AN AMERICAN NATIONAL STANDARD

ASME B89.4.1b-2001

ADDENDA

to

ASME B89.4.1-1997
METHODS FOR
PERFORMANCE EVALUATION OF
COORDINATE MEASURING MACHINES

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
Three Park Avenue • New York, NY 10016

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

ASME B89.4.1b-2001

Following approval by the ASME B89 Committee and ASME, and after public review, ASME B89.4.1b-2001 was approved by the American National Standards Institute on August 31, 2001.

Addenda to the 1997 edition of ASME B89.4.1 are issued in the form of replacement pages. Revisions, additions, and deletions are incorporated directly into the affected pages. It is advisable, however, that this page, the Addenda title and copyright pages, and all replaced pages be retained for reference.

SUMMARY OF CHANGES

This is the second addenda to be published to ASME B89.4.1-1997. A previous addenda was published in 1998.

Replace or insert the pages listed. Changes listed below are identified on the pages by a margin note, **(b)**, placed next to the affected area. Previous addenda changes are indicated by **(a)**. The pages not listed are the reverse sides of the affected pages and contain no changes.

Page	*Location*	*Change*
vi.1	Correspondence With the B89 Committee	Added
vii–ix	Contents	Updated to reflect Addenda
1	Section 1	Fourth paragragh, last two lines added
2	1.1	Subparagraph (d) revised
4	Fig. 1A	Subcategory Settling Time revised
7–7.2	Fig. 1C	(1) First page revised (2) Second and third page added
31, 31.1	5.5.1	(1) First paragraph revised (2) Subparagraphs (a) through (d) added
36	5.5.2.3	Third sentence added
46	5.6.2	(1) Penultimate sentence revised (2) Last sentence added
47	5.6.3	First sentence revised
	Section 6	(1) Title editorially revised (2) Last sentence revised
49	6.2	Revised in its entirety
50	Table 3	Added
	Fig. 38	Added

Page	*Location*	*Change*
50, 51	6.2.1	Revised in its entirety
51	6.2.2	Revised in its entirety
	6.3	Added
	Table 4	Added
	Table 5	Added
52	Table 6	Added
	Table 7	Added
	6.3.1	Added
	6.3.2	Added
	6.3.3	Added
	6.4	Added
52.1	6.4.1	Added
	6.4.2	Added

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Proposed 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.

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Subject:	Cite the applicable paragraph number(s) and provide a concise description.
Edition:	Cite the applicable edition of the standard for which the interpretation is being requested.
Question:	Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation.

Requests that are not in this format may be rewritten in the appropriate format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

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Attending Committee Meetings. The B89 Main Committee regularly holds meetings that are open to the public. Persons wishing to attend any meeting should contact the Secretary of the B89 Main Committee.

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METHODS FOR PERFORMANCE EVALUATION OF COORDINATE MEASURING MACHINES

1 SCOPE

This Standard establishes requirements and methods for specifying and testing the performance of coordinate measuring machines (CMMs) having three linear axes perpendicular to each other and up to one rotary axis positioned arbitrarily with respect to these linear axes. In addition to clarifying the performance evaluation of CMMs, this Standard seeks to facilitate performance comparisons among machines by unifying terminology, general machine classification, and the treatment of environmental effects.

This Standard attempts to define the simplest testing methods capable of yielding adequate results for the majority of CMMs and is not intended to replace more complete tests that may be suitable for special applications. In particular, this Standard is most applicable to machines used in the point-to-point mode rather than the contour measurement mode. Although this Standard provides checks for most of the parameters relevant to coordinate measuring machines used in a contouring mode, the checks do not actually test contouring accuracy, per se. Additions to this Standard to include contouring performance are in process.

This Standard provides definitions of terms applicable to CMMs. These definitions are separated into two parts: first, a glossary covering technical terms used throughout this Standard, and second, an explanation of twelve common machine classifications.

(b) The actual specification of CMMs is subdivided into four sections: general machine classification, machine environmental requirements and responses, machine performance, and machine subsystem performance. Machine classification includes machine type, measurement ranges, position resolution, operating mode, and probing method. Environmental specification includes thermal response, electrical requirements, vibration sensitivity, and utility air requirements. Machine performance specification includes repeatability, linear displacement accuracy, ball bar measurement performance, offset probe performance, diagonal displacement performance (large machines), duplex performance (machines used in the duplex mode), rotary axis performance, performance under loaded conditions, and bidirectional length measurement capability. Subsystem performance consists of procedures to evaluate probing performance during point-to-point coordinate acquisition with single and multiple tips, scanning, and positioning performance when it is required to hit a target position.

One of the most significant features of this Standard is its treatment of environmental specification and testing. The machine user is assigned clear responsibility for providing a suitable performance test environment, either by meeting the supplier's parameters or by accepting reduced performance. Particular emphasis is placed on the performance degradation caused by temperature variation and vibration. The treatment of thermal effects in this Standard is in conceptual conformance to the provisions of ASME B89.6.2. The key feature of this treatment is the relaxation of machine performance requirements if the thermal environment causes excessive uncertainty or variation in the CMM performance and does not meet the supplier's recommendations regarding thermal parameters.

Actual machine performance testing is divided into five major areas: repeatability, linear displacement accuracy, streamlined artifact testing with a ball bar, rotary axis testing, and bidirectional length measurement capability. Supplements to the ball bar testing are provided for large machines and for machines used in the duplex mode. (Note that the supplemental laser interferometer diagonal displacement measurements will give numbers that may be different from those obtained with long ball bars. However, these numbers also adequately reflect the performance of the machine.) Performance tests for machines under loaded conditions are also included. An important feature of these performance tests is the attempt to use normal operating procedures during the tests. This emphasizes the importance of measurement procedure details, such as mode of machine operation and probe type. In addition, the use of normal operating procedures during the tests serves to emphasize the overall approach of this Standard in considering measurement data as the results of the complete measuring system, not just the CMM.

Subsystem performance, at this time, provides a series of tests for systematic point-to-point probing errors, such as lobing. Tests are also provided for machines with multiple-tip probing. This includes the use of probe changers and probe indexing capabilities. Tests for other subsystems, such as software, are of importance but are not included in this Standard.

Throughout this Standard, the concept of range — that is, the spread between the maximum and minimum values in a set of data — is used as the measure of machine performance. This choice was made in favor of more common statistical measures, such as standard deviation, and because the dominant errors in coordinate measuring machines are systematic as opposed to being random. In such cases, no generally accepted statistical procedures currently exist.

Repeatability is defined as the "ability of a measuring instrument to provide closely similar indications for repeated applications of the same measurand under the same conditions of measurement." The specified testing of repeatability requires a series of measurements of the center coordinates of a precision ball, using the same testing procedure as the tests to measure the effect of the thermal environment.

The linear displacement accuracy of the machine is measured along three mutually perpendicular lines in the work zone. The tests may be performed using either a step gage or a laser interferometer. This Standard carefully details the treatment of these data if any mean temperature in the tests departs from 20°C (68°F), at which material length standards are defined.

The overall measuring performance of the machine is evaluated with a ball bar, providing limited but valuable testing of the machine. This method has been chosen due to the speed and simplicity with which a machine can be evaluated using a ball bar to simulate a real measurement procedure. For very large machines, diagonal displacement measurements are used to supplement the ball bar results. For machines used in the duplex mode, measurements of a fixed ball in various positions are performed by both machines as a supplement to ball bar measurements by each machine. Further, the ball bar is measured in four positions with offset probes to obtain the offset probing performance.

The performance of the machine's rotary axis, if applicable, is tested by measuring the locations of two precision balls mounted at specified positions on the rotary table. Again, this test is functional and is intended to reflect the values that would be obtained from actual measurements. The user of this specification is warned that rotary axes are particularly sensitive to the load distribution and the moment of inertia of the part being measured. A separate section is included that allows for performance testing of coordinate measuring systems under loaded conditions.

In order to clarify the use of this Standard, a short guide is included as Appendix A. To assist the user in tracing possible environmental problems, appendices are also provided for thermal environment testing (Appendix B), vibration analysis (Appendix C), electrical power analysis (Appendix D), and utility air analysis (Appendix E). Appendices on hysteresis testing (Appendix F), ball bar test equipment (Appendix G), straightedge tests for ram axis roll (Appendix H), and interim testing of CMM systems (Appendix I), also provide the user with important subsidiary information.

Productivity is an important consideration in the selection of a coordinate measuring machine. There are numerous factors that affect relative productivity of measuring systems, including variables inherent to both the system and the workpiece. This Standard does not address methods to specify and evaluate productivity; rather, productivity should be evaluated with respect to the expected use of the system.

1.1 Contents and Specification Form (b)

Any specification described as complying with this Standard shall include at least the following items.

(a) Machine classification (see para. 2.2). If no machine classification is applicable, the actual configuration shall be described in equivalent detail.

(b) Principal mode of operation (free-floating manual, driven manual, or direct computer control). If desired, repeatability, linear displacement accuracy, volumetric performance, bidirectional length measurement capability, point-to-point probing performance, and multiple-tip probing performance may be specified for more than one mode of operation.

(c) Principal probe type (passive, switching, proportional, or nulling). If desired, repeatability, linear displacement accuracy, volumetric performance, bidirectional length measurement capability, point-to-point probing performance, and multiple-tip probing performance may be specified for more than one probe type.

(d) Probe approach rate, probe approach distance, drive velocity, acceleration, deceleration, drive-move target tolerance, touch-move target tolerance, settling time(s), and any other probing parameters for the principal probe type(s) specified.

(e) Nominal voltage, frequency, and power requirement.

(f) Utility air pressure, pressure variation, flow, temperature, dew point, and particulate content.

(g) Permissible environment vibration amplitude as a function of frequency. The amplitude must be specified at the interface between the equipment supplied by the user and that supplied by the CMM supplier.

(h) Statement of availability of data required for foundation design and machine installation.

(i) Statement of the significant mean temperature change, if available, safe operating temperature range, nominal location for the temperature variation error test, and the availability of other thermal response data for the machine.

(j) Statement of nominal coefficients of thermal expansion of the machine scales, by axis.

(k) Parameters describing a recommended machine thermal environment.

(l) Repeatability.

(m) Linear displacement accuracy defined by measurement with a laser interferometer or a mechanical master. The choice shall be clearly specified.

(n) Volumetric performance including ball bar performance, offset probe performance, volumetric tests for machines with large work zones, tests for duplex machines, rotary axis testing, and tests for machines under loaded conditions.

(o) Bidirectional length measurement capability.

(p) Point-to-point probing performance.

(q) Multiple-tip probing performance.

(r) A sample machine specification form. This form is illustrated in Fig. 1 for a typical machine. It is divided into three sections: General (Fig. 1A), Environmental (Fig. 1B), and Performance (Fig. 1C). The General section is intended to characterize the machine by configuration, size, operation mode, and probe type. The Environmental section is intended to describe environmental requirements for the machine. The Performance section illustrates the parameters used to specify performance within the context of this Standard. In the case that more than one operating mode/probe type combination is specified, performance shall be specified for each combination. This form cannot be effectively used outside the context of this Standard as the Environmental and Performance sections are closely connected through working tolerance derating procedures described in Sections 4 and 5.

1.2 Alternatives

This Standard allows parts of the environmental tests section to be deferred or bypassed and only the performance tests to be carried out. This alternative is acceptable only if it is acceptable to both the user and the supplier and if deferred as specified in Section 4.1.

2 DEFINITIONS

2.1 Glossary

This glossary contains brief definitions of the majority of technical terms used in this Standard. Omissions should be reported to ASME (see Foreword).

Abbe error: the measurement error resulting from angular motion of a movable component and an Abbe offset between the scale measuring the motion of that component and the measurement line (see Fig. 2).

Abbe offset: the instantaneous value of the perpendicular distance between the displacement measuring system (e.g., scale) of a measuring instrument and the measurement line where the displacement in that coordinate is being measured. A schematic illustration of this concept is given in Fig. 2.

acceptable machine load: the machine load that can be applied through the spanned region of contact as defined in the load concentration chart (see Fig. 3). All standard machine specifications will remain unchanged under "acceptable machine loading." (Note: refer to para. 5.5.7 for a detailed testing procedure that describes acceptable machine loading test conditions.)

accuracy: a quantitative measure of the degree of conformance to recognized national or international standards of measurement.

axis direction: the direction of any line parallel to the motion direction of a linearly moving component.

ball bar: a gage consisting of two highly spherical tooling balls of the same diameter connected by a rigid bar. A ball bar, as used in this Standard, must be sufficiently mechanically rigid that its length is constant during the course of a set of measurements but does not have to be calibrated (see Appendix G).

CG location zone: a supplier-specified zone within the loading area in which the machine load center of gravity, CG, must lie.

cosine error: the measurement error in the motion direction caused by angular misalignment between a linear displacement measuring system and the gage (or part) being measured. Equations for computing cosine error are given in para. 5.4.2.3.

dead path: in laser interferometry, that distance between the remote interferometer and the retroreflector at closest approach which is not compensated for changes in the index of refraction of air.

GENERAL

Machine Classification (para. 2.2): (A figure with axis designation and direction of positive machine motion shall be supplied.) For duplex applications, relative positions and common elements of the two machines shall be shown.

Measuring Ranges (full travel):

X ________ mm (in.)
Y ________ mm (in.)
Z ________ mm (in.)
D ________ mm (in.) — diameter of rotary axis, if supplied (see Glossary)

Readout Resolution (least count):

X ________ mm (in.)
Y ________ mm (in.)
Z ________ mm (in.)
α ________ deg. (arc sec) — resolution of rotary table, if supplied

Principal Mode of Operation (more than one mode may be specified):

Free-floating manual ______
Driven manual ______
Direct computer-controlled ______

Principal Probe Type (more than one type may be specified):

Passive ______
Switching ______
Proportional ______
  Nulling ______
  Displacement-measuring ______
  Proximity ______

Operating Parameters:

Probe approach rate ______ mm/sec (in./sec)
Probe approach distance ______ mm (in.)
Settling time
  Passive (solid or hard) probes ______ sec
  Proportional probes ______ sec
  Drive velocity ______ mm/sec (in./sec)
  Acceleration ______ mm/sec^2 (in./sec^2)
  Deceleration ______ mm/sec^2 (in./sec^2)
  Drive-move target tolerance ______ mm (in.)
  Touch-move target tolerance ______ mm (in.)
Probe configuration (describe):

Describe location of machine coordinate system origin:

Maximum acceptable machine load: ______ kg [Notes (1), (2)]
Safe machine load: ______ kg

NOTES:
(1) The correct ISO unit of weight is the Newton (N), but the kilogram (kg) is used customarily. One kg has a weight approximately equal to 10 N in the earth's gravitational field.
(2) 1 kg weighs approx. 2.2 lb.

(b) **FIG. 1A B89.4.1 COORDINATE MEASURING MACHINE SPECIFICATION FORM**

PERFORMANCE — BASIC MACHINES **Page 1 of 4**

For the following parameters, the principal mode of machine operation and the probe type must be specified. If more than one operating mode, probe type, or mode type combination is desired, a separate performance specification sheet shall be used for each combination.

Operating Mode ___________ Probe Type ___________

(For all tests below, the reported value is the maximum range of error.)

Repeatability [Note (1)] — All Linear Axes (para. 5.3)

X ___________ mm (in.)
Y ___________ mm (in.)
Z ___________ mm (in.)

Linear Displacement Accuracy (para. 5.4)

Step gage (para. 5.4.2) _____ or laser interferometer (para. 5.4.3) _____

X ___________ mm (in.)
Y ___________ mm (in.)
Z ___________ mm (in.)

Volumetric Performance (para. 5.5) [Note (2)]

Ball bar _____ or gage block _____

Length (calibrated or nominal) ___________ mm (in.)
Working tolerance ___________ mm (in.)
Offset probe performance (para. 5.5.3) ___________ mm (in.)

Bidirectional Length Measurement Capability (para. 5.6)

Gage block length ___________ mm (in.)
Working tolerance ___________ mm (in.)

Point-to-Point Probing Performance (para. 6.1) [Note (3)]

Working tolerance — 10 mm stylus length ___________ mm (in.)
Working tolerance — 50 mm stylus length ___________ mm (in.)
Working tolerance — 50 mm stylus with a 20 mm offset ___________ mm (in.)

NOTES:
(1) For large machines, the supplier shall specify the second probe approach rate, probe approach distance, and traverse speed to be used (see para. 5.3.3).
(2) The user may supply measuring positions and lengths. If not supplied, then default values are used. Optional lengths and positions shall be attached, if required.
(3) Probe approach rate, probe approach distance, and settling time are the default values unless otherwise specified.

FIG. 1C B89.4.1 PERFORMANCE SPECIFICATION FORM **(b)**

PERFORMANCE — BASIC MACHINES (CONT'D)

Multiple-Tip Probing (para. 6.2)

MAXIMUM PERMITTED ERRORS, MPE_M FOR NONARTICULATING PROBING SYSTEMS WITH* / WITHOUT* CHANGER
(*Delete as necessary)

Nominal Stylus Length, *L*, mm	Stylus Shank Diameter(s), mm	Stylus Shank Material	Actual Stylus Length, mm	MPE_{MF} (form), μm	MPE_{MS} (size), μm	MPE_{ML} (location), μm
10	______	______	______	______	______	______
20	______	______	______	______	______	______
30	______	______	______	______	______	______
50	______	______	______	______	______	______
100	______	______	______	______	______	______
200	______	______	______	______	______	______
400	______	______	______	______	______	______

GENERAL NOTES:
(a) The default stylus length is 20 mm.
(b) If interchangeable arms are supplied instead of extensions, substitute one permitted arm length for the 0 mm extension length.
(c) Stylus length and extension length are both defined in ISO 10360-5.
(d) Radius to tip is defined as the center of head rotation to the center of the tip.

MAXIMUM PERMITTED ERRORS, MPE_A FOR ARTICULATING PROBING SYSTEMS WITH* / WITHOUT* CHANGER
(*Delete as necessary)

Nominal Arm or Extension Length, *L*, mm	Arm or Extension Diameter(s), mm	Arm or Extension Material	Actual Radius to Tip, mm	MPE_{AS} (form), μm	MPE_{AS} (size), μm	MPE_{AL} (location), μm
0	______	______	______	______	______	______
100	______	______	______	______	______	______
200	______	______	______	______	______	______
300	______	______	______	______	______	______

GENERAL NOTES:
(a) The default stylus length is 20 mm.
(b) If interchangeable arms are supplied instead of extensions, substitute one permitted arm length for the 0 mm extension length.
(c) Stylus length and extension length are both defined in ISO 10360-5.
(d) Radius to tip is defined as the center of head rotation to the center of the tip.

(b) FIG. 1C B89.4.1 PERFORMANCE SPECIFICATION FORM (CONT'D)

PERFORMANCE — BASIC MACHINES (CONT'D)

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Probing Analysis Scanning (para. 6.3)

Default Scanning Conditions	Scanning Mode	Working Tolerance for Scanning Performance, mm	Working Tolerance for Scanning Time, sec
Optimal Scanning Time Scanning Speed _______ mm/sec	High density, predefined path		
	Low density, predefined path		
	High density, not predefined path		
	Low density, not predefined path		
Optimal Scanning Performance Scanning Speed _______ mm/sec	High density, predefined path		
	Low density, predefined path		
	High density, not predefined path		
	Low density, not predefined path		
Supplier's Recommended Setting Scanning Speed _______ mm/sec	High density, predefined path		
	Low density, predefined path		
	High density, not predefined path		
	Low density, not predefined path		

Vectoring Performance (para. 6.4) _____ mm (in.)

Vectoring Time (para. 6.4) _____ mm (in.)

GENERAL NOTES:
(a) The user may supply measuring positions, styli lengths, orientations, and scan point densities. If not supplied, then default values are used. Desired options shall be attached, if required.
(b) High-density scanning is defined as 0.1 mm between consecutive points, and low density scanning is defined as 1 mm between consecutive points.

FIG. 1C B89.4.1 PERFORMANCE SPECIFICATION FORM (CONT'D) **(b)**

PERFORMANCE — ADDITIONAL SPECIAL TESTS

Page 4 of 4

For the following parameters, the principal mode of machine operation and the probe type must be specified. If more than one operating mode, probe type, or mode type combination is desired, a separate performance specification sheet shall be used for each combination.

Operating Mode ____________ Probe Type ____________

(For all tests below, the reported value is the maximum range of error.)

Ball Bar and Diagonal Displacement (large machines, para. 5.5.4) ________

Length of ball bar ___900___ mm (in.)
Working tolerance ________ mm (in.)
Length of longest diagonal ________ mm (in.)
Working tolerance ________ mm (in.)

Duplex Performance (machines used in the duplex mode, para. 5.5.5)

Description of test plane:

X ________ mm (in.)
Y ________ mm (in.)
Z ________ mm (in.)

Rotary Axis Performance (para. 5.5.6)

Rotary table position(s) and orientation(s) [Note (1)]:

Radial separation, Rs ________ mm (in.)
Height, Hs ________ mm (in.)

Working tolerances:

3D/alpha radial ________ μm (μin.)
3D/alpha tangential ________ μm (μin.)
3D/alpha axial ________ μm (μin.)

Testing Under Loaded Conditions (para. 5.5.7) [Note (2)]

Machine Load ________ kg (lb)

NOTES:
(1) More than one position and orientation may be specified. If unspecified, default values are provided in this Standard.
(2) Working tolerances for testing machines under loaded conditions are the same as those in the unloaded condition. Tests for ball bar performance and rotary axis performance are conducted.

FIG. 1C B89.4.1 PERFORMANCE SPECIFICATION FORM (CONT'D)

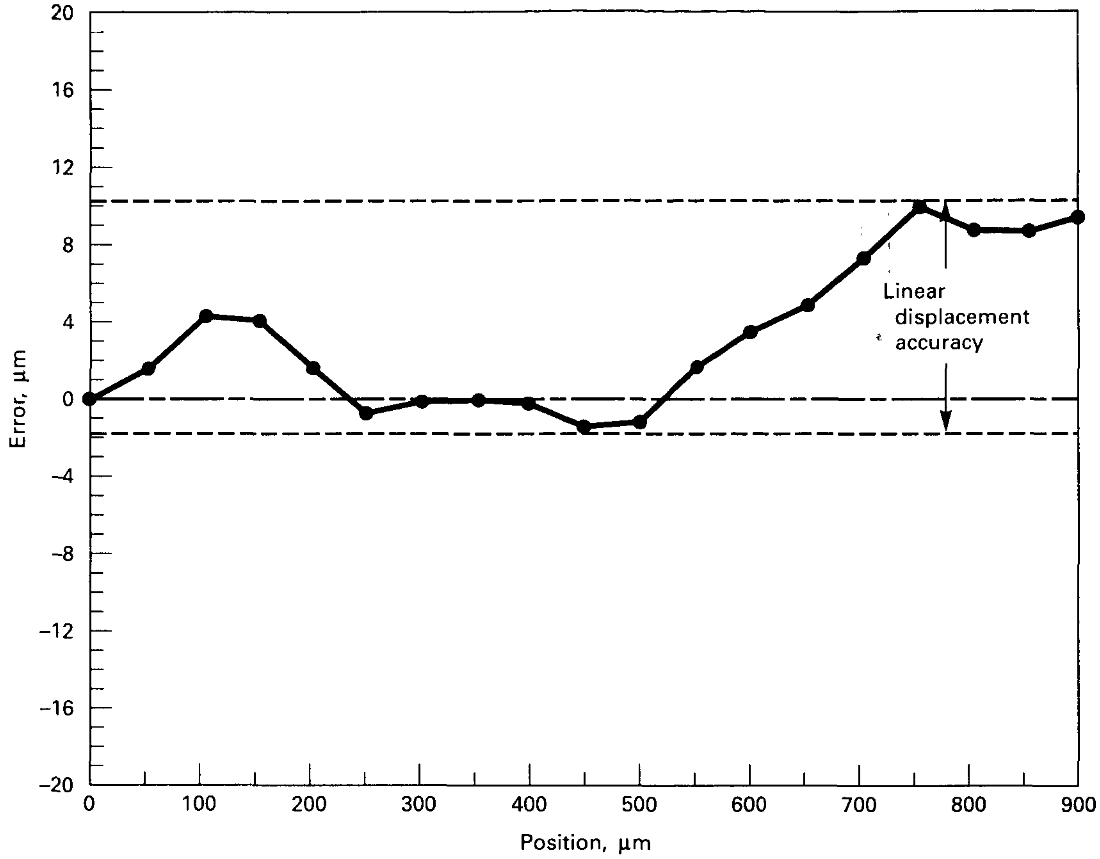


FIG. 25 TYPICAL RESULTS OF A LINEAR DISPLACEMENT ACCURACY TEST USING THE LASER WITH THE LINEAR DISPLACEMENT ACCURACY CLEARLY LABELED (For this example, the linear displacement accuracy is approx. 12 µm.)

readouts shall be calculated. Linear displacement accuracy shall be the maximum spread of the mean differences of the individual points. This is illustrated in Fig. 25.

5.4.4 Linear Displacement Requirements. Linear displacement accuracy, as calculated in para. 5.4.2.7 or 5.4.3.5, shall not exceed the supplier's specification, derated as specified in para. 4.2, if applicable.

5.5 Volumetric Performance

(b) **5.5.1 General.** Complete testing of the volumetric performance of coordinate measuring machines is a difficult and time-consuming process. This Standard has attempted to reduce the time and cost associated with testing by providing, wherever possible, simple self-checking procedures using measurements of uncalibrated artifacts. The primary uncalibrated artifact is the ball bar. Specifications that substitute calibrated artifacts, such as gage blocks, for the ball bar will be considered in conformance with this Standard if these artifacts are of equivalent length and are measured in the positions specified for the ball bar test (para. 5.5.2.1). The use of such calibrated artifacts for these tests does give additional information, but also incurs additional expense. If desired, the ball bar may also be "calibrated" on the CMM before commencing these tests and the average "calibrated" length used for the ball bar data analysis (para. 5.5.2.3). To perform this "calibration", the user shall follow the procedures for bi-directional length measurement capability (para. 5.6) with the following exceptions.

(*a*) The ball bar shall be measured rather than a gage block.

(*b*) The ball bar shall be measured in only three positions. These positions shall be with the ball bar positioned as accurately as possible along the lines used for the measurement of linear displacement accuracy (para. 5.4).

(c) The measurement procedure shall be that recommended by the supplier for precision ball bar measurement.

(d) The average length shall be calculated as the average of the 12 measured lengths, four in each position, corrected for temperature (and for the systematic component of the linear displacement accuracy, if desired).

Ball bars provide a rapid and easily understood check of machine volumetric performance. Properly conducted ball bar tests allow precise comparisons of the length scales on the various machine axes and clearly point out deviations of machine geometry from perfection. They are also extremely useful for quickly rechecking a machine on a periodic basis. In no case should the ball bar tests alone be regarded as providing a measurement of machine accuracy. In this Standard, accuracy is assessed in the linear displacement accuracy section (para. 5.4). In the ball bar tests, as in the repeatability and linear displacement accuracy tests, one should expect that the precise value of error obtained is dependent on the particular mode chosen for that test.

Due to the practical difficulty in transporting and using very long ball bars and in subdividing very large work zones into many subvolumes, significant modifications to the normal ball bar procedures are provided in para. 5.5.4 for machines with large work zones. Here the laser interferometer is introduced because of its ability to measure over very long lengths. The laser interferometer may give a different range of values than would a long ball bar; however, these numbers should be representative of the machine's volumetric performance.

Users of this specification should also be aware that as the work zone aspect ratio increases on a machine, the sensitivity of these tests to the straightness of the longest axis on that machine is reduced. Where straightness is critical, a separate check of this parameter should be performed when the aspect ratio of the machine axes exceeds 4:1.

This section on volumetric performance also contains performance tests for machines with a rotary axis. These tests follow the same philosophy in that no calibrated artifact is used.

5.5.2 Volumetric Performance Procedures Using Ball Bars

5.5.2.1 General Patterns. The ball bar performance tests recommended by this Standard may be accomplished using a single ball bar of length slightly shorter (approx. 100 mm) than the least dimension of the work zone.[4] For nearly cubic machines, this ball bar is measured in 20 positions. The general approach is to position the bar along 10 of the 12 edges of the work zone, along at least six work zone face diagonals to require simultaneous motion of pairs of machine axes, and along the four work zone body diagonals to require simultaneous motion of all three machine axes. Recommended patterns for nearly cubic machines are given in Fig. 26. (The figures showing patterns are oriented for vertical ram machines. They should be rotated for horizontal ram machines.) For machines having work zones with different aspect ratios, the procedure still uses the shorter ball bar but places it at several positions along a long measurement line, in order to require nearly full travel of the machine along that measurement line. Patterns for machines with a single long axis (axis ratio 2:1:1) are shown in Fig. 27. These patterns require measurement of the ball bar in 30 locations. Sample patterns for machines with two long axes and one short axis (axis ratio 2:2:1) are shown in Fig. 28. These machines require 35 measurement positions. The patterns were chosen to provide maximum sensitivity to most angular and squareness errors. They do not completely check angular motions of the ram axis, thus a separate test is provided in para. 5.5.3 to assess ram axis angular error effects when using offset probes. Additionally, articulation of the probe head and length of the stylus during this test can significantly impact the results of the test. It is therefore recommended that such articulation and length changes be minimized. (Articulating probe systems are tested in para. 6.2.)

The figures shown are idealized and, on any given machine, it is possible that the ball bar positions shown will overlap. It is recommended that if positional overlaps between ball bar setups exceed 60% of the ball bar length, then one of the overlapping setups may be eliminated. Most existing cases can be readily obtained by rotations of the configurations in the figures. No detailed recommendations are made regarding ball bar fixturing; however, a limited discussion of fixturing alternatives is given in Appendix G, and a sample fixture used for holding a ball bar with both ends free is shown in Fig. 29.

Care should be taken in handling ball bars so that heat from the hand is not transferred to the ball bar. The use of a plastic insulating sleeve is helpful. The time constant for thermal equilibration of a hollow steel ball bar is approximately 20 min (see ASME B89.6.2, Temperature and Humidity Environment for Dimensional Measurement, for an explanation of thermal time constants). Typical ball bars will stabilize within about one hour after being brought into a temperature-controlled environment.

5.5.2.2 Setup and Measurement Procedure — Ball Bar Tests. The ball bar shall be suitably fixtured in the positions indicated for measurement so that probing access to both balls is available. A fixture based on a knuckle joint is shown in Fig. 29. Such a fixture should be portable so that it can be easily moved around the table and sufficiently rigid so that the ball bar will not significantly deflect or vibrate while the locations of the balls are being measured. For each of the positions specified in the

[4] As with other sections in this Standard, the user is allowed to specify measurements different than the default option. To be in compliance with this Standard, the user may specify measurements of ball bars in up to 40 different locations and is also allowed to specify up to 3 ball bar lengths. These positions and lengths must be clearly stated as part of the machine specification. Furthermore, if more than one length is specified, each length ball bar must be measured in at least 10 different positions.

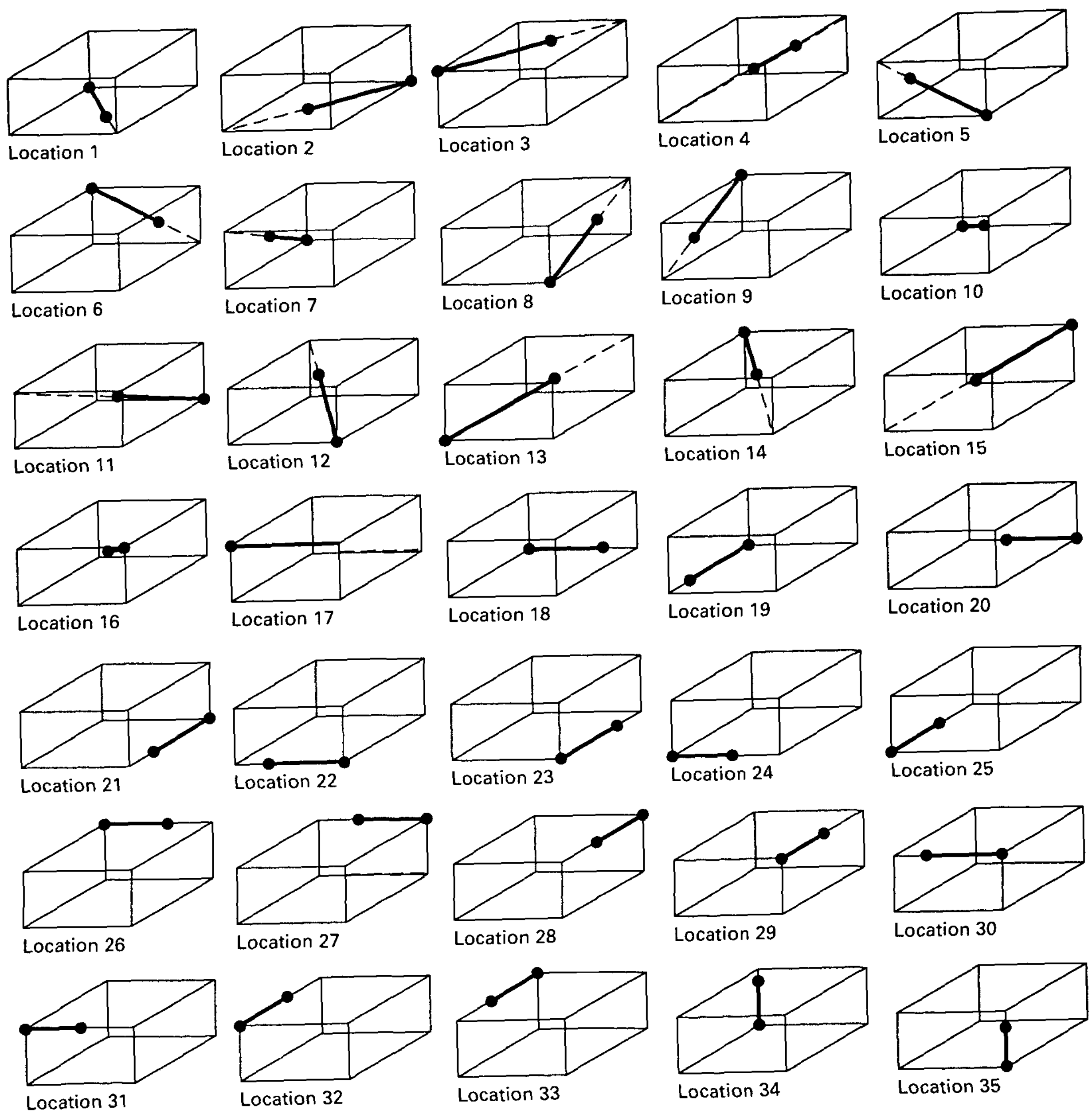


FIG. 28 RECOMMENDED BALL BAR PATTERNS FOR A MACHINE WITH TWO LONG AXES AND ONE SHORT AXIS

(The axis ratio here is 2:2:1. Again, for machines that do not quite correspond, overlapping positions are recommended.)

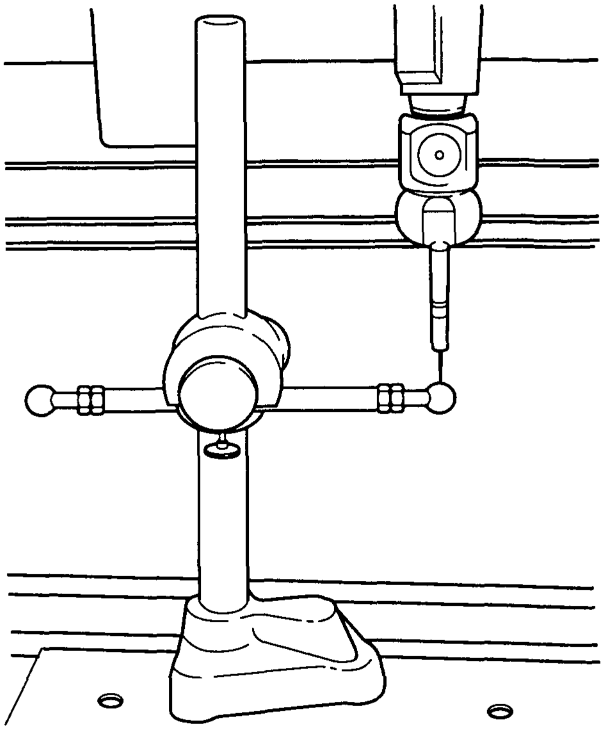


FIG. 29 SAMPLE FIXTURE FOR HOLDING A BALL BAR WITH BOTH ENDS FREE

patterns, both ends of the ball bar shall be measured. At least four probe contacts must be made on both of the balls in order to measure the ball bar length. To achieve better accuracy, eight or more points should be used to determine the center of each ball. These points should be dispersed around the ball as far as the probing system allows. (To check the repeatability of a setup, it is advisable to measure the ball bar length several times, but this is not a requirement of this Standard.) From these probings, center coordinates of the balls and the length of the ball bar shall be calculated for each ball bar position. The total spread of calculated ball bar lengths shall be assessed following the procedure described in para. 5.5.2.3. The range of these lengths shall not exceed the supplier's specifications, derated as specified in paras. 4.2 and 4.3, if applicable.

(b) **5.5.2.3 Ball Bar Data Analysis.** The data from ball bar measurements are analyzed by preparing a simple plot or a simple table of the deviations in the ball bar length without regard to measurement location. An example of a scatter plot is given in Fig. 30. If desired, the calibrated length of the ball bar or gage block should be used instead of the average length when making the scatter plot. The working tolerance of the machine is defined as the range of data in such a plot, as is clearly indicated in the figure, or simply the total range in the values in the table. In cases where there appears to be a single (or several) outlying point(s) that does not conform to the general trend, it is recommended that this measurement be repeated.

The recommended procedure for checking the repeatability of a ball bar measurement is as follows. The ball bar shall be measured twice in the suspected position. If the measurements agree within twice the repeatability (para. 5.3), then the first measurement shall be used and the second measurement discarded. If the measurements do not agree within twice the repeatability, both are discarded and the procedure is repeated. This procedure may be repeated three times; at the end of which time, if repeatability has not been obtained as defined above, the test shall be discontinued and the fault determined and corrected. After correction of the problem, the repeatability test and the ball bar test must be rerun in their entirety.

5.5.3 Offset Probe Performance Test. The angular motion of the ram axis was not tested by the preceding procedure (see para. 5.5.2). This motion is of particular importance when probes with different offset lengths are used. The following test is designed to evaluate the machine performance when offset probes are used. Although the illustrations show vertical spindle machines, this test applies equally to horizontal arm machines.

5.5.3.1 Ball Bar Tests for Offset Probe Performance. The ball bar can be used to place tolerances on the magnitude of offset probing errors by using a probe with a large offset. A typical test setup is shown in Fig. 31. The probe offset length shall be set at a reasonable amount [approximately 150 mm (approx. 6 in.) is recommended], the probe shall be oriented perpendicular to both the ball bar axis and the ram axis, and measurements shall be made of the ball bar length with the offset probe, first with the probe in one position and then rotated 180 deg. about the ram axis with respect to that position. In performing these measurements, the ball bar may be moved to a second position, with nominally the same angle with respect to the ram and probe offset axes, rather than repositioning the cross-slide of the machine, as is shown in Fig. 30. These two procedures may give different results. When the cross-slide is moved, this movement may tilt the ram axis and lead to different results. For the purposes of this Standard, either procedure is allowed. Note that when offset probes are used, it is extremely important that they be properly balanced so as not to place undue moments on the ram. The default ball bar

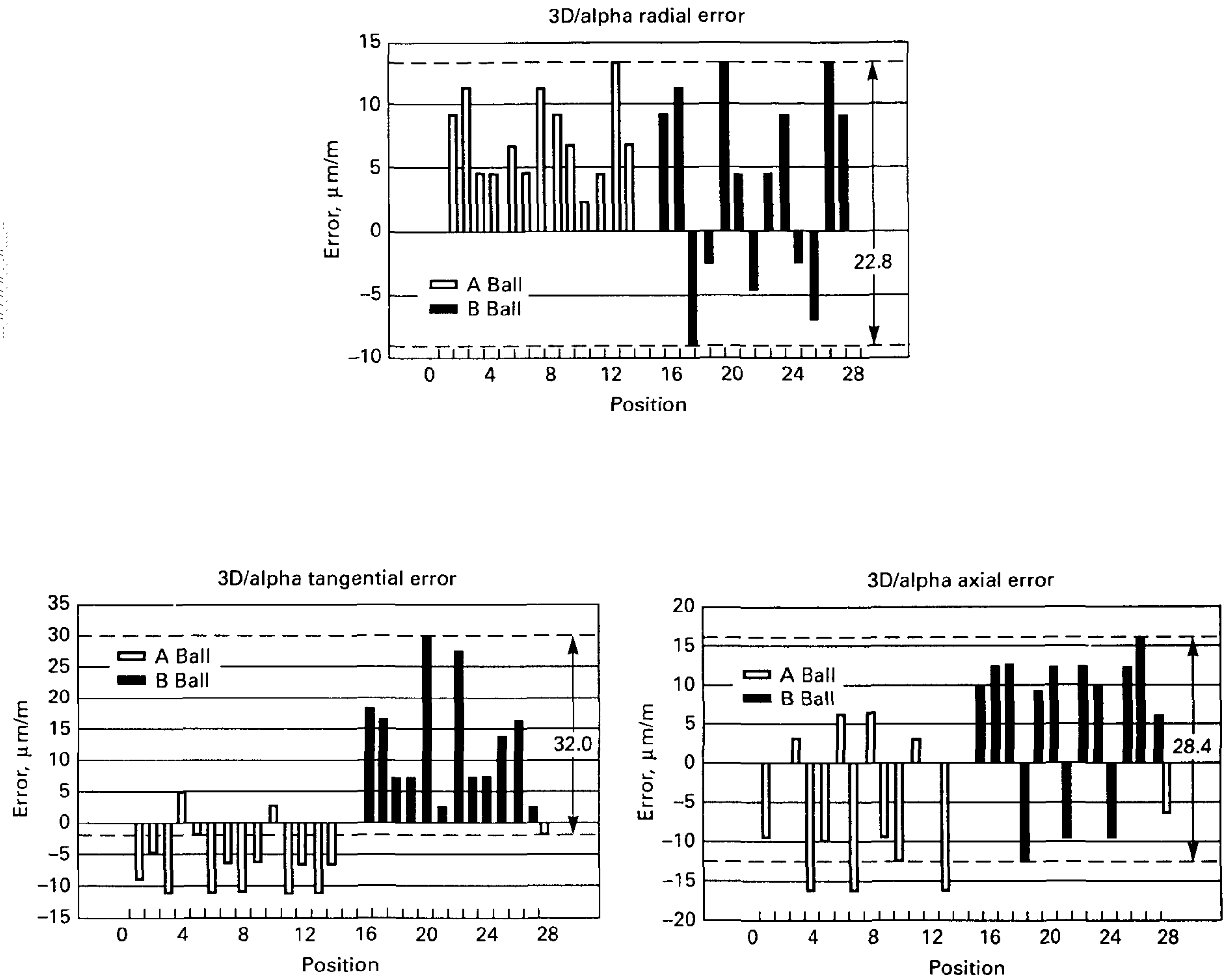


FIG. 36 TYPICAL RESULTS OF A VOLUMETRIC PERFORMANCE TEST FOR A DCC MACHINE WITH A ROTARY AXIS
(The 3D/alpha radial, 3D/alpha tangential, and 3D/alpha axial working tolerances are clearly labeled on the graphs.)

(*d*) The load at any specific contact point will be no greater than twice the load of any other contact point.

(*e*) The center of gravity of the machine load must lie within the CG location zone.

(*f*) The specific test load must fall within acceptable machine load limits, as defined by the Load Concentration Chart (Fig. 3).

The following steps should be taken for the test procedure.

(*a*) Place the test weight on the machine.

(*b*) Perform the repeatability test as described in this Standard (para. 5.3), with the exception of location. Location is optional in this test.

(*c*) Perform six ball bar measurements, as physical constraints allow, selected from the following eleven user-selectable positions:

(*1*) (four) 3D diagonals (as available);

(*2*) planar diagonal (front);

(3) planar diagonal rear (opposite orientation);

(4) planar diagonal (top);

(5) planar diagonal (left side);

(6) planar diagonal (right side — opposite orientation); and

(7) two orthogonal linear axes.

WARNING: Omission of 3D diagonals may prevent seeing the full effect of loading.

(d) Remove weight.

(e) Repeat *(b)* above (repeatability test).

(f) Repeat *(c)* above (ball bar measurements).

(g) Perform a repeatability analysis: results of tests *(b)* and *(e)* shall not exceed the stated repeatability specification.

(h) Perform volumetric analysis:

(1) range of readings of test *(c)* shall not exceed stated machine volumetric performance specification;

(2) range of readings of test *(f)* shall not exceed stated machine volumetric performance specification;

(3) the difference between a measured length in test *(c)* and the measured length from the same position in test *(f)* shall not exceed 50% of the machine volumetric performance specification.

5.5.7.2 Optional Procedure (Laser or Gage Block). Follow the procedure described above using a laser interferometer, gage block, or other equivalent device as the measured artifact. Analyze all data per para. 5.5.7.1.

5.5.7.3 Rotary Table Machine Procedure. For a rotary table machine, the procedure is as follows.

(a) Calibrate the rotary table in an unloaded mode.

(b) Place weight on the machine in compliance with the guidelines of para. 5.5.7.1 above.

(c) Perform the repeatability test as described in para. 5.3, with the exception of location. Location is optional in this test.

(d) Perform the volumetric performance test for DCC machines with a rotary axis (para. 5.5.6) using positions listed in column A1 of Table 2.

(e) Remove weight.

(f) Repeat *(c)* above (repeatability test).

(g) Repeat *(d)* above (volumetric performance test).

(h) Analysis: results of tests *(c)*, *(d)*, *(f)*, and *(g)* shall not exceed the stated machine performance specifications for repeatability, radial, tangential, and axial (3D/alpha) error.

NOTE: It is recommended that a weight with simple geometric form be used for testing purposes to reduce potential difficulties in calculating the CG location.

5.5.8 Volumetric Performance Requirements. Volumetric performance, as calculated in paras. 5.5.2, 5.5.3, 5.5.4 (if applicable), 5.5.5 (if applicable), 5.5.6 (if applicable), and 5.5.7 (if applicable) shall not exceed the supplier's specifications, derated as specified in paras. 4.2 and 4.3, if applicable.

5.6 Bidirectional Length Measurement Capability

5.6.1 General. The preceding tests have produced a meaningful picture of the measurement system performance; however, some errors, such as undue machine or probe hysteresis and improper probe compensation, have not been fully analyzed since no two-sided length measurement has yet been performed. The following tests remove this deficiency by requiring the measurement of a gage block of a convenient length, in four positions in the machine work zone. Three of these positions are roughly aligned with the machine axes, and the fourth position is user-selectable. It is recommended that this fourth position not be aligned with any machine axis. The length of the block shall be within the range of at least 25 mm (approx. 1 in.) to 100 mm (approx. 4 in.), with the default value being 25 mm (approx. 1 in.). The gage block shall be calibrated in accordance with the requirements of para. 7.3.1.

Before performing these tests, the machine probe shall be calibrated and qualified according to the supplier's recommendations for normal operation of the machine when measuring parts. Qualification on the gage block to be used for this test is specifically excluded. The measurements for this test are also to be performed using the probing parameters, probe approach rate, probe approach distance, and settling time specified for normal operation in Fig. 1A.

5.6.2 Measurement Procedure — Bidirectional Length Measurement. (b) The gage block conforming to the requirements of para. 5.6.1 above shall be rigidly mounted in the work zone of the machine on a fixture that allows probing access to the faces of the gage block for the four measurement positions in turn. The mean temperature of the gage block and the appropriate machine scale(s) may be measured during this gage block measurement process for each position, using a thermometer conforming to the requirements of Section 7. The exact location of the gage block in the work zone is not critical; however, it is recommended that this position be near the location in the work zone where parts will most commonly be measured. After mounting and alignment, which may be mechanical or performed by using the appropriate computer algorithm, the length of the gage block shall be measured four times in each position using the method recommended by the supplier for measurement of distance between two parallel planes. The probe shall be calibrated and qualified, following the requirements stated in para. 5.6.1, before each of the measurements.

(b) **5.6.3 Bidirectional Length Measurement Data Analysis.** The length of the gage block shall be calculated using the coordinate measuring machine software for each of the sixteen measurments and may be corrected for temperature as described in para. 5.4.2.6. The worst case (largest) deviation, without regard to sign, between the calibrated and the measured values of the length of the gage block, along with the nominal length of the gage block, is reported as the bidirectional length measurement capability of the machine. In cases where there appears to be a single (or several) outlying point(s) that does not conform to specification, it is recommended that this measurement be repeated in order to ascertain whether the large deviation actually reflects a systematic error. The procedure for checking repeatability is given in para. 5.5.2.3, which states a gage block shall be measured twice in the suspected position. If the measurements agree within twice the repeatability (para. 5.3), the first measurement shall be used and the second one discarded. If the measurements do not agree within twice the repeatability, then both are discarded and the procedure is repeated. This procedure may be repeated three times; at the end of which time, if repeatability has not been obtained as defined above, the test shall be discontinued and the fault determined and corrected.

5.6.4 Bidirectional Length Measurement Capability Requirement. Bidirectional length measurement capability, as calculated in para. 5.6.3, shall not exceed the supplier's specification, derated as specified in paras. 4.2 and 4.3, if applicable.

(b) 6 SUB-SYSTEM PERFORMANCE TESTS

The preceding sections have provided a reasonable test of the coordinate measuring machine as a system. Many errors have, however, either been hidden as part of another measurement or not fully assessed. The purpose of this section is to address those errors attributable to contacting point taking probe systems, which could include scanning probes used in single point-taking mode.

6.1 Probing Analysis — Point-to-Point Probing

A major factor contributing to the total system measuring error is the performance of the probing system, which includes the probe, the probe stylus, the machine dynamics, and other variable parameters. The following tests have been devised to establish the magnitude of the possible errors contributed by the probing sequences for probes used in the point-to-point measuring mode. For the purposes of this Standard, this includes switching probes, proportional probes, and nulling probes capable of performing these measurements as they are used to acquire coordinate data one point at a time (i.e., not in a scanning mode). In all cases in these tests, data are acquired by withdrawing the probe from the specified previously measured point and directing it to the new position to acquire the next point. The measurements for this test are to be performed using the probing parameters, probe approach rate, probe approach distance, and settling time specified for normal operation in Fig. 1A.

6.1.1 Method of Test — Point-to-Point Probing. A precision reference ball conforming to the requirements of para. 7.3.3 shall be rigidly mounted on the workpiece supporting surface in the work zone of the machine on a fixture that allows access by the machine probing system. The illustration (Fig. 37) shows a calibration ball with the default diameter of 6 mm (approx. 0.25 in.). Any position may be chosen for this mounting, with the default position being the TVE position as specified in Fig.1. Three probing tests shall be performed on this ball, using styli with different configurations. The three default styli are as follows: a 10 mm (approx. 0.4 in.) long straight stylus, a 50 mm (approx. 2 in.) long straight stylus, and a 50 mm (approx. 2 in.) long straight stylus with a 20 mm (approx. 0.8 in.) offset perpendicular to the ram axis. The stylus tips can be of any diameter that allows the measurement to be made; however, a 6 mm (approx. 0.25 in.) diameter ball tip [sphericity of 0.25 microns (approx. 10 μin.) or less] is the default for each of these three styli used to probe the test ball. Note that, in order to allow measurement of the test sphere with the offset stylus, the support holding the test ball must be rotated 90 deg. from the position shown in Fig. 37. Furthermore, some types of probes may not be able to perform this test with an offset stylus, thus the machine (probe) supplier shall be consulted before performing this test.

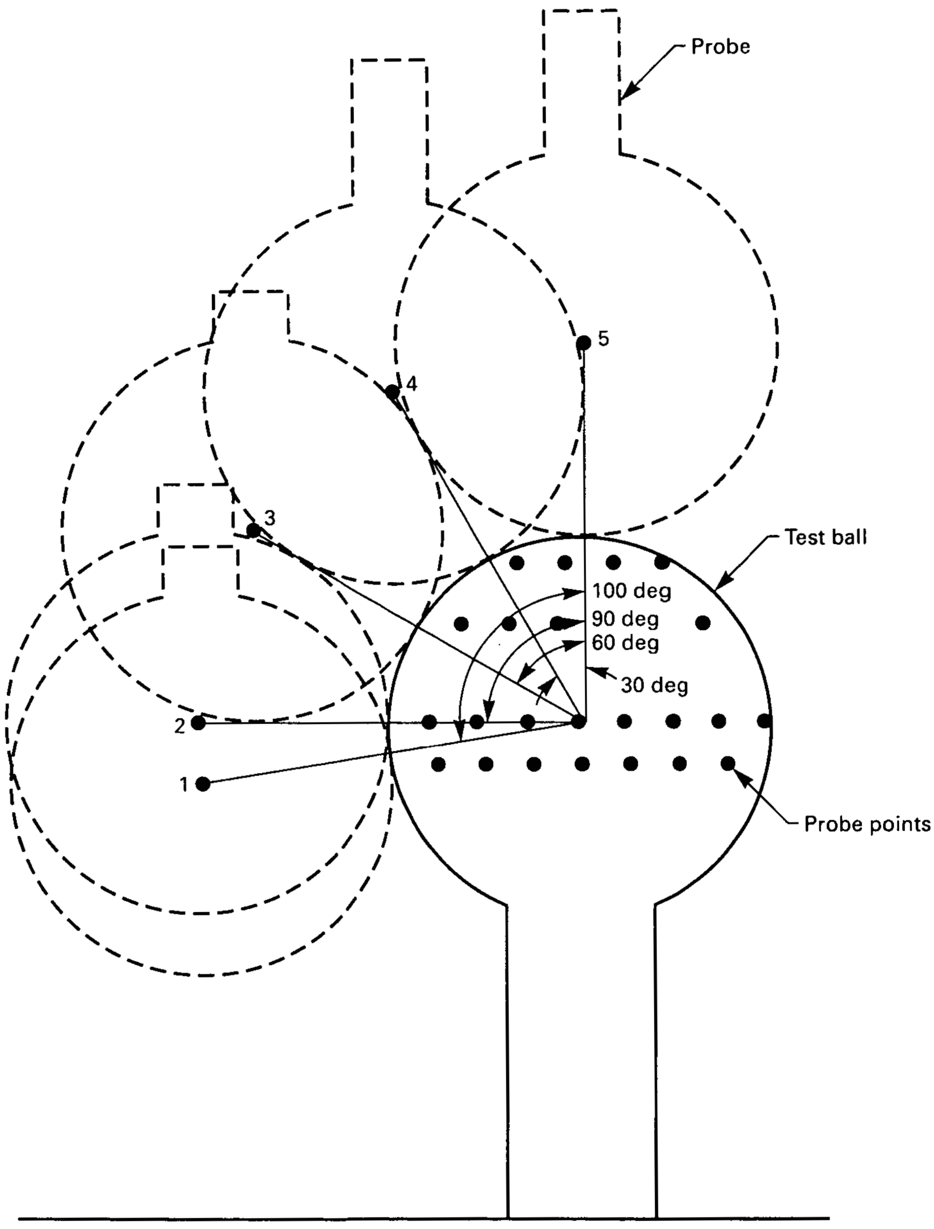


FIG. 37 SCHEMATIC DIAGRAM SHOWING THE LOCATIONS OF PROBING IN THE POINT-TO-POINT PROBING TEST

(Here the test ball is shown having a 6 mm (approx. 0.25 in.) diameter, the same as the stylus ball. Also, the support for the test ball must be rotated 90 deg when performing this test with an offset stylus.)

The user is allowed to specify any test pattern desired containing 49 points. The default test for direct computer-controlled machines is as follows. With each of these styli, 49 points are probed on the test ball at five different heights on that ball: 12 equally spaced on a circle around the test ball when the stylus ball center is approximately 100 deg. from the pole of the test ball in a direction parallel to the shank attached to the stylus ball, 12 equally spaced on the equator with the pattern rotated about the stylus shank 10 deg., 12 equally spaced around the ball with the stylus center approximately 60 deg. from the pole and rotated about the stylus shank an additional 10 deg. relative to the previous pattern, 12 equally spaced with the stylus center approximately 30 deg. from the pole with the pattern again rotated an additional 10 deg., and finally, one on the pole of the test ball. This situation is depicted in Fig. 37, in which the different probe positions are shown with dashed lines and labeled positions 1 to 5. The default test for manual machines is the measurement of 49 points distributed as uniformly as practical over the measurable portion of the test ball.

On direct computer-controlled machines, the probe shall be vector-driven toward the test ball center for each touch, provided this is normal for the machine when measuring parts. On driven manual and free-floating manual machines, where possible, one axis should be locked and the remaining axes moved to contact the ball in order to accurately hit the test ball. In all cases, the supplier's probe approach distance, probe approach rate, and settling time, as given in Fig. 1A, shall be used.

6.1.2 Data Analysis — Point-to-Point Probing. From each set of 49 readings for each stylus, a sphere center is computed using the supplier's recommended algorithms. From this center a radius is then determined for each measurement point. The minimum radius is subtracted from the maximum radius to produce the point-to-point probing performance for each of the stylus lengths. If the result obtained for a particular stylus is less than the working tolerance for the test, then the testing is discontinued for that stylus and the result reported. If the result for any stylus is greater than the working tolerance, then the test shall be repeated. If the new results agree to within the working tolerance for repeatability (para. 5.3), then the second set of data is discarded and the first set used for the analysis. If they do not agree, then a third set shall be taken. If this agrees with either of the two previous sets, then the first of the agreeing sets shall be used in the analysis. If no agreement to within the working tolerance for repeatability is obtained after three measurement sequences for any given stylus, the test is discontinued and the fault determined and corrected. After correction, all of the tests described in this section, even those for stylus lengths that were previously in tolerance, shall be repeated.

6.1.3 Probe Approach Tests — Optional. Many machines/probe systems exhibit vastly different characteristics depending on the probe approach distance and the probe approach rate. For the machine user desiring to use more than one value of these parameters, this test of the machine performance is recommended. The procedure is the same given in paras. 6.1.1 and 6.1.2, except that this test is performed for two different probe approach distances and probe approach rates. The working tolerance for point-to-point probing is specified for each of these options.

6.1.4 Point-to-Point Probing Performance Requirements. Point-to-Point probing performance, as calculated in paras. 6.1.2 and 6.1.3 (if applicable), shall not exceed the supplier's specifications, derated as specified in para. 4.3, if applicable.

6.2 Probing Analysis — Multiple-Tip Probing (b)

In addition to the probing errors highlighted in para. 6.1.1, CMMs that use multiple stylus tip positions can have additional errors. These errors can be due to a number of sources including the uncertainty in location of each of the stylus tips caused by tip calibration errors or by the errors associated with the use of an orienting head or probe changer. This is true for all multiple-tip system configurations, including:

(a) systems using CMM probes and multiple fixed styli such as star clusters;

(b) systems using automatic or manually oriented heads on DCC CMMs which can be prequalified;

(c) systems using automatic probe or stylus changers; and

(d) systems using heads with multiple probes.

The common element of these systems is that different stylus tips or tip locations are used to inspect a workpiece without any recalibration of the different tips. As a result, it is important to understand any additional errors which might be contributed by these systems. Non-contact probing and continuous contact scanning systems are excluded from this multiple-tip probing test, which is not applicable for these sensors.

(b) **6.2.1 Method of Test — Multiple-Tip Probing.** The principle of this test procedure is to measure the form, size, and location of a test sphere using five different stylus tip positions. The detailed test procedures applicable to the multiple-tip configurations defined in para. 6.2 are described below.

(a) Probe and Multiple Fixed Styli, Test Description. Using each of the five fixed sylus tips take 25 measurement points on the test sphere, giving 125 points in total.

(b) System Using Orienting Probe Heads (Either Automatically or Manually Positioned). Using five diffrent angular positions of an orienting probing system, take 25 measurement points on the test sphere at each angular position, for a total of 125 points.[1]

(c) System Using Stylus or Probe Changers. If a stylus or probe changing system is used, then five changes will be performed, one for each set of 25 points pr stylus tip, giving 125 points in total.[1]

(d) System Using Heads With Multiple Probes. Identical procedure to that for multiple-fixed styli above [see para. 6.2.1(a)].

Common to all the above, for each group of 25 points taken with a single stylus, calculate a least squares sphere fit, for a total of five sphere fits. The range of all five sphere center coordinates (X, Y, and Z) is calculated. The largest of these three ranges yields the multiple-fixed stylus location error or the orienting probing system stylus location error for that particular stylus length.

In addition, a least squares sphere fit using all 125 points is examined for form and size errors. This analysis yields either the multiple-fixed stylus size error or the orienting probling system size error, and the multiple fixed stylus form error or the orienting probing systme form error.

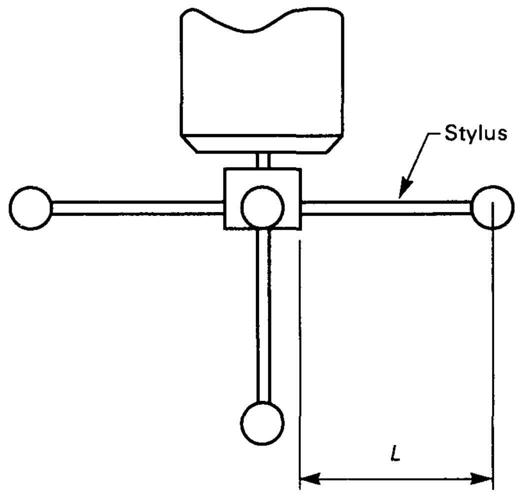
The test sphere should be displaced from the location of the reference sphere used for the probing system qualification in both the X and Y directions a distance at least equal to the largest extension plus stylus length used in the test.

(a) Common Point Sampling Strategy. The distribution of 25 points for a vertical stylus over half a hemisphere, is defined in Table 3, (measuring angles counter-clockwise from the equator to the sphere center).

For situations when the stylus is horizontal (e.g. horizontal arm CMMs, orienting probe systems, or fixed horizontal probes), a similar sampling strategy should be used with the "pole" defined by the direction of the stylus. If a stylus or probe changing system is supplied with the CMM, the five changes shall be performed. Hence, each of the five styli shall be exchanged once. (If fewer than five probe/styli stations are available in the changing system, then the maximum number shall be used and some styli or probes will be exchanged more than once to achieve a total of five exchanges.)

TABLE 3 DEFAULT POINT DISTRIBUTION (b)

Angle, Deg	Number of Equispaced Points
90 Pole	1
67.5	4
45	8
22.5	4
0	8



GENERAL NOTE: Four styli shown for clarity.

FIG. 38 FIXED MULTIPLE-TIP STYLUS ASSEMBLY OF LENGTH, *L* (b)

(b) Fixed Mutiple-Tip Stylus Selection. Construct a "star" stylus system composed of one vertical stylus and four horizontal styli, each oriented 90 deg with respect to each other. The length of each stylus shall be *L*. The distance from the probe to the connection point shall be the minimum distance possible using the stylus components normally supplied with the CMM probing system unless otherwise specified (see Fig. 38).

Since the results of these tests are highly dependent on the stylus assembly, a series of stylus lengths are considered; only those stylus lengths which the CMM

[1] When using manual orienting heads on DCC CMMs, the user is advised to consult the manufacturers operating guide for any special instructions or specifications, for changing either styli, extension bar, or probes with repeatable couplings.

or probing manufacturer specifics as applicable to the probing system shall be tested, see Table 4 (see also Fig. 38).

(c) Orienting Systems Stylus and Extension Selection. Attach a short straight stylus (default length 20 mm), and the manufacturers allowable probe extension component selected from Table 5, to the automatically or manual orienting head probing system.

(d) Default Head Positions. There will be five default angular positions for the automatic or manually orienting heads, one vertical and four horizontals, each at 90 deg to each other.

(e) Common Tip Qualification. For all systems, qualify each stylus tip in accordance with the CMM manufacturers' normal operation procedures. The stylus and extension components shall be those normally sold with the CMM probing system unless otherwise stated.

(f) Common Measuring Equipment. The precision test sphere shall have a diameter no less than 10 mm and no larger than 30 mm. The test sphere must be calibrated for size and form. Use of the CMM calibration sphere as the test sphere is not allowed.

The precision test sphere conforming to the requirements of para. 7.3.3 shall be rigidly mounted on the work piece supporting surface in the work zone of the machine on a fixture that allows access by the machine probing system. Any position may be chosen for this mounting with the default position being the TVE position as specified in Fig. 1B of the Standard.

(b) **6.2.2 Common Data Analysis — Multiple-Tip Probing.** For each group of 25 points taken with a single stylus, perform a least squares sphere fit. Calculate the range of the five sphere centers for each (X, Y, and Z) axis, respectively. The largest of these three ranges is either the multiple-fixed stylus location error or the orienting probing system location error.

Perform a least squares sphere fit on all 125 points taken with all five styli. Record the deviation of the sphere fit diameter from the calibrated value of the material standard of size; this is either the multiple fixed stylus size error or the orienting probing system size error. Similarly, record the range or radii of the 125 points with respect to the least squares sphere center, i.e., the sphere form; this is either the multiple fixed stylus form error, or the orienting probing system form error.

Examples of the results specification sheets for both multiple fixed styli and orienting probing systems are shown in Tables 6 and 7, respectively.

(a) Conditions of Acceptance. If the result obtained is less than the working tolerance for the test, then the result is reported. If the result is greater than the working tolerance, then the test shall be repeated. If the new result agrees with the result of the first test within the working tolerance for repeatability (para. 5.3), then the second set of data is discarded and the first set is used for the evaluation. If they do not agree, then a third set should be taken. If this agrees with either of the two previous sets, then the first of the agreeing sets shall be used in the evaluation. If no agreement to within the working tolerance for repeatablility is obtained after three measurement sequences, this test is discontinued and the fault determined and corrected. After correction, the repeatabiltiy test (para. 5.3.3) and all of the tests described in this section shall be repeated.

Repeat the procedure for each stylus or probe extension length permitted by the manufacturer.

TABLE 4 DEFAULT STYLUS LENGTHS (b)

Stylus L, mm
10
20
30
50
100
200
400

TABLE 5 DEFAULT EXTENSION LENGTHS (b)

Stylus L, mm	Extension, mm
20	0
20	100
20	200
20	300

6.2.3 Multiple-Tip Probing Performance Requirements. Multiple-tip probing performance, as calculated in para. 6.2.2, shall not exceed the supplier's specifications, derated as specified in para. 4.3, if applicable.

6.3 Probing Analysis — Scanning. In addition to the point-to-point probing errors highlighted previously, CMMs that are used in a scanning mode can have additional errors. These errors are due to a number of sources, including the machine and probing system dynamic response to the surface being measured, external vibration, and probe tip calibration errors. The tests in this section are applicable to any CMM equipped with a contact probing system capable of obtaining a large number of consecutive points along a path. The (b)

(b) **TABLE 6 EXAMPLE OF MULTIPLE-TIP PROBING PERFORMANCE WITH FIXED STYLI RESULTS SHEET**

Fixed Multiple Stylus L, mm	Location Error, μm	Size Error, μm	Form Error, μm
10	____	____	____
20	____	____	____
30	____	____	____
50	____	____	____
100	____	____	____
200	____	____	____
400	____	____	____

(b) **TABLE 7 EXAMPLE OF MULTIPLE-TIP PROBING PERFORMANCE WITH ORIENTING PROBING SYSTEM RESULTS SHEET**

Orienting Probing System Extension, L, mm	System Location Error, μm	System Size Error, μm	System Form Error, μm
0	____	____	____
100	____	____	____
200	____	____	____
300	____	____	____

error sources that affect scanning performance have not been fully analyzed by the preceding tests. Therefore, it is important to understand these additional errors if the CMM is going to be used in a scanning mode.

(b) **6.3.1 Method of Test — Scanning.** The scanning performance test is to be done in accordance with the International Standard ISO 10360-4, *Acceptance Test and Reverification Test for CMMs Used in Scanning Measuring Mode*. The ISO 10360-4 Standard shall be consulted for further information on performing these tests. For the purposes of this Standard, additional defaults are prescribed here. The test artifact in the ISO 10360-4 test is a 25 mm diameter steel sphere. Scanning performance can be influenced significantly by the scanning path trajectory. Therefore, the sphere size shall be within 1 mm of the nominal 25 mm diameter. In addition, as is prescribed in the ISO 10360-4 test, the single stylus used in the testing shall have a nominal spherical tip diameter of 3 mm, and deviations from this size can impact significantly the results of this test. The test sphere also shall conform to the requirements of para. 7.3.3, and the diameter of the test sphere must be calibrated with an uncertainty less than one-fifth the scanning performance working tolerance of this test. The default mounting position of the test sphere is the TVE position as specified in Fig. 1B. The default stylus length is 50 mm. The default orientation of the stylus is at an angle of 45 deg to the ram axis of the CMM.

To quantify the scanning capability of a CMM, both the scanning performance and scanning measurement time are required. Since most CMMs with scanning capability allow for various scanning speeds, the optimal scanning time and optimal scanning performance usually will occur under different conditions. Therefore, three default conditions are prescribed for the scanning test as follows:

(a) the optimal scanning time;

(b) the optimal scanning performance; and

(c) the supplier's recommended settings.

As discussd in detail in ISO 10360-4, the scanning tests are to be done using both high point density (10 points/mm) and low point density (1 point/mm) and both predefined and not predefined scanning paths. The supplier shall define the scanning speeds and working tolerances associated with these conditions.

6.3.2 Data Analysis — Scanning. The scanning performance is determined using the procedures described in ISO 10360-4. The reported value for the scanning performance shall be the greater of the "scan probing error" or the "maximum absolute difference" in radius as described in ISO 10360-4 paras. 6.2*(a)* and 6.2*(b)*, respectively. The scanning time shall be the "time taken for scanning measuring mode test" as described in ISO 10360-4 para. 6.2*(c)*. (b)

6.3.3 Scanning Performance Requirements. The scanning performance and scanning time, as calculated in para. 6.3.2, shall not exceed the supplier's specifications, derated as specified in para. 4.3, if applicable. (b)

6.4 Vectoring Performance (b)

The vectoring performanc test is intended for contact probes, with either single- or multiple- styli. This includes switching probes and proportional probes used in the single-point-taking mode. This test is applicable only to machines used in the direct computer control mode.

Vectoring errors of the CMM can, in certain circumstances, result in measurement errors. An example is the case where a design table specifies a contoured surface by tabulating discrete points on the surface. If the CMM fails to follow the commanded vector accurately, an error in the reported surface location may occur, depending on the software and measurement strategy adopted. Vectoring performance also affects a probe's ability to enter very small holes, slots, or narrow ledges on a part. The following test will establish the vectoring performance of the CMM.

(b) **6.4.1 Method of Test — Vectoring Performance.** This test uses the data and methodology (test apparatus and probing equipment) from the point-to-point probing test (para. 6.1). Any position on the table may be chosen for this test with the default being the TVE position as specified in Fig. 1B. The sequence of measurement of the 49 points shall be such that moves are not to the next nearest point but must be randomly selected at times requiring movement to the opposite side of the reference ball. If the points in the point-to-point probing test were measured sequentially, it is then necessary to repeat the 49-point measurements in random order to perform the vectoring performance test. Also, the target points specified for the touch-drive vectors must all lie on a nominal sphere surface, centered on the test sphere but with a radius equal to the sum of the actual test sphere and effective stylus tip radii, not at the test sphere center. The nominal start point for each touch should be on the straight line from the sphere center through the target point.

All point measurements shall be taken using the values specified in Fig. 1A for probe approach rate, probe approach distance, drive velocity, acceleration, deceleration, drive-move target tolerance, touch-move target tolerances, settling time(s), and any other probing parameters.

(b) **6.4.2 Data Analysis — Vectoring Performance.** For each of the 49 points a reference line is established. This is the line through the center of the sphere and the target point for the touch-drive vector. Note that the center of the sphere used to establish the reference line for data analysis is the sphere center used for determining drive and touch moves of the vectoring test. The sphere center is not the center of the measured 49 points. The minimum distance from the tip center coordinates at trigger to the reference line is computed for each of the 49 measurements. The maximum distance found in the 49 masurements is the vectoring performance.

7 TEST EQUIPMENT

7.1 Temperature

The time constant of thermometers shall be no more than one-tenth 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.

The resolution of thermometers need be no greater than one-tenth the amplitude of the lowest-amplitude component of temperature variation of interest in a test.

Thermometers shall be calibrated by suitable means to an accuracy of ±0.1°C over the temperature range of use.

7.2 Vibration

For the purposes of this Standard, relative motion shall be measured using a high-resolution, undamped displacement indicator. Resolution of 0.1 μm (approx. 0.000004 in.) or better is recommended.

7.3 Displacement

7.3.1 Gages. Step gages and gage blocks shall be calibrated to within one-fifth the working tolerance for the repeatability specified for the CMM. Indicating gages shall have a resolution of no more than one-fifth the working tolerance for repeatability. All gages shall be calibrated following the supplier's recommendations.

7.3.2 Laser Interferometer. A laser interferometer conforming to the requirements of this Standard shall have a frequency stability such that this long-term stability represents an error of less than one-fifth the working tolerance for repeatability of the machine (in meters), divided by the length of the longest machine axis (in meters). The resolution of such a system shall be better than one-fifth the working tolerance for repeatability.

7.3.3 Precision Reference Ball(s). The precision reference ball(s) for the repeatability, TVE, and probing performance tests shall be spherical to within one-fifth the working tolerance for repeatability of the CMM.

7.3.4 Ball Bar. The ends of the ball bar shall be spherical to within one-fifth the working tolerance for repeatability of the CMM. For information regarding ball bars, see Appendix G.

7.4 Pressure

The uncertainty of the pressure sensor used for correction of the laser interferometer shall be no greater than ±1 mm Hg.

7.5 Humidity

Humidity measurement for correction of the laser interferometer wavelength shall be sufficiently accurate that it contributes no more than one-fifth the CMM working tolerance for repeatability to laser measurement error.

7.6 Utility Air

For the purposes of this Standard, the utility air pressure shall be measured using the gages supplied with the machine.

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AN AMERICAN NATIONAL STANDARD

ASME B89.4.1a-1998

ADDENDA

to

ASME B89.4.1-1997
METHODS FOR
PERFORMANCE EVALUATION OF
COORDINATE MEASURING MACHINES

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS

Three Park Avenue • New York, NY 10016-5990

Date of Issuance: June 8, 1998

This code or standard was developed under procedures accredited as meeting the criteria for American National Standards. The Standards Committee that approved the code or standard was balanced to assure that individuals from competent and concerned interests have had an opportunity to participate. The proposed code or standard was made available for public review and comment which provides an opportunity for additional public input from industry, academia, regulatory agencies, and the public-at-large.

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ASME B89.4.1a-1998

Following approval by the ASME B89 Committee and ASME, and after public review, ASME B89.4.1a-1998 was approved by the American National Standards Institute on March 3, 1998.

Addenda to the 1997 edition of ASME B89.4.1 are issued in the form of replacement pages. Revisions, additions, and deletions are incorporated directly into the affected pages. It is advisable, however, that this page, the Addenda title and copyright pages, and all replaced pages be retained for reference.

SUMMARY OF CHANGES

This is the first addenda to be published to ASME B89.4.1-1997.

Replace or insert the pages listed. Changes listed below are identified on the pages by a margin note, **(a)**, placed next to the affected area. The pages not listed are the reverse sides of the affected pages and contain no changes.

Page	*Location*	*Change*
ix	Contents	Revised
46	5.5.7.1(g)	Revised
	5.5.7.1(h)	Subparagraphs (1), (2), and (3) revised
	5.5.7.3(h)	Revised
49, 50	6.2.1	Third paragraph revised
57–58.3	Appendix C	Revised in its entirety
78–78.2	Appendix I	Sections I6, I7, I8, and I9 added

Tables

Appendices

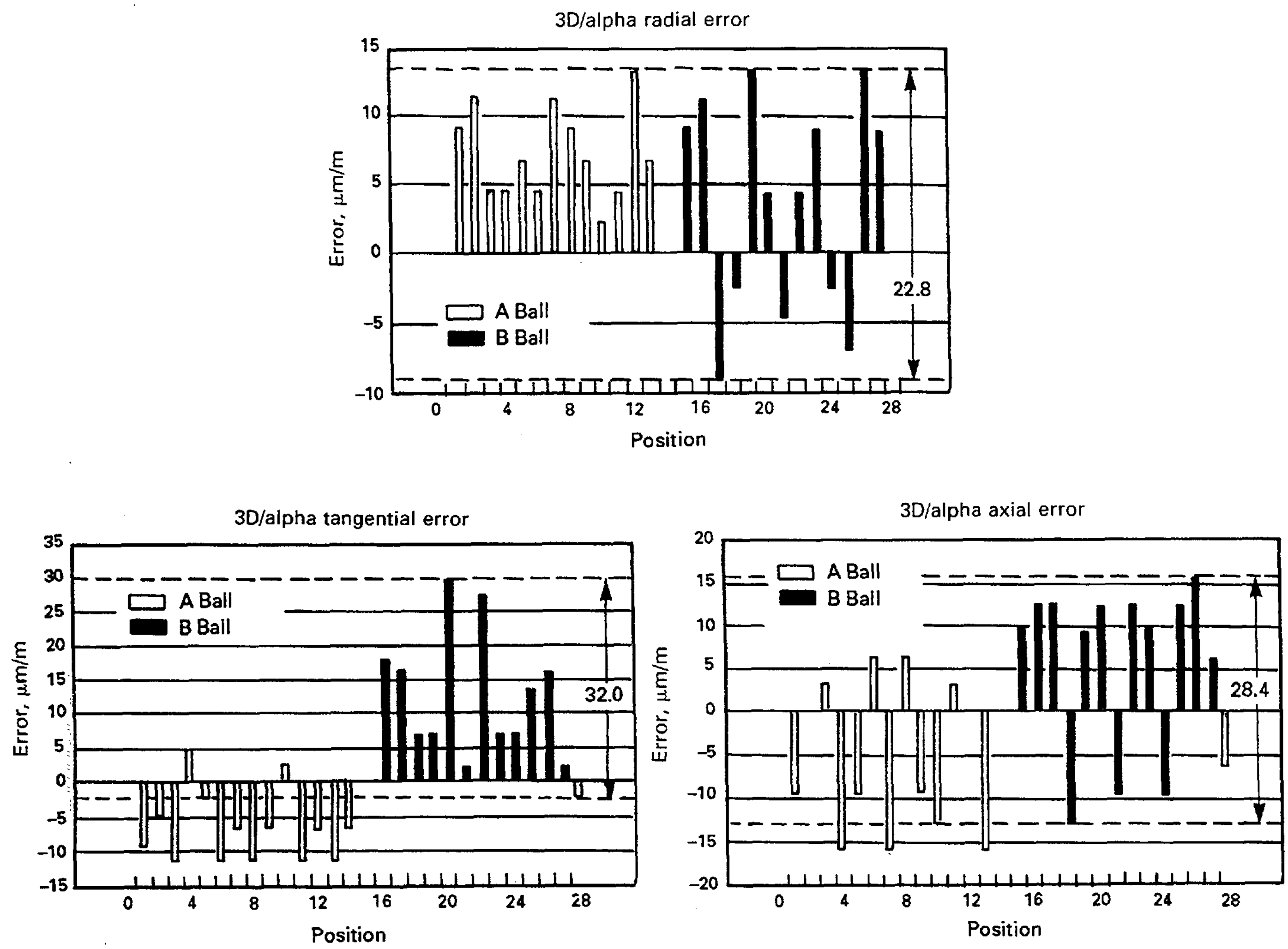

FIG. 36 TYPICAL RESULTS OF A VOLUMETRIC PERFORMANCE TEST FOR A DCC MACHINE WITH A ROTARY AXIS
(The 3D/alpha radial, 3D/alpha tangential, and 3D/alpha axial working tolerances are clearly labeled on the graphs.)

(d) The load at any specific contact point will be no greater than twice the load of any other contact point.

(e) The center of gravity of the machine load must lie within the CG location zone.

(f) The specific test load must fall within acceptable machine load limits, as defined by the Load Concentration Chart (Fig. 3).

The following steps should be taken for the test procedure.

(a) Place the test weight on the machine.

(b) Perform the repeatability test as described in this Standard (para. 5.3), with the exception of location. Location is optional in this test.

(c) Perform six ball bar measurements, as physical constraints allow, selected from the following eleven user-selectable positions:

(1) (four) 3D diagonals (as available);

(2) planar diagonal (front);

(3) planar diagonal rear (opposite orientation);

(4) planar diagonal (top);

(5) planar diagonal (left side);

(6) planar diagonal (right side — opposite orientation); and

(7) two orthogonal linear axes.

WARNING: Omission of 3D diagonals may prevent seeing the full effect of loading.

(d) Remove weight.

(e) Repeat (b) above (repeatability test).

(f) Repeat (c) above (ball bar measurements).

(a) *(g)* Perform a repeatability analysis: results of tests (b) and (e) shall not exceed the stated repeatability specification.

(a) *(h)* Perform volumetric analysis:

(1) range of readings of test (c) shall not exceed stated machine volumetric performance specification;

(2) range of readings of test (f) shall not exceed stated machine volumetric performance specification;

(3) the difference between a measured length in test (c) and the measured length from the same position in test (f) shall not exceed 50% of the machine volumetric performance specification.

5.5.7.2 Optional Procedure (Laser or Gage Block). Follow the procedure described above using a laser interferometer, gage block, or other equivalent device as the measured artifact. Analyze all data per para. 5.5.7.1.

5.5.7.3 Rotary Table Machine Procedure. For a rotary table machine, the procedure is as follows.

(a) Calibrate the rotary table in an unloaded mode.

(b) Place weight on the machine in compliance with the guidelines of para. 5.5.7.1 above.

(c) Perform the repeatability test as described in para. 5.3, with the exception of location. Location is optional in this test.

(d) Perform the volumetric performance test for DCC machines with a rotary axis (para. 5.5.6) using positions listed in column A1 of Table 2.

(e) Remove weight.

(f) Repeat (c) above (repeatability test).

(g) Repeat (d) above (volumetric performance test).

(a) *(h)* Analysis: results of tests (c), (d), (f), and (g) shall not exceed the stated machine performance specifications for repeatability, radial, tangential, and axial (3D/alpha) error.

NOTE: It is recommended that a weight with simple geometric form be used for testing purposes to reduce potential difficulties in calculating the CG location.

5.5.8 Volumetric Performance Requirements. Volumetric performance, as calculated in paras. 5.5.2, 5.5.3, 5.5.4 (if applicable), 5.5.5 (if applicable), 5.5.6 (if applicable), and 5.5.7 (if applicable) shall not exceed the supplier's specifications, derated as specified in paras. 4.2 and 4.3, if applicable.

5.6 Bidirectional Length Measurement Capability

5.6.1 General. The preceding tests have produced a meaningful picture of the measurement system performance; however, some errors, such as undue machine or probe hysteresis and improper probe compensation, have not been fully analyzed since no two-sided length measurement has yet been performed. The following tests remove this deficiency by requiring the measurement of a gage block of a convenient length, in four positions in the machine work zone. Three of these positions are roughly aligned with the machine axes, and the fourth position is user-selectable. It is recommended that this fourth position not be aligned with any machine axis. The length of the block shall be within the range of at least 25 mm (approx. 1 in.) to 100 mm (approx. 4 in.), with the default value being 25 mm (approx. 1 in.). The gage block shall be calibrated in accordance with the requirements of para. 7.3.1.

Before performing these tests, the machine probe shall be calibrated and qualified according to the supplier's recommendations for normal operation of the machine when measuring parts. Qualification on the gage block to be used for this test is specifically excluded. The measurements for this test are also to be performed using the probing parameters, probe approach rate, probe approach distance, and settling time specified for normal operation in Fig. 1A.

5.6.2 Measurement Procedure — Bidirectional Length Measurement. The gage block conforming to the requirements of para. 5.6.1 above shall be rigidly mounted in the work zone of the machine on a fixture that allows probing access to the faces of the gage block for the four measurement positions in turn. The mean temperature of the gage block and the appropriate machine scale(s) may be measured during this gage block measurement process for each position, using a thermometer conforming to the requirements of Section 7. The exact location of the gage block in the work zone is not critical; however, it is recommended that this position be near the location in the work zone where parts will most commonly be measured. After mounting and alignment, which may be center is approximately 100 deg. from the pole of the test ball in a direction parallel to the shank attached to the stylus ball, 12 equally spaced on the equator with the pattern rotated about the stylus shank 10 deg., 12 equally spaced around the ball with the stylus center approximately 60 deg. from the pole and rotated about the stylus shank an additional 10 deg. relative to the previous pattern, 12 equally spaced with the stylus center approximately 30 deg. from the pole with the pattern again rotated an additional 10 deg., and finally, one on the pole of the test ball. This situation is depicted in Fig. 37, in which the different probe positions are shown with dashed lines and labeled positions 1 to 5. The default test for manual machines is the measurement of 49 points distributed as uniformly as practical over the measurable portion of the test ball.

On direct computer-controlled machines, the probe shall be vector-driven toward the test ball center for each touch, provided this is normal for the machine when measuring parts. On driven manual and free-floating manual machines, where possible, one axis should be locked and the remaining axes moved to contact the ball in order to accurately hit the test ball. In all cases, the supplier's probe approach distance, probe approach rate, and settling time, as given in Fig. 1A, shall be used.

6.1.2 Data Analysis — Point-to-Point Probing. From each set of 49 readings for each stylus, a sphere center is computed using the supplier's recommended algorithms. From this center a radius is then determined for each measurement point. The minimum radius is subtracted from the maximum radius to produce the point-to-point probing performance for each of the stylus lengths. If the result obtained for a particular stylus is less than the working tolerance for the test, then the testing is discontinued for that stylus and the result reported. If the result for any stylus is greater than the working tolerance, then the test shall be repeated. If the new results agree to within the working tolerance for repeatability (para. 5.3), then the second set of data is discarded and the first set used for the analysis. If they do not agree, then a third set shall be taken. If this agrees with either of the two previous sets, then the first of the agreeing sets shall be used in the analysis. If no agreement to within the working tolerance for repeatability is obtained after three measurement sequences for any given stylus, the test is discontinued and the fault determined and corrected. After correction, all of the tests described in this section, even those for stylus lengths that were previously in tolerance, shall be repeated.

6.1.3 Probe Approach Tests — Optional. Many machines/probe systems exhibit vastly different characteristics depending on the probe approach distance and the probe approach rate. For the machine user desiring to use more than one value of these parameters, this test of the machine performance is recommended. The procedure is the same given in paras. 6.1.1 and 6.1.2, except that this test is performed for two different probe approach distances and probe approach rates. The working tolerance for point-to-point probing is specified for each of these options.

6.1.4 Point-to-Point Probing Performance Requirements. Point-to-Point probing performance, as calculated in paras. 6.1.2 and 6.1.3 (if applicable), shall not exceed the supplier's specifications, derated as specified in para. 4.3, if applicable.

6.2 Probing Analysis — Multiple-Tip Probing

In addition to the probing errors highlighted in para. 6.1.1, CMMs that use multiple stylus tip positions can have additional errors. These errors can be due to a number of sources including the uncertainty in location of each of the tips caused by tip calibration errors or by the errors associated with the use of an orienting head or probe changer. This is true for all multiple-tip system configurations, including:

(a) systems using multiple styli connected to the CMM probe, such as star clusters;

(b) systems using orienting heads;

(c) systems using probe or stylus changers; and

(d) systems using heads with multiple probes.

The common element of these systems is that different tips or tip locations are used to inspect a workpiece without any recalibration of the tips. As a result, it is important to understand any additional errors which might be contributed by these systems.

6.2.1 Method of Test — Multiple-Tip Probing. The calibration ball diameter and all system configuration dimensions in this Section are default values. Other dimensions may be substituted and it is recommended that this be done if there is any concern that the configurations required to measure actual workpieces are substantially different from the default values. **(a)**

A precision reference ball conforming to the requirements of para. 7.3.3 shall be rigidly mounted on the workpiece supporting surface in the work zone of the machine on a fixture that allows access by the machine probing system. The 6 mm (approx. 0.25 in.) diameter test sphere used in the point-to-point probing test (Section 6.1) may be used for this test. Any position may be chosen for this mounting with the default position being the TVE position as specified in Fig. 1.

Five different probing tip positions shall be used to perform this test. These positions can be created by using a stylus configuration with five tips, five different orientations of an orienting head, or through the use of a probe or stylus changing system using five different tip positions. Two of the probe tip positions shall be on a line perpendicular to the ram axis. Two more shall be on another such line displaced 90 deg. The fifth position shall be on a line parallel to the ram axis through the intersection of the first two lines. The default stylus length, including any extension members, shall be 50 mm (approx. 2 in.) when using any of the above systems or combination of the above.

The user is allowed to specify any test pattern that contains 25 points. These 25 points shall be probed on the test ball as equally spaced as possible and cover as much of the sphere surface as practical. The 25 points shall be taken using five different tips or tip locations and each set of five points probed by each tip shall also be as widespread as possible. As an example, these five points could be four points around the equator of the sphere (assuming the pole position is directly in line with the stylus shaft supporting the tip) plus a point directly in line with the stylus shaft.

6.2.2 Data Analysis — Multiple-Tip Probing. From the set of 25 readings, a sphere center is computed using the supplier's recommended algorithm. From this center a radius is then determined for each measurement point. The minimum radius is subtracted from the maximum radius to produce the multiple-tip probing performance. If the result obtained is less than the working tolerance for the test, then the result is reported. If the result is greater than the working tolerance, then the test shall be repeated. If the new result agrees with the result of the first test within the working tolerance for the repeatability (para. 5.3), then the second set of data is discarded and the first set is used for the evaluation. If they do not agree, then a third set should be taken. If this agrees with either of the two previous sets, then the first of the agreeing sets shall be used in the evaluation. If no agreement to within the working tolerance for repeatability is obtained after three measurement sequences, this test is discontinued and the fault determined and corrected. After correction, the repeatability test (para. 5.3.3) and all of the tests described in this section shall be repeated.

6.2.3 Multiple-Tip Probing Performance Requirements. Multiple-tip probing performance, as calculated in para. 6.2.2, shall not exceed the supplier's specifications, derated as specified in para. 4.3, if applicable.

7 TEST EQUIPMENT

7.1 Temperature

The time constant of thermometers shall be no more than one-tenth 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.

The resolution of thermometers need be no greater than one-tenth the amplitude of the lowest-amplitude component of temperature variation of interest in a test.

Thermometers shall be calibrated by suitable means to an accuracy of ±0.1°C over the temperature range of use.

7.2 Vibration

For the purposes of this Standard, relative motion shall be measured using a high-resolution, undamped displacement indicator. Resolution of 0.1 μm (approx. 0.000004 in.) or better is recommended.

7.3 Displacement

7.3.1 Gages. Step gages and gage blocks shall be calibrated to within one-fifth the working tolerance for the repeatability specified for the CMM. Indicating gages shall have a resolution of no more than one-fifth the working tolerance for repeatability. All gages shall be calibrated following the supplier's recommendations.

7.3.2 Laser Interferometer. A laser interferometer conforming to the requirements of this Standard shall have a frequency stability such that this long-term stability represents an error of less than one-fifth the working tolerance for repeatability of the machine (in meters), divided by the length of the longest machine axis (in meters). The resolution of such a system shall be better than one-fifth the working tolerance for repeatability.

APPENDIX C
CMM SITE VIBRATION MEASUREMENT

(a)

(This Appendix is not part of ASME B89.4.1-1997 and is included for information purposes only.)

C1 SCOPE

The purpose of this Appendix is to recommend vibration measurement instrumentation and procedures for measuring vibration at CMM installation sites. Vibration levels should be measured at the proposed CMM site(s) to compare to allowable site vibration limits established by the CMM supplier. This Appendix also defines the instrumentation and suggested procedures to establish vibration on the CMM for additional analysis. This Appendix does not, however, address the determination of vibration sources or the reduction of vibration levels. Such determination is usually involved and requires the knowledge of vibration specialists.

C2 DEFINITIONS

This Appendix is intended to be self-defining and is written for individuals with an engineering background. Definitions for specific vibration terminology may be found in IES-RP-CC024.1, Measuring and Reporting Vibration in Microelectronics Facilities, published by the Institute of Environmental Sciences.

C3 VIBRATION ACCEPTANCE CRITERIA

The CMM supplier is to provide site vibration levels of acceptability. Below these levels the CMM can operate successfully, and above these levels problems may occur. Each CMM manufacturer has different formats and levels of acceptance. The type of vibration measurements to be taken will depend on format and vibration units used by the CMM supplier. Based on the type of criteria, the vibration specialist should determine the necessary measurement units, frequency range, measurement locations, and instrumentation.

C3.1 Units

Vibration is characterized by amplitude versus time or frequency. The amplitude can usually be defined in displacement, velocity, or acceleration. Depending upon the type of criteria, the amplitude ordinate can be defined in either the time domain or the frequency domain.

C3.1.1 Ordinate Units. Since the CMM is a dimensional measurement tool, units of displacement are most useful in relation to CMM performance. However, velocity and acceleration are also appropriate parameters for measuring CMM site vibration.

C3.1.2 Abscissa Units. The use of time or frequency for the abscissa will depend on the acceptance criteria format of the CMM 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 an ability to diagnose many dynamic events.

C3.2 Format

As defined in B89.4.1, the supplier provides, as part of the machine specification, a statement of acceptable vibration. This criterion should be provided by the supplier, or listed as part of the CMM specification form, if used. At least two criteria format options are presented: Frequency Function and Time History.

The supplied acceptance criteria will define the format in which to present the vibration data for ease of comparison.

C3.2.1 Frequency Response Function. This type of information is 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 (DC) to 100 Hz. Vibration levels have large dynamic range, and it is sometimes helpful to present amplitude data in logarithmic scale. If decibels are used, the standard reference values must also be used.

C3.2.2 Time History. These 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 level can be in units of displacement, velocity, or acceleration.

C3.2.3 As an alternative, the CMM supplier may choose to evaluate vibration related CMM performance degradation on the actual installation site, and compare it with an acceptable level as a basis.

C4 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 use in acquiring this data. It is not the intent of this Section to single out any particular equipment manufacturer, but to recommend types of equipment which meet the requirements of this Appendix.

C4.1 Transducers

Many types of transducers exist for various types of vibration measurements. The measurements specified in this Appendix require a specific accelerometer or a specific type of velocity transducer.

C4.1.1 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 maximum frequency response should be greater than 100 Hz. The sensitivity of the accelerometer should be 10 Volts/g or greater, where g is equal to 9.8 m/sec^2 (386 in./sec^2).

C4.1.2 Velocity Transducers. These sensors are also referred to as geophones. The sensitivity of the geophone should be 0.4 V/mm/sec (10 Volts/in./sec) or greater. The frequency response linearity requirement of the velocity transducer is the same as the accelerometer, 0.5 Hz to 100 Hz.

C4.2 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.

C4.3 Signal Recording/Analysis Instruments

The type of instrumentation to use will depend on the type of criteria and format that have been provided by the CMM supplier. The frequency function criteria requires a Fast Fourier Transform (FFT), a Dynamic Signal Analyzer, and, in some cases, a Digital Recorder. Time History data can be acquired with an oscilloscope, a digital recorder, a FFT analyzer, or a frequency analyzer.

C4.3.1 FFT Signal Analyzers. This type of analyzer offers the most sophisticated means of measuring vibration, by providing 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, hand-held, and PC-based are formats readily available. It should be noted that using a data recorder as specified below will require the use of an FFT analyzer after the data are acquired. It is the user's responsibility to understand their instrument's capabilities and limitations.

The following section offers guidelines for FFT analysis configuration and specifications.

(a) Noise floor. -100 dBV/root Hz.

(b) A/D resolution. The resolution of the analog-to-digital converter should be at least 12 bits. The better analyzers will have 16 bit A/D resolution.

(c) Dynamic range. The dynamic range should be at least 70 dB. Better spectrum analyzers will 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 can have selectable resolution from 100 lines to 1600 lines. The resolution in Hertz is calculated by dividing the frequency range by the number of lines. For example, a 0 to 100 Hz frequency range acquired with a 400 line analysis will have 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. The overall frequency resolution will also be dependent on the transducer frequency response. This information should be complied with and modified only when the CMM manufac-

turer's specification requests otherwise.

(e) Anti-aliasing filter. This filter prevents incorrect reporting of frequency components due to under sampling 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 this feature. When used, it reduces the effects of transient events such as personnel or vehicular activity. It is recommended that 10 averages be taken for all measurements. Some spectrum analyzers have various types of averaging functions such as linear, rms, 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. The Hanning window provides the best compromise in amplitude and frequency accuracy. Other windows provide excellent amplitude accuracy and poor frequency accuracy, and vice versa. The Hanning should be used for all measurements specified in this Appendix.

C4.3.2 Data Recorders. For ease of gathering vibration data in the field, the use of a multi-channel data recorder is found to be 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 FFT analyzers or signal analyzers specified in this Appendix. The recorder format must be digital and use Digital Audio Tape (DAT) because of the excellent signal to noise ratio and dynamic range as compared to analog tape.

C4.3.3 Oscilloscopes. This piece of general laboratory equipment may be easily obtained to make an initial set of Time History readings. Most facilities have an oscilloscope and personnel who can operate the equipment, allowing users to take baseline readings for themselves. 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.

C5 TEST PROCEDURE

The procedures for making vibration measurements are fairly simple once the appropriate analysis equipment is selected and configured as required.

C5.1 Calibration

At a minimum, the vibration measurement equipment should have been calibrated by a qualified laboratory, traceable to NIST, in the past 12 months. Site calibration comparison testing of the transducers at the start of the testing is required.

C5.2 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 transducers incorporate three mutually orthogonal axes in one device. When this mounting arrangement is used, all three channels should be acquired simultaneously. Time independent triaxial measurements should not be performed because simultaneous orthogonal responses will not be achieved.

In case of measurements of floor tilt motions (rocking), two sets of sensors are mounted at a designated distance for simultaneous measurements in two orthogonal vertical planes.

C5.3 Measurement Location

In general, the transducers should be mounted in the general area where the CMM will rest. This area should encompass the outer envelope of the CMM plus 3 m (10 ft) beyond this foot print on a uniform floor surface, or at the CMM support positions.

C5.4 Acquiring/Recording Data

Vibration measurements should be made during normal operations of the facility. Nearby equipment that will be operating when the CMM is expected to be in use 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, such as temporary conditions resulting from construction, repair work, and the like, may be recorded during the test. A test should be repeated if an abnormal event occurs. Normal vehicular traffic should not be excluded. When the environmental conditions are satisfactory, the data should be recorded on tape, saved to memory, printed, or manually recorded.

C5.5 Comparing Vibration Data

After the data acquisition and analysis are complete, the data must be compared to the vibration acceptance criteria.

C5.5.1 Time History. For Time History criteria, this simply involves comparing the measured peak-to-peak vibration levels to the permissible level. The CMM supplier may provide horizontal, vertical, linear, and angular criteria. It is important to compare the acquired data to the criteria in the appropriate direction.

C5.5.2 Frequency Response Function. Comparison of Frequency 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 compare data and criteria with various software programs. 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 down-loaded into 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 is in a software format, it can be manipulated, graphed, and analyzed in a usable format.

C6 SUGGESTED CRITERIA ASSESSMENT

C6.1 Measure Vibration Below Criteria

If the vibration levels measured by the procedure above 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 CMM in order to meet specifications.

C6.2 Measured Vibration Above Criteria

If, on the other hand, the vibration levels exceed the supplier's specifications, it is the responsibility of the user to isolate the vibration in order to conform to the specification or else accept a performance derating as described in ASME B89.4.1. Again, this Appendix does not provide information on how to reduce excessive vibration 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 above equipment. Shock and vibration isolator suppliers specializing in low frequency vibration attenuation should be contacted if vibration isolation or a vibration survey is required.

C7 REPORT

A report should be issued by the vibration specialist within approximately three (3) weeks. The report should include all backup information and analyzed data with a comparison to the CMM specification, and include the following as a minimum: Title, Dates (issued and when data was taken), Contract Number, Revision/Revision Date, Purpose or Scope, Instrumentation Used, Calibration Information, Description and Diagram of Test Setup, Procedure, Analysis, and Summary. It is important to note that the report should serve to archive the baseline vibration data for later review, if problems arise after CMM installation.

C8 FIELD INSTRUMENTATION DIAGRAM

A diagram of typical instrumentation is shown in Fig. C-1.

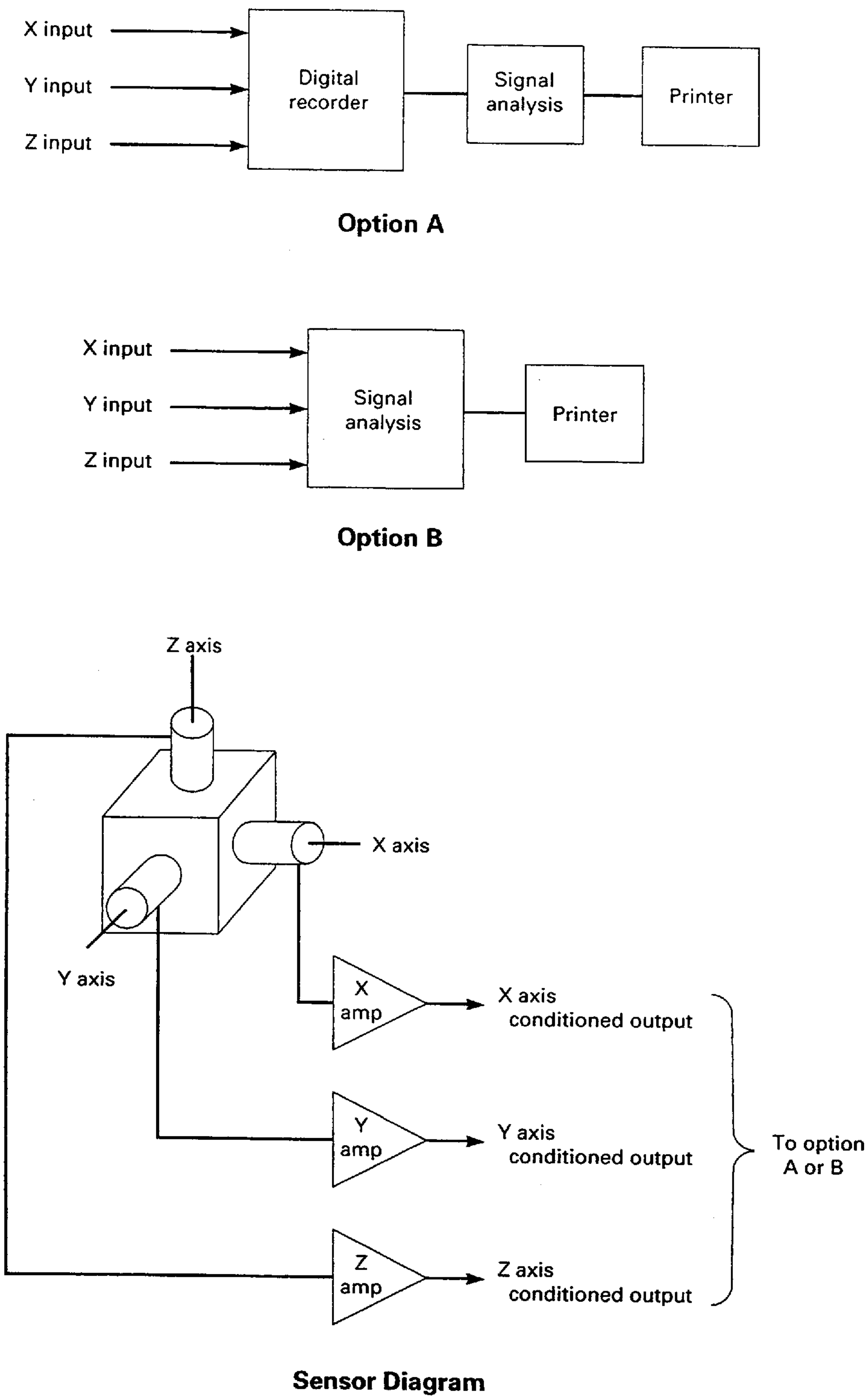

FIG. C-1 FIELD INSTRUMENTATION

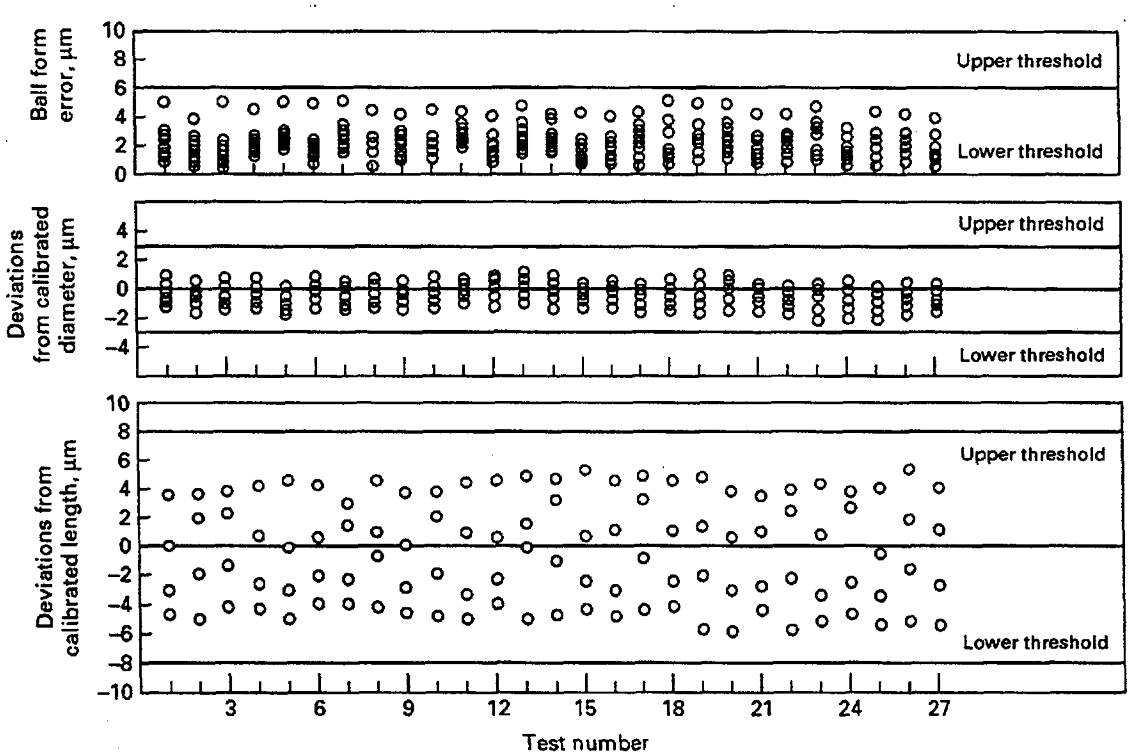

FIG. I5 SUMMARY PLOTS OF SEVERAL INTERIM TEST RESULTS

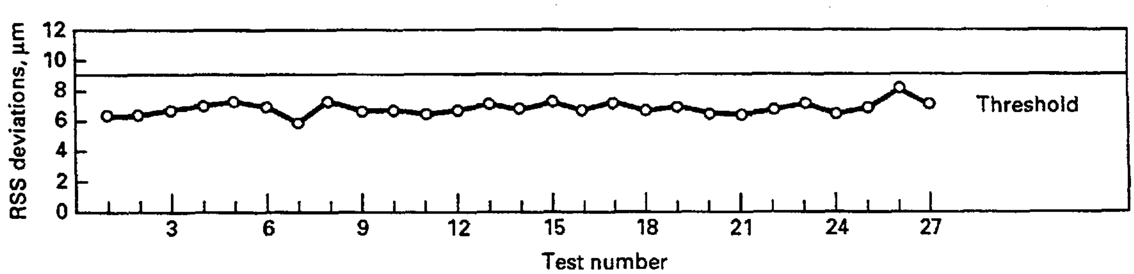

FIG. I6 SUMMARY PLOT OF COMBINED INTERIM TESTING RESULTS

ball location relative to others with different probe head orientations. The final body diagonal position checks for any defective probes present in the probe rack and the rack's probe changing ability. The first ball of the ball bar in this position is measured using the second probe obtained from the probe-changing rack, and the second ball of the ball bar is measured with the final (#3) probe from the probe rack. The form error and diameter, reported for each ball of the ball bar, test each of the two probes for probe lobing effects and stylus size calibration, respectively. (If additional probes are available, these could be checked by measuring each ball of the ball bar, in each ball bar position, with a different probe.)

Figure I5 shows one possible method of data analysis for the interim test. For each interim test, all four center-to-center length deviations, all eight ball diameters, and the eight measured sphere form errors are plotted. The test is passed if all these measurements are within the threshold value limits. Some users may prefer a single plot representing the test results (instead of the three shown in Figs. I4 and I5). Such a plot can easily be constructed, as shown in Fig. I6, by combining the largest length deviation, the largest diameter deviation, and one half the largest form deviation, in a root sum of squares (RSS) manner. (One-half the largest form deviation is used so each of the three contributions is appropriately weighted). This method has the advantage of displaying only a single graph but provides less information as to the sources of error. (If a CMM problem does develop, plots such as those in Fig. I5 could be constructed using data from the previous test results.)

There are many different methods a user can choose to establish testing thresholds. These include using the supplier's stated CMM performance values for the particular CMM under consideration, which might involve specifications from the ASME B89.4.1 or other appropriate national or international Standards. Other methods to determine the thresholds include examining the tightest tolerance of a feature found on the user's workpiece and reducing this by an appropriate ratio. To avoid false alarms, the threshold levels should exceed all variations arising from normal operations. This may include such factors as different operators and different thermal conditions, e.g., time of day or week.

I5 TESTING FREQUENCY

The frequency of interim testing is highly user-dependent. A CMM being operated three shifts a day with multiple operators in a harsh environment is likely to experience many more problems than the same machine being used one shift a day by a single operator in an excellent environment. The frequency of testing is also strongly affected by balancing the cost of interim testing against the consequences of accepting a bad workpiece or rejecting a good one. It may be useful to consider the interim testing interval as a percentage of total CMM operating hours. Some users with high value and/or safety critical workpieces may elect to perform daily tests; other users might test weekly or monthly. Additionally, interim testing should be conducted after any sort of significant event such as a CMM collision, replacement of a subsystem component, or the occurrence of abnormal temperature variations or gradients.

(a) I6 LARGE CMMS

CMMs with large work zones that are approximately cubical (1×1×1) should follow Appendix I with the following supplementary information. (For large CMMs, approximately cubical work zones can include all cases where the ratio of the work zone's longest to shortest axis is less than 2.) Appendix I recommends that a general purpose interim testing artifact should have its length at least 75% of the shortest axis of a CMM with a nearly cubical work zone. This condition may be difficult to fulfill with large CMMs, as the artifacts may become unwieldy, expensive, and difficult to calibrate. Furthermore, large interim testing artifacts may require special fixturing to avoid distortions caused by gravity or the probing force of the CMMs. Since these distortions often increase as the cube of the artifact's length, acceptably small distortions on short artifacts can rapidly become significant error sources as the length of the artifact increases. Consequently, fixturing which minimizes these effects is highly recommended. For example, when using a ball bar as the test artifact, a fixturing system such as the one shown in Fig. G4 is preferred to the free standing design shown in Fig. G1. Finally, thermal effects are especially important on large artifacts. The magnitude of these errors can be estimated by the Nominal Differential Expansion (NDE), and the uncertainty in the NDE (i.e., the UNDE, see para. 4.2).

The following recommendations provide alternative ways of overcoming the testing difficulties of large CMMs.

I6.1 Subwork Zones

Since some large CMMs use a significant fraction of their work zone for part mounting, a smaller work zone (or series of smaller work zones) might be used for the actual measurements (see *work zone* in glossary). In these cases, the testing artifact may comply with the recommendation of using the length equal to 75% of the shortest axis of the subwork zone. An example of such a situation would be a CMM which inspects physically large parts that need to fit into the work zone but with the actual measurement region on the part being a small subvolume of the part's physical size. Accordingly, a 0.9 m ball bar can easily be used to test a measurement work zone having a 1.2 m length side. Similarly, artifacts of length 1.5 m can be used to test measurement work zones having a shortest axis of up to 2 m. Artifacts greater than 1.5 m become increasingly problematic, a fact which represents the limit of practically implementing this approach.

I6.2 Artifact Staging

For very large CMMs, with the shortest work zone axis greater than 2 m, large physical artifacts may become impractical. In this situation a reasonably large artifact (e.g., 0.9 to 1.5 m) can be staged in the work zone. The staging should cover a distance of at least 75% of the shortest axis of the work zone. It is not recommended to stage the artifact more than three times since the artifact's length relative to the work zone size is small in this situation; hence, it loses sensitivity to angular errors (as explained in Appendix I) in addition to becoming very time consuming. Using this strategy with a 1.5 m artifact allows testing of a cubical work zone CMM with an axis of up to 6 m.

I6.3 Testing With Optical Systems

For CMM work zones with a shortest axis of more than 2 m, the use of an optical displacement measuring system (e.g., a laser interferometer) may be desirable. If optical measurements are taken in nonstandard environmental conditions, then the wavelength corrections of para. 5.4.3.3 are recommended. Additionally, long beam paths may have spatial gradients present; this effect should be assessed and reduced (e.g., by air mixing with fans if necessary). The use of an optical system can employ the same procedure recommended for physical artifacts (i.e., the measurement of body diagonals) with at least one length being recorded for every 2 m of displacement traveled. For example, a CMM with a 4 m × 5 m × 6 m work zone could be tested along the body diagonal with at least 3 m of distance checked (75% of 4 m), and with at least one intermediate point recorded. Since for most optical systems the measurement time is a small fraction of the setup time, adding additional measurement points is advisable (e.g., in the above situation a measurement of the body diagonal lines of 7 m with the points spaced at 1 m intervals would be desirable). For large CMMs that are not vector driven (i.e., cannot operate all 3 axes simultaneously), it may be impossible to maintain the necessary optical alignment required by the laser interferometer. For these CMMs, an optical tracking system (e.g., laser tracker) can maintain the optical alignment as the body diagonals are traversed and may be used.

Care must be exercised to ensure that the optical measurement system has a sufficiently low uncertainty relative to the CMM under test. If it becomes necessary to move the beamsplitter/remote interferometer rather than the retroreflector when making length measurements, problems can arise if the beamsplitter is imperfectly made and bends the transmitted light slightly. Under these circumstances it is never possible to obtain good alignment of the beam with the direction of motion; it the laser beam exiting the beamsplitter is well aligned with the direction of motion, then the incoming beam will be misaligned and will walk across the face of the beamsplitter as the beamsplitter is translated. Thus a potential for both signal loss and misalignment errors exists when translating the beamsplitter. The problem is easily avoided by using a good quality optic than does not bend the transmitted light. Additionally, the correction for environmental effects on the wavelength of light over the measured distance should be considered a potential error source (see para. 5.4.3.3). Similarly, the use of optical coordinate systems (e.g., laser trackers) must have a sufficiently small system uncertainty relative to the CMM under test.

Since most optical systems used for interim testing do not involve the CMM probe or related subsystems, additional tests are needed to check these systems. A test sphere, calibrated for form and diameter, can be employed to check the CMM probe, indexable probe head, and CMM probe/stylus changing systems. For example, if all of the above subsystems are available, then a simple test would be to measure a calibrated sphere with a set of points taken using a combination of different probes/styli (accessed thorough probe/stylus changing) and different probe head index positions. This collection of points is (least squares) fitted to a sphere and the resulting form and diameter errors examined. The sphere's diameter error is a bidirectional length test and checks the probe's calibration for features of size (see para. 5.6), whereas the form error checks the probe lobing of the different probes (see para. 6.1), and the index positions relative to each other (see para. 6.2). Additionally, if the CMM has a part temperature compensation system, also known as an Automated Nominal Differential Expansion (ANDE) compensation system, this will not be tested during the optical measurement and should be checked independently; for example, by measuring a reasonably long calibrated artifact having nonzero expansion coefficient. During this measurement, the temperature of the artifact should be measured with the CMM part sensor and used for the ANDE correction. Deviations between the thermally compensated measured value and the calibrated value for the artifact length may indicate problems with the compensation system.

I7 CMMS USED IN THE DUPLEX MODE (a)

For CMMs used in the duplex mode the procedures described in Appendix I can be used with at least some of the artifact measurements taken under the duplex condition. This is achieved by measuring opposite ends of the test artifact (ball bar, step gauge, gauge block, etc.) with different arms of the CMM. Similarly, if a ball plate (or hole plate) artifact is employed, then approximately half of the balls (holes) may be measured with each arm. If the CMM is rarely used in the duplex mode, then each arm may be interim tested independently and a few additional duplex measurements included. For very large CMMs used in the duplex mode, the use of a laser interferometer (or similar optical system) is recommended. In this case, the retroreflector is mounted in the ram of one arm and the interferometer is mounted in the ram of the second arm. (See the precautions above regarding testing with optical systems.) The distance between the two CMM arms is varied along a common direction determined by the laser beam path. If such an optical procedure is used, then the testing of the subsystems (e.g., probe head) is also needed, as described in Section I6.

(a) I8 HIGH ASPECT RATIO CMMS

CMMs having work zones with the ratio of the longest to shortest axis (the aspect ratio) greater than 2 may require modified testing procedures. For CMMs with aspect ratios of ≤ 3, and having body diagonals less than 4 m long, interim testing can be performed using an artifact at least one third the length of the body diagonal. For example, a CMM with axes of 0.5 m × 1 m × 1.5 m has a body diagonal 2 m long, thus a minimal length testing artifact would be 0.7 m. CMMs with aspect ratios greater than 3 are usually designed for a special purpose; for example, measuring the straightness of a long narrow part. In this case, a special purpose test designed around the measurement requirement may be appropriate. In the above example, the use of a straightness interferometer together with subsystem (e.g., probe) tests may be sufficient for the measurement application. In other situations the use of two ball bars may be sufficient to check the CMM. For example, one long bar could be oriented along some combination of body diagonals, long face diagonals, and the long axis of the CMM. A second shorter bar could be oriented along some combination of the short face diagonals and the short axes of the CMM.

I9 ROTARY TABLE CMMS (a)

CMMs having a rotary table can be tested by an abbreviated form of the 3D/alpha test described in para. 5.5.6. In cases where the measurement volume of interest is approximately that of the rotary table, the two ball setup of Fig. 33, with a minimum of four angular positions selected from Table 2, is sufficient to check the CMM. In situations where the measurement volume is substantially larger than that accessible to the rotary table, additional measurements using a method previously described (e.g., measuring a fixed length artifact) are recommended. Note that part loading effects can significantly affect the results of the 3D/alpha test.

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ASME B89.4.1-1997
(Revision of ASME B89.1.12M-1990)

METHODS FOR PERFORMANCE EVALUATION OF COORDINATE MEASURING MACHINES

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METHODS FOR PERFORMANCE EVALUATION OF COORDINATE MEASURING MACHINES

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(Revision of ASME B89.1.12M-1990)

Date of Issuance: June 16, 1997

The 1997 edition of this Standard is being issued with an automatic addenda subscription service. The use of an addenda allows revisions made in response to public review comments or committee actions to be published as necessary. The next edition of this Standard is scheduled for publication in 2000.

The American Society of Mechanical Engineers
345 East 47th Street, New York, NY 10017

FOREWORD

(This Foreword is not part of ASME B89.4.1-1997.)

The ambiguity of coordinate measuring machine (CMM) manufacturers' specifications in 1978 made comparative evaluation of performance extremely difficult. Considering this fact and the increasing use of CMMs, the ASME Metrology Standards Committee B89 formed WG B89.1.12 to develop an American industry standard that would establish equitable means of determining machine performance.

On March 17, 1983, the Standard, having progressed to the application level, was given interim status and released for a one-year trial period. Thereafter, desirable modifications were implemented in the official Standard, which was released in 1985 as ASME/ANSI B89.1.12-1985.

Following this release, the application and use of the document were monitored and opportunities for improvement were noted for inclusion in 1990 as ASME B89.1.12M, Rev. 1.

Subsequent new information is included in this current revision, such as impact of workpiece weight effects, interim testing, large machines, and significant modifications with respect to probing, ball bar tests, and the rotary axis test. Due to changes in the status of the ASME Committee, this Standard is designated ASME B89.4.1-1997.

The American National Standards Institute approved this Standard on January 30, 1997.

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Dimensional Metrology

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METHODS FOR PERFORMANCE EVALUATION OF COORDINATE MEASURING MACHINES

1 SCOPE

This Standard establishes requirements and methods for specifying and testing the performance of coordinate measuring machines (CMMs) having three linear axes perpendicular to each other and up to one rotary axis positioned arbitrarily with respect to these linear axes. In addition to clarifying the performance evaluation of CMMs, this Standard seeks to facilitate performance comparisons among machines by unifying terminology, general machine classification, and the treatment of environmental effects.

This Standard attempts to define the simplest testing methods capable of yielding adequate results for the majority of CMMs and is not intended to replace more complete tests that may be suitable for special applications. In particular, this Standard is most applicable to machines used in the point-to-point mode rather than the contour measurement mode. Although this Standard provides checks for most of the parameters relevant to coordinate measuring machines used in a contouring mode, the checks do not actually test contouring accuracy, per se. Additions to this Standard to include contouring performance are in process.

This Standard provides definitions of terms applicable to CMMs. These definitions are separated into two parts: first, a glossary covering technical terms used throughout this Standard, and second, an explanation of twelve common machine classifications.

The actual specification of CMMs is subdivided into four sections: general machine classification, machine environmental requirements and responses, machine performance, and machine subsystem performance. Machine classification includes machine type, measurement ranges, position resolution, operating mode, and probing method. Environmental specification includes thermal response, electrical requirements, vibration sensitivity, and utility air requirements. Machine performance specification includes repeatability, linear displacement accuracy, ball bar measurement performance, offset probe performance, diagonal displacement performance (large machines), duplex performance (machines used in the duplex mode), rotary axis performance, performance under loaded conditions, and bidirectional length measurement capability. Subsystem performance consists of procedures to evaluate probing performance during point-to-point coordinate acquisition with single and multiple tips.

One of the most significant features of this Standard is its treatment of environmental specification and testing. The machine user is assigned clear responsibility for providing a suitable performance test environment, either by meeting the supplier's parameters or by accepting reduced performance. Particular emphasis is placed on the performance degradation caused by temperature variation and vibration. The treatment of thermal effects in this Standard is in conceptual conformance to the provisions of ASME B89.6.2. The key feature of this treatment is the relaxation of machine performance requirements if the thermal environment causes excessive uncertainty or variation in the CMM performance and does not meet the supplier's recommendations regarding thermal parameters.

Actual machine performance testing is divided into five major areas: repeatability, linear displacement accuracy, streamlined artifact testing with a ball bar, rotary axis testing, and bidirectional length measurement capability. Supplements to the ball bar testing are provided for large machines and for machines used in the duplex mode. (Note that the supplemental laser interferometer diagonal displacement measurements will give numbers that may be different from those obtained with long ball bars. However, these numbers also adequately reflect the performance of the machine.) Performance tests for machines under loaded conditions are also included. An important feature of these performance tests is the attempt to use normal operating procedures during the tests. This emphasizes the importance of measurement procedure details, such as mode of machine operation and probe type. In addition, the use of normal operating procedures during the tests serves to emphasize the overall approach of this Standard in considering measurement data as the results of the complete measuring system, not just the CMM.

Subsystem performance, at this time, provides a series of tests for systematic point-to-point probing errors, such as lobing. Tests are also provided for machines with multiple-tip probing. This includes the use of probe changers and probe indexing capabilities. Tests for other subsystems, such as software, are of importance but are not included in this Standard.

Throughout this Standard, the concept of range — that is, the spread between the maximum and minimum values in a set of data — is used as the measure of machine performance. This choice was made in favor of more common statistical measures, such as standard deviation, and because the dominant errors in coordinate measuring machines are systematic as opposed to being random. In such cases, no generally accepted statistical procedures currently exist.

Repeatability is defined as the "ability of a measuring instrument to provide closely similar indications for repeated applications of the same measurand under the same conditions of measurement." The specified testing of repeatability requires a series of measurements of the center coordinates of a precision ball, using the same testing procedure as the tests to measure the effect of the thermal environment.

The linear displacement accuracy of the machine is measured along three mutually perpendicular lines in the work zone. The tests may be performed using either a step gage or a laser interferometer. This Standard carefully details the treatment of these data if any mean temperature in the tests departs from 20°C (68°F), at which material length standards are defined.

The overall measuring performance of the machine is evaluated with a ball bar, providing limited but valuable testing of the machine. This method has been chosen due to the speed and simplicity with which a machine can be evaluated using a ball bar to simulate a real measurement procedure. For very large machines, diagonal displacement measurements are used to supplement the ball bar results. For machines used in the duplex mode, measurements of a fixed ball in various positions are performed by both machines as a supplement to ball bar measurements by each machine. Further, the ball bar is measured in four positions with offset probes to obtain the offset probing performance.

The performance of the machine's rotary axis, if applicable, is tested by measuring the locations of two precision balls mounted at specified positions on the rotary table. Again, this test is functional and is intended to reflect the values that would be obtained from actual measurements. The user of this specification is warned that rotary axes are particularly sensitive to the load distribution and the moment of inertia of the part being measured. A separate section is included that allows for performance testing of coordinate measuring systems under loaded conditions.

In order to clarify the use of this Standard, a short guide is included as Appendix A. To assist the user in tracing possible environmental problems, appendices are also provided for thermal environment testing (Appendix B), vibration analysis (Appendix C), electrical power analysis (Appendix D), and utility air analysis (Appendix E). Appendices on hysteresis testing (Appendix F), ball bar test equipment (Appendix G), straightedge tests for ram axis roll (Appendix H), and interim testing of CMM systems (Appendix I), also provide the user with important subsidiary information.

Productivity is an important consideration in the selection of a coordinate measuring machine. There are numerous factors that affect relative productivity of measuring systems, including variables inherent to both the system and the workpiece. This Standard does not address methods to specify and evaluate productivity; rather, productivity should be evaluated with respect to the expected use of the system.

1.1 Contents and Specification Form

Any specification described as complying with this Standard shall include at least the following items.

(a) Machine classification (see para. 2.2). If no machine classification is applicable, the actual configuration shall be described in equivalent detail.

(b) Principal mode of operation (free-floating manual, driven manual, or direct computer control). If desired, repeatability, linear displacement accuracy, volumetric performance, bidirectional length measurement capability, point-to-point probing performance, and multiple-tip probing performance may be specified for more than one mode of operation.

(c) Principal probe type (passive, switching, proportional, or nulling). If desired, repeatability, linear displacement accuracy, volumetric performance, bidirectional length measurement capability, point-to-point probing performance, and multiple-tip probing performance may be specified for more than one probe type.

(d) Probe approach rate, probe approach distance, and settling time(s) for the principal probe type(s) specified.

(e) Nominal voltage, frequency, and power requirement.

(f) Utility air pressure, pressure variation, flow, temperature, dew point, and particulate content.

(g) Permissible environment vibration amplitude as a function of frequency. The amplitude must be specified at the interface between the equipment supplied by the user and that supplied by the CMM supplier.

(h) Statement of availability of data required for foundation design and machine installation.

(i) Statement of the significant mean temperature change, if available, safe operating temperature range, nominal location for the temperature variation error test, and the availability of other thermal response data for the machine.

(j) Statement of nominal coefficients of thermal expansion of the machine scales, by axis.

(k) Parameters describing a recommended machine thermal environment.

(l) Repeatability.

(m) Linear displacement accuracy defined by measurement with a laser interferometer or a mechanical master. The choice shall be clearly specified.

(n) Volumetric performance including ball bar performance, offset probe performance, volumetric tests for machines with large work zones, tests for duplex machines, rotary axis testing, and tests for machines under loaded conditions.

(o) Bidirectional length measurement capability.

(p) Point-to-point probing performance.

(q) Multiple-tip probing performance.

(r) A sample machine specification form. This form is illustrated in Fig. 1 for a typical machine. It is divided into three sections: General (Fig. 1A), Environmental (Fig. 1B), and Performance (Fig. 1C). The General section is intended to characterize the machine by configuration, size, operation mode, and probe type. The Environmental section is intended to describe environmental requirements for the machine. The Performance section illustrates the parameters used to specify performance within the context of this Standard. In the case that more than one operating mode/probe type combination is specified, performance shall be specified for each combination. This form cannot be effectively used outside the context of this Standard as the Environmental and Performance sections are closely connected through working tolerance derating procedures described in Sections 4 and 5.

1.2 Alternatives

This Standard allows parts of the environmental tests section to be deferred or bypassed and only the performance tests to be carried out. This alternative is acceptable only if it is acceptable to both the user and the supplier and if deferred as specified in Section 4.1.

2 DEFINITIONS

2.1 Glossary

This glossary contains brief definitions of the majority of technical terms used in this Standard. Omissions should be reported to ASME (see Foreword).

Abbe error: the measurement error resulting from angular motion of a movable component and an Abbe offset between the scale measuring the motion of that component and the measurement line (see Fig. 2).

Abbe offset: the instantaneous value of the perpendicular distance between the displacement measuring system (e.g., scale) of a measuring instrument and the measurement line where the displacement in that coordinate is being measured. A schematic illustration of this concept is given in Fig. 2.

acceptable machine load: the machine load that can be applied through the spanned region of contact as defined in the load concentration chart (see Fig. 3). All standard machine specifications will remain unchanged under "acceptable machine loading." (Note: refer to para. 5.5.7 for a detailed testing procedure that describes acceptable machine loading test conditions.)

accuracy: a quantitative measure of the degree of conformance to recognized national or international standards of measurement.

axis direction: the direction of any line parallel to the motion direction of a linearly moving component.

ball bar: a gage consisting of two highly spherical tooling balls of the same diameter connected by a rigid bar. A ball bar, as used in this Standard, must be sufficiently mechanically rigid that its length is constant during the course of a set of measurements but does not have to be calibrated (see Appendix G).

CG location zone: a supplier-specified zone within the loading area in which the machine load center of gravity, CG, must lie.

cosine error: the measurement error in the motion direction caused by angular misalignment between a linear displacement measuring system and the gage (or part) being measured. Equations for computing cosine error are given in para. 5.4.2.3.

dead path: in laser interferometry, that distance between the remote interferometer and the retroreflector at closest approach which is not compensated for changes in the index of refraction of air.

GENERAL

Machine Classification (para. 2.2): (A figure with axis designation and direction of positive machine motion shall be supplied.) For duplex applications, relative positions and common elements of the two machines shall be shown.

Measuring Ranges (full travel):

X ________ mm (in.)
Y ________ mm (in.)
Z ________ mm (in.)
D ________ mm (in.) — diameter of rotary axis, if supplied (see Glossary)

Readout Resolution (least count):

X ________ mm (in.)
Y ________ mm (in.)
Z ________ mm (in.)
α ________ deg. (arc sec) — resolution of rotary table, if supplied

Principal Mode of Operation (more than one mode may be specified):

Free-floating manual ______
Driven manual ______
Direct computer-controlled ______

Principal Probe Type (more than one type may be specified):

Passive ______
Switching ______
Proportional ______
  Nulling ______
  Displacement-measuring ______
  Proximity ______

Operating Parameters:

Probe approach rate ______ mm/sec (in./sec)
Probe approach distance ______ mm (in.)
Settling time
  Passive (solid or hard) probes ______ sec
  Proportional probes ______ sec
Probe configuration (describe):

Describe location of machine coordinate system origin:

Maximum acceptable machine load: ______ kg [Notes (1), (2)]
Safe machine load: ______ kg

NOTES:
(1) The correct ISO unit of weight is the Newton (N), but the kilogram (kg) is used customarily. One kg has a weight approximately equal to 10 N in the earth's gravitational field.
(2) 1 kg weighs approx. 2.2 lb.

FIG. 1A B89.4.1 COORDINATE MEASURING MACHINE SPECIFICATION FORM

ENVIRONMENTAL **Page 1 of 2**

For the following parameters, the principal mode of machine operation and the probe type must be specified. If more than one operating mode, probe type, or mode type combination is desired, a separate performance specification sheet shall be used for each combination.

Operating Mode __________ Probe Type __________

Significant Mean Temperature Change (para. 4.2.3) __________ °C (°F)

Safe Operating Temperature Range (para. 4.2.3)

Min. __________ °C (°F) Max. __________ °C (°F)

Nominal Location for TVE Test (Machine Coordinates)

X __________ mm (in.)
Y __________ mm (in.)
Z __________ mm (in.)

Nominal Coefficient of Thermal Expansion of Machine Scales [Note (1)]

X __________ ppm per °C (°F)
Y __________ ppm per °C (°F)
Z __________ ppm per °C (°F)

Electrical (para. 3.4 and Appendix D):

Voltage __________ V Frequency __________ Hz
Amperage __________ A Surge/Sag __________ V

Allowable transient voltages (0.5 to 800 μs): Magnitude __________ V

Environmental Vibration (para. 3.3 and Appendix C)

Option 1: Response function data [Note (2)] __________
Option 2: Broad band data __________

Peak-to-peak vibration amplitude __________ μm (μin.)
Frequency range __________ Hz

Utility Air [if applicable (para. 3.5 and Appendix E)]

Pressure __________ ± __________ MPa (psi)
Flow rate __________ l_N/min (SCFM)
Dew Point __________ °C
Particle removal requirements:
Particle size __________ μm __________ % removal

Availability of Foundation/Installation Data:

__________ Yes __________ No

FIG. 1B B89.4.1 ENVIRONMENTAL SPECIFICATION FORM

ENVIRONMENTAL (CONT'D) **Page 2 of 2**

Temperature:

Mean ambient temperature ________ °C (°F)
Daily cycling amplitude (24 hr) ± ________ °C (°F)
Superimposed cycle(s)

Amplitude ± ________ °C (°F)
Frequency ________ cycles/hr

Gradients

Vertical ________ °C/m (°F/ft)
Horizontal ________ °C/m (°F/ft)

Mean Air Speed Surrounding the Machine [Note (3)] ________ m/min (ft/min)

(Additional parameters on machine component placement and special flow requirements are to be attached, if appropriate.)

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 supplier and 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 parameters should also be provided, if possible.

NOTES:
(1) 1 ppm = parts per million = 10^{-6}
(2) Detailed vector vibration spectra shall be attached as part of this specification.
(3) Maximum air speed should not exceed 6 m/min (20 ft/min) at 20°C (68°F). See ASME B89.6.2 for a full discussion of parameters affecting operator comfort.

FIG. 1B B89.4.1 ENVIRONMENTAL SPECIFICATION FORM (CONT'D)

PERFORMANCE — BASIC MACHINES

For the following parameters, the principal mode of machine operation and the probe type must be specified. If more than one operating mode, probe type, or mode type combination is desired, a separate performance specification sheet shall be used for each combination.

Operating Mode __________ Probe Type __________

(For all tests below, the reported value is the maximum range of error.)

Repeatability [Note (1)] — All Linear Axes (para. 5.3)

X __________ mm (in.)
Y __________ mm (in.)
Z __________ mm (in.)

Linear Displacement Accuracy (para. 5.4)

Step gage (para. 5.4.2) _____ or laser interferometer (para. 5.4.3) _____

X __________ mm (in.)
Y __________ mm (in.)
Z __________ mm (in.)

Volumetric Performance (para. 5.5) [Note (2)]

Ball bar _____ or gage block _____

Length __________ mm (in.)
Working tolerance __________ mm (in.)
Offset probe performance (para. 5.5.3) __________ mm (in.)

Bidirectional Length Measurement Capability (para. 5.6)

Gage block length __________ mm (in.)
Working tolerance __________ mm (in.)

Point-to-Point Probing Performance (para. 6.1) [Note (3)]

Working tolerance — 10 mm stylus length __________ mm (in.)
Working tolerance — 50 mm stylus length __________ mm (in.)
Working tolerance — 50 mm stylus with a 20 mm offset __________ mm (in.)

Multiple-Tip Probing (para. 6.2) [Note (4)]

Working tolerance — 50 mm stylus __________ mm (in.)

NOTES:
(1) For large machines, the supplier shall specify the second probe approach rate, probe approach distance, and traverse speed to be used (see para. 5.3.3).
(2) The user may supply measuring positions and lengths. If not supplied, then default values are used. Optional lengths and positions shall be attached, if required.
(3) Probe approach rate, probe approach distance, and settling time are the default values unless otherwise specified.
(4) The user may supply measuring positions and lengths. If not supplied, then default values are used. Optional lengths and positions shall be attached, if required.

FIG. 1C B89.4.1 PERFORMANCE SPECIFICATION FORM

PERFORMANCE — ADDITIONAL SPECIAL TESTS

For the following parameters, the principal mode of machine operation and the probe type must be specified. If more than one operating mode, probe type, or mode type combination is desired, a separate performance specification sheet shall be used for each combination.

Operating Mode ____________ Probe Type ____________

(For all tests below, the reported value is the maximum range of error.)

Ball Bar and Diagonal Displacement (large machines, para. 5.5.4) ________

Length of ball bar ___900___ mm (in.)
Working tolerance __________ mm (in.)
Length of longest diagonal __________ mm (in.)
Working tolerance __________ mm (in.)

Duplex Performance (machines used in the duplex mode, para. 5.5.5)

Description of test plane:

X __________ mm (in.)
Y __________ mm (in.)
Z __________ mm (in.)

Rotary Axis Performance (para. 5.5.6)

Rotary table position(s) and orientation(s) [Note (1)]:

Radial separation, Rs __________ mm (in.)
Height, Hs __________ mm (in.)

Working tolerances:

3D/alpha radial __________ μm (μin.)
3D/alpha tangential __________ μm (μin.)
3D/alpha axial __________ μm (μin.)

Testing Under Loaded Conditions (para. 5.5.7) [Note (2)]

Machine Load __________ kg (lb)

NOTES:
(1) More than one position and orientation may be specified. If unspecified, default values are provided in this Standard.
(2) Working tolerances for testing machines under loaded conditions are the same as those in the unloaded condition. Tests for ball bar performance and rotary axis performance are conducted.

FIG. 1C B89.4.1 PERFORMANCE SPECIFICATION FORM — ADDITIONAL SPECIAL TESTS

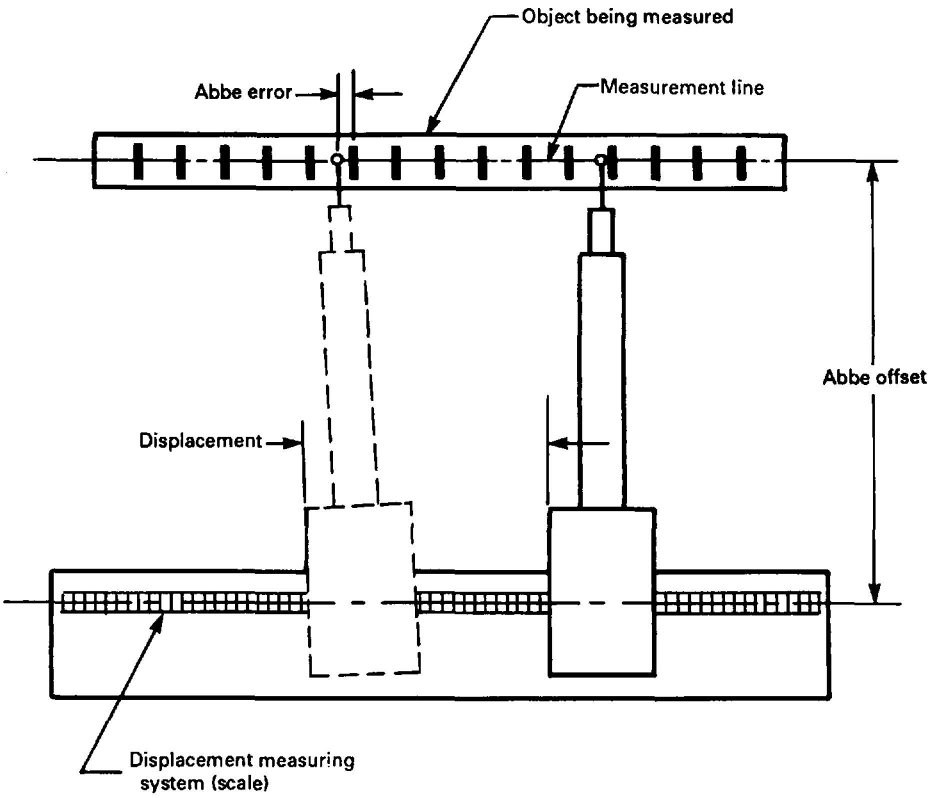

FIG. 2 SCHEMATIC ILLUSTRATION OF ABBE OFFSET AND ABBE ERROR

diagonal displacement: the displacement of the probe on a machine along either a face or body diagonal of its work zone.

diameter of a rotary axis: the maximum diameter of a rotary table (outside diameter) supplied with a measuring machine. This is the maximum diameter along which a part can be fixtured. If it is intended that parts larger than the face of the rotary table or an extension plate be placed on the rotary table, this diameter is either the maximum diameter of the part or the maximum diameter of the extension plate (see para. 5.5.6). If the table is square, then this diameter is the diameter of the maximum inscribed circle that will fit the square table.

drift test (thermal): a type of test used to measure temperature variation error [see *temperature variation error (TVE)*] on a machine. One form of this test consists of continuously recording the output of displacement sensors placed in the position of a probe on the machine reading against a sample part over a period of time. Detailed procedures for conducting drift tests on machines of different types are given in para. 4.2.2.

driven manual mode: a mode of CMM operation in which the probe of a machine is moved from point to point in its work zone using drive mechanisms (gears, lead screws, etc.) that are manually controlled.

duplex mode: an operating mode in which two coordinate measuring machines having a defined relationship between their coordinate systems are used to measure coordinates of points on a common workpiece.

duplex performance: for two machines used in the duplex mode, the difference in the measured position of an artifact reported by the two machines relative to a single coordinate system.

free-floating manual mode: a mode of CMM operation in which the probe of a machine is moved from point to point by direct operator manipulation of the machine ram or probe without use of a motor drive.

gage (gauge): a mechanical artifact 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 indicator, either analog or digital.

gage block: a length standard with rectangular, round, or square cross sections having flat, parallel, opposing gaging surfaces.

hysteresis: as applied to a measuring system, the property of that system whereby its response to a given stimulus depends on the sequence of preceding stimuli. Hysteresis is often caused by drive train clearance, guideway clearance, mechanical deformations, friction, and loose joints (see Appendix F). For the purposes of this Standard, three types of hysteresis are defined:

(a) *machine hysteresis:* the hysteresis of the machine systems when subjected to loads;

(b) *probe hysteresis:* the hysteresis of the mechanical or electrical elements of a probe; and

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

large work zone: a work zone having any one or more of the following characteristics:

(a) the least measuring range (full travel along an axis) of the work zone exceeds 1.0 m (approx. 40 in.);

(b) the greatest measuring range (full travel along an axis) of the work zone exceeds 3.0 m (approx. 120 in.); and

(c) the volume of the work zone exceeds 10 m^3 (approx. 350 ft^3).

laser interferometer: in this Standard, an interferometer for displacement measurement that uses a laser as a light source.

linear displacement accuracy: the difference between a true displacement along a straight line and that indicated by a measuring system. For the purposes of this Standard, this difference is understood to be the maximum systematic error from any point to any other point along the measurement line (see para. 5.4).

load concentration chart: the relationship of the machine load to the spanned region of contact, shown graphically in Fig. 3.

loading area: a specified area (mm^2 or $in.^2$) of the CMM's workpiece mounting surface that is used for supporting the machine load.

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.

machine load: the load, in kilograms (kg), placed on the workpiece mounting surface.

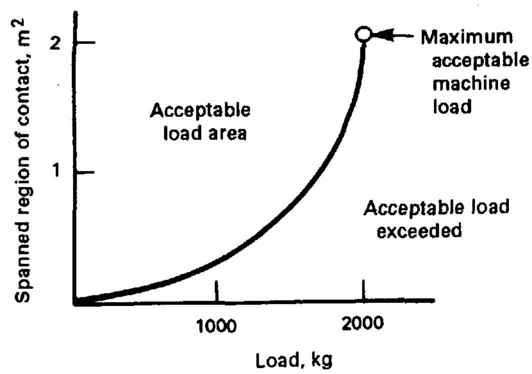

FIG. 3 LOAD CONCENTRATION CHART

machine load effects: the changes in machine performance due to the machine load.

maximum acceptable machine load: the maximum acceptable machine load identified by the load concentration chart (see Fig. 3).

maximum traverse speed: see *traverse speed.*

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 a test. The time between the two readings should be at least two-thirds of the test interval.

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. The time between the two readings should be at least two-thirds of the test interval.

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 required for a test. The time between the two readings should be at least two-thirds of the test interval.

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

measurand: the quantity being measured.

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 machine coordinates are recorded as part of a measurement.

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. [Note that since the true coefficient for a body is unknown, an uncertainty must be applied when making nominal differential expansion corrections (see Section 4).] 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.

nominal differential expansion: the difference between the nominal expansion of the part and the master. (Note that in this Standard the machine's scales shall be considered the master.)

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

periodic error: an error in the linear displacement accuracy of a machine that is cyclic 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 periodic error is usually synchronous with the pitch of the lead 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.

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

(*a*) *displacement-measuring probe:* a probe that gives a signal proportional to a displacement of the probe from its free position.

(*b*) *nulling probe:* a probe that, when referenced to a workpiece, gives a signal which causes the machine to be driven to a position that will null the probe reading.

(*c*) *passive (solid or hard) probe:* a probe that mechanically fixes the movable components relative to the workpiece. Two types are discussed in this Standard: seating probes, which are hard probes that are positively constrained to maintain their location with respect to a measurement point without operator contact; and nonseating probes, which are hard probes that require force applied by a machine operator to maintain their position with respect to a measurement point.

(*d*) *proportional probe:* a probe that gives a signal proportional to a distance between a reference point on the machine ram and the workpiece. Such probes may be displacement-measuring probes, proximity probes, or nulling probes.

(*e*) *proximity probe:* a probe that gives a signal proportional to the distance from the probe tip to the workpiece.

(*f*) *switching probe:* a probe that gives a binary signal as a result of making 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 (used primarily for switching probes).

radial separation: the perpendicular distance from the axis of rotation of a rotary axis to either of the two test spheres used to assess the volumetric performance for a rotary axis (see para. 5.5.6).

ram: the moving component of a machine that carries the probe.

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

repeatability (of a measuring instrument): the ability of a measuring instrument to provide closely similar indications for repeated applications of the same measurand under the same conditions of measurement. These conditions include:

(*a*) reduction to a minimum of the variations due to the observer;

(*b*) the same measurement procedure;

(*c*) the same observer;

(*d*) the same measuring equipment, used under the same conditions;

(*e*) the same location; and

(*f*) repetition over a short period of time.

Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the indications.

repeatability (of results of measurements): the closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement. These conditions are called repeatability conditions and include the following:

(*a*) the same measurement procedure;

(*b*) the same observer;

(*c*) the same measuring instrument, used under the same conditions;
(*d*) the same location; and
(*e*) repetition over a short period of time.
Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results.

resolution (of a displaying device): the smallest difference between indications of a displaying device that can be meaningfully distinguished. (Note that for a digital displaying device, this is the change in the indication when the least significant digit changes by one step. This concept applies also to a recording device.)

resolution (of an indicating device): a quantitative expression of the ability of an indicating device to distinguish meaningfully between immediately adjacent values of the quantity indicated.

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

safe machine load: the maximum machine load that can be applied to the CMM's work area without causing damage, tipping, or other unsafe conditions.

safe operating temperature range: the temperature range in which a measuring instrument may be expected to operate without physical damage to the instrument or its support systems (i.e., computers, probes, etc.).

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

significant mean temperature change: the change in mean ambient temperature surrounding a machine, which, in the supplier's judgment, will cause sufficient degradation in machine performance such that performance evaluation (Section 5) should be repeated.

spanned region of contact: the area bounded by all points of contact between the machine load and the workpiece mounting surface.

specialized machine load: a special loading case wherein the maximum acceptable machine load specification is modified; the resultant of a specially distributed or located machine load.

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

step gage (uni and bidirectional): a gage comprising a rigid bar with calibrated features used for determining the accuracy of distance measurements in the direction of linear motion. (Note that some gages can only be probed from one direction, while others are constructed so that probing can be performed from both directions.)

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

systematic error: the portion of a machine error that remains even after computing the mean of a very large number of similar measurements.

temperature variation error (TVE): an estimate of the maximum possible measurement error induced solely by deviation of the environment from average thermal conditions (see para. 4.2.2 for complete specification).

thermal error index (TEI): the summation, without regard to sign, of the estimates of all thermally induced measurement errors expressed as a percentage of the working tolerance (see para. 4.2 for complete specification).

traverse speed: the speed obtained by the tip of the ram of a measuring machine, measured with respect to the part mounting surface, when the machine is moved between nominal locations without measuring. For the purposes of this Standard, the maximum traverse speed is the maximum speed along any given machine axis.

uncertainty of nominal differential expansion (UNDE): the estimated possible difference between the actual differential expansion and the nominal differential expansion due to uncertainties in the accepted (nominal) coefficients of thermal expansion (see para. 4.2.1).

user: a party who contracts to accept a coordinate measuring machine from a supplier.

vibration amplitude: the peak-to-peak amplitude of a given frequency component of a vibration spectrum.

working tolerance (WT): the maximum acceptable range in the measurements for any performance test in this Standard. In particular, this applies to repeatability, linear displacement accuracy, volumetric performance, duplex mode performance, rotary axis performance, performance under load conditions, bidirectional length measurement capability, point-to-point probing performance, and multiple-tip probing performance measurement results.

workpiece: an object to be measured.

work zone: the measurement volume of a machine as specified by the supplier. More than one work zone may be specified for a given machine, and working tolerances may be specified separately for each work zone.

work zone aspect ratio: the ratio of the greatest axial measuring range (full travel) to the smallest measuring range (full travel) for a 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 must be explicitly specified.

2.2 Machine Classifications

The following classifications of different types of CMMs are provided for ease of machine specification. A place is provided in the standard machine specification form, Fig. 1, that shall be used to designate the machine classification as described below. As part of the specification, a drawing equivalent to Figs. 4 through 15 with the axis designation and direction of positive travel, shall be provided. In the case where rotary axes are supplied, they shall be added to each machine classification in the position of their expected normal use (if movable). Figure 14 shows one example of a machine with a rotary axis. In the case where two machines are used in the duplex mode, a drawing showing the positional relationship of the two machines and any elements common to the two machines shall be provided. Figure 9 shows an example of two moving ram horizontal arm machines having a common base and used in the duplex mode. If a machine is to be supplied that does not conform to one of the described machines, then a drawing similar in content to those shown in this classification section, with axis designations and directions of positive travel, shall be provided as part of the machine specification.

2.2.1 Fixed Table Cantilever. A machine employing three movable components moving along mutually perpendicular guideways. The probe is attached to the first component which moves vertically relative to the second. The second component moves horizontally relative to the third. The third component is supported at one end only, cantilever fashion, and moves horizontally relative to the machine base. The workpiece is supported on the base. A typical machine of this classification is shown in Fig. 4.

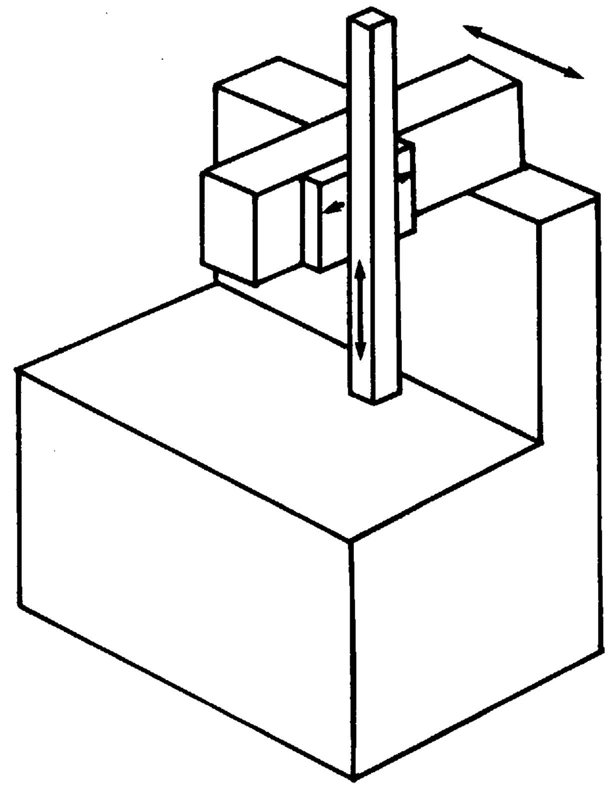

FIG. 4 FIXED TABLE CANTILEVER COORDINATE MEASURING MACHINE

2.2.2 Moving Bridge. A machine employing three movable components moving along mutually perpendicular guideways. The probe is attached to the first component which moves vertically relative to the second. The second component moves horizontally relative to the third. The third component is supported on two legs that reach down to opposite sides of the machine base, and moves horizontally relative to the base. The workpiece is supported on the base. A typical machine of this classification is shown in Fig. 5.

2.2.3 Fixed Bridge. A machine employing three movable components moving along mutually perpendicular guideways. The probe is attached to the first component which moves vertically relative to the second. The second component moves horizontally along a bridge structure above it that is rigidly attached at each end to the machine base. The third component moves horizontally relative to the machine base. The

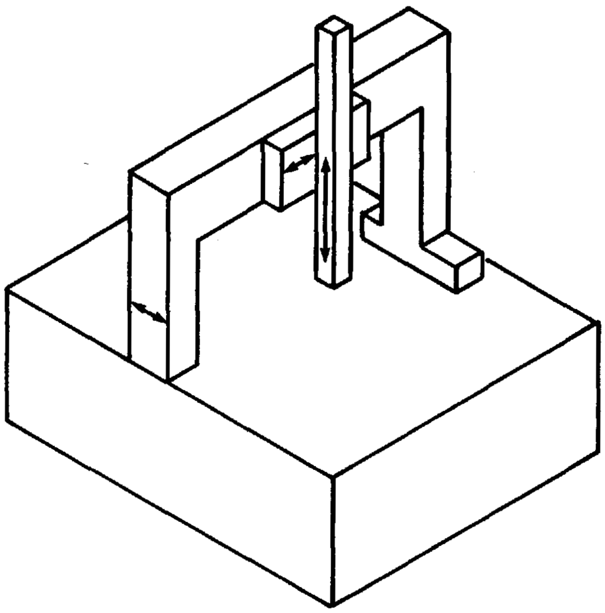

FIG. 5 MOVING BRIDGE COORDINATE MEASURING MACHINE

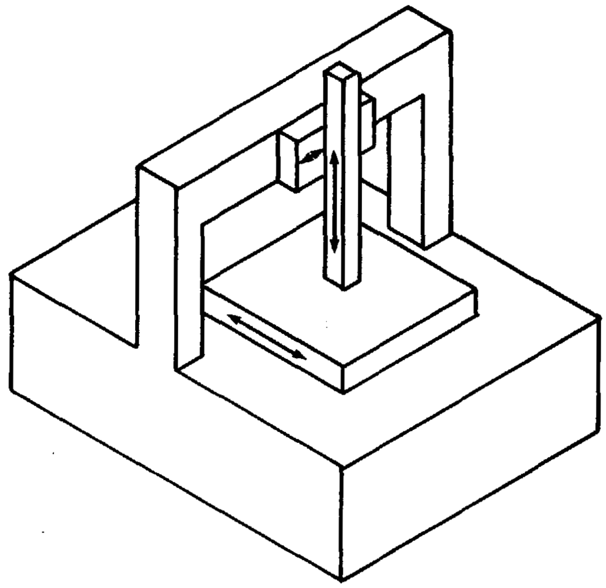

FIG. 6 FIXED BRIDGE COORDINATE MEASURING MACHINE

workpiece is mounted on the third component. A typical machine of this classification is shown in Fig. 6.

2.2.4 Column. A machine employing two movable components moving along mutually perpendicular guideways. The probe is attached to the first component which moves vertically relative to the machine base. The second component moves horizontally relative to the machine base in two directions defining a plane perpendicular to the first component motion. The workpiece is supported on the second component. A typical machine of this classification is shown in Fig. 7.

2.2.5 Moving Ram Horizontal Arm. A machine employing three movable components moving along mutually perpendicular guideways. The probe is attached to the first component which moves horizontally relative to the second component. The second component moves vertically relative to the third component. The third component moves horizontally relative to the machine base. The workpiece is mounted on the machine base. A typical machine of this classification is shown in Fig. 8.

2.2.6 Duplex Mode Machine. Machines used in the duplex mode, a mode in which two machines have a defined relationship between their coordinate systems, are used to measure coordinates of points on a common workpiece. Two moving ram horizontal arm machines

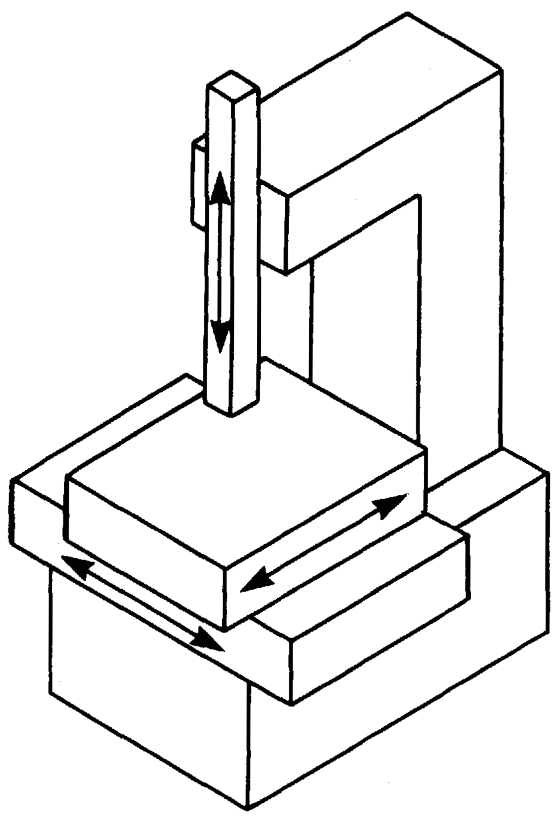

FIG. 7 COLUMN COORDINATE MEASURING MACHINE

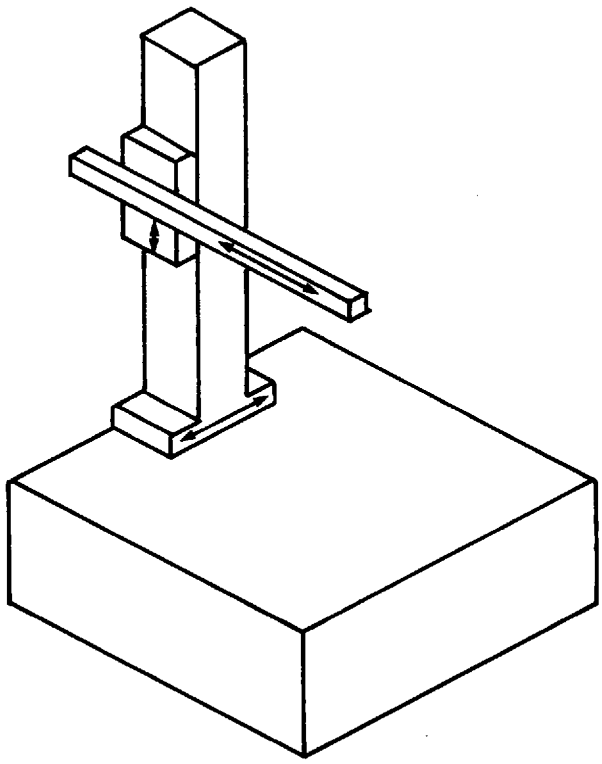

FIG. 8 MOVING RAM HORIZONTAL ARM COORDINATE MEASURING MACHINE

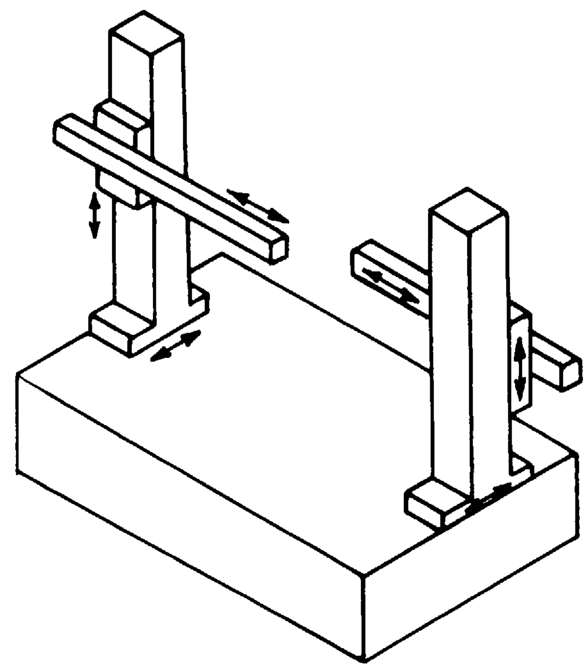

FIG. 9 TWO MOVING RAM HORIZONTAL ARM COORDINATE MEASURING MACHINES WITH A COMMON BASE USED IN THE DUPLEX MODE

having a common base and used in the duplex mode are shown in Fig. 9. Many other machine geometries shown in para. 2.2 can also be used in the duplex mode.

2.2.7 Moving Table Horizontal Arm. A machine employing three movable components moving along mutually perpendicular guideways. The probe is attached to the first component which is supported horizontally at one end only, cantilever fashion, and moves vertically relative to the second. The second and third components move horizontally relative to the machine base. The workpiece is mounted on the third component. A typical machine of this classification is shown in Fig. 10.

2.2.8 Gantry. A machine employing three movable components moving along mutually perpendicular guideways. The probe is attached to the first component which moves vertically relative to the second. The second component moves horizontally relative to the third. The third component moves horizontally on two guide rails raised above the machine base on either side. The workpiece is supported on the base. A typical machine of this classification is shown in Fig. 11.

2.2.9 L-Shaped Bridge. A machine employing three movable components moving along mutually perpendicular guideways. The probe is attached to the first component which moves vertically relative to the second. The second component moves horizontally relative to the third. The third component moves horizontally on two guideways, one at the base level or below, the other raised above the base. The workpiece is supported on the base. A typical machine of this classification is shown in Fig. 12.

2.2.10 Fixed Table Horizontal Arm. A machine employing three movable components moving along mutually perpendicular guideways. The probe is attached to the first component which is supported horizontally at one end only, cantilever fashion, and moves vertically relative to the second component. The second component moves horizontally relative to the third component. The third component moves horizontally relative to the machine base. The workpiece is supported on the base. A typical machine of this classification is shown in Fig. 13. An alternate machine configuration is shown in Fig. 14, where a rotary table is mounted to the machine base with its axis vertical. In this case, the

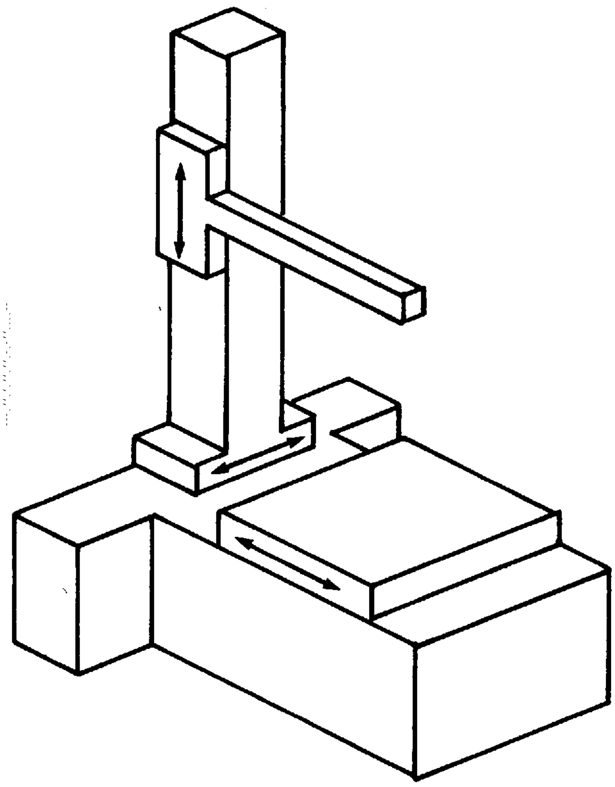

FIG. 10 MOVING TABLE HORIZONTAL ARM COORDINATE MEASURING MACHINE

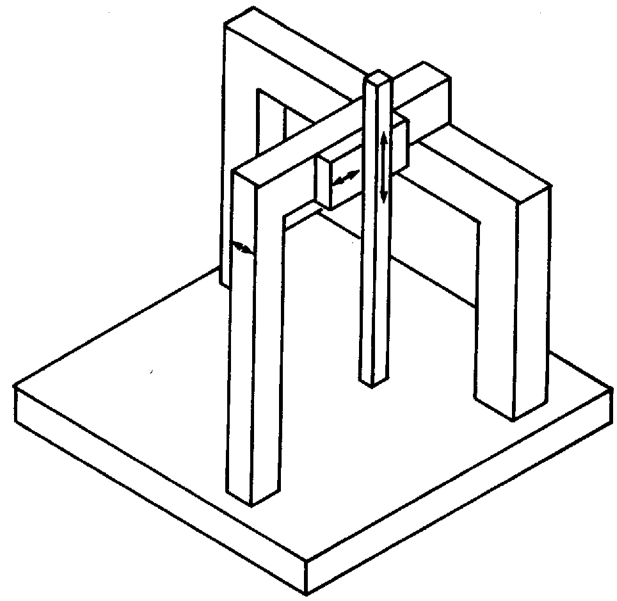

FIG. 12 L-SHAPED BRIDGE COORDINATE MEASURING MACHINE

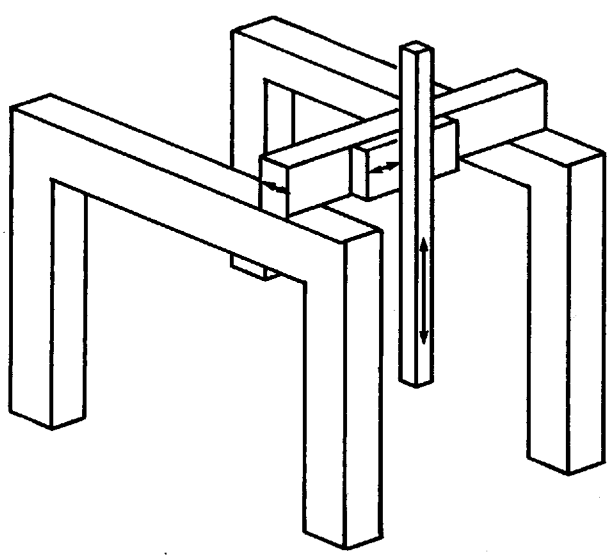

FIG. 11 GANTRY COORDINATE MEASURING MACHINE

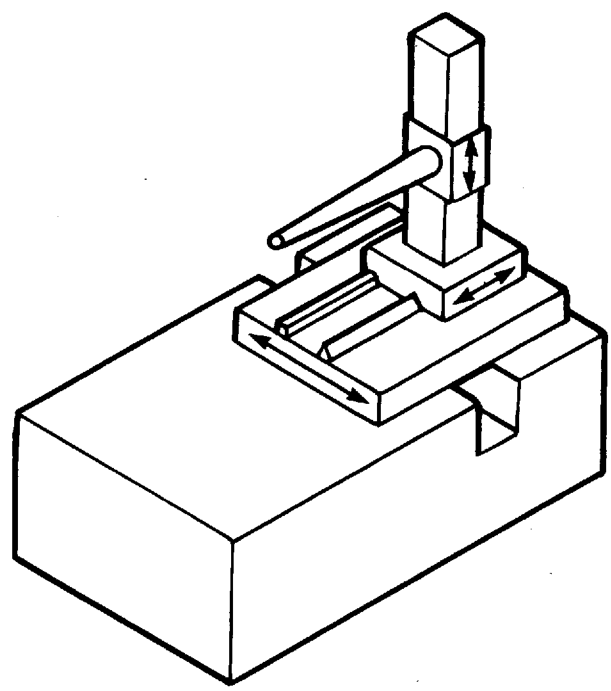

FIG. 13 FIXED TABLE HORIZONTAL ARM COORDINATE MEASURING MACHINE

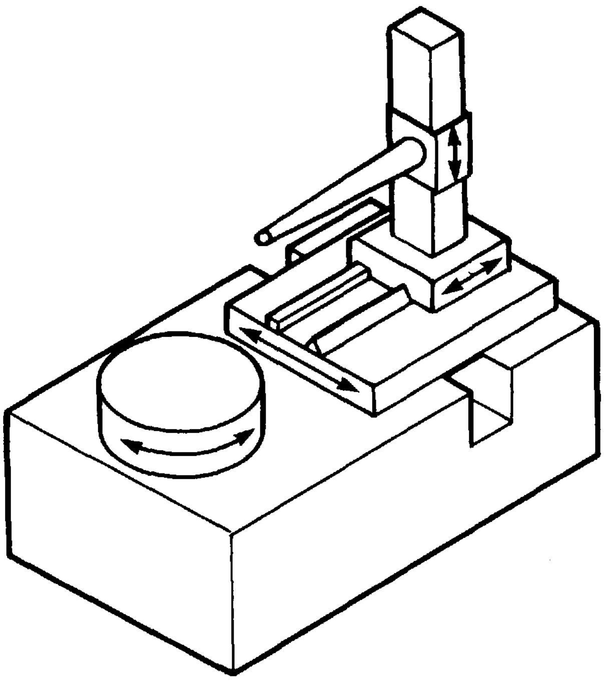

FIG. 14 FIXED TABLE HORIZONTAL ARM COORDINATE MEASURING MACHINE WITH A ROTARY TABLE

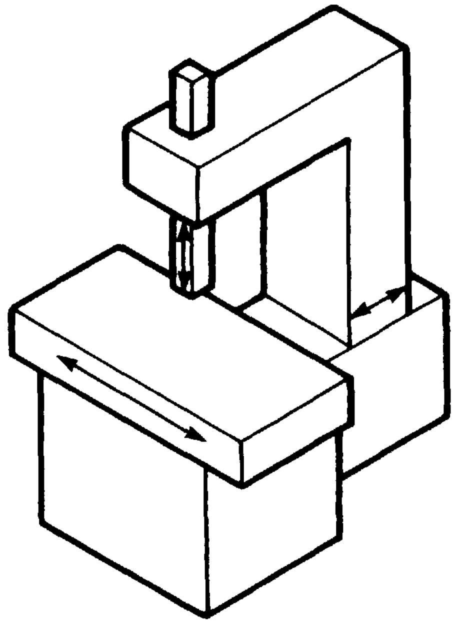

FIG. 15 MOVING TABLE CANTILEVER ARM COORDINATE MEASURING MACHINE

workpiece is mounted to the rotary table. This example is intended to illustrate how rotary tables can be configured on measuring machines. All of the other machines shown could also be equipped with rotary tables.

2.2.11 Moving Table Cantilever Arm. A machine employing three movable components moving along mutually perpendicular guideways. The probe is attached to the first component which moves vertically relative to the second component. The second component is supported at one end only, cantilever fashion, and moves horizontally relative to the machine base. The third component moves horizontally relative to the machine base. The workpiece is mounted to the third component. A typical machine of this classification is shown in Fig. 15.

3 ENVIRONMENTAL SPECIFICATIONS

3.1 General

It shall be the responsibility of the user to provide an acceptable environment for performance testing of the CMM at the installation site. The environment shall be considered acceptable if the requirements of this Section and Section 4 are met. The user shall be responsible for conducting all environmental tests at the installation site. The supplier shall have the right to witness all tests. The supplier shall, on request, supply test equipment as specified in Section 7, as well as support for equipment and tests, at a price to be negotiated between the supplier and user. The user is cautioned that failure to conform to the supplier's recommendations on cleanliness and cleaning procedures can lead to performance degradation. For example, particulates, oils, and water can significantly degrade machine performance, increase friction, and accelerate wear.

3.2 Temperature

3.2.1 General. Temperature has a significant and often misunderstood influence on the accuracy of dimensional measurements. The provisions of ASME B89.6.2 form a part of this Standard, but interpretation is needed for application to coordinate measuring machines. ASME B89.6.2 defines two alternative conditions under which a test environment is thermally acceptable. The first, that all pertinent components of the measuring system be at exactly 20°C (68°F), is generally unobtainable. This Standard is primarily concerned with the second: that the thermal error index (see para. 4.2) be a reasonable percentage of the working tolerance. It is the opinion of the B89.4 Subcommittee and implied in ASME B89.6.2 that it is not yet possible to specify parameters for a thermal environment that will assure a specific value for the thermal error index. Acceptability of an environment that does not comply with the supplier's thermal parameters is therefore specified in terms of its effect on the machine.

3.2.2 Thermal Environment Parameters. The supplier shall provide, as part of the machine specification, a statement of the acceptable thermal environment parameters. Such parameters shall contain a specification on mean room temperature, maximum amplitude and frequency range of deviations from this mean temperature, environmental thermal gradients, and air speed surrounding the machine. The user shall be informed that conformance to these parameters 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 user to supplier. If the user chooses not to conform to the supplied parameters, the tests of environmental sensitivity (see Section 4) may lead to an increase in the acceptable working tolerance for a given performance test; in which case, the degradation in performance shall be solely the responsibility of the user.

3.2.2.1 Thermal Radiant Energy. The machine shall not be exposed to direct sunlight or other powerful radiant energy sources. Other direct radiant energy sources (such as fluorescent lighting) shall not be, whenever possible, closer to any part of the machine than the length of the longest machine axis. Where this distance requirement is impractical, indirect lighting designed for diffuse reflection and increased path length shall be used.

3.3 Vibration

3.3.1 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 CMM by causing relative motions between the probe, the machine axes position measuring transducers, and the workpiece. In addition, certain excessive motion amplitudes can cause damage to the machine.

3.3.2 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.

3.3.3 Environmental Vibrational Parameters. The supplier shall provide, as part of the machine specification, a statement of the acceptable seismic vibration spectra at the user-supplier interface. (This interface may be very different, depending upon details of the contractual arrangement between the supplier and user. For example, if the machine is supplied with isolators, the interface shall 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.) This statement can contain a complete description of the allowable vibration amplitude as a function of frequency for each vector component of the vibration spectrum; or, can simply be a limit on the total vibrational amplitude over a specified frequency range. The sample specification form, Fig. 1, allows for either option. The statement of acceptable vibration spectra applies with the machine in place.

3.3.3.1 Airborne Vibrations. Although not specified in this Standard, measuring machines are susceptible to airborne vibrations in the form of pressure waves, i.e., acoustic noise. Wherever possible, the machine should not be exposed to large levels of acoustic radiation, but if such acoustics are present, the necessity for sound-deadening is the responsibility of the machine user. Excessive vibration due to acoustic coupling will be evidenced in the relative motion test described in para. 4.3.

3.4 Electrical

3.4.1 General. The electrical power supplied to a machine can have a strong effect on its ability to perform accurate and repeatable measurements. This is particularly true when a machine uses some form of computer for any control or readout function.

3.4.2 Responsibilities. It shall be the responsibility of the user to provide electrical power meeting requirements specified by the supplier.

3.4.3 Electrical Parameters. The supplier shall provide, as part of the machine specification, a statement of the steady state voltage(s) requirements of the machine, allowable deviations from this voltage(s), frequency requirements, and amperage requirements. These parameters are listed in the sample specification form, Fig. 1.

3.5 Utility Air

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

3.5.2 Responsibilities. For all machines requiring utility air, it shall be the responsibility of the user to supply utility air meeting requirements specified by the supplier.

3.5.3 Specification. For utility air, the supplier shall provide specification for all air parameters required for the proper operation and maintenance of the machine. For air bearing machines, these shall at least include the mean air temperature, permissible temperature variation, pressure, and pressure variations. Furthermore, on some machines the acceptable dew point and the particulate content shall be specified. These parameters are listed in the sample specification form, Fig. 1. Air quality parameters, such as particulate, oil, and water content, are the sole responsibility of the user, although the supplier shall offer guidelines.

4 ENVIRONMENTAL TESTS

4.1 General

As stated previously, it is the philosophy of this Standard that the environment is the responsibility of the machine user. If the environment complies with the parameters specified by the machine supplier, the responsibility for meeting performance specifications rests solely with the machine supplier. 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. Derating procedures and the tests on which they are based are specified in paras. 4.2 and 4.3.

The supplier and user may agree to defer the environmental test until after performance testing. If the performance fails, the environmental tests may be performed as part of the diagnostic process. However, in such cases, the computations of the uncertainty of nominal differential expansion (UNDE) and the thermal error index (TEI) resulting from this UNDE calculation, with the temperature variation error (TVE) set equal to zero, shall be performed (see paras. 4.2 and 4.2.1).

4.2 Thermal Test

The thermal test shall be performed under conditions equivalent to those pertaining during performance tests (Section 5). The test environment shall be considered acceptable if the thermal error index, as defined below for each test, does not exceed 50% for that performance test. If the thermal error index exceeds 50% and the machine environment does not conform to the supplier's guidelines, either the user shall correct the environment or permissible working tolerance limits for that test shall be automatically increased by an amount such that the greatest thermal error index is 50% of the working tolerance for the specified test. If the thermal error index exceeds 50% and the machine environment conforms to the supplier's parameters, no thermal derating of the permissible working tolerance limits for any performance test is allowed. Methods for testing compliance of the thermal environment to the supplier's environmental parameters are given in Appendix B. The thermal error index shall be calculated for each performance test from the equation:

$$TEI = [(UNDE + TVE)/WT] \times 100$$

where

TEI = thermal error index
TVE = temperature variation error
$UNDE$ = uncertainty of nominal differential expansion
WT = working tolerance for that test

The nominal differential expansion term of the thermal error index expression (ASME B89.6.2) has been deleted because it is a requirement of this Standard that nominal differential expansion corrections be made as indicated in para. 5.4.2.6. All values in the equation are absolute values and are considered positive. The correct TEI value to be used for derating linear displacement accuracy shall be the full TEI value, calculated from the equation above, for the measurement direction. The correct TEI value to be used for volumetric performance derating and 3D/alpha derating shall be the vector sum of the TEIs for the three machine linear axes with the UNDE set equal to zero. The correct TEI value to be used for derating duplex performance (two machines used in the duplex mode) shall be the TEI calculated from a TVE determined as in para. 4.2.2.5. The correct TEI value to be used for derating of the offset probe test performance specification shall be the same as that used for derating the volumetric performance. The correct TEI value to be used for derating the bidirectional length measurement capability shall be the TEI, with the TVE set equal to zero. The TVE may be set equal to zero due to the short duration of the measurement sequences. The working tolerances for repeatability and probing performance may not be thermally derated.

4.2.1 Uncertainty of Nominal Differential Expansion (UNDE). Uncertainty of nominal differential expansion (UNDE) is based on an uncertainty of 1 ppm (1 μm/m)/°C for the scale[1], and an equal uncertainty for the step gage, gage block, etc. It shall be calculated as

$$UNDE = (0.000002)(L)\,|(T_m - 20)|$$

where

T_m = mean ambient temperature, °C
L = the nominal length to be measured in each given test

For example, for linear displacement accuracy, the nominal length L would be the measuring range for the axis under test; for gage block measurement during the bidirectional length measurement test, the nominal length L would be the length of the gage block; etc.

The UNDE above applies even if a laser is used for machine checking. (See ASME B89.6.2 for a further discussion and history of the UNDE.)

4.2.2 Temperature Variation Error (TVE). Temperature variation error (TVE) shall be determined by a drift test. The drift tests specified in this Standard are to be conducted for a period of time equal to the duration of the longest performance test. This short period is a compromise, and users are strongly advised to run this test for a time period of at least 24 hr, as many temperature effects exhibit daily periodicities. The following procedures are to be used for determining

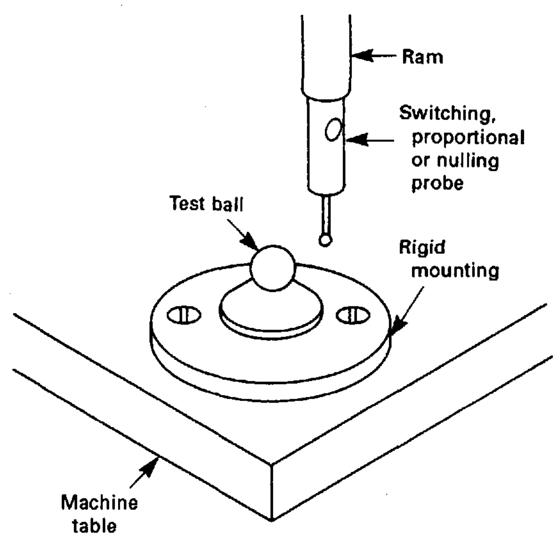

FIG. 16 TYPICAL SETUP FOR PERFORMING THE TVE TEST ON DIRECT COMPUTER-CONTROLLED MACHINES WITH AN ACTIVE PROBE

the TVE on direct computer-controlled machines, driven manual machines, and free-floating passive probe machines. TVE test procedures for DCC machines with large work zones are specified in para. 4.2.2.3. TVE test procedures for machines used in the duplex mode are specified in para. 4.2.2.5. Since some of the tests can be used on more than one type of machine and there are trade-offs between ease and time of testing for the three procedures, it is optional which test(s) should be performed. However, the test(s) chosen shall be clearly stated in the machine specifications.

It should be noted that on some machines there could be variations in the mean value of the supplied air pressure, which can be misinterpreted as TVE. This is due to changes in machine squareness and positional drifts. During this test, care should be taken to ensure proper air pressure regulation.

4.2.2.1 TVE Test for Direct Computer-Controlled Machines and Driven Manual Machines. Immediately prior to initiating this test, the machine shall have been parked at a position geometrically opposite to the test position selected by the machine supplier, for a time period equal to the duration of the TVE test. A test ball shall be mounted to the machine workpiece supporting surface at the position selected by the supplier for the TVE test. A switching, proportional, or nulling probe shall be mounted in the probe holder. This setup is illustrated in Fig. 16. For

[1] This approximation does not apply for scales with a nominal thermal expansion coefficient equal to zero, or to scales with thermal expansion coefficients that are accurately known. In these cases, the user and supplier shall negotiate a correct value for the scale uncertainty to be used for calculation of the UNDE.

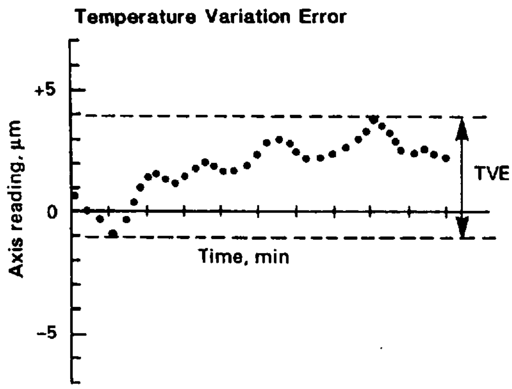

FIG. 17 TYPICAL DATA FROM THE TVE TEST
(The TVE here is approx. 5 μm.)

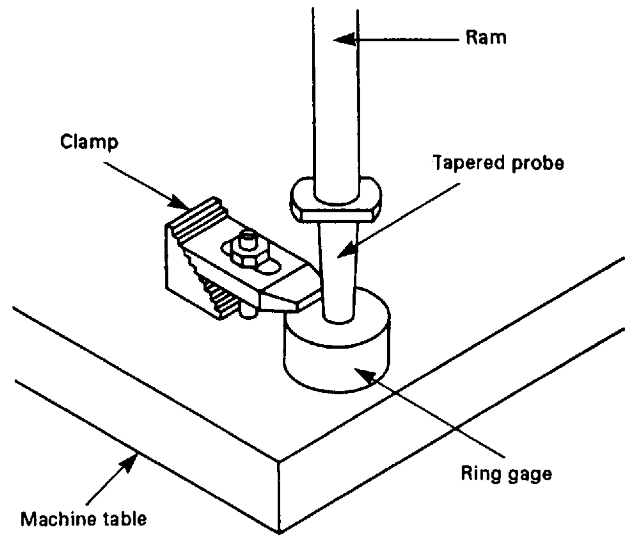

FIG. 18 TYPICAL SETUP FOR THE MEASUREMENT OF TVE ON A FREE-FLOATING MACHINE USING PASSIVE PROBES

direct computer-controlled machines, an automatic cycle shall be established to repeatedly take readings on the ball and establish the ball center coordinates. For driven manual machines, similar measurements shall be taken as quickly as possible. Movement for each probe measurement shall be the minimum necessary to achieve reliable readings. The test shall be conducted for a time period at least as long as the longest performance test of the machine. The test period shall be divided into intervals of approximately one minute or the time required to take a minimum of three readings. In order to minimize the effect of repeatability, the mean value of each coordinate for each interval shall be determined. The range of variation of ball center readings for each coordinate shall be the TVE. Note that data from this test may be used to determine repeatability as specified in para. 5.3, in the case where the location specified for repeatability and the TVE test is the same. Data shall be analyzed as illustrated in Fig. 17.

4.2.2.2 TVE Test for Machines Used in the Free-Floating Mode With Passive Probes. (This test is invalid unless the machine has passed a hysteresis check as described in Appendix F.) The active portion of this test is performed with the machine probe at a position determined by the machine supplier. Immediately prior to conducting this test, the machine shall have been parked at a position geometrically opposite to the test position selected by the machine supplier for the TVE test, for a time period equal to the duration of the TVE test. After this parking cycle, the axes shall be unlocked. A passive probe shall be mounted in the probe holder and secured to the workpiece supporting surface by clamping, or by engaging the probe with some feature of the surface and unbalancing the counterbalance. The probe shall be secured in the position determined by the machine supplier for the TVE test. A sample setup for such a test is shown in Fig. 18. The test shall be conducted for a time period at least as long as the longest performance test, and normal activity shall be continued around the machine. The test period shall be divided into intervals of approximately one minute. The mean value of each coordinate for each interval shall be determined. The range of variations of readings for each axis shall be the TVE for that axis. Typical data for such a test with the TVE labeled are shown in Fig. 17.

4.2.2.3 TVE Test for DCC Machines With Large Work Zones. Due to the large volume occupied by the machine structure and the difficulty in achieving a uniform thermal environment, the results of TVE testing on a large machine will usually be more dependent on the location of the test than they are on a smaller machine. Further, it is more difficult to predict in advance the appropriate location for the TVE test. Therefore, on large machines it is essential to sample several widely spaced locations to determine the TVE. The test specified here requires measuring a quantity similar to the linear displacement accuracy (para. 5.4) along a body diagonal through the machine work zone. Currently, the only practical instrumentation for this test is the laser interferometer. For working in large work zones, careful attention must be given to correcting for wavelength changes due to air temperature and pressure variations during the measurement time, as described in para. 5.4.3.3. Additionally, the setup shall allow only a minimum of dead path. The dead path that exists shall be measured and compensated for according to the laser interferometer supplier's recommendations.

The supplier shall select one of the body diagonals of the work zone as the TVE measurement line. Immediately prior to initiating this test, the machine shall be parked at a position that is the maximum perpendicular distance from this measurement line for a period equal to the duration of the TVE test. Displacement errors shall then be measured along this line for a time period at least as long as the longest performance test, but not less than one hour. The laser shall not be rezeroed during this test. Normal activity shall be continued around the machine. A typical setup for measuring displacement errors along a body diagonal is shown in Fig. 19. The position of the interferometer with respect to the laser head and steering mirror may be extremely critical and should not be altered except by those intimately familiar with the principles of commercial laser interferometry.

In order to minimize the effects of machine repeatability, a group of sequential measurements may be taken at each measurement point along the diagonal and averaged, but the time interval between the first and last reading of such a group shall not exceed one minute. Separate plots of the displacement error versus time shall be made using data from at least the midpoint and the two ends of the measurement line. It is strongly recommended that data from at least one additional position be measured and plotted for each 20 m^3 of work zone volume. A typical plot for three measurement positions is shown in Fig. 20. The greatest range of any of these plots is the TVE. (If the data plots appear to reveal a systematic relaxation that could be due to the machine structure approaching thermal equilibrium, the user may elect to repeat this test to get a better measure of the TVE.)

4.2.2.4 TVE Test for Driven Manual Machines With Large Work Zones. The TVE test for driven manual machines with large work zones is identical to the TVE test described in para. 4.2.2.1 for direct computer-controlled machines and driven manual machines; however, in the case of large machines, this TVE test shall be conducted at three locations within the work zone and the maximum TVE for any axis at any of these three locations shall be reported as the TVE for that axis of the machine. The supplier of the machine shall choose the three locations for these tests. The data from this TVE test shall be reported and analyzed as shown in Fig. 20.

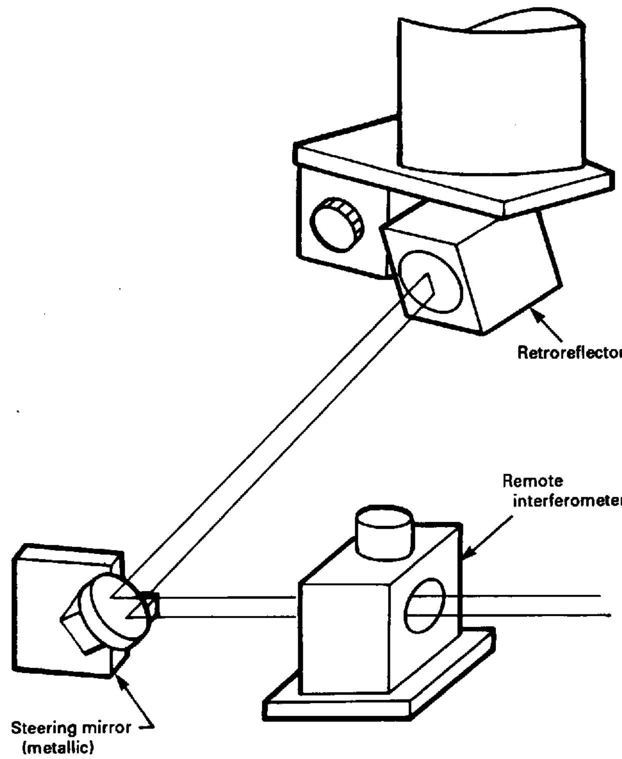

FIG. 19 TYPICAL SETUP FOR MEASURING DISPLACEMENT ERRORS ALONG A BODY DIAGONAL
(In an actual setup, the remote interferometer should be as close to the steering mirror as possible to reduce dead path. This figure shows a large separation for illustration purposes only.)

4.2.2.5 TVE Test for Machines Used in the Duplex Mode. For derating performance specifications of individual machines used in the duplex mode, the method of para. 4.2.2.1, 4.2.2.2, 4.2.2.3, or 4.2.2.4 shall be used, as applicable. For derating the duplex performance specification for two machines used in the duplex mode, an auxiliary test is required.

For the auxiliary test, a reference ball shall be mounted in a position specified by the supplier. The means of mounting shall be the means chosen for the duplex performance test, para. 5.5.5.3. The position of the ball shall be determined repeatedly by both machines by the method specified in para. 5.5.5.3. Differences of position reported by the two machines shall be determined in the three axial directions. The maximum

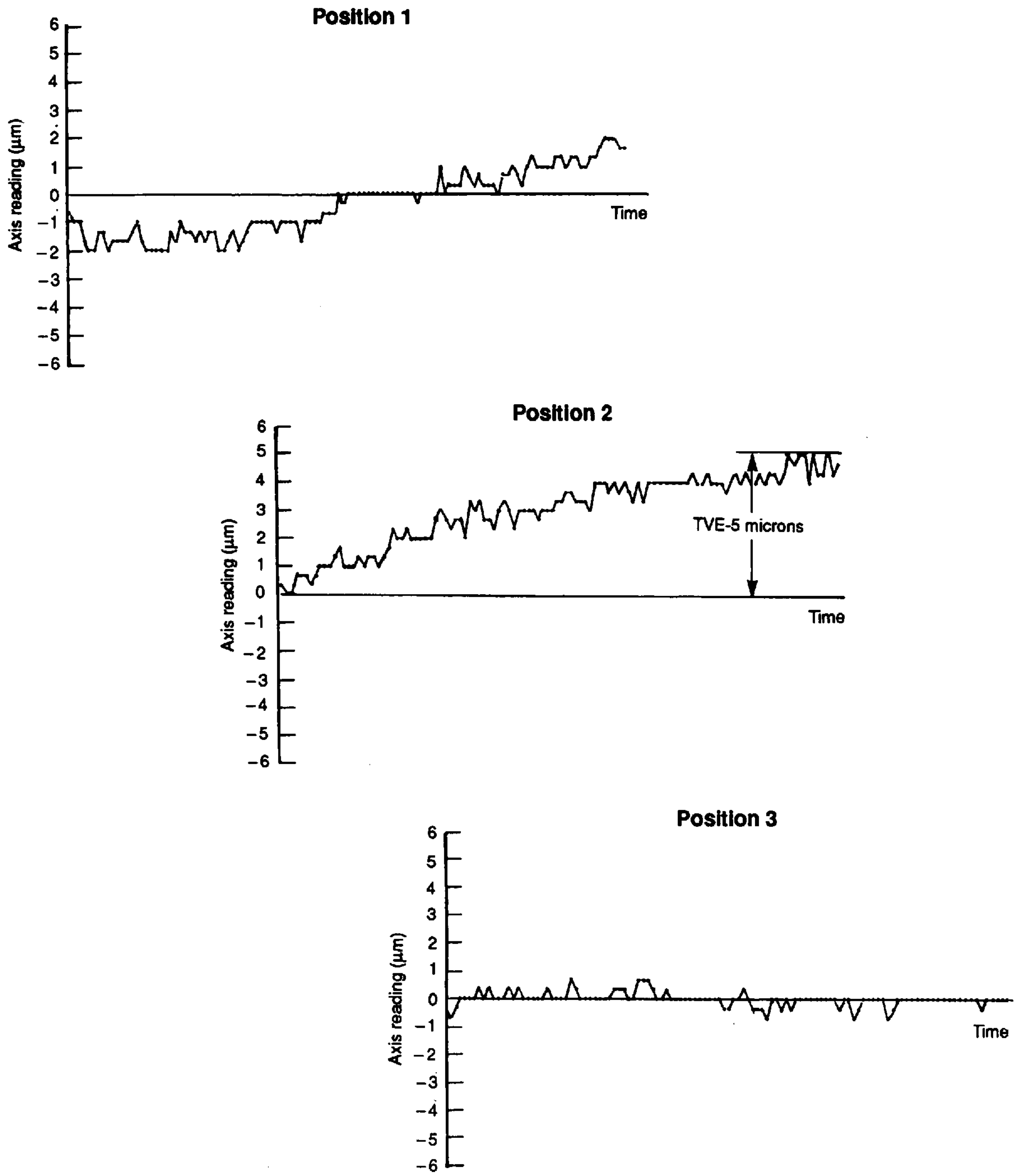

FIG. 20 TYPICAL PLOT OF DATA FOR A TVE TEST PERFORMED ON A LARGE MACHINE BY MEASURING DISPLACEMENT ERRORS ON A BODY DIAGONAL

range of these differences, on an axis-by-axis basis, shall be the duplex TVE for the machine. All other preliminary requirements, test requirements, and data evaluation requirements shall be those used for determining TVE of the individual machines.

For each axial direction, the TVE determined by this auxiliary duplex TVE test shall be compared with the sum of absolute values of TVE determined for the individual machines. The larger of these shall be the TVE used to derate the duplex performance specification.

4.2.3 Other Temperature Effects. The Committee recognizes that when using CMMs, errors caused by differential expansion, scale hysteresis, and other effects can be induced in machines when they are operated at mean temperatures significantly different from the temperature at which they were aligned and calibrated. Unfortunately, it is not within the current state-of-the-art to develop simple tests for these effects. It is therefore the Committee's recommendation that if a machine is to be accepted at a mean temperature significantly different from the one used during alignment and calibration, the linear displacement accuracy, volumetric performance, and bidirectional length measurement capability tests described in Section 5 shall be repeated for each temperature. It is the requirement of this Standard that the supplier specify the significant mean temperature change for a given machine of given working tolerance. Furthermore, the supplier shall specify a safe operating temperature range within which the machine should be kept to prevent physical damage to the machine (see Glossary). In addition, temperature sensors used for compensation need to be periodically verified, as the sensors are subject to damage and drift.

4.3 Relative Motion Tests for Vibration

The relative motion tests shall be performed under the same conditions as those pertaining during the performance tests (Section 5). The test environment shall be considered acceptable if the relative motion amplitude measured between the machine ram and the work table is less than 50% of the machine working tolerance for repeatability. For the purposes of this Standard, this amplitude is to be assessed by the following simple functional tests. The test duration shall be at least 10 min. Both steady-state vibrations and any transients that might occur during normal use shall be included within the test period. These tests are specified with the understanding that they do not constitute a well-defined measurement of vibration amplitude, but rather, some complicated function that only relates in a very general way to vibration amplitude. If the machine does not pass the functional test, Appendix C provides recommended procedures for accurate measurement of the seismic vibration spectra at the user-supplier interface for the purposes of determining conformance to the supplier's specifications.

Should the relative motion amplitude (as measured in this test) exceed the requirements and be traced to sources that are the user's responsibility (see Appendix C), and if the user does not desire to upgrade the machine interface, then the machine specification shall be derated so that the required repeatability will be equal to the measured repeatability on an axis-by-axis basis. Note that the repeatability test (para. 5.3) must be performed before this derating can be accomplished. The absolute value of the worst-case difference between the measured repeatability and the specified repeatability shall be used to derate the repeatability, the volumetric performance, the duplex performance (machines used in the duplex mode), the offset probe performance, the four-axis performance, the 3D/alpha performance, the bidirectional length measurement performance, the probing performance, and the multiple-tip probing performance. This derating is performed by adding the difference to the specified working tolerance. If the machine working tolerance is already subject to derating due to thermal environment, the derating due to relative motion shall be arithmetically added to the thermal derating.

4.3.1 Methodology for Relative Motion Tests — Direct Computer-Controlled Machines and Driven Manual Machines. A single-axis, high-resolution displacement indicator having low damping and conforming to the requirements of Section 7 shall be used; and, with the machine set at a position near the middle of its work zone, set to read relative motion between the ram and the machine table or suitable fixture attached to the table. The direction of displacement indication shall be aligned with each machine linear axis in succession, and the maximum spread of the indicator reading will be judged to be the machine vibration amplitude for that axis.

4.3.2 Methodology for Relative Motion Tests — Free-Floating Passive Probe Machines. On free-floating passive probe machines, the probe shall be engaged with the table using the minimum amount of counter weight force necessary to hold the probe in position [30 g (approx. 1 oz.) is recommended]. Any clamping mechanisms for the axes shall be disengaged. The range of flicker of the machine readout in all three linear axes shall be observed. The maximum spread of the readout flicker shall be judged to be the machine relative motion amplitude for that axis.

4.4 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 opinion of this Committee that such tests are, in the general case, an unwarranted expense and shall 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 of power being suspect, this Standard provides Appendix D which describes the recommended procedure for determining the conformance of the electrical environment to the supplier's guidelines.

4.5 Utility Air Tests

As with the electrical power tests, there also exist many complicated procedures for determining the quality of the utility air supplied to a machine. It is the opinion of this Committee that such exhaustive tests should not be required for checking conformance to specification unless a problem traceable to the air supply is evident. As stated previously, variations in the mean value of the supplied air pressure can cause changes in machine squareness and positional drifts, so that if such changes do occur, then air pressure is a possible suspect. It shall therefore be the responsibility of the supplier to examine, using the gages and filters supplied with the machine, the mean pressure, pressure variations, and cleanliness of the utility air at the input to the machine. If, in the supplier's judgment, the air supply is inadequate, then further tests are described in Appendix E for determining conformance of the utility air to the supplier's specifications. If, however, the supplier judges the air supply to be adequate, then the utility air shall be judged as conforming to specification without further testing.

5 MACHINE PERFORMANCE

5.1 General

The supplier shall be responsible for providing a machine that meets all performance specifications agreed upon between the supplier and user when installed according to the supplier's recommendations in any environment meeting the requirements of Section 3; to include, if required, derating of the acceptable working tolerances as described in Section 4. A machine meeting performance specifications and other conditions agreed upon between the supplier and user shall be accepted by the user. The criterion for meeting performance specifications shall be the satisfactory completion of all tests specified in this Section, except that any test or tests may be omitted by mutual agreement between the supplier and user. It should be emphasized that the performance tests for repeatability, linear displacement accuracy, volumetric performance, and bidirectional length measurement capability described in this Section contain many options, and that these options will not necessarily give the same results on any given machine. This is due to minor differences between what is really being measured when different options are selected. It is the opinion of this Committee that these minor differences are not significant. The choice of any full set — that is, one repeatability option, one linear displacement option, appropriate volumetric performance tests, and the bidirectional length measurement test — will give a fair and complete picture of the machine's capabilities for that mode of operation and that probe type. It may be desirable to use this specification for evaluating machines having large aspect ratios (generally greater than 4:1). The user should be aware that if straightness of the axis with the greatest measuring range (full travel) is critical, then a separate measurement of this parameter should be performed. Where two machines are used in the duplex mode, determination of performance of each machine does not ensure a known relationship between their axis systems. Therefore, a test for duplex performance is specified in para. 5.5.5.

The user shall be responsible for conducting all performance tests at his installation site and the supplier shall have the right to witness all tests. The supplier shall, upon request, supply test equipment as specified in Section 7 including support for equipment and tests, at a price to be negotiated between supplier and user.

5.2 Hysteresis

It is strongly recommended that a mechanical hysteresis test be performed on the machine and on any test setup before time is spent on other testing. Any problems suggested by the hysteresis tests should be corrected before proceeding with other tests. Hysteresis tests are described in Appendix F.

5.3 Repeatability

5.3.1 General. The concept of repeatability testing incorporated in this Standard is that the test must evaluate a complete system, which may include effects due to machine characteristics, human operators, and computer algorithms. Hence, the test must be performed in a manner closely representing the way in which the machine will be used after acceptance. Implementation of this concept requires that different tests be used for different modes of operation. The test chosen for a machine shall be the test for the principal mode of operation, probe type, probe approach rate, probe approach distance, and probe configuration, as specified in Fig. 1A, by the supplier. In general, the stylus of the probe should be parallel to the ram unless agreed upon by the user and supplier. Where alternative principal modes are specified, more than one repeatability test may be required. Specific modifications to the test procedures are provided for machines with large work zones. For these machines, the traverse speed must also be specified. There may be cases where none of the specified test alternatives comply with the concept of this Section. For such cases, the supplier and user shall agree on an alternative test before entering into contract.

5.3.2 Common Features. The requirement in the definition of repeatability to measure the same measurand shall be satisfied by measuring the center coordinates of a precision reference ball rigidly mounted on the workpiece supporting surface at a position where the machine linear axes are approximately at the midpoint of their travel, unless otherwise agreed upon by the user and supplier. Ten determinations of the reference ball center shall be made as rapidly as is practical. For each axis, the range of the ball center coordinate shall be determined as a maximum minus a minimum. Machine repeatability shall be reported as either the largest range in coordinate values measured or the range in coordinate values on a per axis basis. The range of a set of data is defined as the maximum spread of the data. In the event that a data point obtained during a repeatability test appears to be an outlier, then this point may not simply be discarded when defining the range; rather, the complete repeatability test must be repeated and the range for a complete test evaluated. Figure 21 illustrates typical results of a repeatability test.

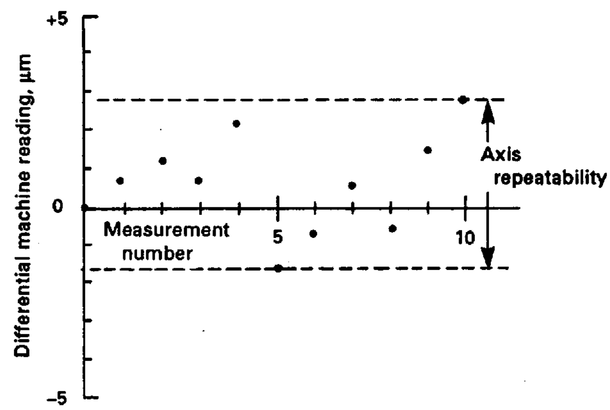

FIG. 21 TYPICAL RESULTS OF A REPEATABILITY TEST WITH THE AXIS REPEATABILITY CLEARLY LABELED (For this test, the repeatability was approx. 4.5 μm.)

5.3.3 Standard Tests for Repeatability

5.3.3.1 Repeatability Tests in the Computer-Controlled Mode or the Manual Mode With a Switching, Proportional, or Nulling Probe. A switching, proportional, or nulling probe shall be mounted in the probe holder. Ten sets of four contacts each shall be made on the ball (for computer-controlled machines these contacts shall be made under computer control). Contact points for each set shall be spaced as widely as possible and not all in the same plane. The center coordinates for each set of four readings shall be calculated, and repeatability shall be determined as in para. 5.3.2.

5.3.3.2 Repeatability Tests With Passive Probes. There are two important classifications of passive probes: seating and nonseating (see Section 2). Since the machine reacts differently to probing depending on the probe type, two tests are required and two repeatabilities must be determined. In both cases, the machine and probe shall be insulated from the operator's hand by some means, such as by a cotton glove.

The first test is for nonseating probes. A ball probe shall be mounted in the probe holder. Rigidity of the reference ball mounting shall be confirmed by engaging the ball probe with the reference ball and applying pressure. Contact pressure shall be estimated at twice that normally used for a ball probe. The check shall be performed in each of the three machine axis directions. Change in the machine readout, as pressure is applied, shall not exceed the working tolerance for repeatability.

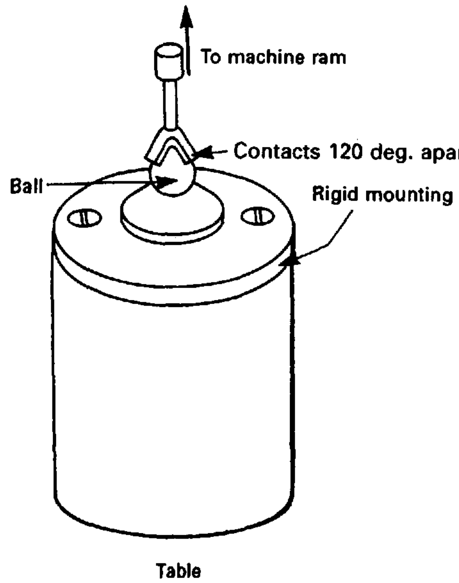

FIG. 22 TYPICAL SETUP FOR REPEATABILITY MEASUREMENT USING A TRIHEDRAL PROBE

Ten sets of four contacts each shall be made on the reference ball, the contact pattern being the same as in para. 5.3.3.1. Coordinates of the ball center shall be calculated for each set. Repeatability shall be determined as in para. 5.3.2.

The second test is for seating probes. An inverted probe of the trihedral type shall be mounted in the probe holder, and ten measurements of the reference ball locations shall be taken approaching the ball from different directions. (Trihedral sockets are preferred over conical sockets, as conical sockets do not provide unique probe seating.) This setup is illustrated in Fig. 22. Repeatability shall be determined as in para. 5.3.2.

5.3.3.3 Repeatability Tests for Machines With Large Work Zones. For large machines, modifications to the repeatability tests are required. Due to the large masses being accelerated and decelerated when positioning large moveable components, several dynamic effects may influence repeatability results. To assess the importance of such effects, all repeatability testing shall be performed with two different values for the test traverse speed, where the test traverse speed is the maximum speed achieved (not commanded) during the machine movement to pre-position the machine immediately prior to contacting the precision reference ball for each touch. (This means that the machine shall reach the test traverse speed between probings.) These two values shall be, respectively, less than 120% of the supplier's recommended probing speed, and greater than 90% of the maximum traverse speed specified for the machine. Insofar as possible, all machine axes shall be significantly exercised during this test. The supplier shall specify probe approach rate, probe approach distance, settling times (if applicable), and traverse speeds to be used for this test. These parameters shall be representative of those used for normal measurement on that machine and shall be explicitly made part of the test procedure. Repeatability shall be determined, as in para. 5.3.2, for each of the test traverse speeds. Also, for large machines, it is strongly recommended that the repeatability test be repeated at one additional work zone location for every 20 m^3 of work zone volume. If the test is repeated, the repeatability shall be determined as above for each of the positions specified.

5.3.4 Repeatability Requirements. Repeatability as calculated in para. 5.3.2 shall not exceed the supplier's specification, derated as specified in para. 4.3, if applicable.

5.4 Linear Displacement Accuracy

5.4.1 General. Complete verification of measuring machine accuracy is a difficult and time-consuming task. All practical tests, therefore, represent some compromise between the cost of testing and the cost of inaccuracy. The tests described in this Standard are meant to represent a minimum requirement to ensure conformance to specification and are not to be considered comprehensive. If more thorough testing is required for the intended use of the machine, then such tests shall be negotiated between the user and supplier. For the purposes of this Standard, only one accuracy test is specified. This test is the measurement of the linear displacement accuracy for all three axes, using either a step gage or a laser interferometer. This test is meant to assess the conformance of the machine scales to the international standards of length. In later sections, the performance of the machine and its geometry is assessed, independent of conformance to international length standards.

5.4.2 Step Gage Test for Linear Displacement Accuracy

5.4.2.1 General. Using a step gage to check measuring machines is a time-honored process. However, the step gage is also used by many suppliers to calibrate (adjust) the machine scales, often at the installation site. For the purposes of checking conformance to specification, it is advisable that a different step gage be used for accuracy checking than the gage used for machine setup. Systematic gage calibration errors and thermal expansion coefficient uncertainties are not thoroughly assessed unless a different gage is used. However, for a very large number of the coordinate measuring machines currently supplied, the step gage, when properly used, is many times more accurate than the basic machine. Therefore, this recommendation is relaxed in those cases and should only be followed when the highest accuracy is required. In any event, it should be clearly stated, as part of the machine specifications, if a different step gage than the gage provided by the machine supplier is to be used for the machine acceptance. It should be noted that step gages are not particularly useful for the evaluation of periodic error. If periodic error is suspected and a step gage is to be used for these measurements, it is advised that a metric step gage be used on a machine with inch scales and vice versa. Furthermore, such a step gage shall meet the requirements of accuracy and calibration as specified in Section 7.

5.4.2.2 Measurement Lines. Measurement lines for step gage tests shall be along three orthogonal lines through the center of the work zone parallel to the three axis directions.

5.4.2.3 Mounting. The gage shall be mounted on the workpiece supporting surface in accordance with the step gage supplier's recommendations. It is extremely important that the mounting be done properly, as the accuracy of some types of step gages is strongly dependent upon proper mounting. Care must be taken to ensure the gage is properly supported and restrained without distortion. The gage shall be aligned with the machine axis (measurement line) with sufficient accuracy that cosine error does not exceed 10% of machine working tolerance for linear displacement accuracy. (Mathematical correction for misalignment is an acceptable alternative to mechanical alignment.) Cosine error is caused by the angular misalignment between the measurement line and the displacement to be measured. The magnitude of the cosine error is given by the following formula:

$$CE = G^2/2D$$

where

CE = cosine error
D = measured displacement
G = misalignment of gage with machine axis

Depending upon the details of the setup and the desired measurement, the cosine error can be either positive or negative. It is therefore important to correctly align the measurement apparatus in order to make this error negligible.

5.4.2.4 Measuring Interval. The measuring interval shall be no more than 25 mm (approx. 1 in.) for axes of 250 mm (approx. 10 in.) length or less. For longer axes, less than 1,000 mm (approx. 40 in.), the interval should be not less than 25 mm (approx. 1 in.) nor more than 1/10 of axis length. For axes of more than 1,000 mm (approx. 40 in.) in length, the measuring interval shall be no more than 100 mm (approx. 4 in.). For all axes, the entire travel along the axis shall be measured.

5.4.2.5 Measurements. Measurements shall be made with the primary type of probe specified for the principal mode of operation. The machine readout shall be zeroed at the first step of the step gage. Three sets of measurements shall be made for each axis. Each set of measurements shall be sequenced in the same direction of machine motion, and each measurement shall be made between gage steps facing in the same direction. Since the data are to be averaged, these measurements may be taken with or without establishing a new zero at the start of each set. The value obtained for the linear displacement accuracy will be the same in either case. The nominal mean of machine readouts for each step of the gage shall be determined.

5.4.2.6 Nominal Differential Expansion Correction. The mean temperature of the step gage and the appropriate machine scale shall be measured during the step gage measurement process for each axis. The machine readings shall be corrected for the mean scale temperature. The machine readings shall be the compensated values on a compensated machine. These values may or may not be what is shown on the display, and the supplier's recommendations shall be used to determine which values apply. Similarly, the step gage length must be corrected for the mean gage temperature. This shall be done using the following expression:

$$CMR = MR[1 + K_s(T_s - 20) - K_g(T_g - 20)]$$

where

CMR = corrected machine reading
K_g = thermal expansion coefficient of calibration gage
K_s = effective thermal expansion coefficient of machine scales
MR = machine reading

T_g = gage temperature during measurements, °C
T_s = scale temperature during measurements, °C

This equation was derived based on the assumption that the machine was adjusted to measure length correctly on the international scale if the machine were at a uniform temperature of 20°C (68°F). If the machine scales are adjusted at a temperature other than 20°C (68°F) and appropriate nominal differential expansion corrections are not made, this equation may not be applicable. It should be noted that the preceding equation assumes that the mean temperatures of the step gage(s) and scale(s) remain constant during the measurement process. This is not always the case in a changing environment where both machine and gages have different time constants. Proper attention should be given to keeping the environment as stable as possible for the duration of the test.

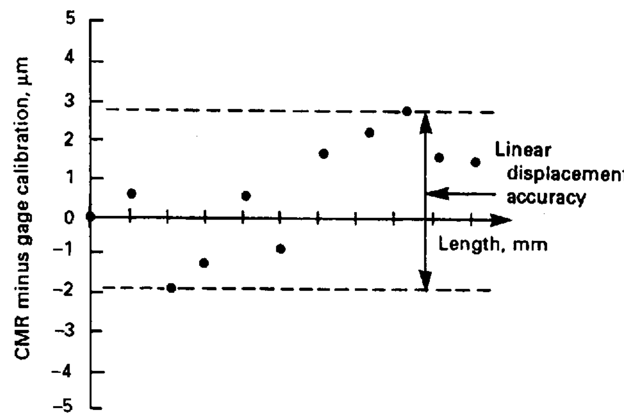

FIG. 23 TYPICAL EXAMPLE OF LINEAR DISPLACEMENT ACCURACY DETERMINED USING STEP GAGES (In this case, the linear displacement accuracy was approx. 4.8 μm.)

5.4.2.7 Linear Displacement Accuracy for an Axis. Linear displacement accuracy for a given axis at a step position shall be the difference between step gage calibration and the mean corrected machine reading (MCMR) for that position. Displacement accuracy is determined by taking the difference between the step gage calibration and the mean corrected machine reading at each step, and then determining the maximum displacement error from any point to any other point in the full travel. This is equivalent to determining the maximum range of the mean differences. Evaluation of linear displacement accuracy is illustrated in Fig. 23, where the linear displacement accuracy is clearly labeled. The measurement of the zero point of the gage shall always be included.

5.4.2.8 Staging. Where the step gage is shorter than an axis, the gage shall be staged. (If staging is required, it is the recommendation of this Standard that the linear displacement accuracy be measured with the laser interferometer (para. 5.4.3) rather than with a step gage). In the staged position, a step of the gage shall be set at the approximate position of the final step of the original position, and the machine shall be zeroed at that step. Corrected machine readings shall be determined as before. The error of the last step of the gage in the previous position shall be algebraically added to the error for each subsequent staged position as a further correction. The step gage shall be staged in a similar manner as many times as required to cover the complete travel of that axis.

5.4.3 Linear Displacement Accuracy Measurements Using a Laser Interferometer. The laser interferometer is an extremely useful tool for measuring displacement accuracy. However, there exist certain machines today that are difficult to check using a laser because they are corrected for systematic errors in their computer systems and the display readouts do not reflect these corrections. The user of a machine should confer with the supplier to ascertain the suitability of these tests before making them part of a machine specification.

5.4.3.1 Lines of Measurements. Lines of measurement for laser interferometer tests shall be those specified in para. 5.4.2.2 for the step gage.

5.4.3.2 Alignment. The laser interferometer shall be mounted in such a fashion as to measure the relative motion between the ram and the workpiece supporting surface. Particular attention should be paid to cosine error, and alignment shall be such that cosine error is less than 10% of the working tolerance of the axis under test. Dead path should also be minimized. A typical laser setup for linear displacement accuracy is shown in Fig. 24.

5.4.3.3 Wavelength Correction and Nominal Differential Expansion Correction. In order to obtain proper results, interferometers must be corrected for air temperature, air pressure, and air humidity. The correction shall be computed according to the following equation for a laser measurement system set to read correctly at 20°C (68°F), 760 mm

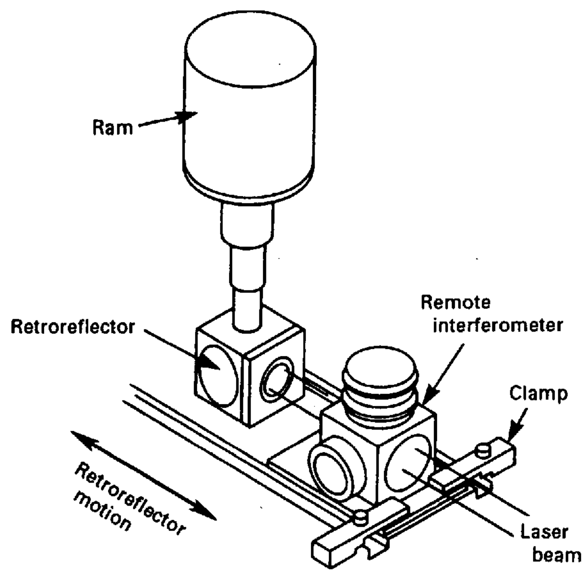

FIG. 24 TYPICAL SETUP FOR THE LASER TEST FOR LINEAR DISPLACEMENT ACCURACY

Hg air pressure, and 10 mm Hg partial pressure of water vapor.[2]

$$CLR = LDR[1 + K_t(T_m - 20) - K_p(P_m - 760) + K_h(V - 10)]$$

where

- CLR = corrected laser reading
- K_h = coefficient of refractive index change due to atmospheric humidity. The current best value is 0.05 ppm/mm Hg partial pressure of water vapor. Because of the low value of this coefficient, the atmospheric humidity can be neglected for most applications.
- K_p = coefficient of refractive index change due to atmospheric pressure. The current best value is 0.36 ppm/mm Hg pressure.
- K_t = coefficient of refractive index change due to atmospheric temperature. The current best value is 0.93 ppm/°C.
- LDR = laser display reading
- P_m = air pressure, mm Hg
- V = partial pressure of water vapor in mm Hg[3]
- T_m = mean air pressure, °C

The preceding equation is a linearization of the Edlén equation and is accurate to approximately 0.1 ppm. Other forms of this equation are equally accurate and are considered suitable for the purposes of this Standard. In order 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

$$CMR = MR[1 + K_s(T_s - 20)]$$

in the case where the machine was set up at 20°C (68°F). Variables are defined in para. 5.4.2.6.

If the laser interferometer used has environmental compensation features, the supplier's recommendations regarding the use of these accessories shall be followed, with the air temperature sensor near the laser beam path and the material sensor placed on the appropriate machine 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 7).

5.4.3.4 Measuring Intervals. Measuring intervals shall be no larger than those specified in para. 5.4.2.4 for step gage measurements; however, due to ease of measurement using laser systems, smaller intervals are strongly recommended with those intervals being chosen such that they are not even multiples of the machine scale spacing. With a laser interferometer 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. Although this measurement is not a requirement of this Standard, it can yield useful information.

5.4.3.5 Sets of Measurements. Three sets of measurements shall be made along each measurement line, all in the same direction. The sets of measurements may be taken with or without rezeroing the machine and the laser. For each measurement point, the mean of differences between corrected machine and laser

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[2] This form of equation also assumes atmospheric air with the normal mixture of gasses. Atmospheres that deviate significantly, particularly in regard to CO_2 and aromatic hydrocarbon concentration, have been observed and can lead to measurable errors. If this situation is suspected, appropriate correction should be applied.

[3] 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. Thus, for example, 50% relative humidity at 20°C would yield a partial pressure of 0.5 × 17.6 = 8.8 mm Hg.

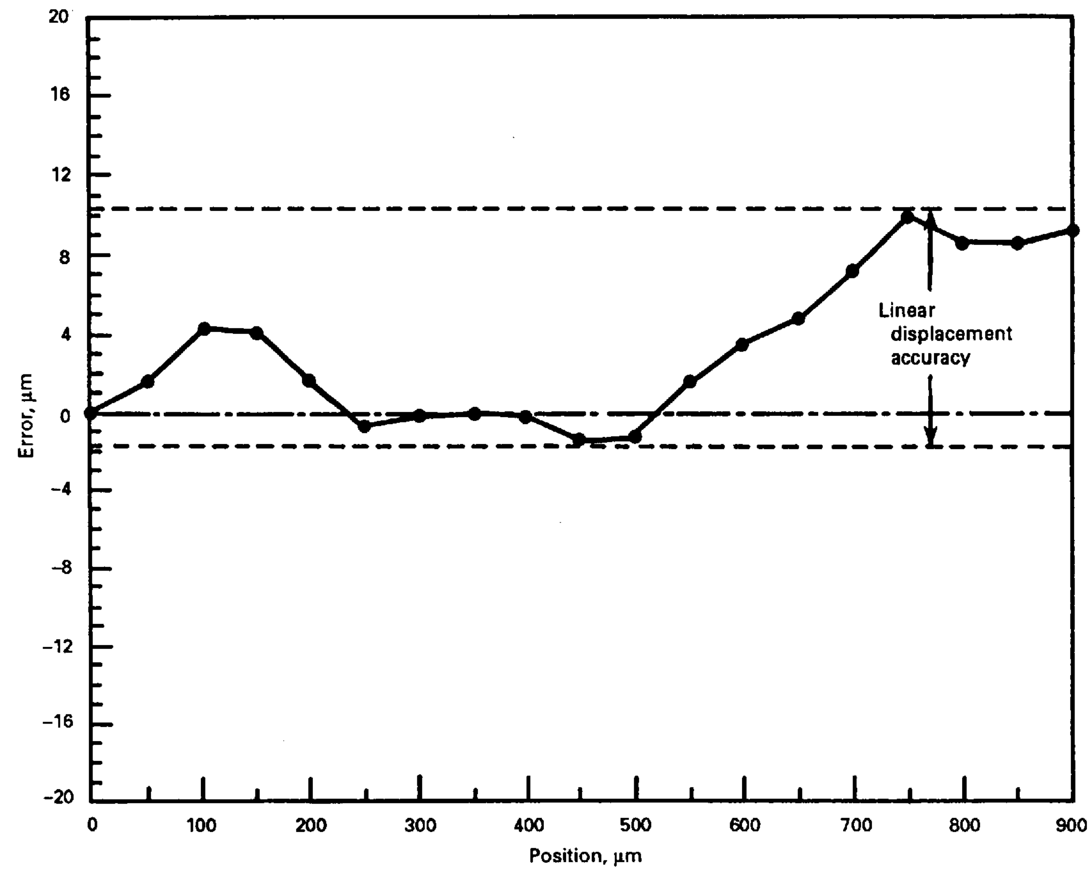


FIG. 25 TYPICAL RESULTS OF A LINEAR DISPLACEMENT ACCURACY TEST USING THE LASER WITH THE LINEAR DISPLACEMENT ACCURACY CLEARLY LABELED
(For this example, the linear displacement accuracy is approx. 12 µm.)

readouts shall be calculated. Linear displacement accuracy shall be the maximum spread of the mean differences of the individual points. This is illustrated in Fig. 25.

5.4.4 Linear Displacement Requirements. Linear displacement accuracy, as calculated in para. 5.4.2.7 or 5.4.3.5, shall not exceed the supplier's specification, derated as specified in para. 4.2, if applicable.

5.5 Volumetric Performance

5.5.1 General. Complete testing of the volumetric performance of coordinate measuring machines is a difficult and time-consuming process. This Standard has attempted to reduce the time and cost associated with testing by providing, wherever possible, simple self-checking procedures using measurements of uncalibrated artifacts. The primary uncalibrated artifact is the ball bar. Specifications that substitute calibrated artifacts, such as gage blocks, for the ball bar will be considered in conformance with this Standard if these artifacts are of equivalent length and are measured in the positions specified for the ball bar test (para. 5.5.2.1). The use of such calibrated artifacts for these tests does give additional information, but also incurs additional expense.

Ball bars provide a rapid and easily understood check of machine volumetric performance. Properly conducted ball bar tests allow precise comparisons of the length scales on the various machine axes and clearly point out deviations of machine geometry from perfection. They are also extremely useful for quickly rechecking a machine on a periodic basis. In no case should the ball bar tests alone be regarded as providing a measurement of machine accuracy. In this Standard, accuracy is assessed in the linear displacement accuracy section (para. 5.4). In the ball bar tests, as in the repeatability and linear displacement accuracy tests, one should expect that the precise value of error obtained is dependent on the particular mode chosen for that test.

Due to the practical difficulty in transporting and using very long ball bars and in subdividing very large work zones into many subvolumes, significant modifications to the normal ball bar procedures are provided in para. 5.5.4 for machines with large work zones. Here the laser interferometer is introduced because of its ability to measure over very long lengths. The laser interferometer may give a different range of values than would a long ball bar; however, these numbers should be representative of the machine's volumetric performance.

Users of this specification should also be aware that as the work zone aspect ratio increases on a machine, the sensitivity of these tests to the straightness of the longest axis on that machine is reduced. Where straightness is critical, a separate check of this parameter should be performed when the aspect ratio of the machine axes exceeds 4:1.

This section on volumetric performance also contains performance tests for machines with a rotary axis. These tests follow the same philosophy in that no calibrated artifact is used.

5.5.2 Volumetric Performance Procedures Using Ball Bars

5.5.2.1 General Patterns. The ball bar performance tests recommended by this Standard may be accomplished using a single ball bar of length slightly shorter (approx. 100 mm) than the least dimension of the work zone.[4] For nearly cubic machines, this ball bar is measured in 20 positions. The general approach is to position the bar along 10 of the 12 edges of the work zone, along at least six work zone face diagonals to require simultaneous motion of pairs of machine axes, and along the four work zone body diagonals to require simultaneous motion of all three machine axes. Recommended patterns for nearly cubic machines are given in Fig. 26. (The figures showing patterns are oriented for vertical ram machines. They should be rotated for horizontal ram machines.) For machines having work zones with different aspect ratios, the procedure still uses the shorter ball bar but places it at several positions along a long measurement line, in order to require nearly full travel of the machine along that measurement line. Patterns for machines with a single long axis (axis ratio 2:1:1) are shown in Fig. 27. These patterns require measurement of the ball bar in 30 locations. Sample patterns for machines with two long axes and one short axis (axis ratio 2:2:1) are shown in Fig. 28. These machines require 35 measurement positions. The patterns were chosen to provide maximum sensitivity to most angular and squareness errors. They do not completely check angular motions of the ram axis, thus a separate test is provided in para. 5.5.3 to assess ram axis angular error effects when using offset probes. Additionally, articulation of the probe head and length of the stylus during this test can significantly impact the results of the test. It is therefore recommended that such articulation and length changes be minimized. (Articulating probe systems are tested in para. 6.2.)

The figures shown are idealized and, on any given machine, it is possible that the ball bar positions shown will overlap. It is recommended that if positional overlaps between ball bar setups exceed 60% of the ball bar length, then one of the overlapping setups may be eliminated. Most existing cases can be readily obtained by rotations of the configurations in the figures. No detailed recommendations are made regarding ball bar fixturing; however, a limited discussion of fixturing alternatives is given in Appendix G, and a sample fixture used for holding a ball bar with both ends free is shown in Fig. 29.

Care should be taken in handling ball bars so that heat from the hand is not transferred to the ball bar. The use of a plastic insulating sleeve is helpful. The time constant for thermal equilibration of a hollow steel ball bar is approximately 20 min (see ASME B89.6.2, Temperature and Humidity Environment for Dimensional Measurement, for an explanation of thermal time constants). Typical ball bars will stabilize within about one hour after being brought into a temperature-controlled environment.

5.5.2.2 Setup and Measurement Procedure — Ball Bar Tests. The ball bar shall be suitably fixtured in the positions indicated for measurement so that probing access to both balls is available. A fixture based on a knuckle joint is shown in Fig. 29. Such a fixture should be portable so that it can be easily moved around the table and sufficiently rigid so that the ball bar will not significantly deflect or vibrate while the locations of the balls are being measured. For each of the positions specified in the

[4] As with other sections in this Standard, the user is allowed to specify measurements different than the default option. To be in compliance with this Standard, the user may specify measurements of ball bars in up to 40 different locations and is also allowed to specify up to 3 ball bar lengths. These positions and lengths must be clearly stated as part of the machine specification. Furthermore, if more than one length is specified, each length ball bar must be measured in at least 10 different positions.

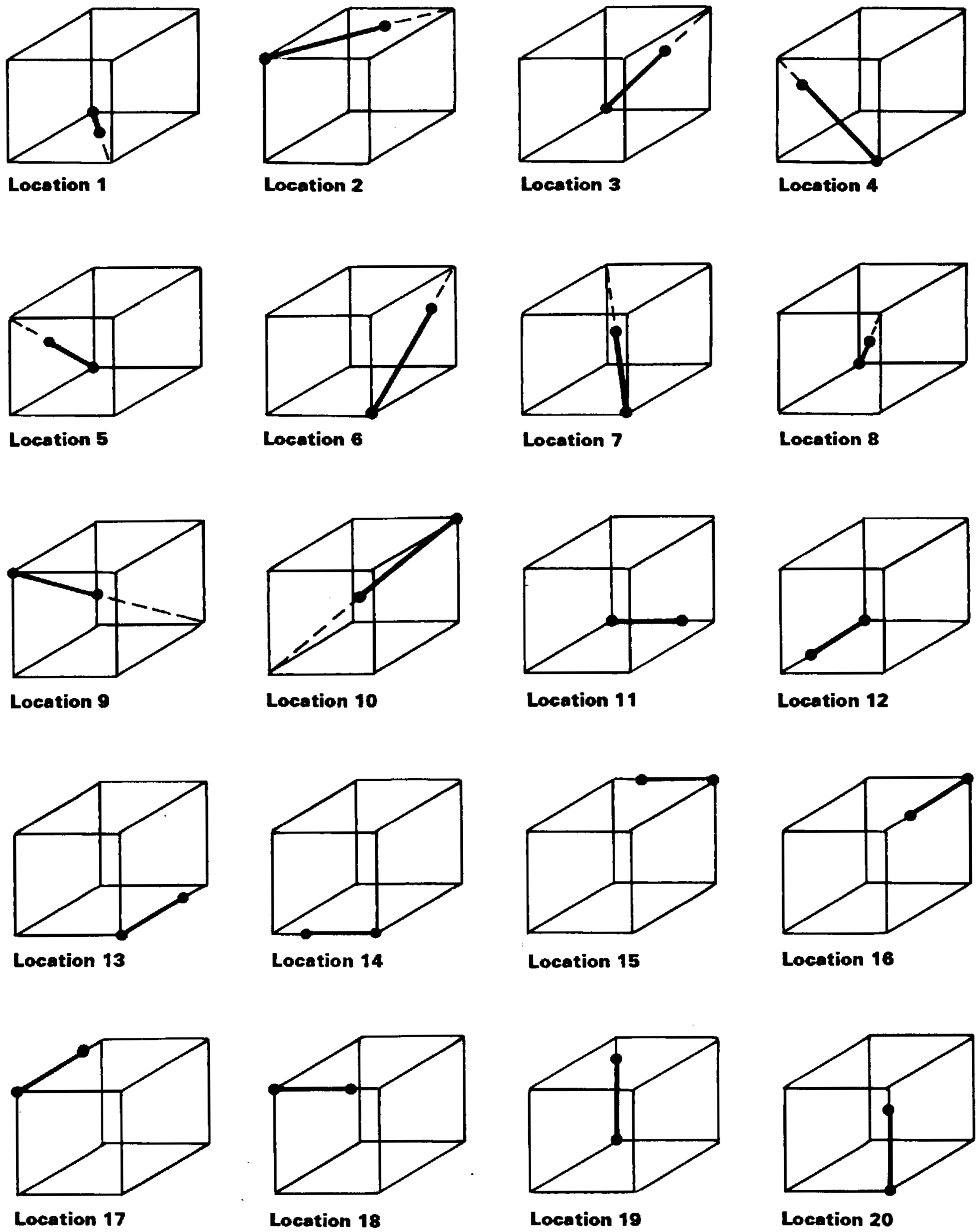


FIG. 26 RECOMMENDED BALL BAR POSITIONS FOR MACHINES WITH NEARLY CUBIC WORK ZONES

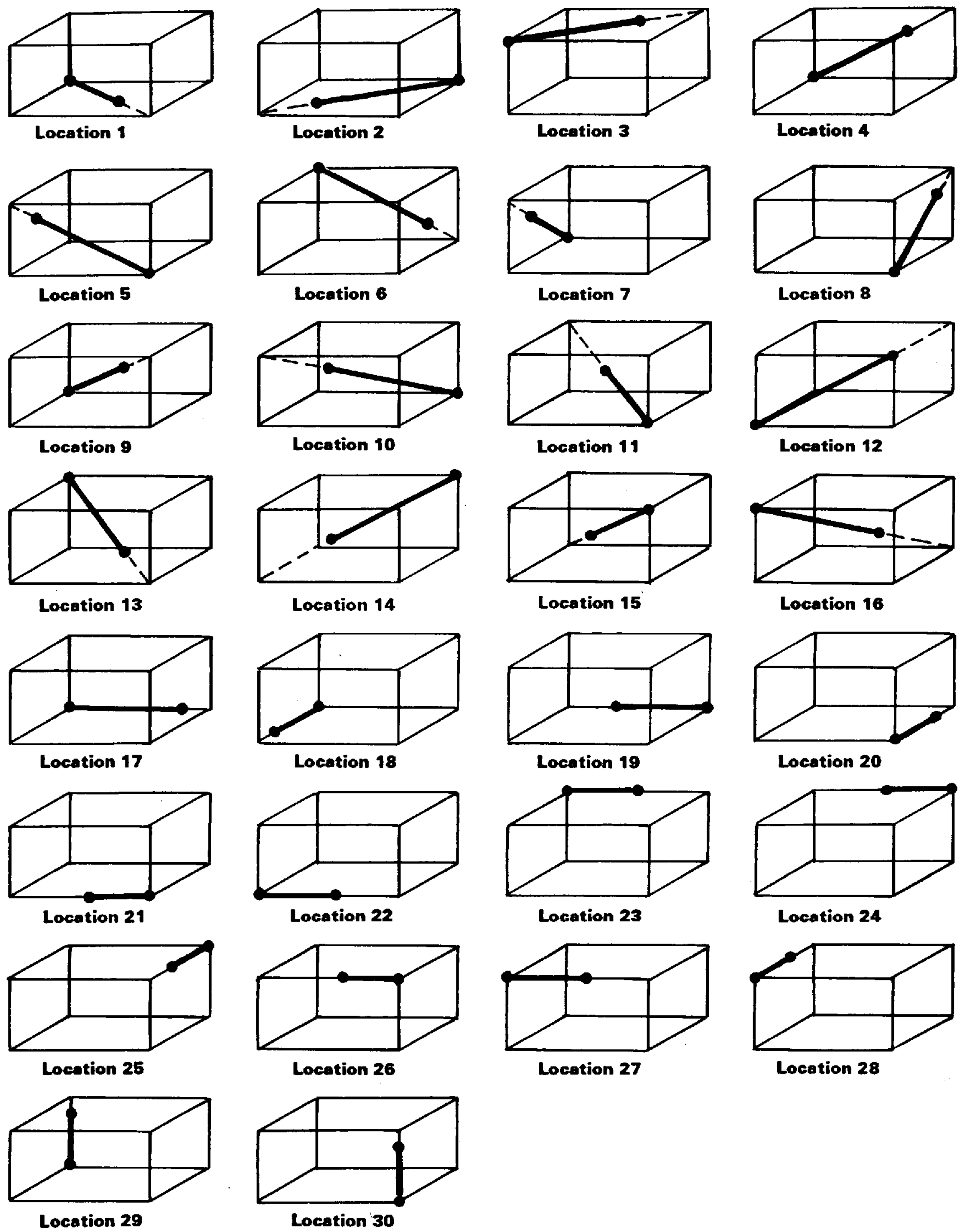


FIG. 27 RECOMMENDED BALL BAR POSITIONS FOR MACHINES WITH A SINGLE LONG AXIS (The axis ratio here is 2:1:1. On machines with slightly different ratios, overlapping patterns are recommended.)

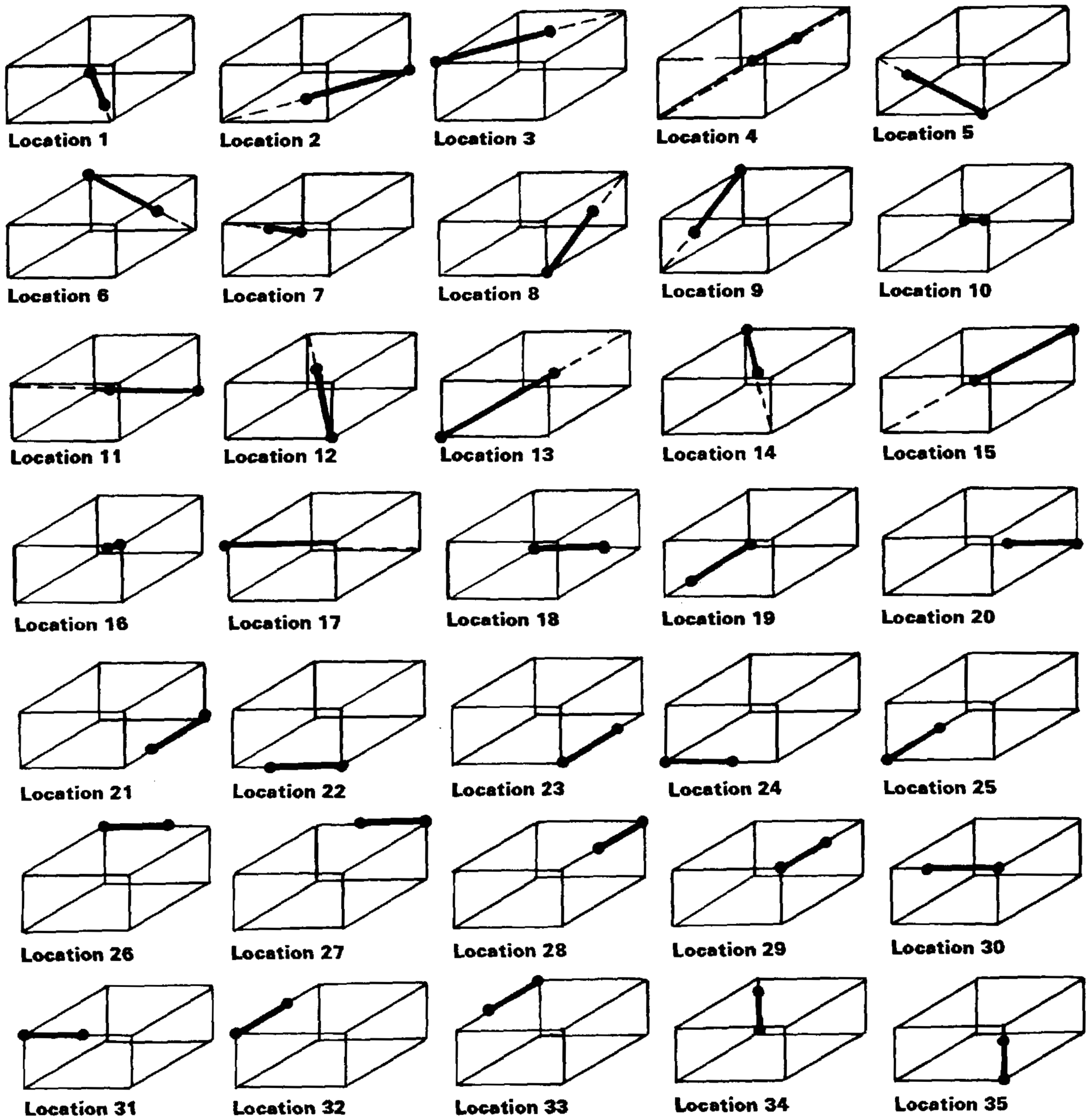


FIG. 28 RECOMMENDED BALL BAR PATTERNS FOR A MACHINE WITH TWO LONG AXES AND ONE SHORT AXIS
(The axis ratio here is 2:2:1. Again, for machines that do not quite correspond, overlapping positions are recommended.)

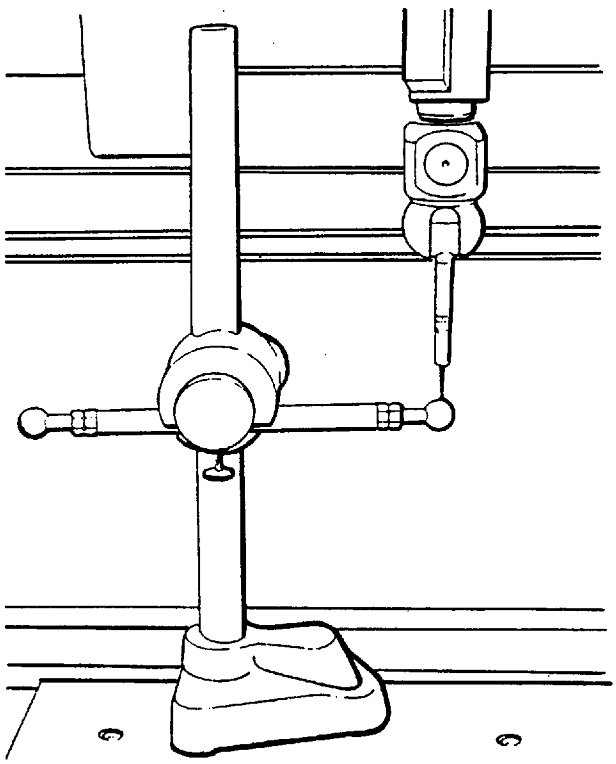


FIG. 29 SAMPLE FIXTURE FOR HOLDING A BALL BAR WITH BOTH ENDS FREE

patterns, both ends of the ball bar shall be measured. At least four probe contacts must be made on both of the balls in order to measure the ball bar length. To achieve better accuracy, eight or more points should be used to determine the center of each ball. These points should be dispersed around the ball as far as the probing system allows. (To check the repeatability of a setup, it is advisable to measure the ball bar length several times, but this is not a requirement of this Standard.) From these probings, center coordinates of the balls and the length of the ball bar shall be calculated for each ball bar position. The total spread of calculated ball bar lengths shall be assessed following the procedure described in para. 5.5.2.3. The range of these lengths shall not exceed the supplier's specifications, derated as specified in paras. 4.2 and 4.3, if applicable.

5.5.2.3 Ball Bar Data Analysis. The data from ball bar measurements are analyzed by preparing a simple plot or a simple table of the deviations in the ball bar length without regard to measurement location. An example of a scatter plot is given in Fig. 30. The working tolerance of the machine is defined as the range of data in such a plot, as is clearly indicated in the figure, or simply the total range in the values in the table. In cases where there appears to be a single (or several) outlying point(s) that does not conform to the general trend, it is recommended that this measurement be repeated.

The recommended procedure for checking the repeatability of a ball bar measurement is as follows. The ball bar shall be measured twice in the suspected position. If the measurements agree within twice the repeatability (para. 5.3), then the first measurement shall be used and the second measurement discarded. If the measurements do not agree within twice the repeatability, both are discarded and the procedure is repeated. This procedure may be repeated three times; at the end of which time, if repeatability has not been obtained as defined above, the test shall be discontinued and the fault determined and corrected. After correction of the problem, the repeatability test and the ball bar test must be rerun in their entirety.

5.5.3 Offset Probe Performance Test. The angular motion of the ram axis was not tested by the preceding procedure (see para. 5.5.2). This motion is of particular importance when probes with different offset lengths are used. The following test is designed to evaluate the machine performance when offset probes are used. Although the illustrations show vertical spindle machines, this test applies equally to horizontal arm machines.

5.5.3.1 Ball Bar Tests for Offset Probe Performance. The ball bar can be used to place tolerances on the magnitude of offset probing errors by using a probe with a large offset. A typical test setup is shown in Fig. 31. The probe offset length shall be set at a reasonable amount [approximately 150 mm (approx. 6 in.) is recommended], the probe shall be oriented perpendicular to both the ball bar axis and the ram axis, and measurements shall be made of the ball bar length with the offset probe, first with the probe in one position and then rotated 180 deg. about the ram axis with respect to that position. In performing these measurements, the ball bar may be moved to a second position, with nominally the same angle with respect to the ram and probe offset axes, rather than repositioning the cross-slide of the machine, as is shown in Fig. 30. These two procedures may give different results. When the cross-slide is moved, this movement may tilt the ram axis and lead to different results. For the purposes of this Standard, either procedure is allowed. Note that when offset probes are used, it is extremely important that they be properly balanced so as not to place undue moments on the ram. The default ball bar

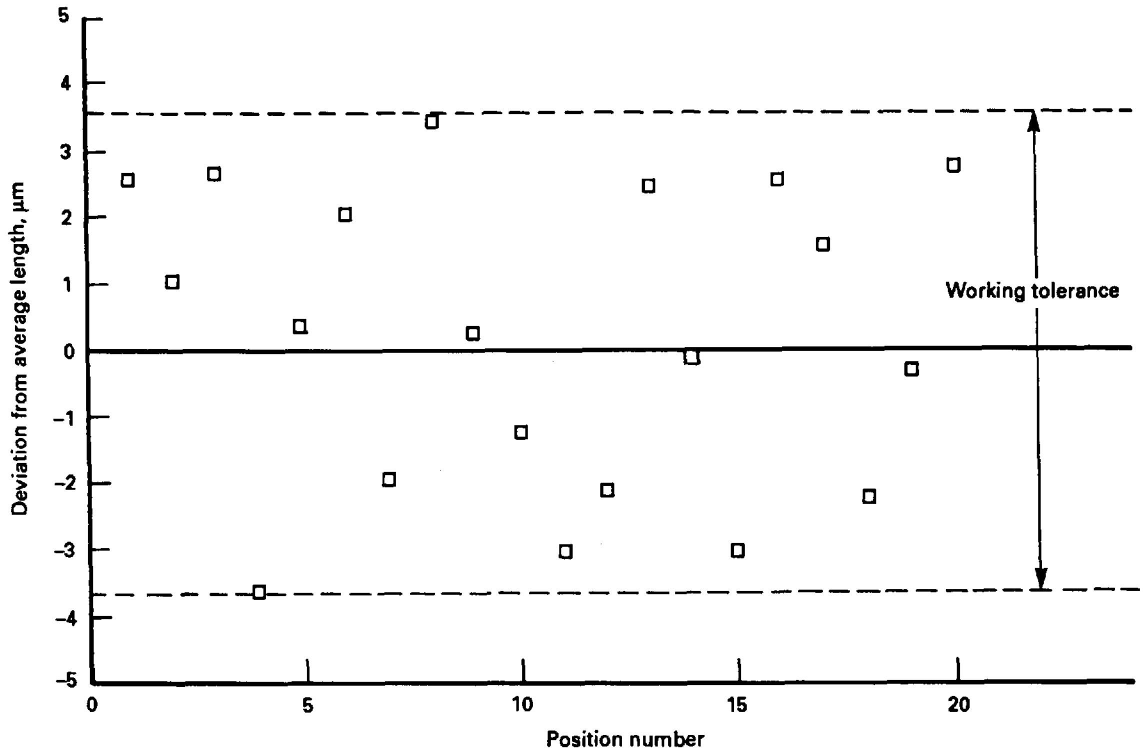


FIG. 30 BALL BAR TEST RESULTS
(In this example, working tolerance is approx. 7 μm.)

length for these tests shall be the ball bar length used for the volumetric performance test (para. 5.5.2).

The ball bar shall be measured in four locations. The user is free to choose any four positions within the machine volume for the ball bar measurements with offset probes; however, the default positions, which are most sensitive to ram axis angular motion, are shown in Fig. 32 for a vertical ram machine. In each position, the ball bar is at 45 deg. to the ram axis. Two locations are sensitive to ram axis roll and yaw and two locations are sensitive to ram axis roll and pitch. (The user should be cautioned that ball bar positions, where the ball bar length is nearly parallel or perpendicular to the ram axis, are insensitive to ram axis roll.) Differences between lengths measured with the two probe offsets shall be computed. The results are calculated as the ratio of these differences to twice the probe offset length. The absolute value of the largest calculated ratio is reported as the offset probe performance and shall not exceed the supplier's performance specifications, derated as specified in paras. 4.2 and 4.3, if applicable. (It should be noted that this test is not a parametric test; those users wishing to assess ram axis roll, specifically, are referred to Appendix H.)

5.5.4 Volumetric Tests for Machines With Large Work Zones. The goal in testing large machines remains the realistic estimation of the expected accuracy of machine measurements under real operating conditions. To accomplish this on large machines, limited ball bar testing is supplemented with specific additional linear displacement accuracy tests. The total number of ball bar measurements is 10 plus one additional position for each 10 m^3 of additional work zone volume over 20 m^3. The length of the ball bar is fixed, and shall be 0.9 m (approx. 35 in.) for all measurements. The locations of the ball bar measurements shall be specified in advance by mutual agreement between the supplier and user.

Additional linear displacement accuracy data shall be collected, as specified in para. 5.4, along six supplementary measurement lines. Four of the supplementary measurement lines shall be the body diagonals of the work zone. A typical setup for these measurements is shown in Fig. 19. The remaining two measurement lines shall be one line parallel to each of the non-ram axes. The location of each of these latter two lines in the work zone shall be chosen to maximize the offset distance from the line to the position measuring system

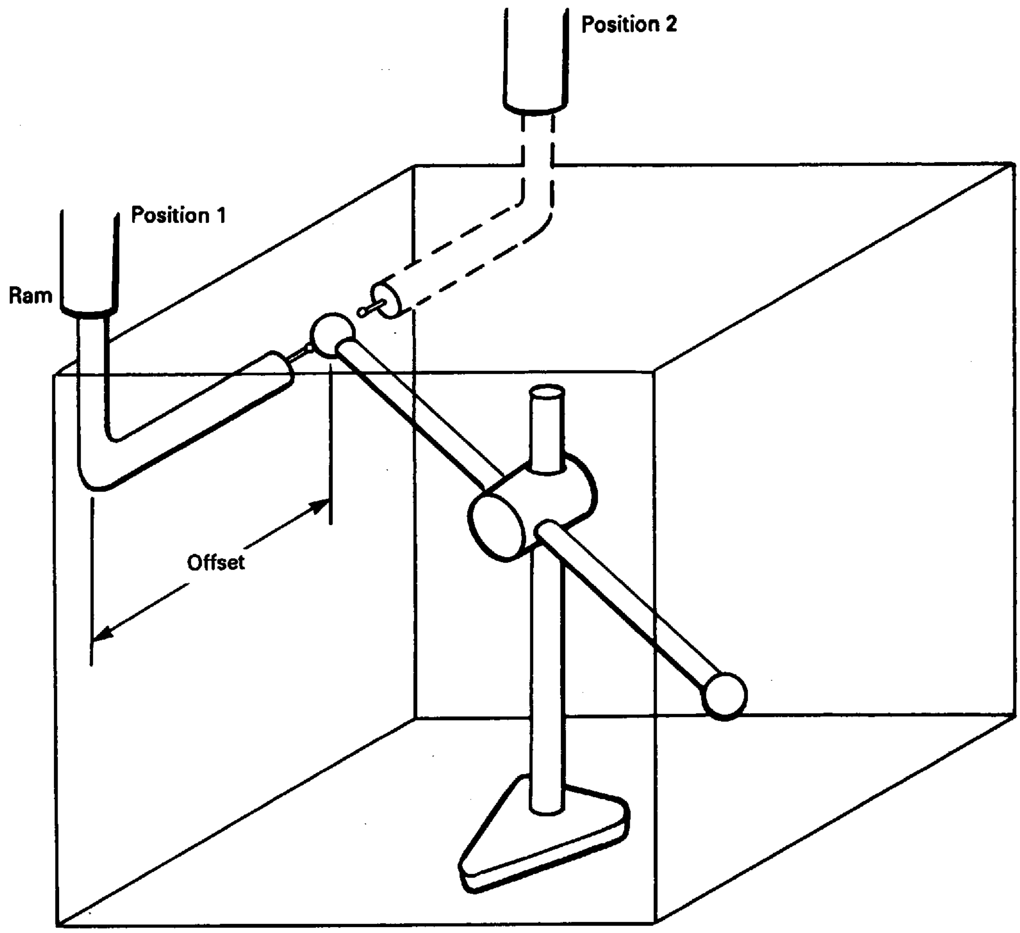


FIG. 31 TYPICAL SETUP FOR OFFSET PROBE PERFORMANCE TESTING

of the axis parallel to that line. The measurement points for each line chosen shall be at the point spacing specified in accordance with para. 5.4.2.4. The range of ball bar measurements and the greatest range of the six supplementary linear displacement measurements shall both be determined. Neither shall exceed the supplier's specifications, derated as specified in paras. 4.2 and 4.3, if applicable.

5.5.5 Performance Tests, Machines Used in the Duplex Mode

5.5.5.1 General. Paras. 5.5.5.2 and 5.5.5.3 specify methods for measuring the performance of machines operating in the duplex mode. Applicability of para. 5.5.5.3 shall be limited to installations where the work zones of the two machines overlap. For other installations, it is recommended that special test procedures be developed and agreed upon between the supplier and user.

Methods specified in these sections are applicable to a wide variety of duplex installations. Examples are large and small machines, all applicable machine configurations, machines with individual rotary tables or a shared rotary table, machines on opposite sides of a shared fixed table, and machines with a shared primary axis. The general principle for testing duplex installations is that each individual machine shall be tested as a separate machine, then the relationship between the two machines shall be tested by measurement of duplex performance.

5.5.5.2 Tests of Individual Machines. The tests for individual machines shall be the appropriate tests of this Standard.

When one of two machines used in the duplex mode is individually tested, the other machine shall be in motion in a manner recommended by the supplier for duplex measurement of a workpiece. Thus, if the sup-

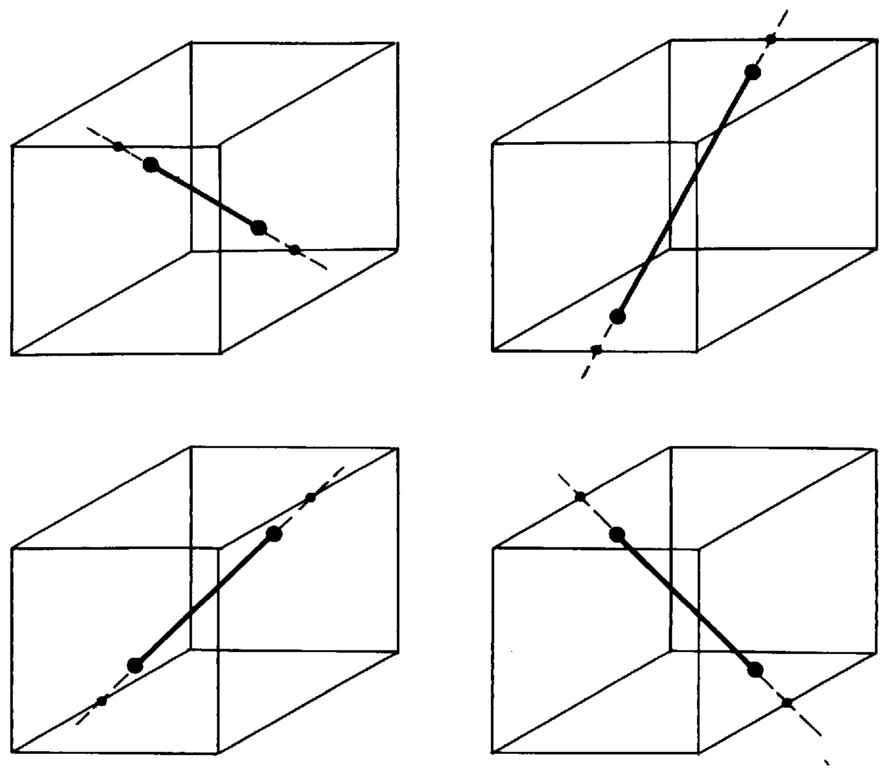


FIG. 32 DEFAULT BALL BAR POSITIONS FOR THE OFFSET PROBE PERFORMANCE TEST ON A VERTICAL RAM MACHINE

plier recommends no limitations on motion of one machine while the other is measuring, there are no limitations on motion during testing. If the supplier recommends one machine be at rest when the other is measuring, then it must be at rest during testing. Within this limitation the user may choose the manner of motion.

5.5.5.3 Duplex Performance Test. There are two options for conducting the duplex performance test: table mount and ram mount. The supplier shall specify which option is to be used unless otherwise contractually agreed upon between the supplier and user.

For the table mount option, a precision reference ball shall be supported in successive specified positions from the table or other workpiece support surface. Optionally, an array of balls may be used. In each position, center coordinates of the reference ball or balls shall be measured by both machines.

For the ram mount option, a precision reference ball shall be mounted to the ram of a first machine in the position normally occupied by the probe tip. The first machine shall be moved to successive specified positions, and center coordinates of the ball shall be measured by the second machine. Measured ball center coordinates for the first machine shall be position coordinates of the probe tip reported by the first machine. All ball center coordinate measurements shall be performed by the methods specified in para. 5.5.2.2.

The ram mount option is generally preferred where it can be used. Because there is only one set of probing errors per pair of ball center determinations, it gives a better indication of the relationship between the axis systems of the two machines. Furthermore, it is faster and requires less hardware. It cannot, however, be used on some machines with built-in proportional probes because there is no suitable method for mounting the reference ball; additionally, it cannot be used on machines that do not have a triggering means for reading the first machine position.

For both options, the two machines shall either be operated in the same coordinate system, or ball center coordinates measured by one machine shall be transformed into the coordinate system of the other machine.

Ball positions shall be in a plane defined by two perpendicular machine axes in the overlap portion of the two work zones. A plane having maximum area shall be chosen. In the interest of clarity, the machine specification shall contain a description of the plane position. For planes of 1 m^2 or less, there shall be 9 ball positions. For planes of 1 to 4 m^2, there shall be 9 ball positions per m^2. For planes over 4 m^2, there shall be at least 36 ball positions. The user may specify the ball positions. The default pattern specification shall be the intersections of a grid of squares covering substantially the entire plane.

For each reference ball position, center coordinates measured by the first machine shall be subtracted from center coordinates measured by the second machine. The range of such differences shall be duplex performance.

5.5.5.4 Duplex Performance Requirements. Duplex performance, as calculated in para. 5.5.5.3, shall not exceed the supplier's specification, derated as specified in paras. 4.2 and 4.3, if applicable.

5.5.6 Volumetric Performance Test for DCC Machines With a Rotary Axis

5.5.6.1 General. The performance test described in this section is applicable only to four-axis machines with three linear axes plus a rotary table. This test is performed in addition to the other tests in Section 5, which are conducted without the use of the rotary table. The user should be aware that this test only indirectly assesses periodic error in the rotary scales. Users particularly concerned with this error are advised to perform the appropriate parametric calibration.

Some coordinate measuring machines allow alternative locations and/or orientations of the rotary table. For such machines, the specified working tolerance for this test must be met when the test is conducted at any permitted table location and/or orientation of the rotary table within the machine work zone. The default option for this test is that the user may select any one position for the performance of this test from the previously specified permitted locations and/or orientations. Performance may also be tested for more than one position and for a preferred rotary table location and orientation, if agreed.

The working tolerances for a rotary axis are called the 3D/alpha working tolerances. They are determined by using all four axes of the machine to measure the centers of the two spheres on the rotary table, and by analyzing the ranges of the measured center displacements for each sphere. Since this test does not use a calibrated artifact, it does not directly check accuracy; rather, it checks a complex combination of rotary table geometry, rotary table alignment, probing, linear accuracy, and measuring machine coordinate transformation algorithms. Users interested in analyzing the geometry of the rotary table as a separate element are referred to ASME B89.3.4M-1985 and ASME B5.54M-1992, Methods for Performance Evaluation of Computer Numerically Controlled Machine Centers.

TABLE 1
LOCATION OF THE REFERENCE SPHERE ON THE ROTARY TABLE

Heights H_S, mm	Radii R_S, mm
200	200
400	200
400	400
800	400
800	800

5.5.6.2 Setup. At each of the locations chosen for the performance of this test, the rotary table shall be aligned following the procedures specified by the supplier for table alignment during normal four-axis measurements on the machine. This alignment is critical. Next, two precision spheres are mounted to the rotary table in the position shown in Fig. 33. H_s and R_s shall be the largest applicable corresponding values from Table 1. The value of H_s shall be such that the high sphere can be measured by the machine. The value of R_s shall be less than the table radius R_t and shall be such that the low sphere can be mounted on the table near the table surface. R_t is half the diameter of the rotary axis as defined in the Glossary. In the case where axis motion limitations prevent use of the H_s value from Table 1, H_s shall be the maximum distance allowed by the machine geometry. The precision spheres shall meet the requirements for precision reference balls, para. 7.3.3. If an extensible ball bar conforming to the requirements of Appendix G was used in the preceding tests, the balls and extensions in this set can be readily adapted to perform this function.

5.5.6.3 Measurement Procedure. The general procedure is as follows. The rotary table is rotated through a series of angular positions and the position of one of the two spheres is measured. Recommended sets of angular positions, in which the rotary table is completely accessible to the CMM and where it is partially accessible, are given in Table 2. (Certain measuring machines use the rotary table as a means of extending the measuring range, so that only a portion of the rotary table is accessible to a probe. On such machines, the starting angular position of the rotary table must be such that the positions of both balls can be measured.) The angular positions given are default values. The user may choose these or any other set

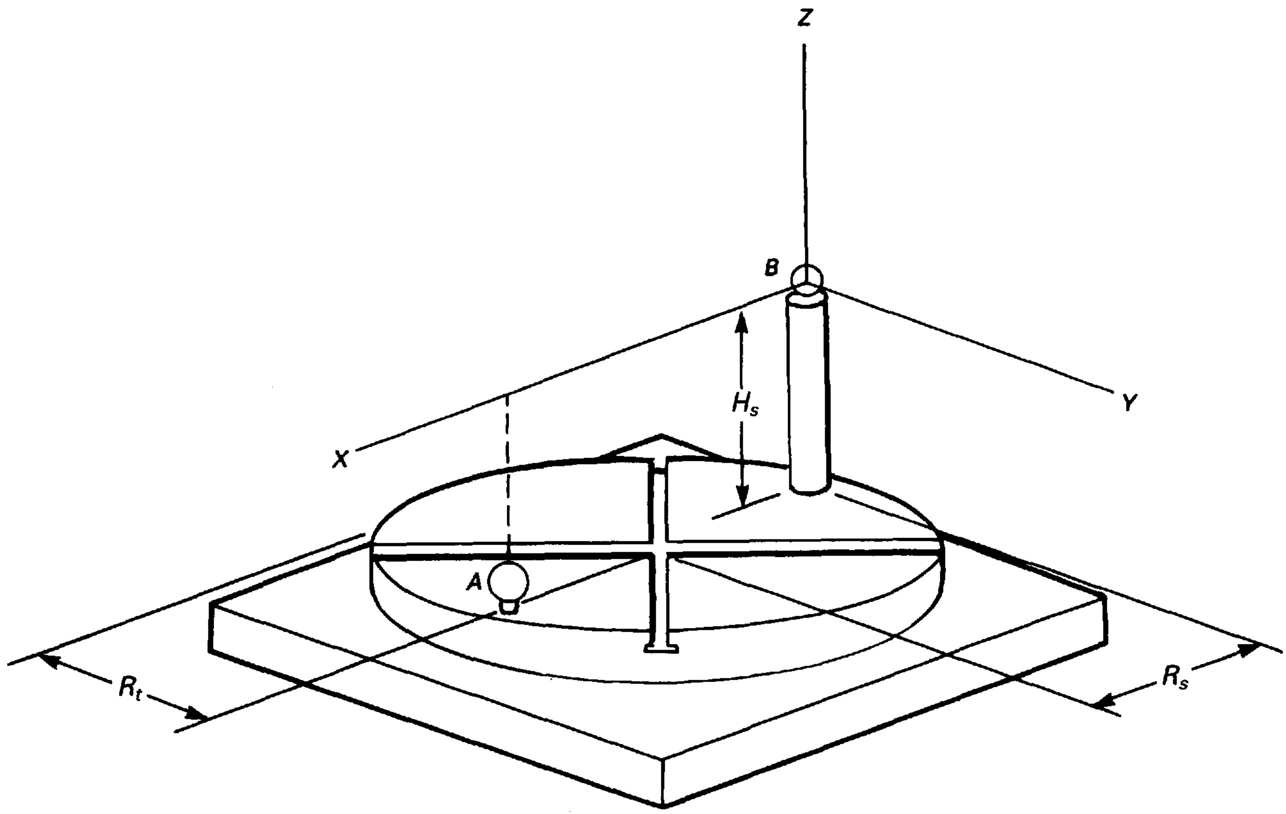


FIG. 33 DIAGRAM OF TEST BALL POSITIONS FOR THE PERFORMANCE TEST ON A ROTARY AXIS
(The *X*, *Y*, and *Z* designations in this figure are used to illustrate directions with respect to the rotary table base and do not necessarily represent machine axis designations.)

of values, provided the chosen set is made part of the specification and contains the same number of points. All results of the measurements are reported in a part coordinate system. Users having machines without the software to enable this transformation can still perform this test; however, the analysis is complex and is not included in this Standard.

In the following discussion, *X*, *Y*, and *Z* are directions relative to the rotary table illustrated in Fig. 33. They do not necessarily correspond to the supplier's labeling of the machine axes.

The following procedure shall be followed. The rotary table is put in the starting position, position zero (0) in Fig. 34, and the positions of sphere *A* (the low sphere) and sphere *B* (the high sphere) are measured using the procedures described in para. 5.5.2.2 for measuring the center coordinates of a sphere during the ball bar test. The machine software is set so that the measurement results will be reported in the part coordinate system with the measured center of sphere *B* set as the zero datum in this system, the *X*, *Y* plane set normal to the rotary table axis, and the *Z*, *X* plane set through the measured sphere centers. The coordinates of the center of sphere *A* are calculated in this system.

The rotary table is then rotated 13 times to different nominal angular positions (for example, those given in Table 2). At each angular position, the position of sphere *A* is measured using the appropriate probing sequence and these positions are recorded as in Table 2. When the rotary table is returned to its starting angular position (point 14 in Table 2), the locations of both spheres are again measured, retaining the original datum on sphere *B*. The apparent *X*, *Y*, *Z* positions of the centers of spheres *A* and *B* are calculated and recorded. The rotary table is then rotated 13 more times to the positions as shown in Table 2 and Fig. 34. At each angle the apparent *X*, *Y*, *Z* position of the center of sphere *B* is recorded. (Note that since the part coordinate system is being used with sphere *B* as

TABLE 2
DEFAULT NOMINAL ANGULAR POSITIONS AND SAMPLE DATA SHEET FOR OBTAINING VOLUMETRIC PERFORMANCE WITH A ROTARY AXIS

Point No.	A1 Deg. [Note (1)]	A2 Deg. [Note (2)]	Sphere *A*			Sphere *B*		
			XA	*YA*	*ZA*	*XB*	*YB*	*ZB*
0	0	0	XA_0	0	ZA_0	0	0	0
1	75	135	XA_1	YA_1	ZA_1	...	...	...
2	125	225	XA_2	YA_2	ZA_2	...	...	...
3	175	315	XA_3	YA_3	ZA_3	...	...	...
4	385	405	XA_4	YA_4	ZA_4	...	...	...
5	410	540	XA_5	YA_5	ZA_5	...	...	...
6	510	630	XA_6	YA_6	ZA_6	...	...	...
7	820	810	XA_7	YA_7	ZA_7	...	...	...
8	510	630	XA_8	YA_8	ZA_8	...	...	...
9	410	540	XA_9	YA_9	ZA_9	...	...	...
10	385	405	XA_{10}	YA_{10}	ZA_{10}	...	...	...
11	175	315	XA_{11}	YA_{11}	ZA_{11}	...	...	...
12	125	225	XA_{12}	YA_{12}	ZA_{12}	...	...	...
13	75	135	XA_{13}	YA_{13}	ZA_{13}	...	...	...
14	0	0	XA_{14}	YA_{14}	ZA_{14}	XB_{14}	YB_{14}	ZB_{14}
15	−75	−135	...	...	...	XB_{15}	YB_{15}	ZB_{15}
16	−125	−225	...	...	...	XB_{16}	YB_{16}	ZB_{16}
17	−175	−315	...	...	...	XB_{17}	YB_{17}	ZB_{17}
18	−385	−405	...	...	...	XB_{18}	YB_{18}	ZB_{18}
19	−410	−540	...	...	...	XB_{19}	YB_{19}	ZB_{19}
20	−510	−630	...	...	...	XB_{20}	YB_{20}	ZB_{20}
21	−820	−810	...	...	...	XB_{21}	YB_{21}	ZB_{21}
22	−510	−630	...	...	...	XB_{22}	YB_{22}	ZB_{22}
23	−410	−540	...	...	...	XB_{23}	YB_{23}	ZB_{23}
24	−385	−405	...	...	...	XB_{24}	YB_{24}	ZB_{24}
25	−175	−315	...	...	...	XB_{25}	YB_{25}	ZB_{25}
26	−125	−225	...	...	...	XB_{26}	YB_{26}	ZB_{26}
27	−75	−135	...	...	...	XB_{27}	YB_{27}	ZB_{27}
28	0	0	XA_{28}	YA_{28}	ZA_{28}	XB_{28}	YB_{28}	ZB_{28}

GENERAL NOTES:
(a) In this table, an ellipsis (. . .) means that no measurement is made of the location of that sphere in that angular position (see para. 5.5.6.3).
(b) Only one of the columns "A1" or "A2" applies to a specific machine being tested.

NOTES:
(1) Angular positions "A1" apply to CMMs with partial coverage of the rotary table (Fig. 33).
(2) Angular positions "A2" apply to CMMs with full coverage of the rotary table (Fig. 33).

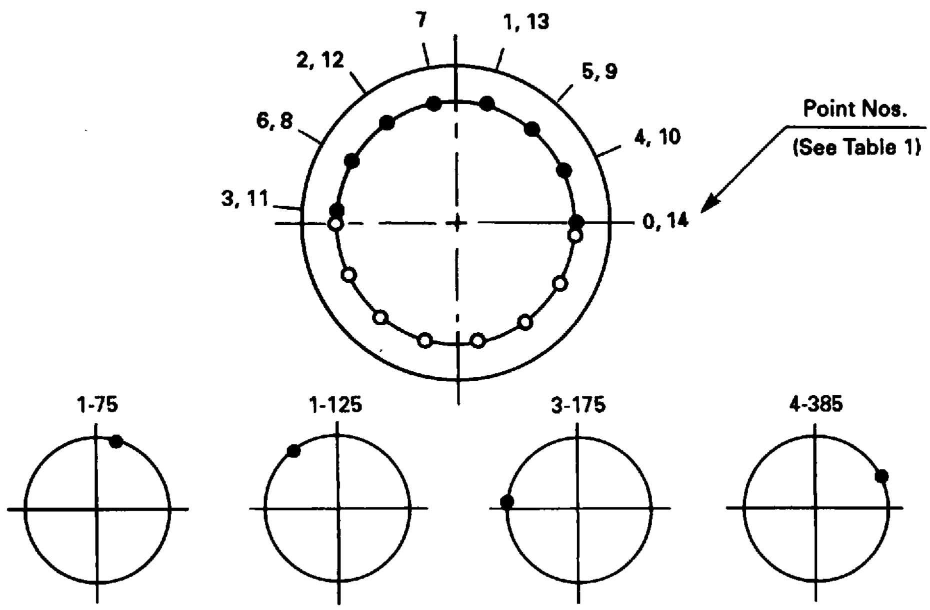
the datum, its measured center would remain at zero on a perfect machine.)

The rotary table is then returned to its original position and spheres *A* and *B* are remeasured, retaining the original datum on sphere *B*. The apparent *X*, *Y*, *Z* positions of the centers of spheres *A* and *B* are calculated and recorded.

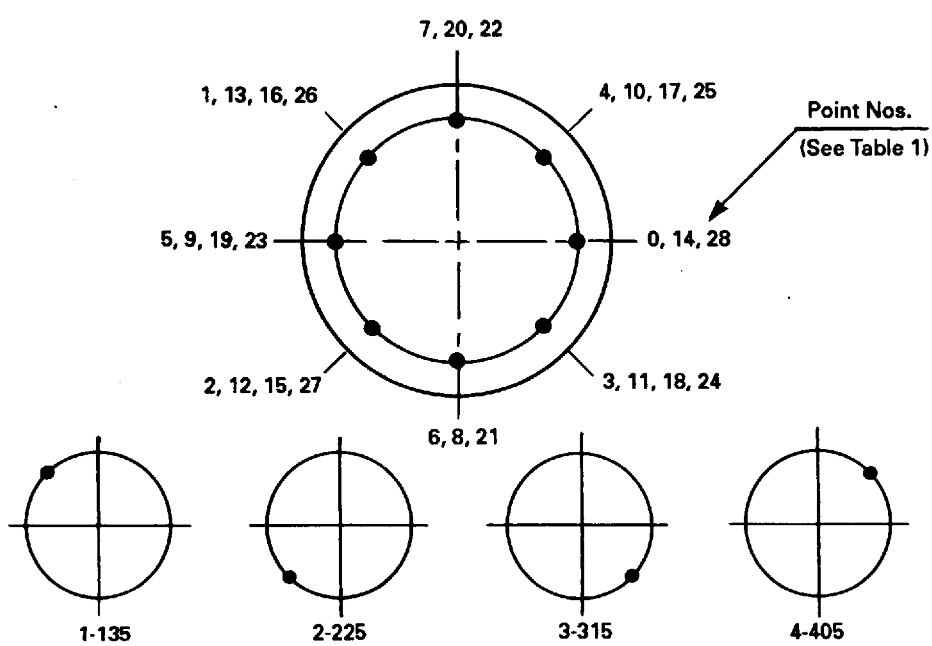
Users are free to select their own angular positions for the performance of this test, as long as the same number (14) of angular positions is included and rotations exceeding 360 deg. are allowed.

5.5.6.4 Rotary Table Performance Data Analysis. The data set is analyzed to obtain the 3D/alpha working tolerance. Here the *X*, *Y* and *Z* coordinate values obtained for spheres *A* and *B* are plotted on similar scatter plots. The range of the *X* values for spheres *A* and *B* are compared, and the largest range reported as the working tolerance for 3D/alpha radial performance. Similarly, the greater of the ranges of the *Y* values for spheres *A* and *B* is reported as the working tolerance for 3D/alpha tangential performance. Finally, the greater of the *Z* ranges for spheres *A* and *B* is reported as the working tolerance for 3D/alpha axial performance. The geometric meaning of these parameters is conceptually illustrated in Fig. 35.

5.5.6.5 Rotary Table Performance Requirements. 3D/alpha performance shall not exceed the

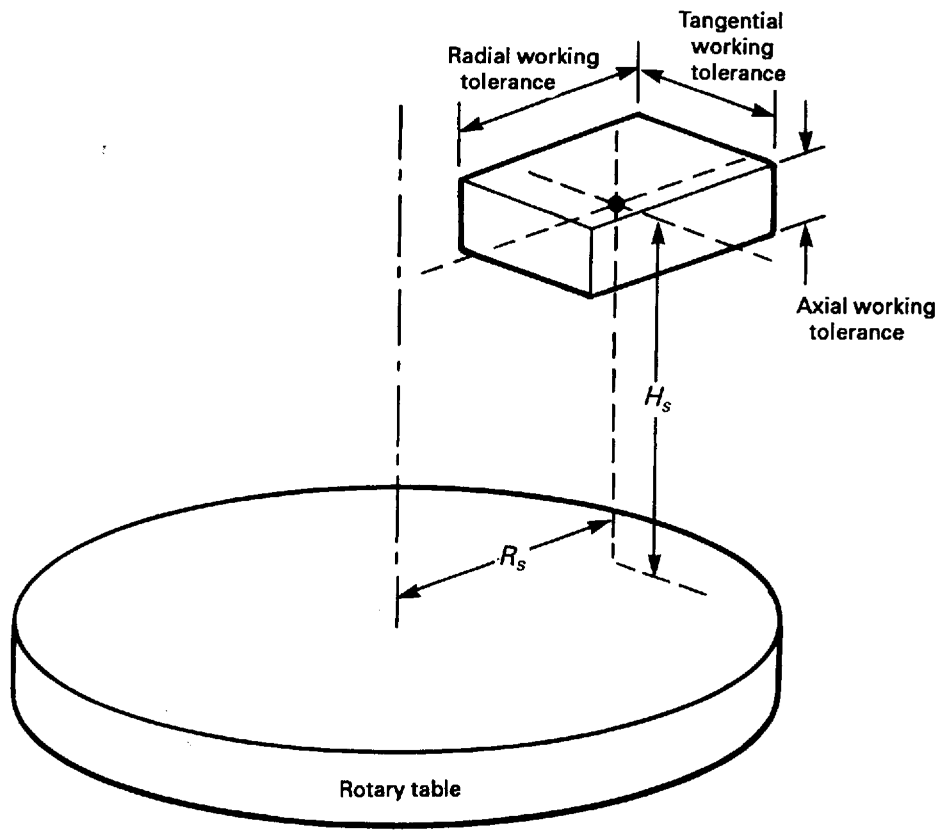


A1 — CMM has access to $\frac{1}{2}$ of rotary table



A2 — CMM has access to full rotary table

FIG. 34 DEFAULT POSITIONS FOR SPHERE LOCATIONS ON THE ROTARY AXIS PERFORMANCE TEST



GENERAL NOTES:
(a) R_s is the radius of Sphere *B* from the rotary table center.
(b) H_s is the height of Sphere *B* from the rotary table face.

FIG. 35 DIAGRAM SCHEMATICALLY REPRESENTING THE MEANINGS OF THE RADIAL, TANGENTIAL, AND AXIAL WORKING TOLERANCES FOR THE ROTARY AXIS PERFORMANCE TEST

supplier's specification, derated as specified in paras. 4.2 and 4.3, if applicable.

5.5.7 Performance Testing Coordinate Measuring Systems Under Loaded Conditions. The following procedures for evaluating machine load effects (and definitions supplied in the Glossary) are intended to be used primarily for informational purposes. They will allow the purchaser of a coordinate measuring machine to better understand the result of utilizing incorrect loading methods or overloading the CMM. In general, this procedure is not intended to be used as an "acceptance" test at the time of machine purchase. It should be used to differentiate machine models and their relative "robustness" under load, and to ensure that machines have appropriate weight capacities for their intended application. In cases where a specialized machine load is required, the supplier and user shall agree upon alternate specifications.

5.5.7.1 Testing Procedure — Acceptable Machine Loading. The general requirements for this test include the following:

(a) Weight used to perform testing shall not exceed the maximum acceptable machine load specification.

(b) The CMM supplier shall perform tests that comply with all procedural requirements and shall meet or exceed specified performance levels.

(c) The physical volume of the weight supplied for testing must lie within the measuring cube of the CMM and the weight must be free-standing.

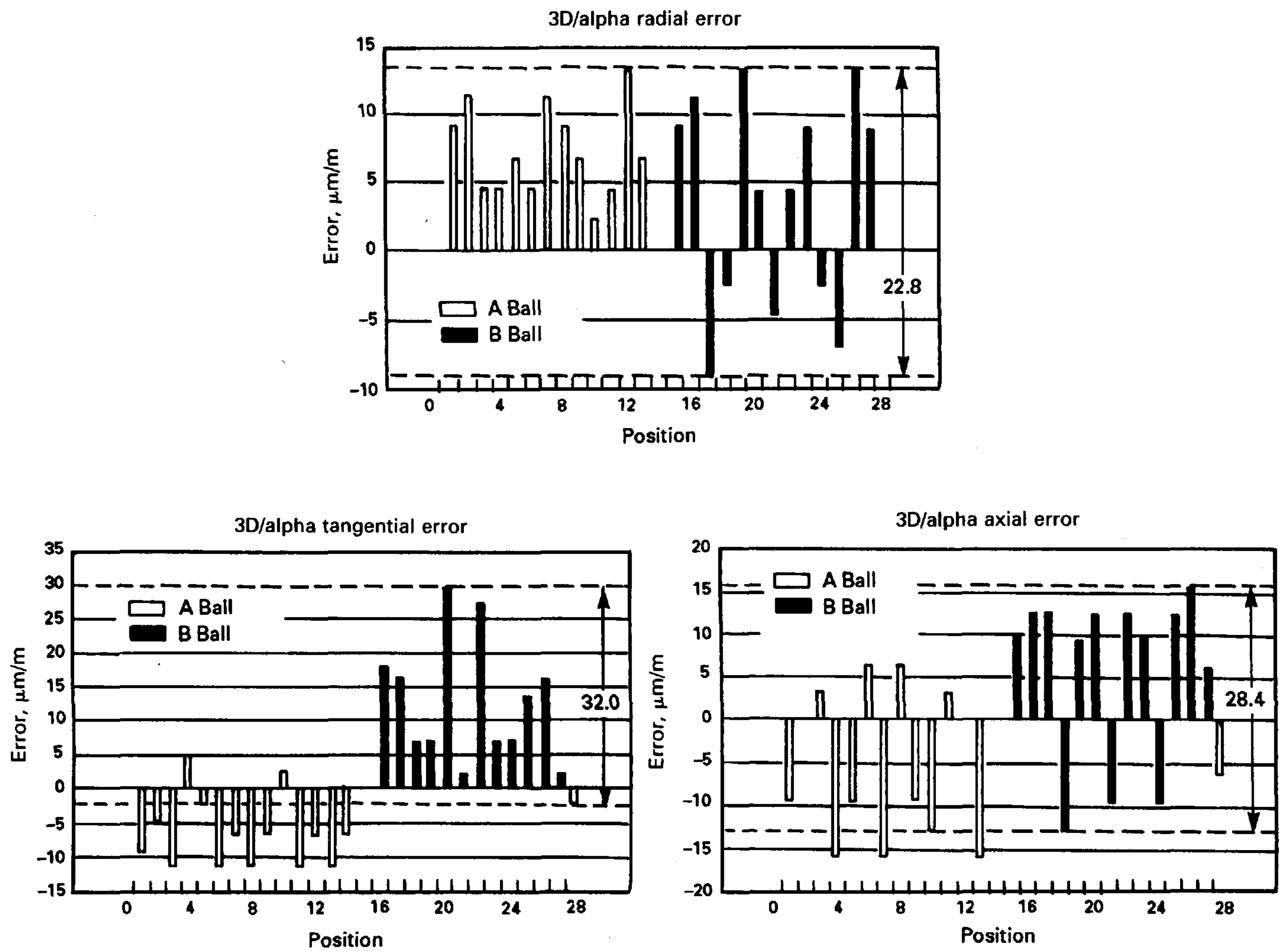


FIG. 36 TYPICAL RESULTS OF A VOLUMETRIC PERFORMANCE TEST FOR A DCC MACHINE WITH A ROTARY AXIS
(The 3D/alpha radial, 3D/alpha tangential, and 3D/alpha axial working tolerances are clearly labeled on the graphs.)

(d) The load at any specific contact point will be no greater than twice the load of any other contact point.

(e) The center of gravity of the machine load must lie within the CG location zone.

(f) The specific test load must fall within acceptable machine load limits, as defined by the Load Concentration Chart (Fig. 3).

The following steps should be taken for the test procedure.

(a) Place the test weight on the machine.

(b) Perform the repeatability test as described in this Standard (para. 5.3), with the exception of location. Location is optional in this test.

(c) Perform six ball bar measurements, as physical constraints allow, selected from the following eleven user-selectable positions:

(1) (four) 3D diagonals (as available);

(2) planar diagonal (front);

(3) planar diagonal rear (opposite orientation);
(4) planar diagonal (top);
(5) planar diagonal (left side);
(6) planar diagonal (right side — opposite orientation); and
(7) two orthogonal linear axes.

WARNING: Omission of 3D diagonals may prevent seeing the full effect of loading.

(d) Remove weight.
(e) Repeat *(b)* above (repeatability test).
(f) Repeat *(c)* above (ball bar measurements).
(g) Perform a repeatability analysis: results of tests 2 and 5 shall not exceed the stated repeatability specification.
(h) Perform volumetric analysis:
(1) range of readings of test 3 shall not exceed stated machine volumetric performance specification;
(2) range of readings of test 6 shall not exceed stated machine volumetric performance specification;
(3) the difference between a measured length in test 3 and the measured length from the same position in test 6 shall not exceed 50% of the machine volumetric performance specification.

5.5.7.2 Optional Procedure (Laser or Gage Block). Follow the procedure described above using a laser interferometer, gage block, or other equivalent device as the measured artifact. Analyze all data per para. 5.5.7.1.

5.5.7.3 Rotary Table Machine Procedure. For a rotary table machine, the procedure is as follows.
(a) Calibrate the rotary table in an unloaded mode.
(b) Place weight on the machine in compliance with the guidelines of para. 5.5.7.1 above.
(c) Perform the repeatability test as described in para. 5.3, with the exception of location. Location is optional in this test.
(d) Perform the volumetric performance test for DCC machines with a rotary axis (para. 5.5.6) using positions listed in column A1 of Table 2.
(e) Remove weight.
(f) Repeat *(c)* above (repeatability test).
(g) Repeat *(d)* above (volumetric performance test).
(h) Analysis: results of tests 3, 4, 6, and 7 shall not exceed the stated machine performance specifications for repeatability, radial, tangential, and axial (3D/alpha) error.

NOTE: It is recommended that a weight with simple geometric form be used for testing purposes to reduce potential difficulties in calculating the CG location.

5.5.8 Volumetric Performance Requirements. Volumetric performance, as calculated in paras. 5.5.2, 5.5.3, 5.5.4 (if applicable), 5.5.5 (if applicable), 5.5.6 (if applicable), and 5.5.7 (if applicable) shall not exceed the supplier's specifications, derated as specified in paras. 4.2 and 4.3, if applicable.

5.6 Bidirectional Length Measurement Capability

5.6.1 General. The preceding tests have produced a meaningful picture of the measurement system performance; however, some errors, such as undue machine or probe hysteresis and improper probe compensation, have not been fully analyzed since no two-sided length measurement has yet been performed. The following tests remove this deficiency by requiring the measurement of a gage block of a convenient length, in four positions in the machine work zone. Three of these positions are roughly aligned with the machine axes, and the fourth position is user-selectable. It is recommended that this fourth position not be aligned with any machine axis. The length of the block shall be within the range of at least 25 mm (approx. 1 in.) to 100 mm (approx. 4 in.), with the default value being 25 mm (approx. 1 in.). The gage block shall be calibrated in accordance with the requirements of para. 7.3.1.

Before performing these tests, the machine probe shall be calibrated and qualified according to the supplier's recommendations for normal operation of the machine when measuring parts. Qualification on the gage block to be used for this test is specifically excluded. The measurements for this test are also to be performed using the probing parameters, probe approach rate, probe approach distance, and settling time specified for normal operation in Fig. 1A.

5.6.2 Measurement Procedure — Bidirectional Length Measurement. The gage block conforming to the requirements of para. 5.6.1 above shall be rigidly mounted in the work zone of the machine on a fixture that allows probing access to the faces of the gage block for the four measurement positions in turn. The mean temperature of the gage block and the appropriate machine scale(s) may be measured during this gage block measurement process for each position, using a thermometer conforming to the requirements of Section 7. The exact location of the gage block in the work zone is not critical; however, it is recommended that this position be near the location in the work zone where parts will most commonly be measured. After mounting and alignment, which may be mechanical or performed by using the appropriate computer algorithm, the length of the gage block shall be measured in each position using the method recommended by the supplier for measurement of distance between two parallel planes.

5.6.3 Bidirectional Length Measurement Data Analysis. The length of the gage block shall be calculated using the coordinate measuring machine software in each of the positions and may be corrected for temperature as described in para. 5.4.2.6. The worst case (largest) deviation, without regard to sign, between the calibrated and the measured values of the length of the gage block, along with the nominal length of the gage block, is reported as the bidirectional length measurement capability of the machine. In cases where there appears to be a single (or several) outlying point(s) that does not conform to specification, it is recommended that this measurement be repeated in order to ascertain whether the large deviation actually reflects a systematic error. The procedure for checking repeatability is given in para. 5.5.2.3, which states a gage block shall be measured twice in the suspected position. If the measurements agree within twice the repeatability (para. 5.3), the first measurement shall be used and the second one discarded. If the measurements do not agree within twice the repeatability, then both are discarded and the procedure is repeated. This procedure may be repeated three times; at the end of which time, if repeatability has not been obtained as defined above, the test shall be discontinued and the fault determined and corrected.

5.6.4 Bidirectional Length Measurement Capability Requirement. Bidirectional length measurement capability, as calculated in para. 5.6.3, shall not exceed the supplier's specification, derated as specified in paras. 4.2 and 4.3, if applicable.

6 SUBSYSTEM PERFORMANCE TESTS

The preceding sections have provided a reasonable test of the coordinate measuring machine as a system. Many errors have, however, either been hidden as part of another measurement or not fully assessed. The purpose of this section is to address the errors caused by the most important subsystems of the machine.

6.1 Probing Analysis — Point-to-Point Probing

A major factor contributing to the total system measuring error is the performance of the probing system, which includes the probe, the probe stylus, the machine dynamics, and other variable parameters. The following tests have been devised to establish the magnitude of the possible errors contributed by the probing sequences for probes used in the point-to-point measuring mode. For the purposes of this Standard, this includes switching probes, proportional probes, and nulling probes capable of performing these measurements as they are used to acquire coordinate data one point at a time (i.e., not in a scanning mode). In all cases in these tests, data are acquired by withdrawing the probe from the specified previously measured point and directing it to the new position to acquire the next point. The measurements for this test are to be performed using the probing parameters, probe approach rate, probe approach distance, and settling time specified for normal operation in Fig. 1A.

6.1.1 Method of Test — Point-to-Point Probing. A precision reference ball conforming to the requirements of para. 7.3.3 shall be rigidly mounted on the workpiece supporting surface in the work zone of the machine on a fixture that allows access by the machine probing system. The illustration (Fig. 37) shows a calibration ball with the default diameter of 6 mm (approx. 0.25 in.). Any position may be chosen for this mounting, with the default position being the TVE position as specified in Fig.1. Three probing tests shall be performed on this ball, using styli with different configurations. The three default styli are as follows: a 10 mm (approx. 0.4 in.) long straight stylus, a 50 mm (approx. 2 in.) long straight stylus, and a 50 mm (approx. 2 in.) long straight stylus with a 20 mm (approx. 0.8 in.) offset perpendicular to the ram axis. The stylus tips can be of any diameter that allows the measurement to be made; however, a 6 mm (approx. 0.25 in.) diameter ball tip [sphericity of 0.25 microns (approx. 10 μin.) or less] is the default for each of these three styli used to probe the test ball. Note that, in order to allow measurement of the test sphere with the offset stylus, the support holding the test ball must be rotated 90 deg. from the position shown in Fig. 37. Furthermore, some types of probes may not be able to perform this test with an offset stylus, thus the machine (probe) supplier shall be consulted before performing this test.

The user is allowed to specify any test pattern desired containing 49 points. The default test for direct computer-controlled machines is as follows. With each of these styli, 49 points are probed on the test ball at five different heights on that ball: 12 equally spaced on a circle around the test ball when the stylus ball

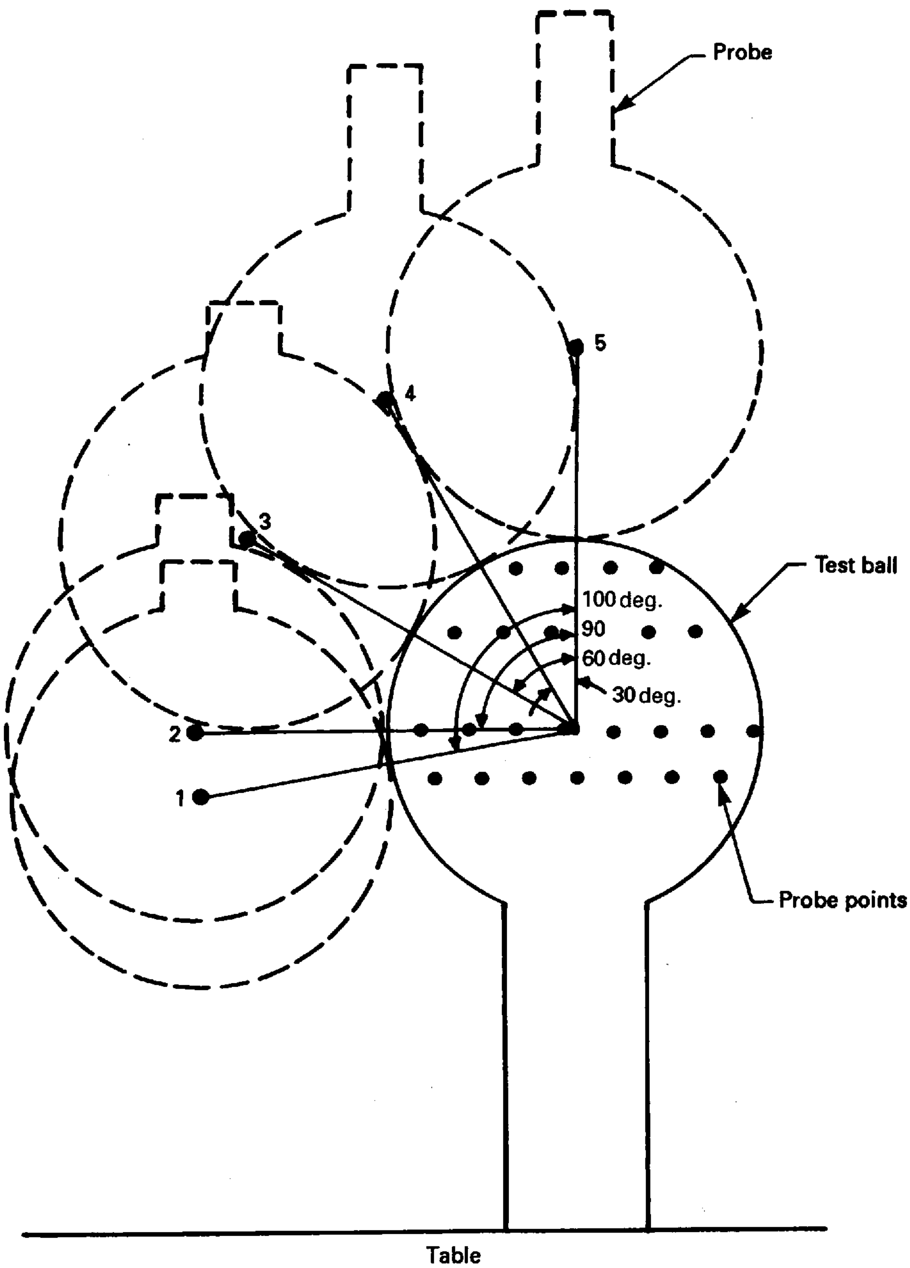


FIG. 37 SCHEMATIC DIAGRAM SHOWING THE LOCATIONS OF PROBING IN THE POINT-TO-POINT PROBING TEST

(Here the test ball is shown having a 6 mm (approx. 0.25 in.) diameter, the same as the stylus ball. Also, the support for the test ball must be rotated 90 deg. when performing this test with an offset stylus.)

center is approximately 100 deg. from the pole of the test ball in a direction parallel to the shank attached to the stylus ball, 12 equally spaced on the equator with the pattern rotated about the stylus shank 10 deg., 12 equally spaced around the ball with the stylus center approximately 60 deg. from the pole and rotated about the stylus shank an additional 10 deg. relative to the previous pattern, 12 equally spaced with the stylus center approximately 30 deg. from the pole with the pattern again rotated an additional 10 deg., and finally, one on the pole of the test ball. This situation is depicted in Fig. 37, in which the different probe positions are shown with dashed lines and labeled positions 1 to 5. The default test for manual machines is the measurement of 49 points distributed as uniformly as practical over the measurable portion of the test ball.

On direct computer-controlled machines, the probe shall be vector-driven toward the test ball center for each touch, provided this is normal for the machine when measuring parts. On driven manual and free-floating manual machines, where possible, one axis should be locked and the remaining axes moved to contact the ball in order to accurately hit the test ball. In all cases, the supplier's probe approach distance, probe approach rate, and settling time, as given in Fig. 1A, shall be used.

6.1.2 Data Analysis — Point-to-Point Probing. From each set of 49 readings for each stylus, a sphere center is computed using the supplier's recommended algorithms. From this center a radius is then determined for each measurement point. The minimum radius is subtracted from the maximum radius to produce the point-to-point probing performance for each of the stylus lengths. If the result obtained for a particular stylus is less than the working tolerance for the test, then the testing is discontinued for that stylus and the result reported. If the result for any stylus is greater than the working tolerance, then the test shall be repeated. If the new results agree to within the working tolerance for repeatability (para. 5.3), then the second set of data is discarded and the first set used for the analysis. If they do not agree, then a third set shall be taken. If this agrees with either of the two previous sets, then the first of the agreeing sets shall be used in the analysis. If no agreement to within the working tolerance for repeatability is obtained after three measurement sequences for any given stylus, the test is discontinued and the fault determined and corrected. After correction, all of the tests described in this section, even those for stylus lengths that were previously in tolerance, shall be repeated.

6.1.3 Probe Aproach Tests — Optional. Many machines/probe systems exhibit vastly different characteristics depending on the probe approach distance and the probe approach rate. For the machine user desiring to use more than one value of these parameters, this test of the machine performance is recommended. The procedure is the same given in paras. 6.1.1 and 6.1.2, except that this test is performed for two different probe approach distances and probe approach rates. The working tolerance for point-to-point probing is specified for each of these options.

6.1.4 Point-to-Point Probing Performance Requirements. Point-to-Point probing performance, as calculated in paras. 6.1.2 and 6.1.3 (if applicable), shall not exceed the supplier's specifications, derated as specified in para. 4.3, if applicable.

6.2 Probing Analysis — Multiple-Tip Probing

In addition to the probing errors highlighted in para. 6.1.1, CMMs that use multiple stylus tip positions can have additional errors. These errors can be due to a number of sources including the uncertainty in location of each of the tips caused by tip calibration errors or by the errors associated with the use of an orienting head or probe changer. This is true for all multiple-tip system configurations, including:

(a) systems using multiple styli connected to the CMM probe, such as star clusters;

(b) systems using orienting heads;

(c) systems using probe or stylus changers; and

(d) systems using heads with multiple probes.

The common element of these systems is that different tips or tip locations are used to inspect a workpiece without any recalibration of the tips. As a result, it is important to understand any additional errors which might be contributed by these systems.

6.2.1 Method of Test — Multiple-Tip Probing. The calibration ball diameter and all system configuration dimensions in this Section are default values. Other dimensions may be substituted and it is recommended that this be done if there is any concern that the configurations required to measure actual workpieces are substantially different from the default values.

A precision reference ball conforming to the requirements of para. 7.3.3 shall be rigidly mounted on the workpiece supporting surface in the work zone of the machine on a fixture that allows access by the machine probing system. The 6 mm (approx. 0.25 in.) diameter test sphere used in the point-to-point probing test (Section 6.1) may be used for this test. Any position may be chosen for this mounting with the default position being the TVE position as specified in Fig. 1.

Five different probing tip positions shall be used to perform this test. These positions can be created by using a stylus configuration with five tips, five different orientations of an orienting head, or through the use of a probe or stylus changing system using five different tip positions. Two of the probe tip positions shall be on a line perpendicular to the ram axis. Two more shall be on another such line displaced 90 deg. The fifth position shall be on a line parallel to the ram axis through the intersection of the first two lines. The default stylus length, including any extension members, measured from the intersection of the above lines, shall be 50 mm (approx. 2 in.) when using any of the above systems or combination of the above.

The user is allowed to specify any test pattern that contains 25 points. These 25 points shall be probed on the test ball as equally spaced as possible and cover as much of the sphere surface as practical. The 25 points shall be taken using five different tips or tip locations and each set of five points probed by each tip shall also be as widespread as possible. As an example, these five points could be four points around the equator of the sphere (assuming the pole position is directly in line with the stylus shaft supporting the tip) plus a point directly in line with the stylus shaft.

6.2.2 Data Analysis — Multiple-Tip Probing. From the set of 25 readings, a sphere center is computed using the supplier's recommended algorithm. From this center a radius is then determined for each measurement point. The minimum radius is subtracted from the maximum radius to produce the multiple-tip probing performance. If the result obtained is less than the working tolerance for the test, then the result is reported. If the result is greater than the working tolerance, then the test shall be repeated. If the new result agrees with the result of the first test within the working tolerance for the repeatability (para. 5.3), then the second set of data is discarded and the first set is used for the evaluation. If they do not agree, then a third set should be taken. If this agrees with either of the two previous sets, then the first of the agreeing sets shall be used in the evaluation. If no agreement to within the working tolerance for repeatability is obtained after three measurement sequences, this test is discontinued and the fault determined and corrected. After correction, the repeatability test (para. 5.3.3) and all of the tests described in this section shall be repeated.

6.2.3 Multiple-Tip Probing Performance Requirements. Multiple-tip probing performance, as calculated in para. 6.2.2, shall not exceed the supplier's specifications, derated as specified in para. 4.3, if applicable.

7 TEST EQUIPMENT

7.1 Temperature

The time constant of thermometers shall be no more than one-tenth 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.

The resolution of thermometers need be no greater than one-tenth the amplitude of the lowest-amplitude component of temperature variation of interest in a test.

Thermometers shall be calibrated by suitable means to an accuracy of ±0.1°C over the temperature range of use.

7.2 Vibration

For the purposes of this Standard, relative motion shall be measured using a high-resolution, undamped displacement indicator. Resolution of 0.1 μm (approx. 0.000004 in.) or better is recommended.

7.3 Displacement

7.3.1 Gages. Step gages and gage blocks shall be calibrated to within one-fifth the working tolerance for the repeatability specified for the CMM. Indicating gages shall have a resolution of no more than one-fifth the working tolerance for repeatability. All gages shall be calibrated following the supplier's recommendations.

7.3.2 Laser Interferometer. A laser interferometer conforming to the requirements of this Standard shall have a frequency stability such that this long-term stability represents an error of less than one-fifth the working tolerance for repeatability of the machine (in meters), divided by the length of the longest machine axis (in meters). The resolution of such a system shall be better than one-fifth the working tolerance for repeatability.

7.3.3 Precision Reference Ball(s). The precision reference ball(s) for the repeatability, TVE, and probing performance tests shall be spherical to within one-fifth the working tolerance for repeatability of the CMM.

7.3.4 Ball Bar. The ends of the ball bar shall be spherical to within one-fifth the working tolerance for repeatability of the CMM. For information regarding ball bars, see Appendix G.

7.4 Pressure

The uncertainty of the pressure sensor used for correction of the laser interferometer shall be no greater than ±1 mm Hg.

7.5 Humidity

Humidity measurement for correction of the laser interferometer wavelength shall be sufficiently accurate that it contributes no more than one-fifth the CMM working tolerance for repeatability to laser measurement error.

7.6 Utility Air

For the purposes of this Standard, the utility air pressure shall be measured using the gages supplied with the machine.

APPENDIX A
USER'S GUIDE TO ASME B89.4.1

(This Appendix is not part of ASME B89.4.1-1997 and is included for information purposes only.)

A1 PURPOSE

This user's guide is intended to provide a framework for applying this Standard. The guide is written in checklist form to make it easier for first-time users to begin using this Standard. Also, cross-references are provided from the guide text to the main body of this Standard for further detail on each test procedure.

A2 SUMMARY OF USAGE

The use of this Standard may be divided into two distinct parts. First, this Standard is used to provide a clear, common method for specifying coordinate measuring machines during negotiations between users and suppliers. Second, this Standard provides uniform test procedures to be used during machine acceptance to establish conformance to the specification.

A2.1 Machine Specification

Use para. 1.1 of this Standard to establish a clear understanding between supplier and user of the characteristics of the coordinate measuring machine. Detailed specifications of the machine can be itemized using the three-part specification form provided as Fig. 1. The first-time user is strongly urged to refer to the technical glossary provided in para. 2.1 for clarification of the terminology used on the specification form.

In reaching agreement on the general machine specification, the principal mode of operation and the principal probe type must be selected. If more than one combination is specified, the supplier may choose to provide separate performance data for each combination. In specifying the performance of a machine, several choices[1] must be made:

(a) accuracy test method (step gage or laser interferometer);

(b) ball bar or gage block length(s) for volumetric performance;

(c) ball bar or gage block placement for volumetric performance;

(d) probe offset for offset probe performance test;

(e) position of the laser diagonals and additional linear displacements (large machines);

(f) table mount or ram mount for the reference ball (machines used in the duplex mode);

(g) radial separation and ball height (machines with a rotary axis);

(h) bidirectional length measurement gage block length;

(i) load, loading technique, location of load, and ball bar positions for testing performance under loaded conditions;

(j) test ball diameter and stylus lengths and offsets for probing performance and multiple-tip probing performance.

Step gage tests are discussed in para. 5.4.2, and laser interferometer tests are covered in para. 5.4.3. Recommendations on ball bar length and placement are provided in para. 5.5.2. The default lines for volumetric tests on machines with large work zones are given in para. 5.5.4, the choice of table mount or ram mount of the reference ball for duplex performance tests is covered in para. 5.5.5, the rotary axis parameters in para. 5.5.6, guidelines for loading performance tests in para. 5.5.7, the bidirectional length measurement capability defaults in para. 5.6, the probing test ball diameters and stylus lengths in para. 6.1, and the multiple-tip probing offsets and stylus lengths in para. 6.2.

A2.2 Machine Acceptance

For installation acceptance, the machine must pass performance in an accepted environment. Acceptability of the environment may be demonstrated in any of four ways: by passing performance tests, by showing compliance with the supplier's environmental parameters, by showing an acceptable level of performance

[1] Default values and/or positional suggestions are offered for all tests described in this Standard. If the user chooses to use the default values and the position recommendations, only the accuracy test method needs to be specified.

degradation due to environment, or by derating machine performance specifications to suit the environment. The recommended procedure is to perform all of the environmental tests before proceeding with the performance tests. However, many installations may not require the full environmental testing to assure conformance to the performance specification. Therefore, as detailed below, parts of the environmental tests may be deferred by mutual agreement between the supplier and the user. If the machine passes the subsequent performance tests, performance of the deferred parts of the environmental tests is not required.

A3 ACCEPTANCE TESTING CHECKLIST

Before proceeding to the following list, we assume that the supplier and user are in general agreement that the machine is properly installed and the utilities are working satisfactorily. The numbers in parentheses following each item are references to the main body of this Standard.

_____ Perform or omit hysteresis test (para. 5.2 and Appendix F).

_____ Determine if temperature environment meets supplier parameters; or, defer subject to later testing or later elimination.

_____ Compute the uncertainty of nominal differential expansion (UNDE) (para. 4.2.1).

_____ Measure the temperature variation error (TVE), as appropriate for machine and probe configuration (para. 4.2.2); or, defer TVE testing by setting TVE = 0, subject to later testing or later elimination.

_____ Compute TEI for all tests and enter test on record (para. 4.2). If TEI exceeds 50% for any specified working tolerance and the thermal environment parameters are not met, compute derated working tolerances and enter on the acceptance test record.

_____ Measure relative vibration as appropriate for machine configuration, or accept vibration subject to later discovery of vibration induced performance problems (para. 4.3). If the vibration effects are unacceptable due to excessive environmental sources and the user chooses not to improve the environment, working tolerances will be derated after performing the repeatability tests.

_____ Accept electrical utility, subject to later discovery of electrical utility induced performance problems (para. 4.4).

_____ Accept utility air, subject to later discovery of utility air induced performance problems (para. 4.5).

_____ Perform repeatability test, as appropriate for machine and probe configuration (para. 5.3.3). If the vibration test failed, use these repeatability data to derate the working tolerances (para. 4.3).

_____ Perform linear displacement accuracy tests by the method previously chosen (para. 5.4.2 or 5.4.3).

_____ Determine the range of the deviations, either arithmetically or graphically, and enter the value on the acceptance test record (para. 5.4.2.7 or 5.4.3.5).

_____ Perform ball bar test, as appropriate for machine configuration, using the previously chosen bar length(s) and positions (para. 5.5.2). It is strongly recommended that a sketch or description of numbered ball bar positions be attached to the test results.

_____ Determine the range of ball bar lengths for each nominal bar length and enter on the acceptance test record (para. 5.5.2).

_____ Perform the offset probe performance test (para. 5.5.3). Again, it is strongly recommended that a sketch or description of numbered ball bar positions be attached to the test results.

_____ Compute the range of the differences between positive offset and negative offset measurements at the same nominal locations, divide this by twice the nominal length of the probe offset, and enter the value on the acceptance test record (para. 5.5.3).

_____ For large machines, supplement the ball bar tests with displacement measurements (para. 5.5.4).

_____ For machines used in the duplex mode, measure duplex performance (para. 5.5.5).

_____ Perform rotary axis performance tests, if required (para. 5.5.6), and record results as in Table 2.

_____ Ensure machine supplier has proper documentation supporting loading effect specifications (para. 5.5.7).

_____ Perform bidirectional length measurement capability tests (para. 5.6), and enter the results on the acceptance test record.

_____ Perform probe tests (paras. 6.1 and 6.2).

APPENDIX B
THERMAL ENVIRONMENT TESTING

(This Appendix is not part of ASME B89.4.1-1997 and is included for information purposes only.)

B1 PURPOSE

The performance of coordinate measuring machines is strongly affected by the detailed characteristics of the thermal environment that surrounds them. Parameters of importance include the cooling medium (usually, but not always, air), the velocity of the cooling medium, the frequency and amplitude of temperature variations of the cooling medium, the mean temperature of that medium, and the temperature gradients within that medium. The effects of these parameters and others are discussed in detail in ASME B89.6.2. It is the thesis of ASME B89.6.2 and of this Standard that currently it is not possible to specify parameters of a thermal environment that will ensure a specific value for the thermal error index (TEI). For a thorough discussion of the technical situation, the reader is referred to ASME B89.6.2. The purpose of this Appendix is, however, to specify procedures and responsibilities for testing the thermal environment in the event the TEI, as measured in Section 4, exceeds the 50% required for the machine, and the machine user contends that his environment meets the supplier's parameters. For the purposes 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.

B2 METHOD OF TEST

In order to ensure that the environment itself is tested rather than any characteristic of the coordinate measuring machine supplied, these tests are to be conducted with the CMM, support computers (if supplied), and any other auxiliary equipment related to the CMM, turned off for a period of 24 hr preceding the test to allow adequate soak-out of CMM-induced thermal gradients. Normal activity, however, should be continued around the machine as this constitutes part of the user-supplied environment. With these constraints the following tests should be performed.[1]

B2.1 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 could be suitable. These instruments and a discussion of the associated measurement problems are given in Tables B1 and B2 of ASME B89.6.2. It is recommended that the instruments used be properly calibrated and the test personnel 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.

B2.2 Mean Ambient Temperature

The mean ambient temperature shall be measured using a thermometer with characteristics as specified in Section 7 of this Standard. 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).

[1] This 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 TVE of the machine is still not within specification, then radiation coupling should be seriously examined.

B2.3 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 hr). The maximum peak-to-valley temperature variation shall be determined from the recorded data. The data shall be analyzed to determine the range 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 hr, 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 one-hour interval, subject to the same condition.

B2.4 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 to be the difference between the maximum and 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 time at least as long as the longest acceptance test (or 24 hr) and the greatest value of the gradient reported.

B3 ANALYSIS

If any of the parameters measured in B2 exceed the supplier's specified parameters, it is the responsibility of the user to correct the problem in order to conform with those specified parameters, or else to be willing to accept the performance derating described in Section 4 of this Standard. If the parameters so measured meet the supplier's specified parameters, it is the supplier's responsibility to correct the performance of the measuring machine to meet the specified working tolerances.

APPENDIX C
VIBRATION ANALYSIS

(This Appendix is not part of ASME B89.4.1-1997 and is included for information purposes only.)

C1 PURPOSE

The purpose of these tests is to establish the vertical and horizontal vibration environment at the interface between the CMM and the support system provided by the user, in order to divide responsibility between the user and supplier.

C2 METHOD OF TEST

The survey shall be made using directionally sensitive, low frequency (0.5 to 100 Hz) transducers. Use of accelerometers having typical natural frequencies above 25 Hz should be discouraged, as these devices cannot measure the low frequency disturbances that are the main cause of measuring machine accuracy degradation. The transducers should be capable of discriminating motion amplitudes of 0.25 μm at 0.5 Hz (for example, Hall-Sears HS-10-1 geophones). A band pass filter of corresponding frequency range should be used to discriminate between the different signals sensed by the transducers. A signal generator of known voltage should be used to determine the attenuation of the band pass filters at the frequency being studied. This is to ensure that accurate data are being recorded on the strip chart recorder or the oscilloscope (or other recording medium).

Outputs of velocity or acceleration transducers must be converted to displacement. The following formulas may be used:

$$D = V/(6.28 \times F)$$

$$D = A/(39.44 \times F^2)$$

$$V = (E/C)/A_t$$

$$A = 6.28 \times V \times F$$

where

A = acceleration, mm/sec^2 (in./sec^2)
A_t = band pass filter attenuation factor
C = geophone calibration factor, V/mm/sec (V/in./sec)
D = peak-to-peak displacement, mm (in.)
E = output transducer peak-to-peak voltage, V
F = frequency, Hz
V = peak-to-peak velocity, mm/sec (in./sec)

Vibration between the probe and the workpiece can result from forces external to the CMM, or from forces generated within the CMM itself. Therefore, it is generally advisable to first test to see if the CMM is the source of vibration prior to conducting a full vibration measurement and analysis. If the CMM is motorized, the power to all motors should be removed and the CMM tested to determine if the vibration is still present. If the CMM uses air bearings, the air pressure to the bearings should be varied sufficiently to establish whether air bearing instability is causing vibration.

If the CMM is not the source of the vibration, then a complete vibration analysis at the machine-to-support interface should be performed and the frequency spectrum analyzed to determine if frequencies and amplitudes are present that exceed the CMM supplier's defined limits. Measurements should be made in the vertical axis direction and the two mutually perpendicular horizontal directions that approximately correspond to the horizontal axis directions of the CMM.

Care must be taken that the survey is run at a suitable time and for a long enough period to ensure that conditions represent machine operating conditions. Attention should also be paid to differentiating between nominally steady state conditions and transient conditions.

C3 ANALYSIS

If any of the vibration parameters measured by the procedure described above exceed the supplier's specification, it is the responsibility of the user to correct the problem in order to conform to the specification or else accept a performance derating as described in Section 4. If, on the other hand, the vibration parameters are within the supplier's guidelines, then it is the sole responsibility of the supplier to correct the performance of the CMM in order to meet specification.

APPENDIX D
ELECTRICAL POWER ANALYSIS

(This Appendix is not part of ASME B89.4.1-1997 and is included for information purposes only.)

D1 PURPOSE

The purpose of this Appendix is to specify test procedures for analyzing the electrical power supplied to a CMM and its support equipment in the event that the electrical power is suspected to be causing inadequate machine performance.

D2 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 (an acceptable example of such an instrument would be the BMI 2400 series or the Dranetz Model 626-PA-600X). 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 that are detected by analyzing each cycle and comparing its root-mean-square level to a long time constant averaged steady state voltage value. When the cycle-to-cycle level deviates by more than the preselected threshold, a sag is detected.

Surges are sudden voltage increases that are normally detected with the same techniques 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 (approx. 1 to 1,000 μsec) 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 such instruments. Changes in frequency are self-explanatory.

D3 METHOD

In order to ensure proper monitoring, the power supply to the machine should be monitored for a period that includes the normal cycle of CMM operation. In the one-shift plant, this should include a complete shift. In the three-shift plant, complete 24 hr monitoring is required. Additionally, care should be taken that the power line monitoring occurs over a representative period which 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 CMM. 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 previously 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 CMM specification. Monitoring should continue for a sufficient period to ensure that all of the effects mentioned are included.

D4 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 above, 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 measuring machine in order that machine specifications are met.

APPENDIX E
UTILITY AIR

(This Appendix is not part of ASME B89.4.1-1997 and is included for information purposes only.)

E1 PURPOSE

The purpose of this Appendix is to specify procedures and responsibilities with respect to utility air in the event that excessive pressure fluctuation, inadequate supply pressure at the required flow rate, excessive machine thermal drift, or bearing contamination is evidenced.

It should be noted that high frequency pressure spikes in the air supply caused by external factors can cause significant performance degradation, and thus attention should be given to measuring these pulses.

E2 TEST EQUIPMENT

For the following tests, an air pressure gage, air flow gage, and a temperature measuring system will be required. The air pressure gage should be calibrated to cover the range between the minimum and maximum utility air pressure specified by the machine supplier. The resolution of the air pressure gage shall be 20% of the permissible utility air pressure fluctuation as specified by the supplier. The air flow gage shall have an accuracy better than 20% of the maximum air flow rate specified by the supplier. The temperature measuring system shall be calibrated to the accuracy specified in Section 7.

E3 METHODS

E3.1 Pressure Fluctuation

An air pressure gage shall be mounted in the supply line upstream of the machine air filter. The pressure shall be observed under the condition(s) which resulted in evidence of excessive pressure fluctuation.

E3.2 Supply Pressure and Flow

With the same gage setup, the pressure shall be observed under the condition(s) which resulted in evidence of inadequate pressure. If the pressure is inadequate, an air flow gage shall be mounted in the supply line upstream of the machine air filter. Flow shall be observed under the condition(s) which resulted in evidence of inadequate pressure.

Measured flow rate shall be converted to standard (normal) flow rate using the relationship

$$V_N = V(P_l/P_S)(293)/(T_l + 273)$$

where

V_N = air flow in standard (normal), m_N^3/min or l_N/min (ft^3/min)
V = air flow at line pressure, m^3/min or l/min (ft^3/min)
P_l = absolute line pressure = gage pressure + 0.981 MPa (14.7 psi)
P_S = standard (normal) pressure, MPa (psi)
T_l = line temperature, °C

E3.3 Machine Thermal Drift

A temperature measuring system pickup shall be mounted in the air line upstream of the machine air filter; or, if this is impractical, on a metallic part of the supply line. If the pickup is mounted on the line, the line and pickup must be insulated from ambient air to ensure that the temperature of the utility air is being measured. The temperature shall be measured under the condition(s) which resulted in evidence of excessive machine thermal drift.

E3.4 Contamination

Surfaces near air exhaust points shall be examined for water, oil, or solid particulates. Machine filters shall also be checked for excessive water, oil, and other contaminants. If it is suspected that the filters are inadequate, the machine supplier shall make appropriate recommendations as to correct filtering parameters.

E4 TEST ANALYSIS

E4.1 Pressure Fluctuation

If fluctuation exceeds the supplier's specification, it is the responsibility of the user to correct the problem (for example, by installing an accumulator). Of interest here are not just the short-term fluctuations that one would be able to observe using a normal pressure gage, but also high-frequency pressure spikes in the air supply which can cause performance degradation. If such spikes are suspected, further corrective action may be required.

E4.2 Supply Pressure and Flow

If the flow rate exceeds the supplier's specification, it is the responsibility of the supplier to reduce the flow required by the CMM. If the flow rate meets the supplier's specification but the line pressure does not, it is the responsibility of the user to increase the supply pressure (for example, by removing other devices using air from the line).

E4.3 Machine Thermal Drift

If the temperature of the air supply line does not meet the supplier's specification, it is the responsibility of the user to correct the temperature (for example, by installing a heat exchanger) and retest the machine. If the temperature meets the supplier's specification, it is the responsibility of the supplier to correct the performance of the measuring machine to meet specification.

E4.4 Contamination

If contamination is present, it is the responsibility of the user to change the air filter cartridge, clean the machine air system using procedures recommended by the supplier, and correct the supply contamination problem. Two methods of correction are available: reduce supply contamination or decrease the interval between filter servicings.

APPENDIX F
HYSTERESIS TEST DESIGN RECOMMENDATIONS

(This Appendix is not part of ASME B89.4.1-1997 and is included for information purposes only.)

F1 PURPOSE

This Standard strongly recommends that a machine hysteresis test be performed before starting performance tests and that each test setup be subjected to a setup hysteresis check before each test. This is to prevent wasted time and work. If these hysteresis tests are not performed, any excessive hysteresis is likely to be revealed as a lack of repeatability in later testing. The purpose of this Appendix is to provide general guidelines for performing such tests without unduly constraining the user, especially since, due to the variety of machine types and setups, any single test may not be suitable.

F2 GENERAL

A basic caution for all machine hysteresis tests is to ensure that hysteresis of the machine, not of the test setup, is being measured. All test hardware must be rigid and tightly secured. A test setup is checked for hysteresis by applying light forces, with the hand, to the test setup, checking for any change in the appropriate readout. Sometimes a light tap, using a pencil or light hammer, can also be effective for showing lack of suitability of a test setup.

F2.1 Machine Hysteresis — Machines Used in the Free-Floating Mode

For machines used in the free-floating mode, it is recommended that a ball probe be inserted in the probe holder and carefully tightened, that the ram be biased toward the workpiece supporting surface, and that the probe be inserted in a socket in either a rigid workpiece or in the workpiece supporting surface. The machine is then gently pushed and released in various directions. Force should be about twice that required to hold a passive probe in contact with a workpiece. Hysteresis is revealed by differences in machine readout after release.

F2.2 Machine Hysteresis — Driven Manual and Direct Computer-Controlled Machines

For driven manual and direct computer-controlled machines, it is recommended that an indicator, such as a flexure-type indicator or LVDT, be mounted on the workpiece supporting surface to measure motion of the probe holder. The machine is then pushed and released as in the previous case, with the force not exceeding the amount specified by the supplier. Hysteresis is revealed by differences between indicator readout and machine readout after release.

APPENDIX G
BALL BAR TEST EQUIPMENT DESIGN RECOMMENDATIONS

(This Appendix is not part of ASME B89.4.1-1997 but is included for information purposes.)

G1 PURPOSE

This appendix contains information regarding ball bars and ball bar mounting platforms.

G2 BALL BAR DESIGN RECOMMENDATIONS

For ball bars conforming to this Standard, the fixed length bar must be adequately rigid and stable to maintain a constant distance between the balls while positioning the ball bar in different orientations, and to not deflect during probing. The bar is usually made of tubing to increase its natural frequency and reduce its weight.

The stand must also be stable and rigid to hold the ball bar in its positions and to not deflect while probing the balls. It must not obstruct access to the balls when the bar is oriented in the various positions. At present, the most commonly used fixture is the free-standing ball bar system shown in Fig. G1. For low and moderately accurate CMMs, most stands will be adequate for testing volumetric performance. For more accurate CMMs (less than 10 μm over 1 m^3) the stiffness of the ball bar system must follow proper design guidelines.

Table G1 lists recommended cross-sections for ball bars and stands when used in the free-standing mode to check high-accuracy CMMs. These sizes were selected to maintain a 1 μm error in the ball bar system. Other ball bars of equivalent geometrical precision and stiffness are equally suitable.

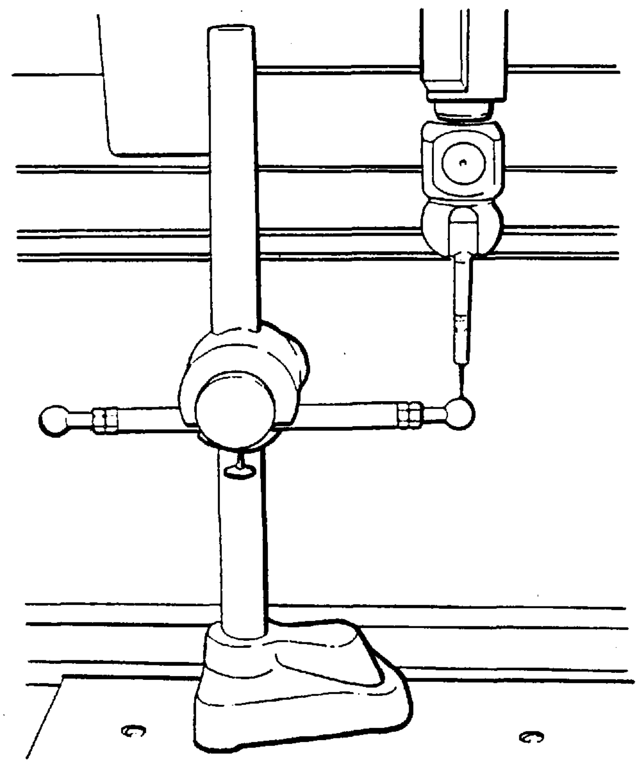


FIG. G1 FREE-STANDING BALL BAR SYSTEM

G3 ERROR SOURCES

There are various sources of error that can contribute to the total error of a ball bar system. Brief descriptions of these errors are listed below and typical values are given in Table G2. The ball sphericity as defined in the Standard should be less than 20% of the CMM repeatability. Balls 25 mm or less in diameter can be purchased to a sphericity of 0.2 μm or less which will meet this requirement.

Hysteresis errors (see Glossary and Appendix F) can be checked by applying a force parallel to the ball bar in one direction and reversing it to the opposite direction. Measure the lost motion of the system to return to the null position. The applied force should be twice the probing force. The test should then be repeated, but this time by applying the force perpendicular to the ball bar axis. The hysteresis should be less than 20% of the CMM repeatability.

Deflections due to gravity cause a foreshorting of the ball bar due to the sag of the cantilevered bar. This sag is most pronounced when the bar is in the horizontal position. The foreshortening is shown as ($\Delta\ell$) in Fig. G2. This is a cosine error of deflection and usually a small error.

Probing forces may cause deflections in the ball bar and stand. Lateral deflections have a direct influence

TABLE G1
BALL BAR CROSS-SECTIONS FOR VARIOUS LENGTH SYSTEMS FOR FREE-STANDING BALL BAR SYSTEMS MADE OF STEEL

Ball Bar Design	Shortest CMM Axis, mm (in.)	Ball Bar Length, mm (in.)	Bar Outside Diameter, mm (in.)	Bar Inside Diameter, mm (in.)	Post Height, mm (in.)	Post Outside Diameter, mm (in.)	Post Inside Diameter, mm (in.)
1	1,000 (40)	900 (36)	25 (1)	19 (0.75)	900 (36)	63 (2.5)	38 (1.5)
2	600 (24)	500 (20)	19 (0.75)	13 (0.50)	500 (20)	50 (2)	32 (1.25)
3	400 (16)	300 (12)	19 (0.75)	13 (0.50)	300 (12)	38 (1.5)	25 (1)

TABLE G2
ERRORS FOR A HIGH-ACCURACY FREE-STANDING BALL BAR SYSTEM

Ball Bar Design, μm (μin.)	Ball Sphercity, μm (μin.)	System Hysteresis, μm (μin.)	Vertical Distortion, μm (μin.)	Horizontal Sag, μm (μin.)	Post Bending, μm (μin.)	Vibration, μm (μin.)
1	0.14 (5.5)	0.08 (3.0)	0.02 (0.8)	0.01 (0.2)	0.52 (20.5)	0.35 (13.8)
2	0.14 (5.5)	0.05 (2.0)	0.01 (0.5)	0.0 (0.0)	0.22 (8.8)	0.27 (8.8)
3	0.14 (5.5)	0.05 (2.0)	0.01 (0.3)	0.00 (0.0)	0.16 (6.4)	0.20 (7.9)

GENERAL NOTE:
Values were calculated in microinches and rounded when converted to micrometers.

TABLE G3
UNCORRECTED THERMAL ERRORS (μm) WHEN THE ENVIRONMENT AND BALL BAR ARE AT DIFFERENT TEMPERATURES

		Uncorrected Thermal Errors, μm					
		Steel			Invar		
Length/Time, min	Δ T, °C [Note (1)]	900 mm	500 mm	300 mm	900 mm	500 mm	300 mm
0	10	100	58	35	11	6.0	3.6
15	3.7	38	21	13	4.0	2.2	1.3
30	1.4	14	8.1	4.8	1.5	0.8	0.5
60	0.18	1.9	1.0	0.6	0.2	0.1	0.1
90	0.02	0.26	0.14	0.09	0.03	0.01	0.01
120	0.003	0.03	0.02	0.01	0.003	0.002	0.001

GENERAL NOTES:
(a) Errors shown are for an initial temperature difference of 10°C when time = 0 min.
(b) Example: After 30 min the temperature of a 500 mm steel ball bar would be 1.4°C different from the CMM and the length error would be 8.1 μm. After 60 min the error is 1.0 μm.

NOTE:
(1) Δ T is the temperature difference between the environment and ball bar.

on determining the distance between ball centers because deflections cause the balls to appear smaller to the CMM and thus a longer ball bar length (center-to-center distance) is calculated. Using switching probes with probing speeds of 5–10 mm/sec does not permit the ball bar system to deflect before the point is taken,due to its system inertia. If a nulling or scanning probe is used, the probing forces may deflect the ball position a significant amount unless a rigid system is used. Errors are presented in Table G2 for typical probing forces. For high-accuracy measurements, to avoid bending in the free-standing ball bar, one can

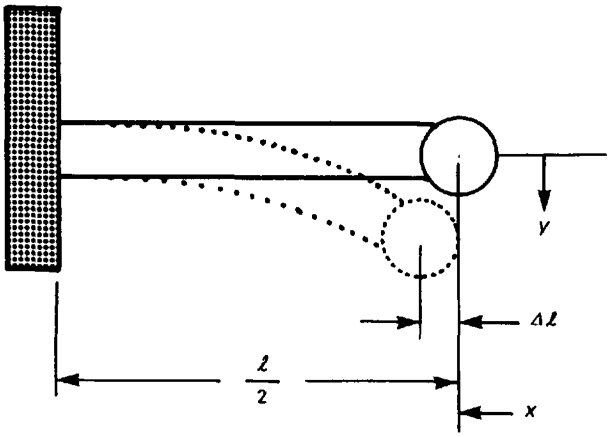


FIG. G2 STATIC DEFLECTION OF A BALL BAR

use the method of first finding the ball bar in space and then only touching the ends. This does not eliminate bending of the stand.

Free-standing ball bar systems can be very susceptible to vibrations. Both the post and the ball bar act as cantilever beams with no restraints to dampen the motion. The vibration can be caused by external floor vibrations or internally produced by the CMM. The CMM will induce vibration when accelerating or decelerating during servo drive moves. Many times the CMM is resting on an isolation system to prevent floor vibrations from being transferred to the CMM structures. With these soft isolation systems, when the CMM moves it induces a rocking motion of the machine. If the ball bar system is not rigid enough or securely fastened to the table, a vibration is produced that can cause measuring errors. Moving table CMMs are the worst for inducing these vibrations.

Temperature changes have a detrimental effect on accurately measuring a ball bar. One event that causes temperature errors is moving a ball bar system from one environment to another at a different temperature. This is particularly true when bringing the ball bar from the outside into a laboratory. Temperature changes of 10–20°C are common. Table G3 shows calculated values of temperature and length error for ball bars with a thermal time constant of 15 min. This time constant would be typical of steel ball bars in still air sitting on a CMM. The values show the change in ball bar length for various temperature changes and how long one should wait before the ball bar is used for making measurements. To maintain a stability of less than 1 μm, one should wait 30 to 90 min before using a steel ball bar. Steel and Invar ball bars are considered. Invar greatly reduces the thermal errors, as

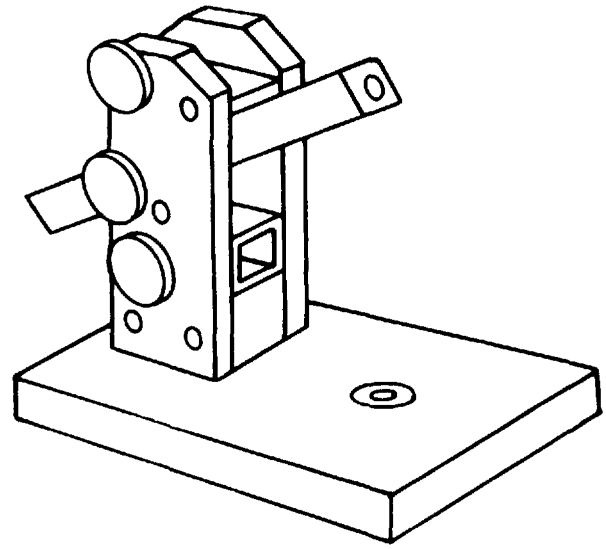


FIG. G3 GAGE BLOCK STAND FOR SHORT BLOCKS
(Less than 300 mm)

shown in Table G3. Temperature compensation can greatly reduce these values.

Thermal errors are also caused by handling the ball bar. This can occur during assembly of the ball bar to add or remove an extension or by grabbing hold of the bar to reorient it. Using gloves when handling the bar will reduce the heat transfer from ones hand to the bar. Also, a plastic sleeve on the bar will reduce the thermal growth when handling the bar. Experiments have determined that a typical steel ball bar will return to its original length to within 1 μm in 30 min after minor handling. Invar ball bars did not exceed 1 μm change in length during a similar test.

A more thorough treatment of measurement errors in free-standing ball bars is presented in a technical paper, "Properties of Free Standing Ball Bar Systems," published in the Journal of Precision Engineering, January 1993, Vol. 15, No. 1.

G4 BALL BAR MOUNTING PLATFORMS FOR USE WITH SWITCHING, PROPORTIONAL, AND NULLING PROBES

In this Standard, several options are provided for the measurement of ball bars or length standards using switching, proportional, and nulling probes. The first option, which is most commonly used today, is that the ball bar be supported so that both balls are accessible to probing. When using a setup of this type, the stand must provide stable support to the ball bar in defined

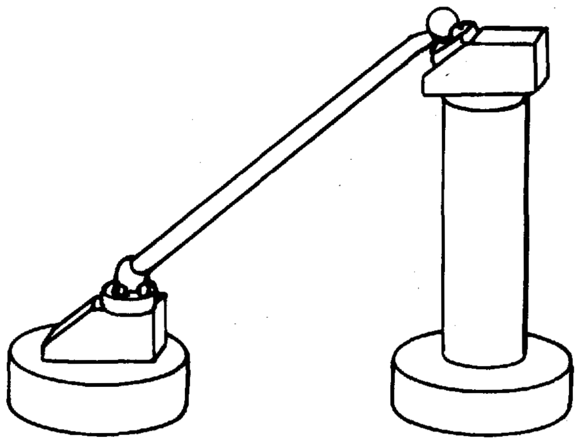


FIG. G4 COLUMN-TYPE BALL BAR STAND

orientations in the machine's work zone. The stand should be of a height slightly shorter than the CMM's vertical travel. The stand should have the ability to raise and lower the ball bar height to a specific position. A good stand should also allow the ball bar to be rotated to the proper angle. Stands of this type are shown in Figs. G1, G3, and G4. Note that the stand shown in Fig. G3 is holding a gage block, but, with modification, it could be suitable for a ball bar. Stands of the type shown in Figs. G3 and G4 can support ball bars up to one meter in length, but the stand height should not exceed one meter unless it is appropriately braced.

APPENDIX H
STRAIGHTEDGE TESTS FOR RAM AXIS ROLL

(This Appendix is not part of ASME B89.4.1-1997 and is included for information purposes only.)

H1 GENERAL

A straightedge may be used for measuring ram axis roll. In classical measuring machine metrology, this is accomplished using an indicator in the machine ram, but it can also be accomplished using the machine's built-in probing system. When the machine's probing system is used, other effects, such as machine dynamics, probing performance, etc., alter the test results somewhat; however, the main parameter measured is still ram axis roll. The test in this Appendix uses the machine's probe.

H2 PROCEDURE

A straightedge of reasonable quality is placed on the table with the straight surface parallel to the ram axis. On a vertical ram machine this would be in an approximately vertical direction, as shown in Fig. H1. The setup is most convenient if the perpendicular to the straight surface is roughly aligned with the machine axis (X or Y). A number of points on the straightedge, encompassing the range of the ram axis, are chosen for sampling. If the straightedge is reasonably smooth, the location of these points may be easily marked with masking tape and a pencil. For the purpose of this Appendix, "reasonably smooth" is defined as being flat within the working tolerance for linear displacement accuracy over a distance of 10 mm. The positions of these points are measured using an offset probe of reasonable length, for example, 150 mm (approx. 6 in.). Measurements are made at each point with the probe in the first position, shown in Fig. H1, and then in the second position. It is necessary to move the cross-slide in order to allow probe access to the straightedge surface, which possibly introduces a small error due to roll in this axis as the machine is moved. Should a machine appear to have excessive ram axis roll, the roll caused by the cross-slide motion should be measured and subtracted from the results in order to determine the cause of this condition. The ram axis roll, in radians, is the ratio of the differences in the coordinate perpendicular to the face of the straightedge to twice the probe offset length. It is possible for wide straightedges that probe interference can occur in this test, unless the probe is slightly angled with respect to the line parallel to the straightedge surface. This situation is depicted in Fig. H2, along with a diagram indicating the correct offset to use when the probe must be angled.

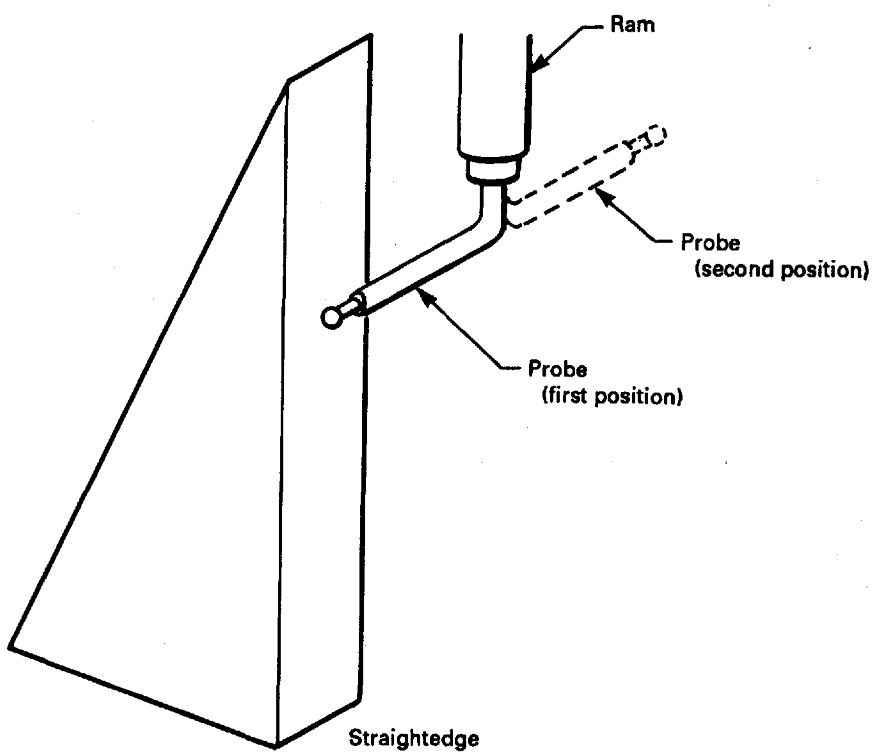
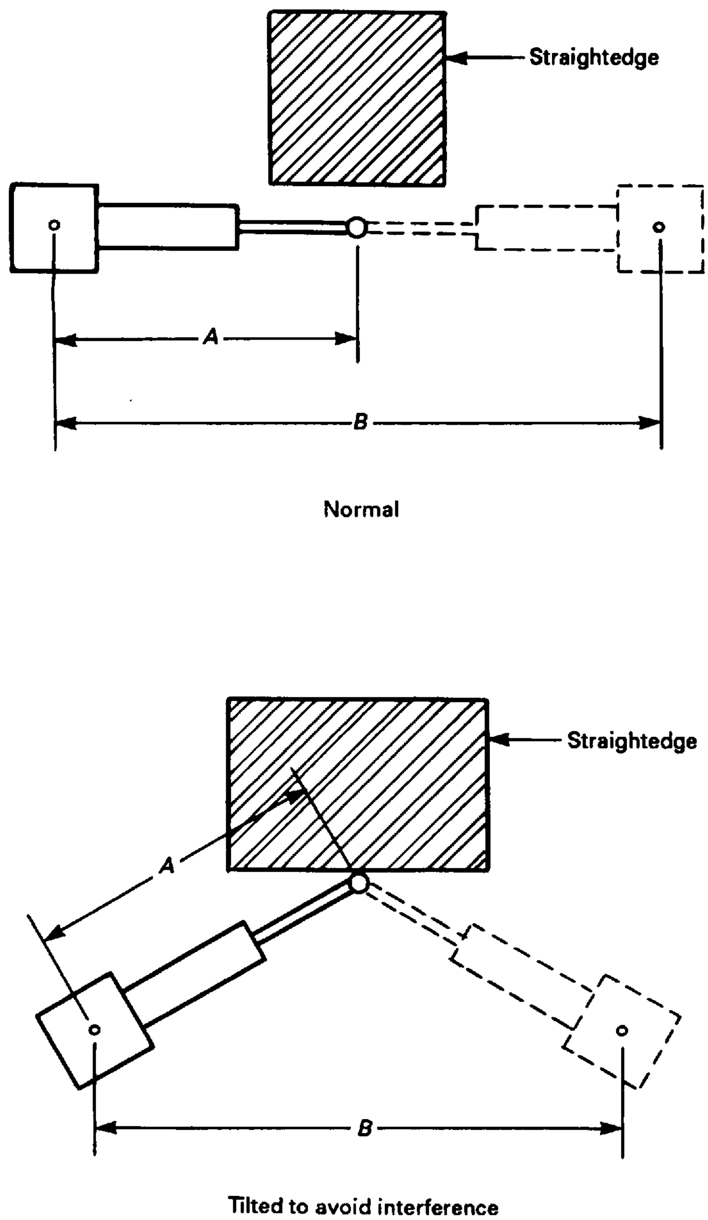


FIG. H1 SETUP FOR STRAIGHTEDGE MEASUREMENT OF RAM AXIS ROLL ON A VERTICAL RAM MEASURING MACHINE



GENERAL NOTE:
In either case, the distance *B* should be used to compute probe axis roll.

FIG. H2 ILLUSTRATION OF THE USE OF A PROBE AT A SLIGHT ANGLE IN ORDER TO AVOID INTERFERENCE WHEN MEASURING RAM AXIS ROLL ON A MACHINE WITH A WIDE STRAIGHTEDGE

APPENDIX I
INTERIM TESTING OF CMM SYSTEMS

(This Appendix is not part of ASME B89.4.1-1997 and is included for information purposes only.)

I1 INTRODUCTION

The goal of CMM interim testing is to identify and rapidly remove from service defective CMMs before significant numbers of good parts are rejected or bad parts are accepted. The frequent application of interim testing will increase confidence in CMM performance between CMM calibrations. Interim testing is not a substitute or replacement for CMM calibration, and is not normally diagnostic in nature. Rather, it checks the validity of the calibration by detecting common CMM performance failures. It is recommended that users regularly apply interim testing to their CMMs. An effective interim test checks the CMM measurement system as well as subsystem components that are used in the normal operation of the CMM. This may include such components as probes, probe heads, temperature compensation systems, and rotary tables. This document assists CMM users by providing information on efficient interim CMM testing.

I2 GENERAL INTERIM TESTING GUIDELINES

Limited time is available for performing interim testing, hence an efficient test must concentrate on sources of performance degradation that commonly occur. The goal is to test for as many errors as possible with a minimum number of measurements. If the test fails, additional actions are needed. These might involve further diagnostic testing or involve CMM servicing and calibration. CMM subsystem components need to be included in the interim test to broaden its scope and insure that the entire measurement system is operating correctly. Each user has special needs, so interim testing procedures and artifacts may vary from user to user; however, the following guidelines may provide some guidance in the matter.

CMM errors, whether systematic or random, reveal themselves as deviations from known lengths or as variations of several measurements of a fixed (perhaps unknown) length. The use of a known length artifact supplies additional useful information from the test. If a known length artifact is used, the uncertainty in its length determination should be small compared to the threshold level at which the interim test fails. Similarly, the form and surface finish of the artifact should not significantly affect the measurement. (These conditions are similar to those stated in Section 7 of the Standard which typically require the uncertainty of an artifact to be $\pm 20\%$ of the CMM stated performance.)

Thermal properties of the artifact are also important for workpieces measured at a temperature other than 20°C. In general, the user should select an artifact that has a thermal expansion coefficient similar to that of the workpieces commonly measured with the CMM. The uncertainty in the thermal expansion coefficient of the artifact must also be considered, as discussed in para. 4.2 of the Standard. If the user commonly applies a correction for the thermal expansion of the workpiece, then a thermal compensation should be applied to the interim artifact. This will allow testing of the thermal compensation system as a part of the interim test procedure. Note that the temperature sensors are a part of the thermal compensation system and are subject to damage and drift. Since environmental conditions may affect the performance of a CMM, it is advisable to record the temperature and other environmental parameters during an interim test, particularly if unusual conditions are present.

It is important that the artifact be dimensionally stable between interim tests, so that the measurements obtained during an interim test can be compared to those from previous interim tests, and, if available, to the artifact's known length. Certain materials are dimensionally unstable and may change in length by many parts per million (micrometers per meter) over one year. It is important that the dimensional stability (including any possible damage) of the artifact be substantially less than the smallest CMM error of significance to the user. The interim artifact should be securely located on the CMM table to prevent any possible rocking or slippage during the measurement procedure. To compare interim test results to one another, it is advisable to locate the artifact in approximately the same position and orientation for all tests. Similarly, the inspection plan, such as the number of probing points taken on the artifact, should be kept constant for all tests. Widely distributing the probing points over the gaging surface will aid in producing consistent interim testing results.

I3 INTERIM TESTING STRATEGIES

There are several different strategies for choosing an interim artifact depending upon the application of the user. For discussion purposes, we will consider two categories: those strategies which employ an artifact representing a typical workpiece (the artifact may be an actual workpiece from the production line) and those strategies which employ an artifact specifically designed for CMM testing. For all strategies, it is recommended that ten consecutive interim testing runs be conducted immediately after the CMM is calibrated. The mean of these ten measurements can be used to establish a baseline value for the interim artifact, and the range of values indicates the typical variation that may be expected under these conditions. Additional factors such as thermal conditions or different operators, may further expand the range of interim testing results. If upon recalibration of a CMM the new interim baseline measurements differ significantly from the previous baseline, then the interim artifact or the CMM calibration (or both) may be suspect and further investigation is warranted.

Some CMMs are dedicated to measurements of a single type of workpiece or a family of similar workpieces. In this situation an actual workpiece may be used as the interim testing artifact. This type of artifact will be sensitive to errors that are important to actual workpiece measurements. An additional benefit is that the user is familiar with the required workpiece measurements and consequently may have a CMM program available that can be used for the interim testing. The selected workpiece and the measured features on that workpiece should span the largest volume of the CMM work zone that is encountered during actual workpiece measurements, which will ensure that the relevant volume of the CMM is tested. For users measuring many small workpieces located all over the CMM work zone, it is suggested that the small interim test artifact be measured at several different locations to insure that an adequate region of the work zone is tested. It is not necessary to measure every feature on the test workpiece; rather, a representative group should be selected (both for feature type and location) for the interim testing procedure. The tolerance of these selected features should be set comparable to those of the tightest tolerances found in the actual production workpieces. In general, the interim artifact should be treated, fixtured, and measured in a manner similar to that of actual workpieces to reflect the actual measurement situation. Although the use of a test workpiece as an interim artifact has merit, it is important to note that the testing results are valid only for workpieces of a similar design and may not indicate the errors present when measuring a workpiece significantly different from the test artifact.

An artifact specifically designed for interim testing should be sensitive to common CMM errors. CMM angular geometry errors typically increase in magnitude in direct proportion to the length of the artifact. For example, a squareness error of 10 arc seconds can produce an error of 5 μm over a distance of 0.1 m, but it becomes an error of 50 μm over 1.0 m. This illustrates a useful principle: to increase the sensitivity to angular errors, measure long artifacts. Ideally, the artifact should be as long as practical, typically between 75%–125% of the shortest axis on a CMM with a nearly cubical work zone. On artifacts that produce several lengths upon measurement, e.g., ball plates, the longest length present will provide the greatest sensitivity to angular errors. (A short artifact positioned in several locations in the CMM work zone is not equivalent and will not have the same sensitivity to angular errors as a long artifact.)

The orientation and position of the artifact is also important. Certain artifact orientations can maximize the effect of geometry errors and hence allow them to be detected. As an example, consider the squareness error shown in Fig. I1. In the figure, L_1 is the true length of the ball bar as measured in a square coordinate system and L_2 is the (apparently foreshortened) length as measured in an out-of-square coordinate system. Note that L_1 is not equal to L_2. It is apparent that the measured length of the artifact in the square coordinate system (X_1, Y_1) is longer than that of the out-of-square system (X_2, Y_2). If the artifact is a known length, then this discrepancy appears as a measurement error. Even if the artifact length is unknown, this property can be exploited by measuring the same artifact in two "crossed" orientations as shown in Fig. I2. By this technique, the angular deviation from squareness (shown as α in Fig. I2) can be determined in the absence of other errors. In Fig. I2, the XY squareness (in the absence of other errors) can be estimated using the same artifact measured in two crossed positions at approximately 45 and 135 deg. In three dimensions, the analogous situation is carried out by reorienting the artifact along all four of the body diagonals of the

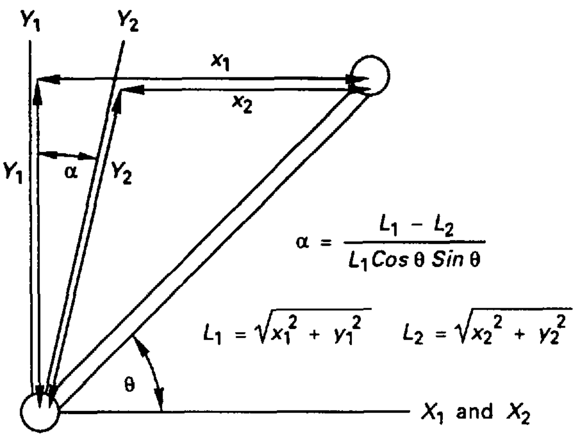


FIG. I1 AN EXAMPLE OF SQUARENESS ERROR

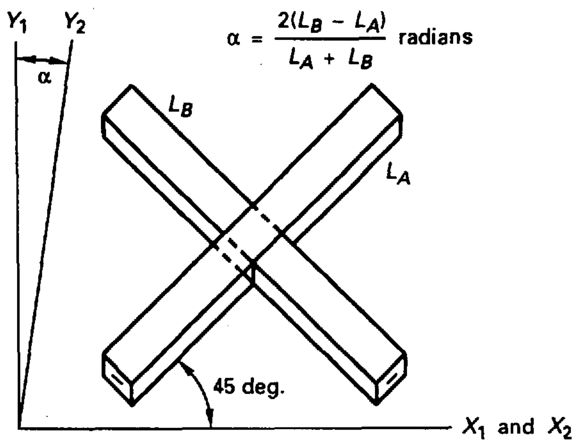


FIG. I2 ANGULAR DEVIATION FROM SQUARENESS, REPRESENTED AS α (α may be computed from the length measurements L_A and L_B.)

work zone as seen in Fig. I3. This procedure can be conducted with many different artifacts such as a ball bar, a step gage, or a long gage block. Alternatively, the use of calibrated ball or hole plates may allow more than one such body diagonal to be measured in each orientation.

An artifact specifically designed for interim testing should provide assurance that the entire measurement system is performing correctly. If only four body diagonal positions are tested, the artifact should be of known length to test the accuracy of the scale on each CMM axis. (If the artifact is of unknown length, then measurements in additional positions can identify relative errors between the scales, but at least one known length is required to establish the true accuracy of the scales.)

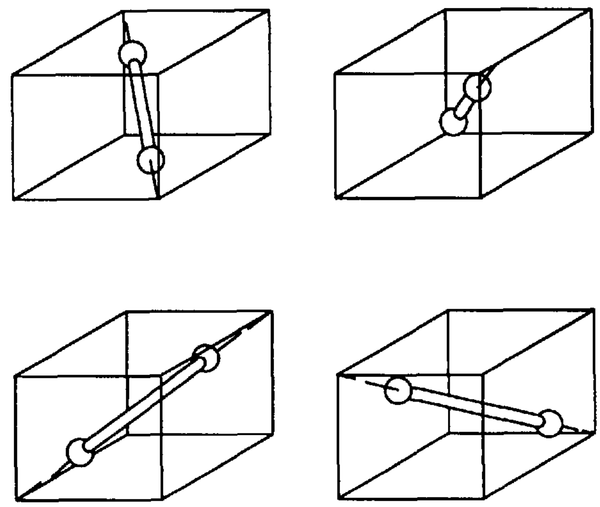


FIG. I3 BALL BAR INDEXED THROUGH THE BODY DIAGONALS OF THE CMM WORK ZONE (These positions are sensitive to the squareness errors of all three axes.)

The CMM probe should be checked to ensure it is in good working order. This may involve an explicit probe test that checks the directional sensitivity of the probe, i.e., probe lobing (such as described in para. 6.1 of the Standard); or may be incorporated into part of the general CMM geometry test, such as measuring a long gage block that is oriented in several different directions. Similarly, to test the probe calibration, which involves the accuracy of the CMM probe calibration artifact (typically a sphere with a calibrated diameter), a true bidirectional measurement of known length is required. This might be the length of a gage block (as described in para. 5.6.2 of the Standard) or the diameter of a ring gage or of a precision sphere. It is important to note that the measurement of a unidirectional step gage or the center-to-center distance between spheres of a ball bar does not check the probe calibration. If multiple styli are used (either with a stylus cluster, e.g., "star probe," or with an indexable probe head), then a test should be included that checks the ability to locate one stylus ball relative to another. Such a test would include multiple styli used in a single measurement (e.g., see para. 6.2 of the Standard, "Probing Analysis — Multiple-Tip Probing"). If a probe-changing rack is available, then this subsystem should be tested by swapping probes in and out of the rack. This not only checks the repeatability of probe changing, but defective probes in the rack may also be discovered.

For CMMs that include a rotary table, an appropriate test (such as the DCC rotary axis test, para. 5.5.5 of the Standard) should be included as part of the interim testing procedure. In summary, an effective interim test artifact should examine the complete CMM measurement system to assure confidence in the entire measurement process.

I4 INTERIM TESTING EXAMPLE

The details of an interim test are highly user dependent since users have different types of CMMs, different accuracy requirements, measure different types of workpieces made of different materials, and their operators and facilities are different. Given the short time to carry out the interim test, different users will optimize the interim test in different ways to suit their needs. The following example is for a vertical ram CMM with a nearly cubical (1×1×1) work zone having an indexable probe head, a probe-changing rack containing two additional probes, and a temperature compensation system. This specific example is given to provide general guidance to CMM users; however, the actual CMM system may require different or further tests. Additionally, some users may desire more extensive testing or employ alternative strategies from the procedures listed below.

As an example of a specific interim test, the user chooses a ball bar calibrated for ball roundness, ball size, and center-to-center distance. The ball bar temperature is measured in each position using the part temperature sensor and the appropriate thermal correction is applied to all test results. A basic test involves measuring the four body diagonals of the CMM. In each position, the user decides to take eight points on each ball of the ball bar. The user determines the apparent form error of the ball, the difference between the best fit sphere diameter and the calibrated diameter and the differences between the measured ball bar (center-to-center) lengths and the calibrated value. These results are plotted as shown in Fig. I4.

In the first body diagonal position, the user employs a single probe (oriented along the ram axis). In this position, the measured form error of the balls shows the repeatability of the CMM and the probe, and any probe lobing effects. The ball diameter measurements check the probe calibration (i.e., stylus ball size) and the short-range scale errors. The bar (center-to-center) length measurement checks for long-range (CMM geometry or thermal expansion) errors in that orientation.

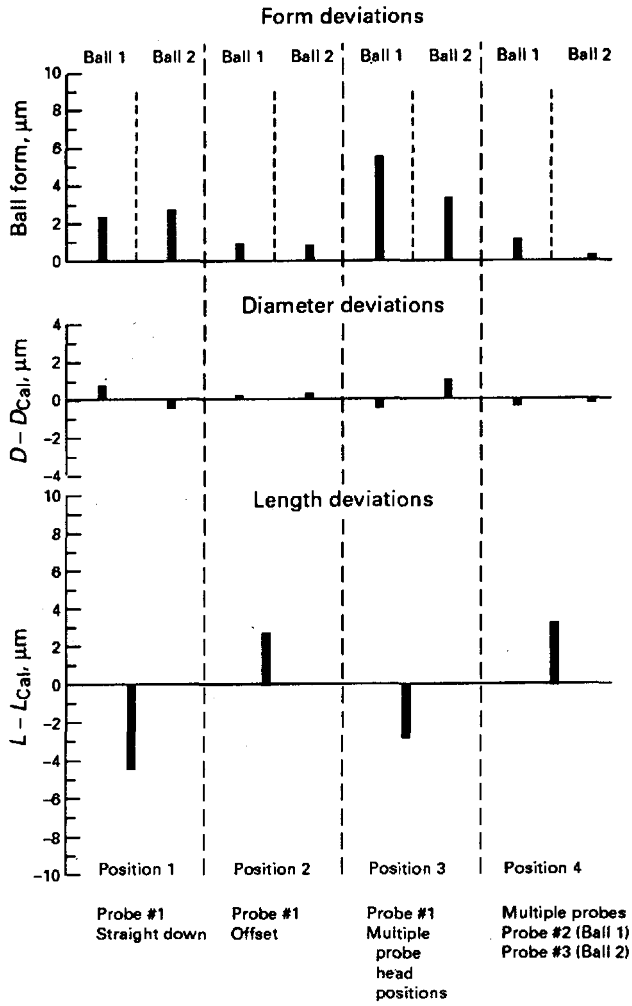


FIG. I4 RESULTS OF AN INTERIM TEST USING ONE BALL BAR IN FOUR (BODY DIAGONAL) POSITIONS
(The test includes checking temperature compensation system, the indexable probe head, and testing three different probes available in a probe-changing rack.)

For the second body diagonal a similar measurement is conducted, but with the probe head indexed so that the probe is perpendicular to the ram axis. This measurement will produce similar information to that of the first body diagonal position, but will include any Z axis roll error in the CMM geometry. In the third body diagonal position, each ball of the ball bar is measured with the probe head indexed in several positions; this will supply information on probe head repeatability and the ability to accurately find a stylus

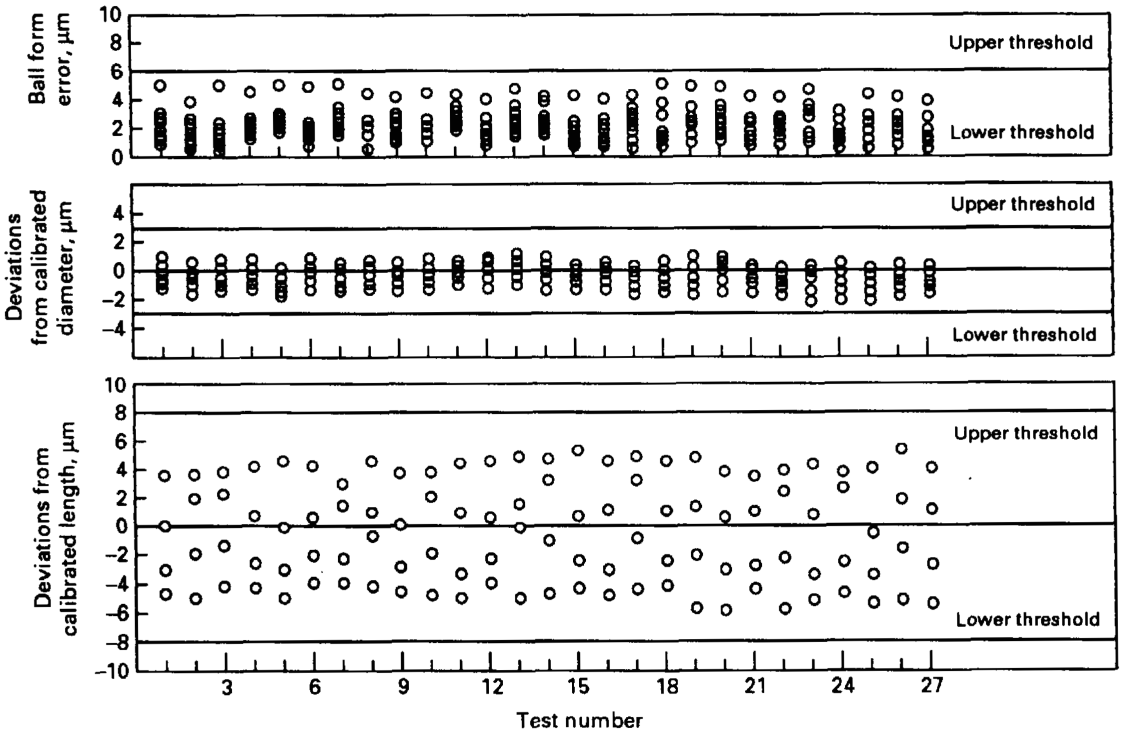


FIG. I5 SUMMARY PLOTS OF SEVERAL INTERIM TEST RESULTS

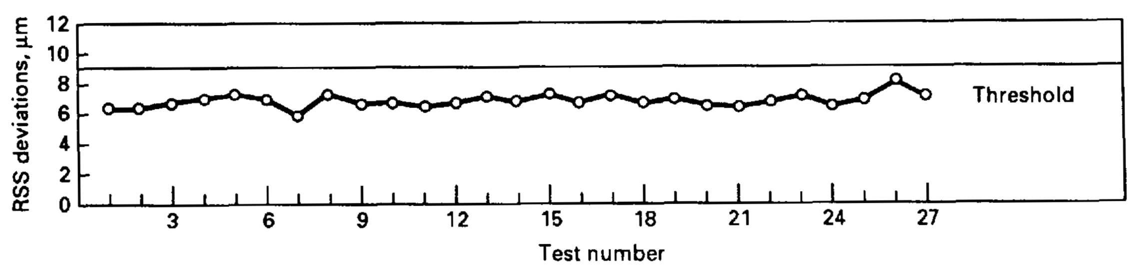


FIG. I6 SUMMARY PLOT OF COMBINED INTERIM TESTING RESULTS

ball location relative to others with different probe head orientations. The final body diagonal position checks for any defective probes present in the probe rack and the rack's probe changing ability. The first ball of the ball bar in this position is measured using the second probe obtained from the probe-changing rack, and the second ball of the ball bar is measured with the final (#3) probe from the probe rack. The form error and diameter, reported for each ball of the ball bar, test each of the two probes for probe lobing effects and stylus size calibration, respectively. (If additional probes are available, these could be checked by measuring each ball of the ball bar, in each ball bar position, with a different probe.)

Figure I5 shows one possible method of data analysis for the interim test. For each interim test, all four center-to-center length deviations, all eight ball diameters, and the eight measured sphere form errors are plotted. The test is passed if all these measurements are within the threshold value limits. Some users may prefer a single plot representing the test results (instead of the three shown in Figs. I4 and I5). Such a plot can easily be constructed, as shown in Fig. I6, by combining the largest length deviation, the largest diameter deviation, and one half the largest form deviation, in a root sum of squares (RSS) manner. (One-half the largest form deviation is used so each of the three contributions is appropriately weighted). This method has the advantage of displaying only a single graph but provides less information as to the sources of error. (If a CMM problem does develop, plots such as those in Fig. I5 could be constructed using data from the previous test results.)

There are many different methods a user can choose to establish testing thresholds. These include using the supplier's stated CMM performance values for the particular CMM under consideration, which might involve specifications from the ASME B89.4.1 or other appropriate national or international Standards. Other methods to determine the thresholds include examining the tightest tolerance of a feature found on the user's workpiece and reducing this by an appropriate ratio. To avoid false alarms, the threshold levels should exceed all variations arising from normal operations. This may include such factors as different operators and different thermal conditions, e.g., time of day or week.

I5 TESTING FREQUENCY

The frequency of interim testing is highly user-dependent. A CMM being operated three shifts a day with multiple operators in a harsh environment is likely to experience many more problems than the same machine being used one shift a day by a single operator in an excellent environment. The frequency of testing is also strongly affected by balancing the cost of interim testing against the consequences of accepting a bad workpiece or rejecting a good one. It may be useful to consider the interim testing interval as a percentage of total CMM operating hours. Some users with high value and/or safety critical workpieces may elect to perform daily tests; other users might test weekly or monthly. Additionally, interim testing should be conducted after any sort of significant event such as a CMM collision, replacement of a subsystem component, or the occurrence of abnormal temperature variations or gradients.