear axes (para. 7.2), or more densely, if desired, in both the forward and reverse directions. Note that if a straightness interferometer is used, each data point should be obtained from an average of many laser readings, as described in para. 7.3.1.4. The straightness deviations should now be averaged and a standard uncertainty computed at each measurement position. The procedure is conceptually similar to that used for linear positioning, except that no distinction is made between forward and reverse readings. That is, at each of the i^{th} measurement positions, compute a mean straightness deviation and the standard uncertainty. The standard uncertainty is given by

$$s_i = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(y_{ij} - \overline{y}_i)^2}$$

where

n = 10
s_i = the estimate of the standard uncertainty of the straightness deviation at position i
y_i = the mean straightness deviation at position i
y_{ij} = the j^{th} straightness deviation at position i

Next, for each of the two lines the mean straightness deviations, which are functions of the axis positions where the straightness deviations are measured, x_i (or z_i), should be linear least-squares fit to a straight line using a least-squares fit weighted with the standard uncertainties of the straightness deviations.[2]

The standard uncertainties for the slopes of each line may be combined in quadrature to yield the square of the standard uncertainty for the alignment angle. That is

$$u_w{}^2 = u_{B1}{}^2 + u_{B2}{}^2$$

where

u_{B1} = the standard uncertainty for the slope of the first line
u_{B2} = the standard uncertainty for the slope of the second line

M-4.4 Contouring Performance Using Circular Tests

For the contouring performance, the circular hysteresis,[3] H; the circular deviations for clockwise, $G\uparrow$, and counterclockwise, $G\downarrow$, contouring; and the radial deviations, F_{max} and F_{min}, for clockwise ($\uparrow$) and counterclockwise ($\downarrow$) contouring, corrected to 20°C, shall be reported, as well as the measured feed rates in the clockwise and counterclockwise directions. The circular hysteresis is the maximum radial difference between the two actual tool paths in the clockwise and counterclockwise directions at any given angle. The circular deviation is the minimum radial separation of two concentric circles that will envelope the actual path. Finally, the radial deviations are the maximum and minimum deviations from the circle radius, corrected to 20°C. To compute the standard uncertainties of these quantities, the circular test should be conducted 10 times in both the clockwise and counterclockwise directions. For each set of 10 measurements, the artifact (ball bar, disk, or grid encoder) temperature should be measured at the beginning and the end of the 10 measurements and the mean value of the temperature recorded. In the following discussion, it is assumed that data are acquired at n intervals over the measured arc. After least-squares fitting to remove residual eccentricity, the data should be analyzed as follows. At each interval, i, compute the standard uncertainty in the circular deviation following the normal procedure. That is

$$s_i\uparrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(d_{ij} - \overline{d}_i\uparrow)^2}$$

$$s_i\downarrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(d_{ij} - \overline{d}_i\downarrow)^2}$$

where

d_i = the mean circular deviation at the i^{th} angular position
d_{ij} = the j^{th} circular deviation at the i^{th} angular position
n = 10
s_i = the estimate of the standard uncertainty of the circular deviations; $\uparrow$ and $\downarrow$ denote clockwise and counterclockwise rotation, respectively

M-4.4.1 Circular Hysteresis. To compute the uncertainty in the circular hysteresis, determine the angular position where the maximum radial difference between the mean circular deviation curves occurs. This difference is reported as the circular hysteresis. The square of the uncertainty in this value is given by

$$u_H{}^2 = s\uparrow_k{}^2 + s\downarrow_k{}^2$$

where

k = the angular position where the maximum radial difference between the mean circular deviations occurred

M-4.4.2 Circular Deviation. For determining the uncertainty in circular deviation, both the clockwise and counterclockwise data are treated the same. Only the clockwise case is given below. The procedure is to note the angles at which the maximum and minimum deviations in the *mean* circular deviation plot occurred for the appropriate rotation direction. Then the uncertainty is given by

$$u_{G\uparrow}{}^2 = s\uparrow_k{}^2 + s\uparrow_m{}^2$$

where

k = the position where the maximum deviation occurred
m = the position where the minimum deviation occurred

M-4.4.3 Radial Deviation. As with the circular deviation, the clockwise and counterclockwise data analysis is the same. Only the clockwise case is given below. The procedure is to locate the angular position where the maximum radial deviation between the calibrated

[2] The procedures for performing such fits are available in almost any elementary statistics textbook. The weighting is necessary because, in general, the standard uncertainty of the straightness deviations will be a function of the axis position.

[3] When performing this test, care should be taken that the machine is moving at the correct feed rate. If the feed rate is different in the counterclockwise and clockwise directions, the circular hysteresis will be measured erroneously.

radius and the mean measured radius occurred. This comparison is performed after the ball bar length has been corrected to 20°C, using its mean temperature measured as described in para. M-4.4. The square of the uncertainty is then computed as follows (where ↑ or ↓ has been eliminated for simplicity):

$$u_F^2 = s_k^2 + L_s^2(T_s - 20)^2 u^2(\alpha_s) + L^2(T - 20)^2 u^2(\alpha) + L_s^2 \alpha_s^2 u^2(T_s) + L^2 \alpha^2 u^2(T)$$

where

k = the angular position where the maximum radial deviation occurred
L = the effective machine scale length, which is equal to the ball bar length
L_s = the calibrated ball bar length
T = the temperature of the machine scales, which should be assumed to be equal to T_s
T_s = the mean temperature of the ball bar
$u(q)$ = the standard uncertainty in the quantity, q
u_F = the standard uncertainty of the radial deviation
α = the thermal expansion coefficient of the machine scales
α_s = the thermal expansion coefficient of the ball bar

Although it is not a requirement of this Standard, a better estimate of the uncertainty could be obtained if the temperatures of the relevant machine scales were measured during this test and the actual measured values then used for the computation. In that case, the average of the two scale temperatures should be used in the computation above.

M-4.5 Coaxiality of Axes of Rotation

For computing the uncertainty in the coaxiality of axes of rotation (para. 8.2), the procedures outlined in this Standard should be followed, except that the measurements should be performed 10 times rather than 3. The uncertainties for directly measured quantities should be computed using the general equation given in para. M-4.1.

M-4.5.1 Rim-and-Face Method. The standard uncertainties of the vertical and horizontal angles and offsets should be estimated as

$$u_{VO}^2 = \frac{(u_{RR0}^2 + u_{RR6}^2 + u_{SR_s}^2)}{4}$$

$$u_{VA}^2 \approx \frac{(u_{FR6}^2 + u_{FR0}^2 + u_{FR_s}^2)}{DIA^2}$$

$$u_{HO}^2 = \frac{(u_{RR3}^2 + u_{RR9}^2)}{4}$$

$$u_{HA}^2 \approx \frac{(u_{FR9}^2 + u_{FR3}^2)}{DIA^2}$$

where the subscripts indicate the quantity whose uncertainty is estimated. The notation is defined in para. 8.2.1.

M-4.5.2 Reverse Indicator Method. The standard uncertainties of the vertical and horizontal angles and offsets should be estimated as

$$u_{VO}^2 = \frac{(u^2{}_{SR0} + u^2{}_{SR6} + u^2{}_{SR_s})}{4}$$

$$u_{VA}^2 = \frac{(u^2{}_{SR0} + u^2{}_{SR6} + u^2{}_{SR_s} + u^2{}_{MR0} + u^2{}_{MR6} + u^2{}_{MR_s})}{4D_g^2}$$

$$u_{HO}^2 = \frac{(u^2{}_{SR3} + u^2{}_{SR9})}{4}$$

$$u_{HA}^2 = \frac{(u^2{}_{SR3} + u^2{}_{SR9} + u^2{}_{MR3} + u^2{}_{MR9})}{4D_g^2}$$

Again, the subscripts indicate a quantity whose uncertainty is estimated. The notation is defined in para. 8.2.2.

M-4.5.3 Optical Tail Stock Alignment. If optical systems are used for tail stock alignment, the instrument manufacturer's recommendations for uncertainty calculations should be followed. The instruments currently on the market function differently from one another, so no specific equations can be provided.

M-4.5.4 Two-Sphere Axis Alignment. The standard uncertainties of the vertical and horizontal angles and offsets are given by

$$u_{HO}^2 = u_{HO_1}^2 = u_{CX_1}^2$$

$$u_{HO_2}^2 = u_{CX_2}^2$$

$$u_{VO}^2 = u_{VO_1}^2 = u_{CY_1}^2 + \frac{u_{SR_1}^2}{4}$$

$$u_{VO_2}^2 = u_{CY_2}^2 + \frac{u_{SR_2}^2}{4}$$

$$u_{HA}^2 = \frac{(u_{HO_2}^2 + u_{HO_1}^2)}{D_g^2}$$

$$u_{VA}^2 = \frac{(u_{VO_2}^2 + u_{VO_1}^2)}{D_g^2}$$

The notation is defined in para. 8.2.4.

M-4.5.5 Parallelism of the Z-Axis With Other Linear Axes and the C-Axis. Paragraphs 8.2.5 and 8.2.6 describe Z-axis alignment measurements. The uncertainties in these alignments should be computed following the procedures of para. M-4.3.

NONMANDATORY APPENDIX N
SIGN CONVENTIONS FOR ERROR VALUES

N-1 GENERAL

This Standard does not require that the User to use specific signs for the error values. However, it is customary to define errors as the actual response of the machine tool, minus the nominal or anticipated response. Errors are reported using the machine coordinate system. Positive values of displacement errors (e.g., positioning and straightness errors) indicate error motion in the positive direction of a coordinate axis. Thus, a positive positioning error of an axis indicates that the carriage moved farther along that axis than commanded. Positive angular errors (e.g., angular positioning, roll, pitch, and yaw) indicate positive angular motions about a coordinate axis. These are customarily defined to be positive counterclockwise for rotation about an axis, using the right-hand rule.

N-2 RELATIVE MEASUREMENTS

The sign of an error is affected by the reference relative to which the error motion is defined and measured. If a single axis is tested whose function is to carry the workpiece, measurements are made with respect to a nominal tool position. In all other cases, measurements are made with respect to a nominal workpiece. For example, the main spindle carries the workpiece. Therefore, the spindle measurements are made with respect to the nominal tool position. In this case, a positive axial error motion of the spindle indicates movement of the spindle axis and the workpiece in the positive Z direction. For the positioning accuracy test of an axis that moves the turret, measurements are made relative to a nominal workpiece. In this case, a positive error indicates a positive error in the position of the tool relative to the workpiece.

N-3 CRITICAL ALIGNMENTS

For critical alignments, the following sign convention should be used. The squareness error between two axes should be reported as positive if the angle between the respective positive coordinate axes exceeds 90 deg. The parallelism error of axis X2 to axis X1 should be reported as positive if the actual angle of axis X2 relative to axis X1 exceeds the respective nominal angle. A positive angle corresponds to positive angular motion around the machine coordinate axis, orthogonal to the plane of the parallelism measurement. The offset of axis X2 to axis X1 should be reported as positive if axis X2 is displaced in a positive coordinate direction relative to axis X1.

NOTE: The sign convention used in the compensation tables of the machine tool controller does not necessarily comply with the convention outlined in this Nonmandatory Appendix.

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