ASME B89.4.22-2004

Methods for Performance Evaluation of Articulated Arm Coordinate Measuring Machines

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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Three Park Avenue • New York, NY 10016

Date of Issuance: August 12, 2005

This Standard will be revised when the Society approves the issuance of a new edition. There will be no addenda issued to this edition.

ASME will issue written replies to inquiries concerning interpretation of technical aspects of this Standard.

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

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FOREWORD

The ambiguity of articulated arm coordinate measuring machines (AACMM) specifications makes comparative evaluations of performance characteristics very difficult. Because of this and the increasing use of this class of measurement equipment, the ASME Standards Committee B89 elected to establish a USA industry standard applicable to these machines. At the October 1994 meeting, Project Team B89.4.22 was established to develop the Standard.

As far as possible, this Standard parallels ASME B89.4.1b-2001 for "conventional" coordinate measuring machines. An attempt has also been made to make the Standard compatible with existing and emerging international standards.

This Standard addresses the performance evaluation of AACMM by supplying definitions and test procedures. These procedures should enable users to determine if an AACMM is appropriate for their specific requirements. It should also provide accurate comparison of machines from different suppliers and provide a determination of whether an AACMM meets contractual requirements without negotiations after the machine has been purchased.

The intent of this Standard is to specify the simplest methods that can be used for reasonable performance evaluation. It is recognized that a more complex evaluation may be appropriate for special applications. These methods, however, must be specified in adequate detail in the AACMM specification.

This Standard was approved by the American National Standards Institute on August 9, 2004.

ASME B89 STANDARDS COMMITTEE
Dimensional Metrology

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

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SUBCOMMITTEE 4 — COORDINATE MEASURING TECHNOLOGY

PERSONNEL OF WORKING GROUP B89.4.22 — ARTICULATED ARM COORDINATE MEASURING MACHINES

SPECIAL ACKNOWLEDGEMENT

While not a member of the Project Team when the document was approved, we would like to acknowledge the work performed and significant contributions made by Michael O'Laughlin, while an employee of Romer Inc. Mike was the Secretary since the inception of the Project Team and, thanks to his diligent minutes, kept the remainder of us on track.

CORRESPONDENCE WITH THE B89 COMMITTEE

General. ASME Standards are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Standard may interact with the Committee by requesting interpretations, proposing revisions, and attending Committee meetings. Correspondence should be addressed to:

Secretary, B89 Standards Committee
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Proposing Revisions. Revisions are made periodically to the Standard to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Standard. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Interpretations. Upon request, the B89 Committee will render an interpretation of any requirement of the Standard. Interpretations can only be rendered in response to a written request sent to the Secretary of the B89 Standards Committee.

The request for interpretation should be clear and unambiguous. It is further recommended that the inquirer submit his/her request in the following format:

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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METHODS FOR PERFORMANCE EVALUATION OF ARTICULATED ARM COORDINATE MEASURING MACHINES

INTRODUCTION

The primary purpose of this Standard is to clarify the performance evaluation of articulated arm coordinate measuring machines (AACMMs). A secondary purpose is to facilitate performance comparisons between machines. Definitions, environmental requirements, and test methods are specified. This Standard defines the test methods capable of yielding adequate results for the majority of articulated arm coordinate measuring machines and is not intended to replace more complete tests that may be required for special applications.

1 SCOPE

The scope of this Standard pertains to the performance evaluation of articulated arm coordinate measuring machines. While any number of rotational joints can be evaluated, the Standard focuses on the more common configurations commercially available today and is limited to seven joints. The Standard addresses purely manual machines, so no motorized axes are addressed in the current document. While the application of this class of measuring machine continues to grow, at this point in time only contact probes are considered and optical noncontact probes are specifically excluded.

This Standard establishes requirements and methods for specifying and testing the performance of AACMMs. In addition to clarifying the performance evaluation of AACMMs, this Standard seeks to facilitate performance comparisons among machines by unifying terminology, general machine classification, the treatment of environmental effects, and data analysis. This Standard attempts to define the simplest testing methods capable of yielding adequate results for most AACMMs and it is not intended to replace more complete tests that may be suitable for special applications.

This Standard provides definitions of terms applicable to AACMMs. These definitions are separated into two parts. The first part is a glossary covering technical terms used throughout this and other ASME Standards. The second part defines a number of common machine classifications.

The actual specification is subdivided into three sections: general machine classification, machine environmental requirements, and machine performance. Machine classification includes machine type, measurement ranges, and rotary axis encoder resolution. Environmental specification includes thermal response, electrical requirements, and vibration sensitivity. Machine performance specification includes effective diameter test, single-point articulation performance, and volumetric performance tests.

Within this Standard, performance values are reported as the maximum deviation, the range, and the standard deviation. This is done to bring the Standard more into line with existing national and international standards.

In order to clarify the use of this Standard, a short guide on how to use it is included as Appendix A.

Productivity is an important consideration in the selection of an articulated arm coordinate measuring machine. There are numerous factors that affect the relative productivity of measuring systems, which include variables attributable to both the measurement system and the workpiece. This Standard does not address methods to specify and evaluate productivity. Productivity should be evaluated with respect to the expected use of the system, including such aspects as software, ergonomics, and the frequency of calibration.

1.1 Contents and Specification Forms

Any specification described as complying with this Standard shall include, as a minimum, the following items:

(*a*) a machine classification form (see Fig. 1). If no classification is applicable, the actual configuration shall be described in equivalent detail.

(*b*) an environmental specification form (see Fig. 2).

(*c*) a performance specification form (see Fig. 3).

1.2 Alternatives

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

2 DEFINITIONS

2.1 Glossary

2.1.1 Terms. This glossary contains brief definitions of the majority of technical terms used in this Standard. Some of the definitions listed are used in the non-

B89.4.22 MACHINE CLASSIFICATION FORM

Machine Classification: __________

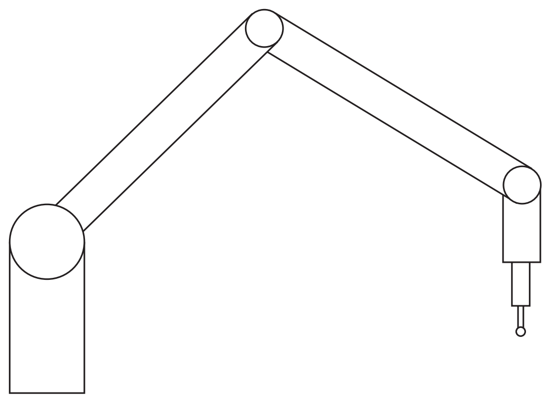
Axis	*a*	*b*	*c*	*d*	*e*	*f*	*g*
Degrees of rotation							

Nominal arm length: ________________________ **mm**

Rotary axis encoder resolution in counts/revolution:

Axis	*a*	*b*	*c*	*d*	*e*	*f*	*g*
Resolution							

Special, nonstandard configurations, including such features as external rails (both horizontal and vertical) should be indicated on the following diagram:



Nominal voltage ________________________________ **V**
Amperage ____________________________________ **A**
Frequency ____________________________________ **Hz**
Surge/sag ____________________________________ **V**

Fig. 1 AACMM Classification Form

mandatory appendices, but are included here for reference purposes. Omissions and clarifications should be reported to ASME (see Correspondence).

ball bar: 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.

bias (of a measuring instrument): systematic error of the indication of a measuring instrument.

NOTE: The bias of a measuring instrument is normally estimated by averaging the error of indication over an appropriate number of repeated measurements.

drift: slow change of a metrological characteristic of a measuring instrument.

drift test (thermal): type of test used to measure the environmental temperature variation error (ETVE) 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 workpiece over a period of time. Detailed procedures for conducting drift tests on machines are given in Appendix H.

environmental temperature variation error (ETVE): estimate of the maximum possible measurement uncertainty induced solely by deviation of the environment from average conditions.

gage: mechanical artifact used either for checking a workpiece or for checking the performance of a machine, or measuring device with a proportional range and some form of indicator, either analog or digital.

hysteresis: as applied to a measuring system, the property of that system whereby its response to a given stimulus depends on the sequence of the preceding stimuli.

B89.4.22 ENVIRONMENTAL SPECIFICATION FORM

Thermal Requirements

Significant mean temperature range
Min. ________ °C Max. _______ °C

Safe operating temperature range
Min. ________ °C Max. _______ °C

Gradients	Temporal	Spatial
Vertical	________ °C/h	________ °C/m
Horizontal	________ °C/h	________ °C/m

Thermal settling time _________________ min

Vibration Requirements

Total vibration amplitude _____________ μm

Frequency range _____________ Hz

Mounting Requirements

Maximum applied forces and torques at the mounting interface:

X-direction translational force __________________________________ N
Y-direction translational force __________________________________ N
Z-direction translational force __________________________________ N
X-direction torque ____ N-mm
Y-direction torque ____ N-mm
Z-direction torque ____ N-mm

Maximum distances and displacements acceptable at the mounting interface:

X-direction translational distances ____________________________________ mm
Y-direction translational distances ____________________________________ mm
Z-direction translational distances ____________________________________ mm
X-direction torsional displacement ____ μrad
Y-direction torsional displacement ____ μrad
Z-direction torsional displacement ____ μrad

Limitations on AACMM mounting orientation (please describe fully any limitations in the space below):

Fig. 2 Environmental Specification Form

B89.4.22 PERFORMANCE SPECIFICATION FORM

Probe type ________________ **Probe tip diameter** __________ **mm**

Test procedure used **5.3.2.1** ___________ **5.3.2.2** ___________	**Max. Diameter Deviations, μm**
Effective diameter performance test	

	Max. Dev., μm	**$2s_{SPAT}$, μm**
Single-point articulation performance test within 20% of the arm length at AACMM location (X, Y, Z) =		
Single-point articulation performance test between 20%–80% of the arm length at AACMM location (X, Y, Z) =		
Single-point articulation performance test outside 80% of the arm length at AACMM location (X, Y, Z) =		

	Max. Dev., μm	**Range, μm**	**2 RMS, μm**
Volumetric performance test			

Fig. 3 Performance Specification Form

mean ambient temperature: 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 performance test. The time between the two readings should be at least two-thirds of the test interval.

measurement point: point in the work zone of a machine at which machine coordinates are recorded as part of a measurement.

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

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

(*a*) *passive (solid or hard) probe:* probe that mechanically fixes the movable component relative to the workpiece.

(*b*) *switching probe:* probe that gives a binary signal as a result of contact with or in proximity to a workpiece.

range: set of values bounded by the extreme indications.

significant mean temperature range: range of mean ambient temperature over which the AACMM will still meet the performance specifications stated by the supplier for the tests defined in para. 5.

single point articulation performance: ability of the AACMM to provide similar values of a point coordinate (*X, Y, Z*) when the AACMM is articulated through the maximum possible range of motion for that single point.

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

thermal error index: summation, without regard to sign, of the estimates of all thermally induced measurement errors expressed as a percentage of the working tolerance.

NOTE: It should be noted that for historical reasons and to maintain compatibility with other B89 standards, the term *thermal error index* is retained in this Standard, even though by definition it is not an error. By definition, an error is the difference between the measured value and the true value, and even the best estimate of the true value for the TEI test is never known. As no calibrated artifact is used, it should be more correctly thought of as a thermal effect index. The index is a measure of the variation over a period of time. If a calibrated artifact is used referenced back to the standard temperature, the error may well be considerably bigger than the variation.

thermal settling time: time interval that in the supplier's estimation is sufficient to allow the AACMM to meet performance specifications after a temperature change of ±5.0°C (±9.0°F). This parameter can be used as a guide to estimate when measurements can commence after the machine is moved between differing thermal environments.

working tolerance: maximum acceptable range in the measurements for any performance test in this Standard.

workpiece: object to be measured.

work zone: 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.

2.1.2 Stand Versus Fixture. Throughout this Standard, the machine is mounted on a stand, while any artifact, such as ball bar, is mounted in a fixture.

2.2 Machine Classifications

The following classifications of AACMMs are provided for ease of machine specification. A place is provided in the standard machine classification form, Fig. 1, that shall be used to designate the machine classification as described below. For AACMMs that do not conform to these standard configurations, an equivalent drawing as in Fig. 1 shall be provided.

An articulated arm coordinate measuring machine employs a series of rotating components around generally perpendicular axes. The arm can be thought of as consisting of three joints, namely the shoulder, elbow, and wrist. As an example, for the 2-1-2 configuration AACMM shown in Fig. 4, the shoulder would consist of the A and B rotary axes; the elbow, the D rotary axis; and the wrist, the E and F rotary axes. A probe is attached to the last rotating axis and is manually manipulated to contact measurement points on a workpiece mounted within the AACMM work zone. The configuration of an articulated arm CMM is defined by three numbers (e.g., 2-1-2) corresponding to the shoulder-elbow-wrist joints, respectively, that describe the rotational degrees of freedom for that joint. Each rotating component is further defined by the limits of rotation about its axis (e.g., *a*, *b*, *c*, etc.), in degrees. Common configurations of the AACMM, along with their designations, are given in Figs. 4, 5, 6, and 7.

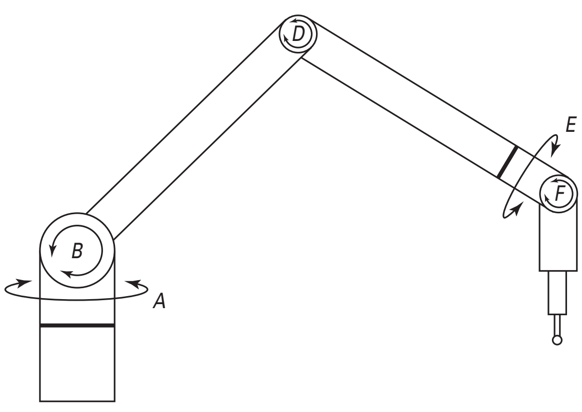


Fig. 4 Typical Machine of the 2-1-2 Configuration, With *a-b-d-e-f* deg Rotation

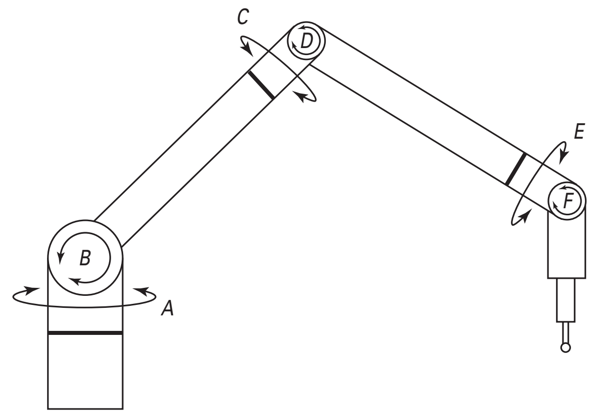


Fig. 5 Typical Machine of the 2-2-2 Configuration, With *a-b-c-d-e-f* deg Rotation

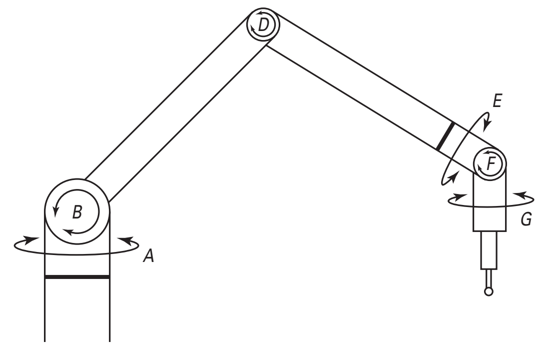


Fig. 6 Typical Machine of the 2-1-3 Configuration, With *a-b-d-e-f-g* deg Rotation

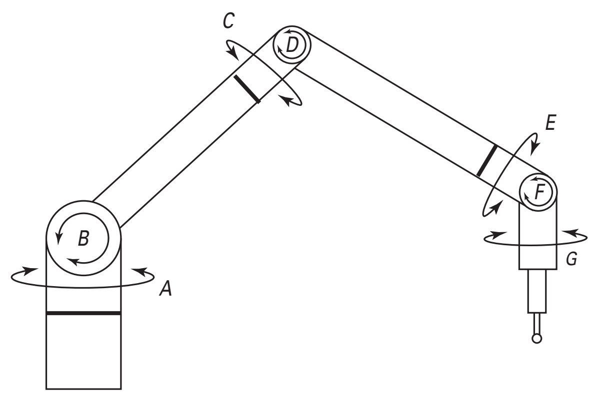


Fig. 7 Typical Machine of the 2-2-3 Configuration, With *a-b-c-d-e-f-g* deg Rotation

3 ENVIRONMENTAL SPECIFICATIONS

3.1 General

It shall be the responsibility of the user to provide an acceptable environment for conducting the performance evaluation testing. The environment shall be considered acceptable if the requirements of this paragraph and para. 4 are met. The user shall be responsible for conducting all of the environmental tests at their facility. The supplier shall have the right to witness this testing. The supplier shall, upon request, supply test equipment as specified in para. 6, as well as support for equipment and tests, at a cost negotiated between the supplier and the user. The user is cautioned that failure to conform to the supplier's recommendations on cleanliness and cleaning procedures can lead to significant performance degradation. For example, particulates, oils, and water can significantly degrade the machine's performance, increase friction, and accelerate wear.

3.2 Temperature and Humidity

3.2.1 General. Taking measurements when not at the standard temperature of 20°C can have a significant and often misunderstood influence on the quality of those measurements. The provisions outlined in ISO/TR 16015 form a part of this Standard, but interpretation is provided for the application to the class of machine covered by this Standard. It is recognized that some machines, because of their portability, will be used in widely varying thermal environments. The portable nature of these devices ensures that they will be used for measurements in most of the wide spectrum of manufacturing environments found today. ISO/TR 16015 defines two alternative conditions under which a test environment is thermally acceptable. The first is that all measurements are taken at the standard temperature, which for all practical purposes can never be done. The second condition is that the *thermal error index* (TEI; see para. 6.5, ASME B89.6.2) is a reasonable percentage of the working tolerance. This leads to the potential problem that errors, caused by differential thermal expansion, hysteresis, etc., can be induced in machines when they are used at temperatures different from the temperature at which they were aligned and calibrated. Similarly, the measurement of a workpiece at a temperature different from its design temperature can cause the workpiece to change size or distort. However, it is not within the current scope of this Standard to develop simple tests or procedures for quantifying these individual effects. In those cases where the machine is to be operated at temperatures outside the supplier's specified temperature range, the user should refer to the calculation of TEI in Appendix H, for a better understanding of the potential effects this will have on the machine's performance. 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.

In general, nominal variations in humidity do not have an adverse effect on the performance of the machine, but over a period of time may be detrimental.

3.2.2 Thermal Environment Parameters. The supplier shall provide, as part of the machine specification, a statement of the acceptable thermal environment parameters. It should be noted that the thermal environment is not limited to the environment within the work zone, but includes the environment that is in contact with the machine, i.e., the impact of the external thermal influences on the machine itself. The thermal parameters shall contain a specification on the range of temperatures within which the specified performance will be attained, as well as the maximum permissible vertical and horizontal temporal and spatial gradients. While not part of the thermal testing, the safe operating temperature range and the thermal settling time shall also be stated.

3.2.2.1 Thermal Radiant Energy. Care should be taken to minimize the machine exposure to direct sunlight or other powerful radiant energy sources. Other direct radiant energy sources (such as lighting) shall not be, whenever possible, closer to any part of the machine than twice the nominal arm length. Where this distance requirement is impractical, indirect lighting designed for diffuse reflection and increased path shall be used.

3.3 Vibration

3.3.1 General. The support surface (floor, foundation, tooling stand, etc.) upon which the machine is mounted can have motion induced as a result of external forces in the surrounding area (due to other machines, transportation vehicles, compressors, motors, etc.). This motion can range from a continuous vibration to interrupted shock or a combination of both. Such motion, if transmitted to the machine, has a degrading effect on the overall performance and repeatability of the machine, causing relative motions between the probe tip, the machine axes measuring system, and the workpiece, resulting in increased measurement uncertainty. In addition, certain excessive amplitudes of motion can cause damage to the machine.

3.3.2 Responsibilities. The user shall be responsible for site selection, environmental shock and vibration analysis, and for any additional special isolators deemed necessary 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 Vibration 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 supplier and user. This statement shall contain a complete description of the allowable total vibration amplitude over a specified frequency range.

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 requirements of the machine, allowable deviations from this voltage, frequency requirements, and amperage requirements. These parameters are listed in Fig. 1.

3.5 Mounting Stiffness and Orientation

3.5.1 General. It is the nature of AACMMs that they are often portable and therefore can be mounted in a variety of locations and orientations. This paragraph is added to environmental specifications since the performance of the AACMM may be influenced by the mounting orientation, and the stability and stiffness of the installation.

The AACMM is by design a manually manipulated and supported measuring instrument. This leads to operator-induced external forces and moments applied to the instrument that can cause deflections within the instrument as well as at the mounting interface and in the mount itself. Additionally, AACMMs are available in either counterbalanced or non-counterbalanced configurations. The counterbalanced models employ restoring forces to one or more of the arm's links to make the instrument easier to manipulate and use over long periods of time. However, these restoring forces also represent another potential source for deflections.

As neither the magnitude nor direction of the deflections is constant, varying with operators and for a given operator, varying with location and orientation of the arm within its work volume, they cannot easily be mapped and compensated. If these deflections are sufficiently large (i.e., the deflection magnitude is near the order of the AACMM single-point articulating performance as defined in para. 5.3), any measurements made with such a mounted device should be highly suspect and the instability in the mounting should be corrected before measurements are made.

As previously stated, the AACMM by design is intended to be highly portable and adaptable to mounting in a variety of locations and orientations. As the stability of the mounting can affect performance, the supplier may prescribe limitations to mounting orientation for their instrument. Additionally, mounting orientations other than those used during performance testing will result in different loading of the AACMM's components (links and rotary axes) and may allow the AACMM to reach locations in the measurement envelope that were not previously tested. This is shown in Figs. 8 and 9.

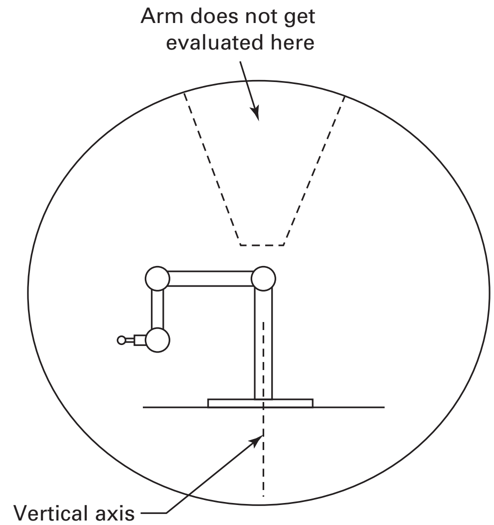


Fig. 8 AACMM Mounted Vertically for Evaluation

Therefore, it is strongly recommended that testing be performed in the orientation(s) in which the arm is to be used, and that these orientations be within any prescribed limits designated by the supplier.

3.5.2 Responsibilities. It is the responsibility of the supplier to provide the maximum expected forces and moments that the AACMM will generate, the maximum acceptable deformations at certification as depicted in the *Mounting Requirements* portion (see Fig. 2), and to

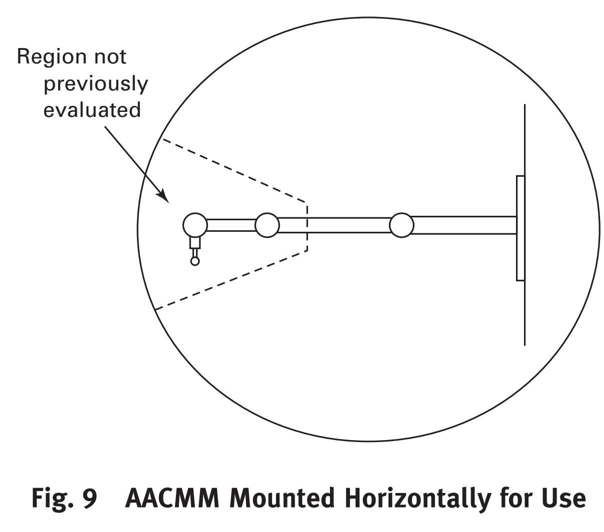


Fig. 9 AACMM Mounted Horizontally for Use

state any limitations on the mounting orientation. It is the responsibility of the user to determine the appropriateness of the mounting and to mount the AACMM within the limits specified by the vendor.

3.5.3 Parameters. The supplier shall provide, as part of the machine specification, a statement of mounting requirements, including the maximum applied forces and torques at the mounting interface, the maximum distances and displacements acceptable at the mounting interface, and any limits to the mounting orientation. These parameters are to be listed (see Fig. 2).

4 ENVIRONMENTAL TESTS

4.1 General

It is the recommendation of this Committee that, if a machine is to be operated in an environment that is significantly different from that used during the performance testing, a subset of the performance tests be repeated in order to assess the performance of the AACMM in the new environment. Those tests that are recommended for this mini performance evaluation are the effective diameter test and a sampling of the Volumetric Performance Test positions, which should include both radial and tangential artifact orientations. These tests should only be performed after adhering to any supplier's stated procedures for ensuring the integrity of the AACMM measurements at temperatures other than that at which they were calibrated.

As stated previously, it is the philosophy of this Standard that the operating 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. It is the position of this Committee that the performance tests in this Standard must be performed under conditions that conform to the supplier's environmental specifications. As such, this Standard does not provide procedures for derating the performance due to nonconformance to these specifications.

4.2 Temperature Tests

It is the position of this Committee that all tests be performed in a thermal environment that conforms to the supplier's specification. The thermal environment specification parameters, significant mean temperature range and the thermal settling time, can each have a significant effect on AACMM performance. However, constant monitoring of all of these parameters would represent an undue burden on either the user or the supplier. Therefore, it is the requirement of this Standard that the mean ambient temperature shall be established both before and after each performance test to ensure conformance to the supplier's specification. Should the machine fail to meet performance specification and the thermal environment is suspect, the environmental tests that are part of Appendix B can be conducted in order to determine complete conformance to the supplier's thermal environment requirements. If any of the parameters measured in Appendix B exceed the supplier's specified parameters, then the performance tests are suspended until such time that the user is able to correct the problem in order to conform with those specified parameters. 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.

If the machine is frequently moved between varying thermal environments, an alternate (or supplemental) procedure is to perform the ETVE test, as defined in Appendix H, after moving the AACMM between thermal environments and following the supplier's recommendations for thermal settling time between moves. While this test is somewhat of a compromise, in that it does not provide a full picture of how the AACMM will perform in the new environment, it does show the previously unaddressed effects of a rapidly changing thermal environment on the performance of the AACMM.

4.3 Vibration Tests

It is the position of this Committee that all tests be performed in a vibration environment that conforms to the supplier's specification. The vibration environment specification parameters, total amplitude and frequency range, can each have a significant effect on AACMM performance. However, constant monitoring of all of these parameters would represent an undue burden on either the user or the supplier. Should the machine fail to meet performance specification and the vibration environment is suspect, the environmental tests that are part of Appendix C can be conducted in order to determine complete conformance to the supplier's vibration environment requirements. If any of the parameters measured in Appendix C exceed the supplier's specified parameters, then the performance tests are suspended until such time that the user is able to correct the problem in order to conform with those specified parameters. 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.

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 that are difficult to link to mechanical causes. In the case that the power is 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 Mounting Stiffness Test

It is the position of this Committee that the testing of the mounting stiffness be carried out for the user-supplied portion of the mount. For example, if the user supplies a tooling stand, then the stiffness of the stand is tested by the user. If, as part of a complete measurement system, the supplier provides a stand which is then mounted to a steel table, then the mounting stiffness test is performed on the steel table. This is not to say that deflections in the supplier stand are negligible, nor should they be ignored. However, it is the supplier's's responsibility to provide a mount, if provided as part of the measurement system, that meets their own stiffness requirements. In this situation, responsibility for any degradation in the AACMM performance due to deflections in the supplier-provided mount is borne by the supplier.

The primary forces applied to the mounting of AACMMs are translational and torsional. These forces will tend to either move the entire measurement system along an axis (or combination of axes) or cause the measurement system to rotate about an axis (or combination of axes). These forces are illustrated in Fig. 10, illustration (a). The forces can be further described as acting along or about the three major axes of the coordinate system at the mounting base. The translational forces, *F*, along the axes and the moments, *M*, about the axes will tend to induce deflections of the base.

The deformation due to the translational force can be measured as shown in Fig. 10, illustration (b). The user must apply a *force* (N) using a calibrated load cell at the mounting interface to the maximum level required and measure the *displacement due to the force*, *D* (mm). Using a calibrated torque wrench, a torque can generate the torsional forces or moments at the base. The torque is applied about an axis and an indicator, mounted at a distance, *L*, from the applied torque, measures the displacement. The deflections can be described as a slope (mm/mm) and can be measured as depicted in Fig. 10. In either case, the deflections must not exceed the deformation in the mounting requirements specified in Fig. 2.

Care must be exercised when applying the torque with a torque wrench, as this can also induce a force. An alternative method is to use two indicators, one positioned to the left of the center and the other to the right, and apply a static load with a dead weight and suitable mounting bar. In this case, the slope can be measured.

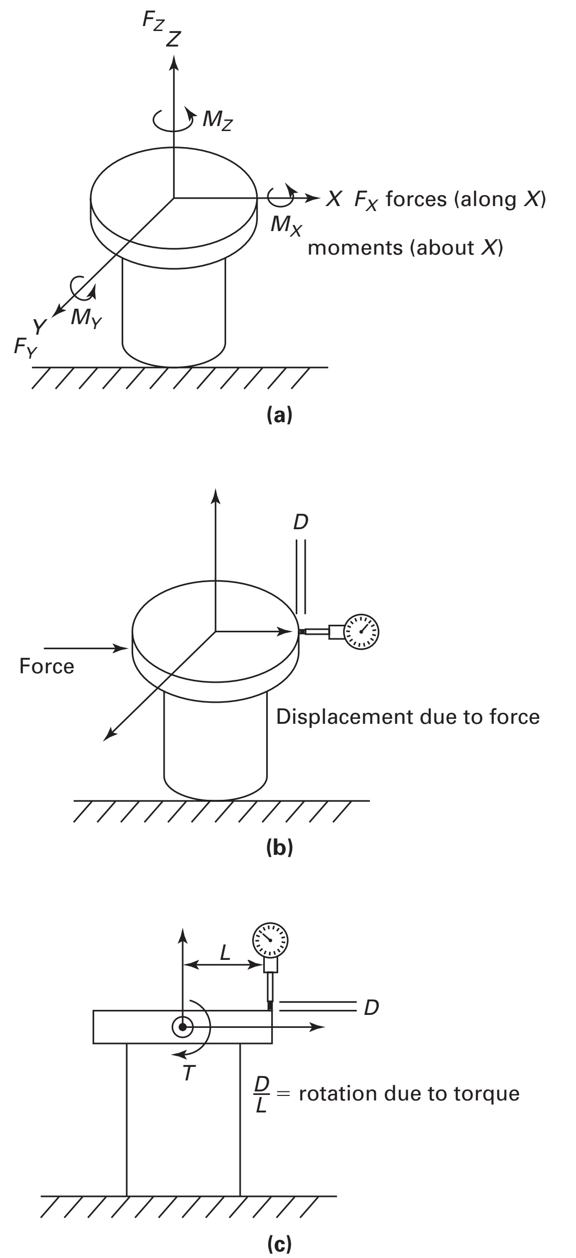


Fig. 10 Mounting Stiffness Test Setup

As noted above, the deflections must not exceed the deformation in the mounting requirements specified in Fig. 2.

5 MACHINE PERFORMANCE

5.1 General

Prior to conducting the performance tests, the machine shall be mounted in accordance with the supplier's recommended procedures. Additionally, the principal probe type (i.e., hard or switching probe) must be specified and shall remain the same for all subsequent tests. The selected probe type is then to be mounted in the AACMM and calibrated in accordance with the supplier's recommended procedures. In the case where an AACMM is to be used with more than one probe type, the user is encouraged to repeat the performance tests with all candidate probe types. However, testing with more than one probe type is not a requirement of this Standard. Because of the portability of these instruments, any recommendation for calibration after shipping should be agreed to prior to testing per this Standard. It is possible, depending on the treatment during transport, that some AACMMs may suffer performance degradation and require recalibration after any transportation.

The supplier shall have the responsibility 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 para. 3. 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 paragraph, 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 effective diameter, single point articulation performance, and volumetric performance that are described in this paragraph contain several options, and that these options will not necessarily give exactly the same results on any given machine.

5.2 Effective Diameter Performance Test

5.2.1 General Techniques. The requirement in the definition of the effective diameter performance test shall be satisfied by measuring the diameter of a calibrated sphere using nine probing points. The diameter measurement is repeated three times and the largest test deviation from the calibrated value is reported.

5.2.2 Setup and Measurement Procedures. Using a rigidly mounted calibrated reference sphere with a diameter between 10 mm and 50 mm, conforming to the requirements of para. 6.2.2, measure the sphere three times at the same location, in approximately the middle of the reach of the arm. Measure the sphere diameter using nine points per sphere measurement with the following distribution: four points equally distributed approximately on the equator, four points equally distributed at an approximate latitude of 45 deg and rotated at approximately 45 deg to those on the equator, and one point at the pole. During this test, the articulation of the AACMM should be minimized for each measurement.

5.2.3 Data Analysis. The nine points are used to determine a sphere using the AACMM software and the diameter calculated. The difference between the measured and the calibrated diameters of the sphere is reported as the diameter deviation. The effective diameter performance test value is reported as the maximum deviation regardless of sign. This method is used to harmonize the result with the B89.4.1b bidirectional length test, which is analogous to the effective diameter performance test.

A typical format for recording data is shown in Table 1.

Table 1 Diameter Deviations

Formula	Diameter Deviation, μm
$D_1 - D_{cal}$	
$D_2 - D_{cal}$	
$D_3 - D_{cal}$	
Max. deviation	

The results may reveal a number of problems, which may include either excessive machine or probe hysteresis, or improper probe calibration.

In cases where there appears to be a single or several outlying diameter(s) that do not conform to specification, it is recommended that the entire effective diameter test be repeated in order to ascertain whether the large deviation reflects a systematic error. If, after a maximum of three repeats of the test, the results still do not conform to the working tolerance for the effective diameter test, the test shall be discontinued, and the fault determined and corrected, before proceeding with any additional performance testing. Upon correction of any identified fault(s), the entire test shall begin anew and the results of this retest are the only data to be considered.

5.3 Single-Point Articulation Performance Test

5.3.1 General Techniques. The single-point articulation performance test is intended to assess the AACMM's ability to provide similar values of a point coordinate when the AACMM is articulated through the maximum possible range of motion for that single point. It should be noted that the single-point articulation performance test result is different from repeatability in the strict definition of the term. This test, by design, incorporates aspects of both repeatability and reproducibility that are necessary because of the unique nature of the AACMM. Unlike a conventional linear axis CMM, a single point may be measured from a nearly infinite number of directions and orientations of the AACMM's axes. Additionally, the construction of the AACMM does not map one-to-one from what is physically measured by the instrument and the parameters that define the instrument's coordinate system, i.e., there are no physical X, Y, and Z axes as in a Cartesian system or R, θ, and ϕ axes as in a spherical system, etc. Rather, the AACMM uses a series of kinematic transformations to express the probe tip position, in one of any natural coordinate system, using the predetermined arm segment lengths and current rotary axis positions. As such, what this test tries to convey is not the re-

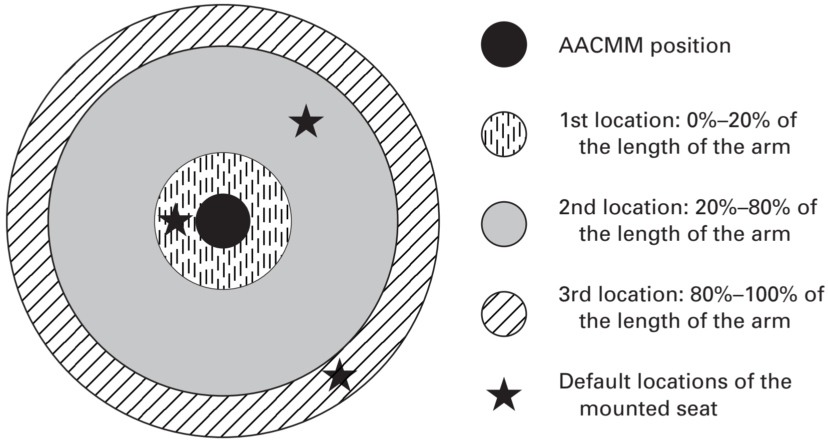


Fig. 11 Three Default Locations of the Mounted Seat During the Single-Point Articulation Performance Test

peatability of any physical attribute of the measurement instrument, but rather the system's combined ability to reproduce the coordinates of a fixed point in space.

To maximize the articulation of all of the arm encoders, the single-point articulation performance test shall be performed using an artifact placed at three different locations within the working volume. Figure 11 illustrates the three default measurement locations within the working volume for the single-point articulation performance test. The first location shall be within a radius up to 20% of the length of the arm, centered at the first rotational axis of the AACMM. The second location shall be within a zone defined by two radii between 20% and 80% of the length of the arm. The third location shall be outside of a radius greater than 80% of the length of the arm. Experience indicates that if the probe is kept in contact with the artifact, the force applied by the operator tends to increase. Therefore, after each point is taken, the physical contact between the artifact and probe shall be broken.

5.3.2 Setup and Measurement Procedures

5.3.2.1 Single-Point Articulation Performance Test Using a Hard Probe. The single-point articulation performance test is performed by measuring the center coordinates of the AACMM ball probe in a rigidly mounted kinematic seat. The seat may be a chamfered hole, a conical socket, or a trihedral socket, conforming to the requirements of para. 6.2.4. During the test, the supplier's recommended default probe is placed in the kinematic seat and the AACMM arm is articulated to ten different orientations, maximizing the possible orientations of the AACMM axes. As a default condition, and noting the orientation of the wrist, the first five of the ten orientations shall be performed as follows: If the operator is facing the machine, the five arm positions may be defined as

(*a*) AACMM arm elbow to the left and down
(*b*) elbow to the left and up
(*c*) elbow up
(*d*) elbow to the right and up
(*e*) elbow to the right and down

The same pattern is repeated with the wrist rotated approximately 180 deg about the axis of the probe. These positions are shown in Fig. 12.

For each of the ten orientations, the probe location is recorded, after which the probe is removed from the seat and then replaced prior to generating the next axes combination and taking the next point. This process is then repeated for the three test locations specified in para. 5.3.1.

5.3.2.2 Single-Point Articulation Performance Test With a Switching Probe. The following procedure is required when using a switching probe, but may be op-

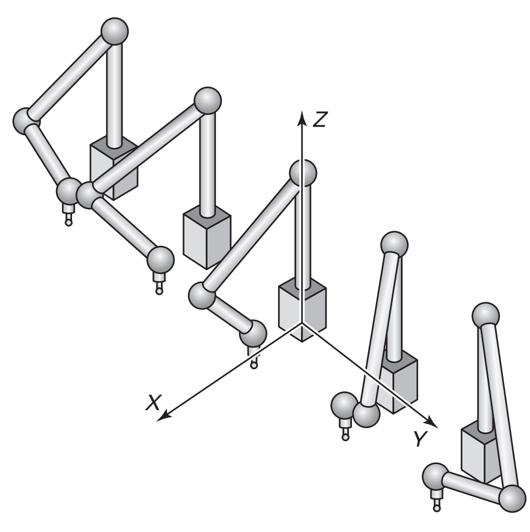


Fig. 12 Isometric View of Default Articulations

tionally used with the hard probe. However, the procedure described in para. 5.3.2.1 is the default method for use with a hard probe. The requirement in the definition of the single-point articulation performance test to sense the same quantity shall be satisfied by measuring the center coordinates of a calibrated sphere. The rigidly mounted calibrated reference sphere shall have a diameter of between 10 mm to 50 mm and must conform to the requirements of para. 6.2.2.

The test is conducted by measuring the location of the sphere ten times at three different positions within the work zone as defined in para. 5.3.1. For each sphere position, the arm is articulated through the same ten orientations as in para. 5.3.2.1. For each of the ten arm orientations, five points are measured and fit to a sphere to obtain the calculated sphere center coordinates. The default pattern for the five points shall be four points approximately on a great circle and one point on a pole. A typical five-point measurement pattern is illustrated in Fig. 13. The arm must be kept at approximately the same orientation for all five points during a sphere center measurement.

The process is repeated for each of the ten sphere center measurements, taking care to articulate the AACMM to a significantly different set of joint orientations and rotations between each sphere measurement. Hence, the ten sphere center measurements should be performed with ten significantly different joint orientations and rotations (including rotating the probe end joint), ensuring that the rotational axes are exercised over a significant portion of their range.

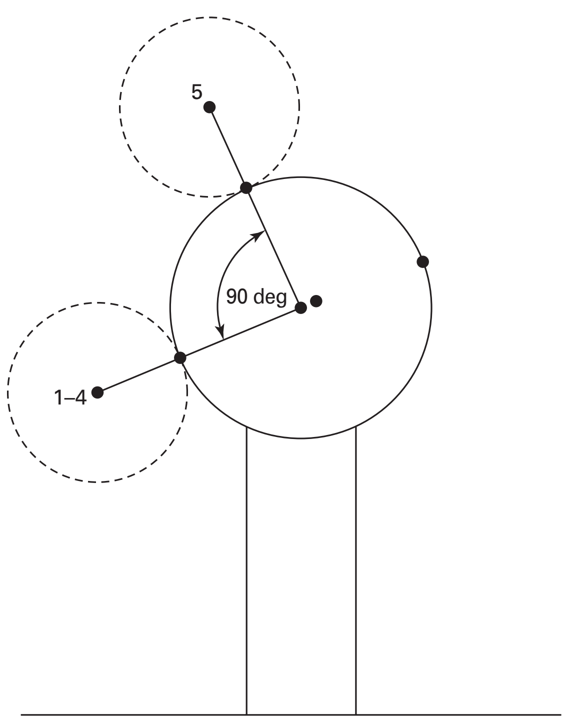


Fig. 13 Default Five-Point Probe Pattern

The entire process of ten sphere center measurements is then repeated at the remaining sphere positions shown in Fig. 11.

5.3.3 Data Analysis. The statistics used to represent the single-point articulation performance are the maximum deviation of the points from a mean value and twice the standard deviation of the point location. These statistics provide a measure of the combined variability in three mutually perpendicular axes. In this case, the standard deviation is actually a combination of the variances of the individual coordinates (X, Y, Z).

The procedure for determining the single-point articulating performance at each of the three measurement locations is as follows. First, calculate the average coordinates (X, Y, Z) of either the ten single-point measurements (hard probe procedure) or the ten calculated sphere centers (switching probe procedure). Using Eq. (1), calculate the three-dimensional deviations (δ_i) from the average coordinates to each of the corresponding ten points/sphere centers used to compute that average

$$\delta_i = \sqrt{(X_i - X_a)^2 + (Y_i - Y_a)^2 + (Z_i - Z_a)^2} \tag{1}$$

where

X_i, Y_i, Z_i = measured coordinates
X_a, Y_a, Z_a = average coordinates

From these values, the maximum deviation can be determined and the $2s_{SPAT}$ value calculated using Eq. (2). A typical format for recording the data and the calculated results for each measurement location is shown in Table 2.

$$2s_{SPAT} = 2\sqrt{\frac{\Sigma \delta_i^2}{(n-1)}} \tag{2}$$

where

n = number of measurements (in this case, $n = 10$)

The results of the SPAT test then consist of both the $\delta_{\max}$ and $2s_{SPAT}$ values for each measurement location. If the result obtained for each of the three measurement locations is less than the working tolerance for the single-point articulation performance test, then the AACMM has passed the test and the results are reported along with the nominal locations of the test. In the case where it is desired to report only a single set of results for this test, the $\delta_{\max}$ and $2s_{SPAT}$ value for the measurement location with the largest $\delta_{\max}$ shall be reported. If, the result for any measurement location is greater than the working tolerance, then the entire test shall be repeated. If, after a maximum of three repetitions of the test, the results still do not conform to the working tolerance for the single-point articulation performance test, the test shall be discontinued and the fault determined and corrected before proceeding with any additional performance testing. Upon correction of any identified fault(s), the entire test shall begin anew and the results of this retest are the only data to be considered for the single-point articulation performance analysis.

Table 2 Single-Point Articulation Performance Test

Reading No.	*X*-Axis X_i	*Y*-Axis Y_i	*Z*-Axis Z_i	δ_i [Eq. (1)]	δ_i^2
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
Average	$X_a =$	$Y_a =$	$Z_a =$	. . .	. . .
$\delta_{max} =$					. . .
[Eq. (2)] $2s_{SPAT} =$					

GENERAL NOTE: X_i, Y_i, and Z_i are either points from hard probe measurements or calculated sphere centers from switching probe measurements.

5.4 Volumetric Performance Test

5.4.1 General Techniques. The approach to accessing the AACMM's performance throughout its volume is necessarily different from that taken by the ASME B89.4.1b standard for traditional linear axis CMMs. Unlike a linear axis CMM, for which any point within the work zone uniquely defines the position of the three machine axes, there is an infinite number of arm orientations that can result in the same location of the AACMM probe. This characteristic of the AACMM means that an independent test of the machine "scales" along three lines at a regular spacing, as done in the ASME B89.4.1b linear displacement accuracy (LDA) test, will not reveal a great deal of information about the AACMM. Alternatively, requiring a test similar to the ASME B89.4.1b LDA but at many more locations and orientations would be too time consuming. Therefore, aspects of the linear displacement accuracy and volumetric performance tests are combined into the volumetric performance test. This test, as detailed in the following paragraphs, requires an ASME B89.4.1b distance measurement with a calibrated artifact, similar to the LDA, but requires length measurements at many locations within the machine volume, as in the ASME B89.4.1b volumetric performance test.

The general approach is to position the artifact in two vertical orientations, ten horizontal orientations, and eight 45 deg orientations. For each length measurement, the operator must record five measurement points per gage feature on the length artifact.

5.4.2 Setup and Measurement Procedures. As the default is for a calibrated bar to be used, a suitable thermal correction must be made prior to analyzing the data. The ball length, corrected for thermal expansion, can be obtained by using a temperature sensor integrated with a part-thermal-expansion-correction function in the AACMM software (if available) or by measuring the ball bar temperature using a third-party temperature system and making the correction using the equation below. Unless otherwise agreed between the supplier and the user, the default coefficient of thermal expansion (COTE) used for correction shall be as shown in Table H-1 and the thermometry used shall conform to the requirements for such equipment given in para. 6. It is recommended that the temperature of the artifact be recorded at the start and finish of each specific test and an average of these two values used.

$$L_c = L_m\,[1 - \alpha_{BB} \times (T_m - 20°\mathrm{C})]$$

where
- L_c, L_m = corrected and measured ball bar lengths, respectively
- T_m = average temperature during the measurements
- α_{BB} = coefficient of thermal expansion of the ball bar material

The default length artifact is the ball bar, which is calibrated for center-to-center length, but other artifacts such as a step gage can be used. The following details the procedure for ball bars: Two ball bars of different lengths are required. The short ball bar shall be between 50% and 75% of the radial length of the AACMM arm. The long ball bar shall be between 120% and 150% of the radial length of the AACMM arm. The length artifact is measured in 20 default positions. Other positions are acceptable, provided the work zone is adequately covered. The ball bar shall be suitably fixtured in the positions indicated for measurement so that probing access to both balls is achievable. The fixture should be portable for easy movement, but at the same time must be sufficiently rigid so that the ball bar will not significantly deflect or vibrate while the locations of the balls are being measured. For additional information on the use of ball bar, refer to Appendix F.

For the purpose of this test, the working volume of the AACMM will be divided into eight approximately equal octants. The working volume of the AACMM is, by nature, a sphere whose radius is defined by the full length of the arm and is centered at the first encoder joint. This sphere is divided into upper and lower hemispheres by an equatorial plane parallel to the surface on which the machine is mounted. The equatorial plane is divided into four quadrants, which creates eight equal volumes: four quadrants in the upper hemisphere and four quadrants in the lower hemisphere. The supplier specifies what is to be considered the front of the AACMM. Figure 14 illustrates the numbering scheme of the eight octants, for a horizontal equatorial plane. The octants are numbered 1 to 4 in the upper hemisphere, beginning with the back right octant and working around in a counterclockwise direction. The octants are numbered 5 to 8 in the lower hemisphere, beginning with the back right octant and working around in a counterclockwise direction.

The artifact shall be positioned in three inclinations, namely vertical, horizontal, and 45 deg, as shown in Fig. 15. The distance the artifact is from the center of the measurement volume is defined as near or far. Near is within one-half of the arm length from the center. Far is greater than one-half of the arm length from the center. The horizontal and 45 deg inclinations can be additionally defined by a direction of radial or tangential. The radial direction is defined as outward from the center. The tangential direction is defined as perpendicular to the radial direction. In summary, there are five characteristics to consider when positioning an artifact: length of the artifact, octant, artifact inclination, artifact distance, and direction relative to the center. Table 3 defines the recommended 20 ball bar positions.

For each length measurement, the operator must record five measurement points per sphere. The points should be well dispersed on the surface of the sphere. The sphere centers are then used to calculate a center-to-center distance for the ball bar. In order to attain an accurate center-to-center distance, it is necessary not to cause deflections of the ball bar during the measurement process. By monitoring the measured diameter of the spheres, it is possible to detect whether there was significant deflection during measurement. Typically, any deflection will cause the measured diameter of the sphere to appear smaller in size than the calibrated diameter.

5.4.3 Data Analysis. The center-to-center length value, L_i, is calculated and recorded for each ball bar position. The data from all the length measurements are analyzed by preparing a simple plot or a simple

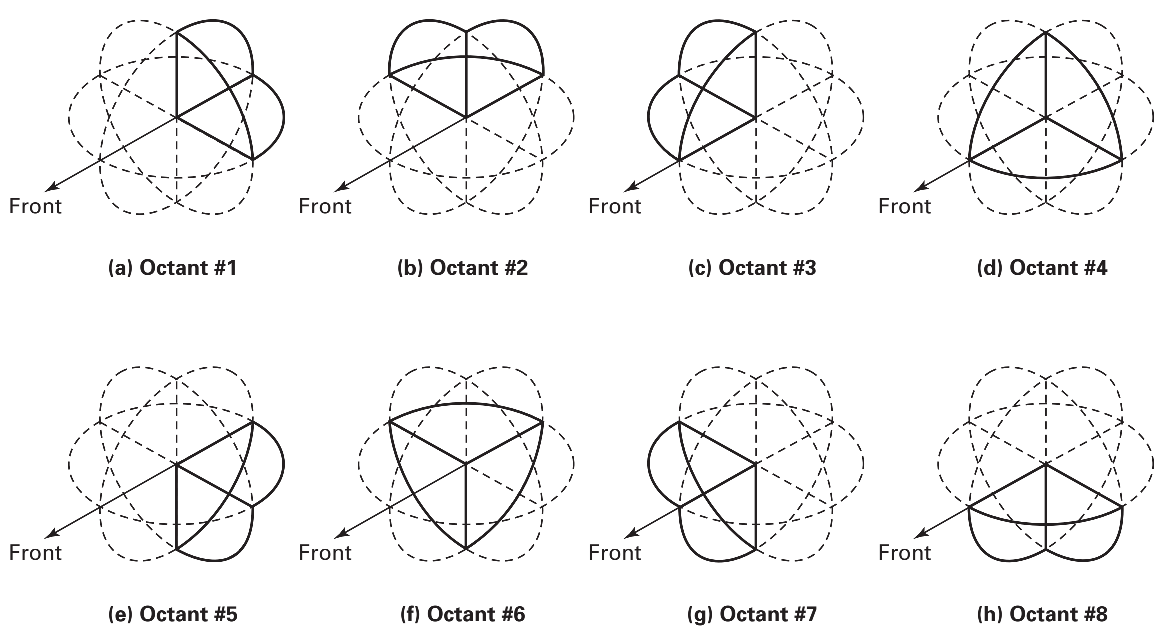


Fig. 14 Octant Numbering Scheme

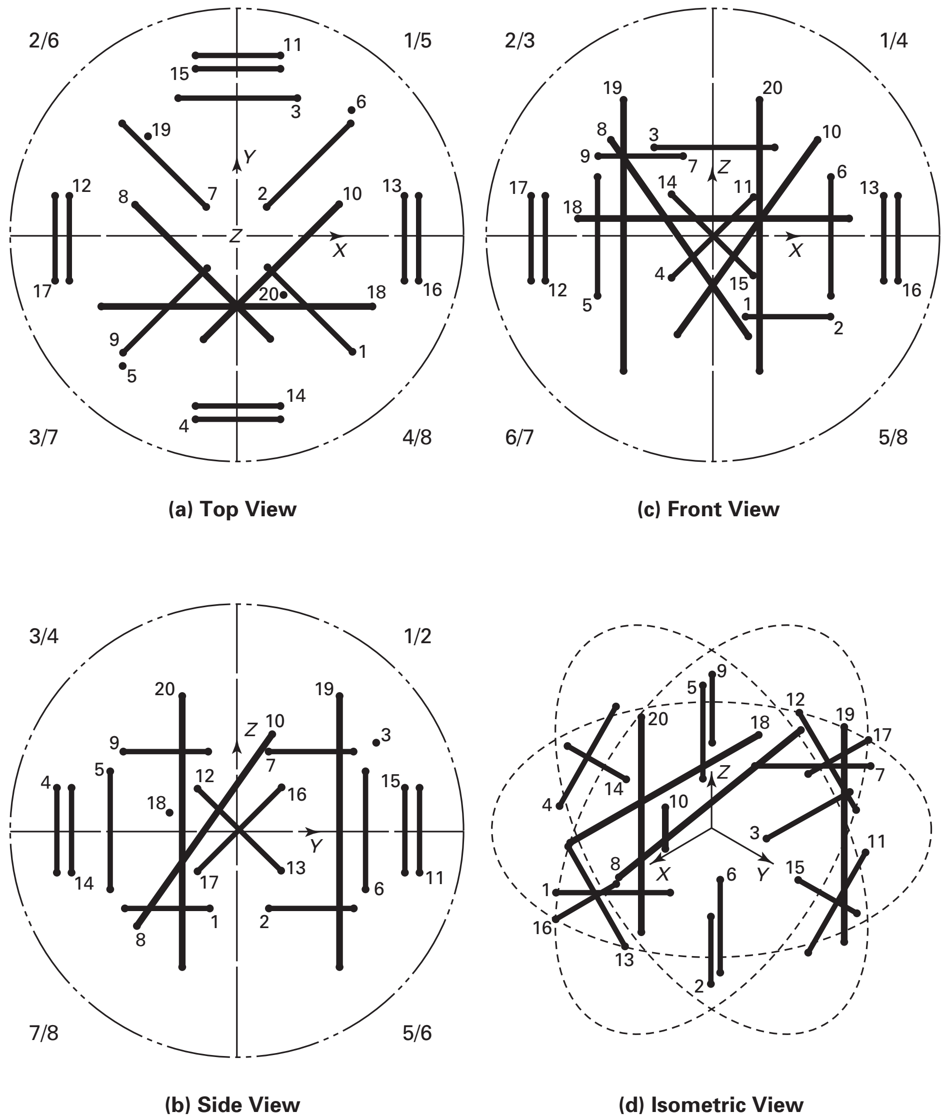


Fig. 15 Recommended Ball Bar Locations

table, as in Table 4 and Fig. 16, comprised of the length deviations, D_i, from the calibrated ball bar value, L_{cal}.

$$D_i = L_i - L_{cal} \tag{3}$$

The results of this test will be reported as three quantities: the maximum deviation, the range of the deviations, and two times the root-mean-square of the deviations. The range and maximum deviation of the data are clearly indicated in Fig. 16; the range is the difference between the maximum length deviation and the minimum length deviation. Two times the root-mean-square deviation is calculated from

$$2RMS = 2\sqrt{\frac{\Sigma D_i^2}{n}} \tag{4}$$

where

$n = 20$ in this case

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 the measurements at that specific position be repeated. The recommended procedure for checking the length measurement is as follows: The ball bar shall be measured twice in the suspected position. If the difference between the two length measurements is within twice the single-point articulation performance, the first measurement shall be used and the second discarded. If the difference between the two length measurements is not within twice the single-point articulation performance, both are discarded and the procedure is repeated. This procedure may be re-

Table 3 Recommended Artifact Positions

Position No.	Artifact Length	Octants	Inclination	Distance	Direction
1	Short	8	Horizontal	Near	Radial
2	Short	5	Horizontal	Near	Radial
3	Short	1 & 2	Horizontal	Far	Tangential
4	Short	4 & 7	45 deg	Far	Tangential
5	Short	7 & 3	Vertical	Far	Tangential
6	Short	1 & 5	Vertical	Far	Tangential
7	Short	2	Horizontal	Near	Radial
8	Long	2 & 8	45 deg	Near	Tangential
9	Short	3	Horizontal	Near	Radial
10	Long	1 & 7	45 deg	Near	Tangential
11	Short	1 & 6	45 deg	Far	Tangential
12	Short	6 & 3	45 deg	Far	Tangential
13	Short	5 & 4	45 deg	Far	Tangential
14	Short	3 & 8	45 deg	Far	Tangential
15	Short	5 & 2	45 deg	Far	Tangential
16	Short	1 & 8	45 deg	Far	Tangential
17	Short	2 & 7	45 deg	Far	Tangential
18	Long	3 & 4	Horizontal	Near	Tangential
19	Long	2 & 6	Vertical	Far	Tangential
20	Long	4 & 8	Vertical	Near	Tangential

peated three times. At the end of that time, if agreement based on the single-point articulation performance value has not been obtained as defined above, then the test shall be discontinued and the fault determined and corrected. After correction of the problem, the effective diameter test, the single-point articulation performance test, and the volumetric performance test shall be rerun in their entirety.

Table 4 Volumetric Performance Test Results

Position No.	L_i	L_{cal}	D_i [Eq. (3)]	D_i^2
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
Maximum deviation =				. . .
Range ($D_{max} - D_{min}$) =				. . .
$2RMS$ [Eq. (4)] =				

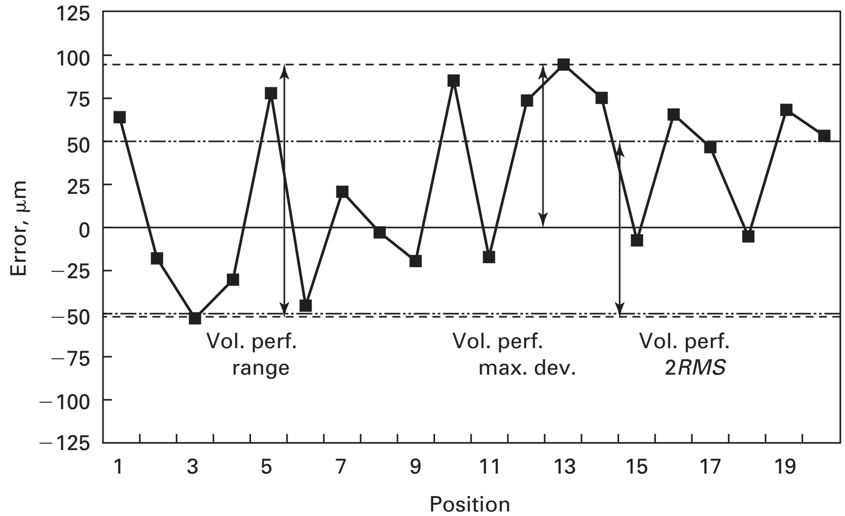


Fig. 16 Volumetric Performance Test Results

6 TEST EQUIPMENT

6.1 Temperature

The time constant of temperature recorders shall be no more than one-tenth of the cycle time of the highest frequency component of the temperature variation of interest in a test. The time constant is the time required for the temperature recorder to indicate 63.2% of its final change due to a step change in temperature.

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

Temperature recorders shall be calibrated by suitable means to an uncertainty of ±0.1°C over the temperature range of use.

6.2 Displacement

6.2.1 Indicating Gages. Indicating gages shall have a resolution of less than one-fifth of the working tolerance for the single-point articulation performance test. All gages shall be calibrated in accordance with the supplier's recommendations.

6.2.2 Precision Reference Ball(s). The precision reference spheres for the effective diameter performance test and the single-point articulation performance test shall be spherical to within one-fifth of the working tolerance for the single-point articulation performance test of the AACMM. The surface finish of the reference sphere shall be such as not to exceed one-fifth of the working tolerance for the single-point articulation performance test of the machine. The combined sphericity and surface finish of the sphere shall not exceed one-third of the working tolerance for the single-point articulation performance test of the machine.

6.2.3 Ball Bar. The ends of the ball bar shall be spherical to within one-fifth of the working tolerance for the single-point articulation performance of the AACMM. The ball bar shall be calibrated for center-to-center length to within one-fifth of the working tolerance for the volumetric performance test. For information on ball bar design recommendations, see Appendix F.

6.2.4 Seats for Hard Probes. A single-point articulation performance test using a hard spherical probe may be performed on either of the two types of positioning seats detailed below. The primary requirement is that a sphere placed in the seat assumes a position repeatable to one-fifth of the working tolerance of the AACMM during the repeated seating required for the test.

6.2.4.1 Trihedral Seat. The trihedral seat is designed on the premise that two non-deformable objects will contact each other at a maximum of three points. The trihedral design requires that the same three points be contacted upon each seating of the ball. A seat created by three hardened spheres approaches this ideal condition. See Appendix G for a more detailed discussion on seat design. Alternatively, a chamfered hole with three circumferential sections removed from the chamfered edge may also approximate a true trihedral seat.

6.2.4.2 Chamfered Hole Seat. A chamfered hole may also be used as a single-point test artifact. Since, in theory, only three points of the chamfered edge will contact the ball probe, care must be taken that the three points do not change during the course of the test. The likelihood of such a problem occurring is minimized by giving careful consideration to the design of the artifact, the selection of the material, and the material properties. As this type of artifact may be custom designed, a number of design considerations are discussed more fully in Appendix G.

NONMANDATORY APPENDIX A
USER'S GUIDE TO ASME B89.4.22

A-1 PURPOSE

This user's guide is intended to provide a framework for applying this Standard. The guide is written in a 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 details on each test procedure.

A-2 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 articulated arm 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.

A-2.1 Machine Specification

Use para. 1.1 of this Standard to establish a clear understanding between supplier and user of the characteristics of the 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.

A-2.2 Machine Acceptance

For initial acceptance, the machine must pass all performance tests in an acceptable environment. Acceptability of the environment may be demonstrated in one of two ways: by passing the performance tests or by showing compliance with the supplier's environmental parameters. The recommended procedure is to perform all of the environmental tests before proceeding with the performance tests. However, many applications 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.

A-3 ACCEPTANCE TESTING CHECKLIST

Before proceeding to the following list, it is assumed that the supplier and user are in general agreement that the machine is properly installed and the utilities are working satisfactorily.

___ Determine if temperature environment meets supplier's parameters, or defer subject to later testing or later elimination (para. 4.2).

___ 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, discontinue testing until a testing location conforming to supplier's specifications can be found.)

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

___ Validate mounting stiffness (para. 4.5).

Prior to any testing in accordance with para. 5, verify that all test equipment used conforms to the requirements of para. 6.

____ Perform effective diameter test (para. 5.2).

____ Perform single-point articulation performance test, as appropriate for machine and probe configuration (para. 5.3).

____ Perform volumetric performance tests by the method previously chosen (para. 5.4).

It is strongly recommended that a sketch or description of numbered length bar positions be attached to the test results.

NONMANDATORY APPENDIX B
THERMAL ENVIRONMENT TESTING

B-1 PURPOSE

The performance of articulated arm coordinate measuring machines is strongly affected by the detailed characteristics of the thermal environment that surrounds them. Parameters of importance include cooling medium (usually, but not always, air), velocity of cooling medium, frequency and amplitude of temperature variations of the cooling medium, mean temperature of that medium, and temperature gradients within that medium. The effects of these parameters and others are discussed in detail in ASME B89.6.2. Additionally, a summary of this concept is given in Appendix H of this Standard. 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 machine fails to meet performance specifications and the machine user contends that his/her environment meets the supplier's parameters. For the purpose of this Standard, these parameters include nominal mean ambient temperature, frequency and amplitude range of temperature variation, and maximum spatial temperature gradient. The following tests are designed to measure these parameters for the purposes of assuring conformance to the supplier's parameters.

B-2 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 AACMM, support computers (if supplied), and any other auxiliary equipment related to the AACMM turned off for a period of 24 hr preceding the test, to allow adequate soak-out of AACMM-induced thermal gradients. Normal activity, however, should be continued about the machine, as this constitutes part of the user-supplied environment. With these constraints, the following tests should be performed.

B-2.1 Mean Ambient Temperature

The mean ambient temperature shall be measured using a thermometer with characteristics as specified in para. 6 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).

B-2.2 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 1 hr interval, subject to the same condition.

B-2.3 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 maximum thermal gradient shall be determined to be the difference between the maximum and the minimum temperatures anywhere within the machine work zone divided by the distance between the measurement point of these extreme temperatures. These readings shall be taken over a period of at least as long as the longest acceptance test (or 24 hr) and the greatest value of the gradient reported.

B-3 ANALYSIS

If any of the parameters measured in para. B-2 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. 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.

NONMANDATORY APPENDIX C
SEISMIC VIBRATION VERIFICATION TESTS

C-1 SCOPE

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

C-2 DEFINITIONS

To the extent possible, this document is intended to be self-defining. It is written for individuals with an engineering background. Definitions for specific vibration terminology may be found in the Institute of Environmental Sciences and Technology document IEST-RP-CC024.1, Measuring and Reporting Vibration in Microelectronics Facilities.

C-3 VIBRATION ACCEPTANCE CRITERIA

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

C-3.1 Criteria Units

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

C-3.1.1 Amplitude Units. Since the machine is a measurement tool, units of displacement are most useful in relation to machine performance. However, velocity and acceleration are more appropriate parameters for measuring machine site vibration. Displacement may be suitable for specific situations, but it is not recommended for general vibration measurements.

C-3.1.2 Ordinate Units. The use of time or frequency for the ordinate will depend on the acceptance criteria format of the machine supplier. Time-based criteria are referred to as a *time history* that 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 that provides ability to diagnose many dynamic events.

C-3.2 Criteria Format

As defined in para. 5.3, the supplier shall provide, as part of the machine specification, a statement of acceptable vibration. The criteria should be provided by the supplier or listed as part of the machine specification form (Fig. 2), if used. At least two criteria format options are presented: (frequency) response function and time history. The supplied acceptance criteria will define the format to present the vibration data for ease of comparison.

C-3.2.1 Frequency Response Function Criteria. These types of criteria are specified as a vibration amplitude as a function at specific frequencies. The criteria are usually presented as allowable vibration amplitude versus frequency, in hertz. The frequency range may vary from supplier to supplier. In general, seismic vibrations are applicable over a range of 0 (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 be used.

C-3.2.2 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 amplitude could be in units of velocity or acceleration.

C-4 INSTRUMENTATION

This paragraph describes various instruments required to perform on-site vibration measurements. Various types of sensors, signal conditioners, recorders, computer programs, and signal analyzers are available that will acquire these data. It is not intended to single out any particular equipment manufacturer, but to recommend types of equipment that meet the requirements of this Standard.

C-4.1 Transducers

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

C-4.1.1 Seismic Accelerometers. The two most important requirements for the accelerometer are frequency response and sensitivity. Site vibration measurements generally require low frequency and high sensitivity. The minimum frequency response linearity should be less than 1 Hz, preferably 0.5 Hz. The frequency response should be greater than 100 Hz. The sensitivity of the accelerometer should be 10 V/g or greater, where g is equal to 9.8 m/s^2.

C-4.1.2 Velocity Transducers. These sensors are also referred to as geophones. The sensitivity of the geophone should be 4 V/cm/s. The frequency response linearity requirement of the velocity transducer is the same as the accelerometer, 0.5 Hz to 100 Hz.

C-4.2 Amplifiers and Signal Conditioners

The transducers require amplifiers and signal conditioners. Most seismic accelerometers require an amplifier, but some models may have built-in electronics that do not require signal conditioning. Velocity transducers may require amplification and signal conditioning, depending upon the sensitivity and signal-to-noise ratio. It is the responsibility of the vibration specialist to use the proper signal conditioners.

C-4.3 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 machine supplier. The frequency response criteria require a Fast Fourier Transform (FFT) dynamic signal analyzer or digital recorder. Time history data can be acquired with an oscilloscope, a digital recorder, or an FFT analyzer.

C-4.3.1 FFT Signal Analyzers. This type of analyzer is 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 the instrument, its capabilities, and its limitations. The following list offers guidelines for FFT analysis configuration and specifications:

(*a*) *Noise Floor.* 100 dB/$\sqrt{\text{Hz}}$.

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

(*c*) *Dynamic Range.* The dynamic range should be at least 70 dB. Better spectrum analyzers will have a 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 is calculated by dividing the frequency range by the number of lines. For example, a 0–100 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. For example, 0–100 Hz criteria defined every $^1/_2$ Hz would need to be acquired with 200 lines of resolution. This document recommends that 0–100 Hz data be acquired with 400 lines of resolution, producing 0.25 Hz resolution data. The overall frequency resolution will also be dependent on the transducer frequency response. The procedure above should be followed and modified only when the machine supplier'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. It is used to reduce the effects of transient events such as personnel or vehicular activity. It is recommended that ten 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. 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.

C-4.3.2 Data Recorders. For ease of gathering vibration data in the field, the use of a multichannel 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 specified in the paragraph above. The recorder format must be digital and use digital audio tape (DAT) because of its excellent signal-to-noise ratio and dynamic range, as compared to analog tape.

C-4.3.3 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, which allows a user to take baseline readings. The oscilloscope is also useful for viewing beat signals, transient events, and hourly and daily vibratory changes. The oscilloscope should be set to AC-coupled and free-run triggering. Viewing the signal, determining the peak-to-peak voltage amplitude, and using the transducer sensitivity for converting to appropriate amplitude units, determine the vibration amplitude.

C-5 TEST PROCEDURES

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

C-5.1 Calibration

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

C-5.2 Transducer Mounting

For all measurements, the transducers should be mounted directly and firmly to the floor or a common interface for measuring three mutually orthogonal axes. Such mounting arrangements are referred to as *triaxial*. Some accelerometers incorporate three triaxial transducers in one device. When this mounting arrangement is used, all three channels should be acquired simultaneously. Time-independent triaxial measurements should not be performed.

C-5.3 Measurement Location

In general, the transducers should be mounted in the general area where the machine will rest. This area should encompass the outer envelope of the machine plus 3 m (approximately 10 ft) beyond this footprint.

C-5.4 Acquiring/Recording Data

Vibration measurements should be made during normal operations of the facility. Nearby equipment that will be operating when the machine is expected to be used should be running during the vibration testing. A written test log or voice channel on a data recorder should be maintained by the individual performing the test so that any abnormal events during the test may be recorded. A test should be repeated if abnormal events occur. Normal vehicular traffic should not be excluded. When the environmental conditions are satisfactory, the data should be recorded on tape, saved to memory, and printed or manually recorded.

C-5.4.1 Time History. For time history criteria, simply compare the measured peak-to-peak vibration levels to the permissible level. The machine supplier may provide vertical and horizontal criteria. It is important to compare the acquired data to the criteria in the appropriate direction.

C-5.4.2 Frequency Response Function. Comparison of frequency response function criteria to frequency domain vibration data can require 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 downloaded 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 are in a software format, they can be manipulated, graphed, and analyzed in a usable format.

C-6 CRITERIA ASSESSMENT

C-6.1 Measured 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 machine in order to meet specifications.

C-6.2 Measured Vibration Above Criteria

If the vibration levels exceed the supplier's specifications, it is the responsibility of the user to isolate the vibration in order to conform to the specification, or else accept a performance derating. 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 who specialize in low fre-

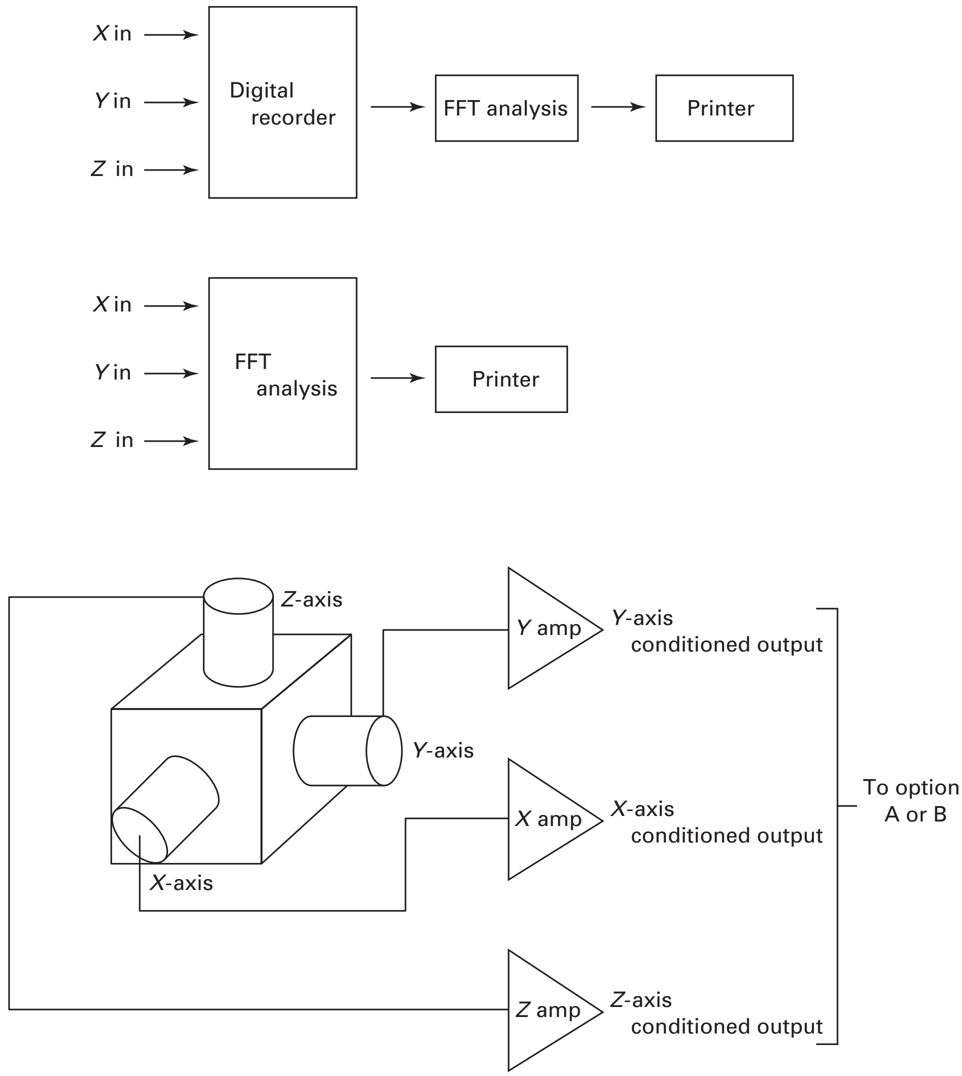


Fig. C-1 Diagram of Sensor Arrangement and Instrumentation Configuration

quency vibration attenuation should be contacted if vibration isolation or a vibration survey is required.

C-7 REPORT

A report shall be issued by the vibration specialist and shall include all backup information and analyzed data with a comparison to the machine specification. The report shall include the following as a minimum:

(*a*) title
(*b*) dates (issued and when data were taken)
(*c*) calibration information
(*d*) description and diagram of test setup
(*e*) procedure
(*f*) analysis
(*g*) summary

It is important to note that the report should serve to archive the baseline vibration data for later review, if problems arise after machine installation.

C-8 FIELD INSTRUMENTATION DIAGRAM

A diagram of the instrumentation is given in Fig. C-1.

NONMANDATORY APPENDIX D
ELECTRICAL POWER MONITORING TESTS

D-1 PURPOSE

The purpose of this Appendix is to specify test procedures for analyzing the electrical power supplied to the machine and its support equipment in the event that the electrical power is suspected to be causing inadequate machine performance.

D-2 TEST EQUIPMENT

The parameters describing the electrical power supplied to a machine can be measured by a variety of instruments (voltmeters, oscilloscopes, and the like). However, 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 other instruments are used. 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, swells, transients, and line frequency. IEEE 1159-1995, Recommended Practice in Monitoring Electric Power Quality, is an accepted standard for defining types of electric power phenomena.

D-3 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 machine tool 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 that includes all normal or even intermittent electrical activity within the plant that could affect the machine. (As an obvious example, consider the case when arc welding is done only a few days a week at a location that uses the same feeder as the machine. 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, swell, and transients) should be set at the values corresponding to those levels set by the supplier in the machine specification. Monitoring should continue for a sufficient period to ensure that all of the effects mentioned are included.

D-4 ANALYSIS

Typical power line monitors provide printouts of both the levels and times at which deviations from the accepted thresholds occur. If the monitor is set with the thresholds described 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 machine in order that machine specifications are met.

NONMANDATORY APPENDIX E
INTERIM TESTING OF AACMM SYSTEMS

E-1 INTRODUCTION

The goal of AACMM interim testing is to identify and rapidly remove from service defective AACMMs before significant numbers of good parts are rejected or bad parts are accepted. The frequent application of interim testing will increase confidence in AACMM performance between AACMM calibrations. Interim testing is not a substitute or replacement for AACMM calibration, and is not normally diagnostic in nature. Rather, it checks the validity of the calibration by detecting common AACMM performance failures. It is recommended that users regularly apply interim testing to their AACMMs. An effective interim test checks the AACMM measurement system including subsystem components that are used in the normal operation of the AACMM. This may include such components as probes, probe heads, temperature compensation systems, and rotary tables. This document assists AACMM users by providing information on efficient interim AACMM testing.

E-2 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 AACMM servicing and calibration. AACMM 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 may provide some guidance.

AACMM 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 para. 6 of the Standard, which typically require the uncertainty of an artifact to be less than 20% of the AACMM 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 that is similar to that of the workpieces commonly measured with the AACMM. The uncertainty in the thermal expansion coefficient of the artifact must also be considered, as discussed in para. 4.2. 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 an AACMM, 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 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 AACMM error of significance to the user. The interim artifact should be securely located on the AACMM 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. Additionally, 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.

E-3 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 that employ an artifact that represents a typical workpiece (the artifact may be an actual workpiece from the production line) and those strategies that employ an artifact specifically designed for AACMM testing. For all strategies, it is recommended that ten consecutive interim testing runs be conducted immediately after the AACMM 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 an AACMM, the new interim baseline measurements differ significantly from the previous baseline, then the interim artifact or the AACMM calibration (or both) may be suspect and further investigation is warranted.

Some AACMMs 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 an AACMM program available which can be used for the interim testing. The selected workpiece and the measured features on that workpiece should span the largest volume of the AACMM work zone that is encountered during actual workpiece measurements, to insure that the relevant volume of the AACMM is tested. For users measuring many small workpieces located all over the AACMM 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 the actual workpiece 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 AACMM errors. On artifacts that produce several lengths upon measurement (e.g., ball plates), the longest length present will provide the greatest sensitivity to errors. 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 be sensitive to common AACMM errors. The AACMM 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, or may be incorporated into part of the general AACMM 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 AACMM probe calibration artifact (typically a sphere with a calibrated diameter), a true bidirectional measurement of a known length is required.

E-4 INTERIM TESTING EXAMPLE

In this example, a user with an AACMM employing a hard probe has selected an interim testing artifact, consisting of a 25 mm diameter sphere connected at one end of a rod, and a conical socket at the other end. The rod length is roughly 75% of the AACMM length. The sphere is calibrated for form and diameter. Similarly, the length of the rod from the sphere center to the hard probe tip center (when placed in the conical socket) is also calibrated. The sphere is mounted in a three-point kinematic magnetic mount that allows the rod to rotate about the sphere center, sweeping out an arc of constant radius.

The user measures the sphere while it is in the kinematic mount with many points well distributed over its surface. The form, diameter, and center location are computed using a least squares fit. The reported form error is an indication of short-range errors of the AACMM, especially those due to repeatability problems. The diameter of the sphere is a feature of size, i.e., a bidirectional length measurement, that checks the ability to correctly account for the probe tip size.

The point-to-point length from the center of the sphere to the center of the probe tip (located in the conical socket) checks the ability to measure large lengths. Rotating the bar into different orientations (leaving the sphere end in the kinematic mount) allows many different orientations to be rapidly checked. At least four different lengths (each in a different octant) should be checked and compared against the calibrated rod length. If the AACMM is equipped with temperature compensation capability, this should also be used when making the rod length measurements.

The user records the ball diameter error, the calculated sphere form error, and the largest point-to-point rod length error of the interim test. If desired, these three values can be further combined (in a root sum of squares manner) to yield a single value indicative of the AACMM performance.

E-5 TESTING FREQUENCY

The frequency of interim testing is highly user-dependent. An AACMM 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 AACMM operating hours. Some users with high value and/or safety critical workpieces may elect to perform daily tests, where other users might test weekly or monthly. Additionally, interim testing should be conducted after any sort of significant event, such as an AACMM collision, replacement of a subsystem component, or the occurrence of abnormal temperature variations or gradients.

NONMANDATORY APPENDIX F
BALL BAR DESIGN AND MOUNTING RECOMMENDATIONS

F-1 PURPOSE

This Appendix contains information regarding ball bars and ball bar mounting.

F-2 GENERAL

It is recognized that the length of the ball bar becomes quite large for the evaluation of the volumetric performance of some models of AACMMs. In these cases, the mounting of the bar becomes particularly important. While the bar can be made from any cross section and be of any size and material, for a number of reasons the most commonly used ball bars are made from either a solid cylinder or a round tube, frequently made from steel or invar. Invar is an iron–nickel alloy, with trace elements of silicon and manganese, that has a very low coefficient of thermal expansion.

F-3 BALL BAR DESIGN RECOMMENDATIONS

For ball bars conforming to this Standard, the fixed length bar must be 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 frequently made of tubing to increase its natural frequency of vibration and at the same time reduce its weight.

To minimize the effect on repeatability due to the static deflection, it is highly recommended that the bar should be supported as close as possible to the ends, or in the case of the double-sphere ball bar, under the inboard spheres. When used for the volumetric test, the ball bar will be mounted both horizontally and vertically. Some ball bar system designs incorporate magnets in the mounting sockets. These magnets provide sufficient force to restrain the bar from falling. For the case where magnets are not used, the deflections shown in Table F-1 are for a ball bar that is assumed to be clamped at one end and, while horizontal, simply supported at the other. When in a vertical orientation, the bar will be supported at the top and will, in theory, simply hang straight down. If the support is considered rigid, then the measuring force will cause zero deflection of the bar.

Table F-1 Maximum Static Deflection of a Ball Bar Occurring at 0.5785*L*

Case	Bar Dimensions	Length, mm				
		500	1 000	1 500	2 000	2 500
1	20 mm dia.	0.005	0.085	0.429	1.355	3.307
2	25 mm dia.	0.003	0.054	0.274	0.867	2.118
3	40 mm dia.	0.001	0.021	0.107	0.339	0.827
4	20 mm OD, 10 mm ID	0.004	0.068	0.343	1.083	2.645
5	25 mm OD, 20 mm ID	0.002	0.033	0.167	0.529	1.290
6	40 mm OD, 25 mm ID	0.001	0.015	0.077	0.243	0.594
7	20 mm dia.	0.008	0.124	0.627	1.982	4.839
8	25 mm dia.	0.005	0.079	0.402	1.269	3.099
9	40 mm dia.	0.002	0.031	0.157	0.495	1.210
10	20 mm OD, 10 mm ID	0.006	0.099	0.502	1.585	3.871
11	25 mm OD, 20 mm ID	0.003	0.048	0.245	0.774	1.888
12	40 mm OD, 25 mm ID	0.001	0.022	0.113	0.356	0.870

For the assumed mounting condition, the bar, loaded under its own weight, will have a maximum static deflection of $WL^3/185EI$ that will occur at $0.5785L$ from the clamped end, where W is the total weight of the ball bar. The deflection at the center of the bar, i.e., at $L/2$, will be $WL^3/192EI$.

Table F-1 shows the maximum deflections, in millimeters, for various bar cross sections and lengths. As the density of steel (7 530–8 140 kg/m^3) and the density of invar (8 080 kg/m^3) are so similar, the weights will, for practical purposes, be the same for either material. However, as the modulus of elasticity for steel (205 GPa) is larger than that for invar (148 GPa), the deflection of the invar bars will be larger than that for the steel bars. In Table F-1, Cases 1 through 6 are for steel, while Cases 7 through 12 are for invar bars of the same cross section.

F-4 ERROR SOURCES

There are various sources of error that can contribute to the total error of a ball bar system. A brief discussion of these errors follows.

F-5 MOUNTING CONFIGURATION ERRORS

Two types of bar are commercially available, one with two spheres at each end and one with a single sphere at each end. These are shown in Figs. F-1 and F-2.

As the spheres are being probed, a significant difference in the force used by different operators may exist. 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.

As noted in para. F-3, the bar should be supported as close to the end as possible. If this is not done, as the support is moved further away from the end, the overhanging portion can be modeled as a cantilever. The excessive deflection will cause an apparent shortening of the ball bar. In this case, the static deflection at the end of the bar due to the probing force can be found from

$$\delta_1,\ \text{mm} = \frac{FL^3}{3EI}$$

where

E = modulus of elasticity
F = force
I = second moment of area of the bar
L = distance from the support

The weight of the bar will cause an additional deflection of

$$\delta_2,\ \text{mm} = \frac{qL^4}{8EI}$$

where

q = weight per unit length of the overhanging bar

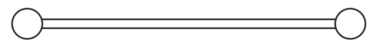


Fig. F-1 Single-Ended Ball Bar

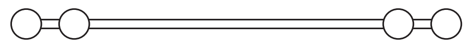


Fig. F-2 Double-Ended Ball Bar

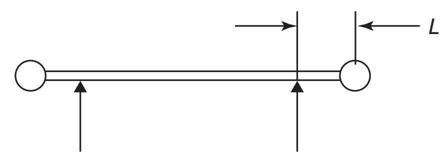


Fig. F-3 Ball Bar Mounted With Overhang at Each End

The total static deflection when the bar is mounted horizontally and points are being taken around the equator is then

$$\delta_{\text{total}},\ \text{mm} = \delta_1 + \delta_2 = \frac{L^3}{24EI}(8F + 3qL)$$

Note that the deflection is a function of the length cubed or to the fourth power.

Consider the following example of a ball bar mounted as shown in Fig. F-3. For a 20 mm diameter steel ball bar, the second moment of area is found from

$$I = \frac{\pi d^4}{64} = 7\ 854\ \text{mm}^4$$

The resultant end deflection (ignoring the weight of the ball itself) as a function of overhang distance for various forces is shown in Fig. F-4 for a 20 mm diameter bar. Figure F-5 is the same plot for a 25 mm OD, 20 mm ID invar tube. For this cross section,

$$I = \frac{\pi}{64}\left(D^4 - d^4\right) = 11\ 321\ \text{mm}^4$$

The fixture 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. For low and moderate accuracy AACMMs, most fixtures will be adequate for testing volumetric performance. For more accurate AACMMs, the stiffness of the ball bar system must follow proper design guidelines. In general, the objective is to keep the deflection as low as possible, which again illustrates why the bar should be mounted as close to the end as possible.

It should be noted that a major attribute of the artifact mounting is I (the area moment of inertia, more correctly termed the second moment of area). For a circular or tu-

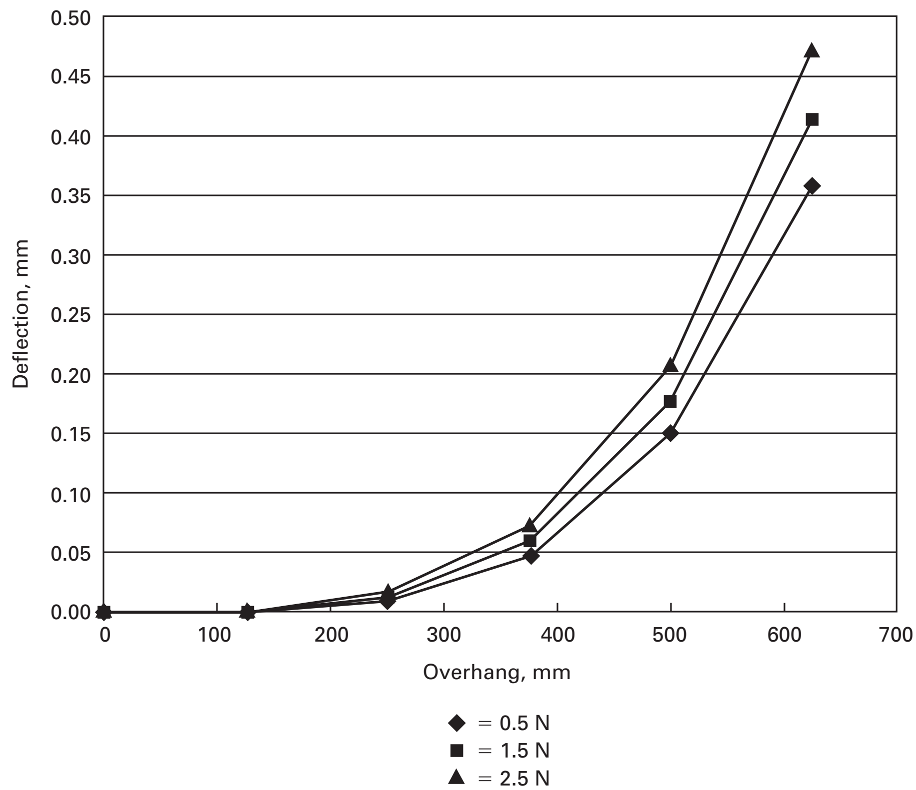


Fig. F-4 Static Deflection as a Function of Force and Overhang Length for a Steel Bar

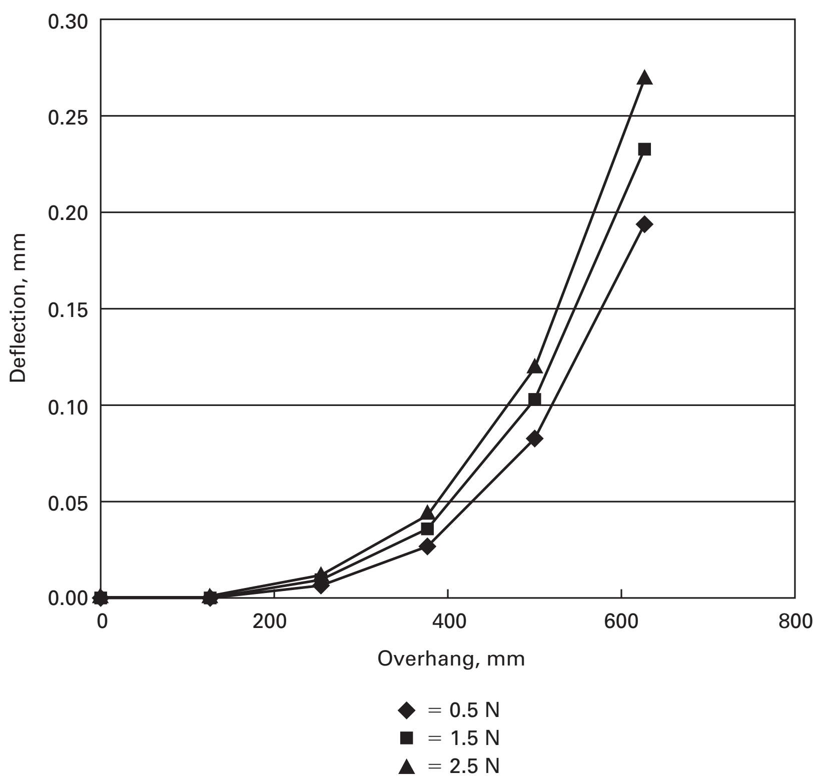


Fig. F-5 Static Deflection as a Function of Force and Overhang Length for an Invar Tube

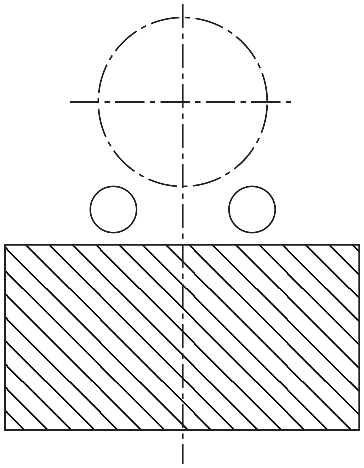


Fig. F-6 Support Bar Mounted Horizontally

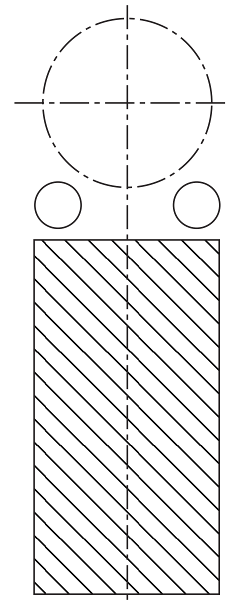


Fig. F-7 Support Bar Mounted Vertically

bular section, this is obviously a nonissue because of symmetry. For a support bar made from a rectangular section, the second moment of area is found from

$$I,\ \mathrm{mm}^4 = \frac{b_d^3}{12}$$

For a rectangular bar 25 mm × 10 mm, the second moment of area can be either 2 083 or 13 021 mm^4, depending on the orientation. This is illustrated in Figs. F-6 and F-7.

When the ball bar is being used for the volumetric testing and is mounted in a vertical orientation, a foreshortening error will occur due to gravitational effects.

The end compression in millimeters can be found (with a consistent set of units) from $\gamma L^2/2E$, where γ is the specific weight. The foreshortening, in mm, of 20 mm diameter steel bars and 25 mm OD invar tubes of various lengths is shown in Table F-2.

F-6 THERMAL ERRORS

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°C–15°C are not uncommon. When this situation occurs, it is desirable to have some estimate of the thermal soak time.

The thermal soak time is based on a thermal time constant, τ, for an item and its surrounding environment. The thermal time constant depends on the thermal capacitance, volume, and surface area of an item, and the properties and movement of the surrounding environment.

The temperature of an item over time, after experiencing a sudden change in the temperature of its surrounding environment, may be expressed as

$$f(t) = (T_f - T_i)(1 - e^{-t/\tau})$$

where

$f(t)$ = change in temperature of the item for a given time interval t

t = time interval from the start of the change in environmental temperature to any later time

Table F-2 Foreshortening of Bars as a Function of Length

Bar Dimensions	Length, mm				
	500	1 000	1 500	2 000	2 500
Solid steel, 20 mm OD	0.0001	0.0002	0.0004	0.0008	0.0012
Tube invar, 25 mm OD, 20 mm ID	0.0001	0.0003	0.0006	0.0011	0.0017

T_f = final temperature of the item, which is the temperature of the surrounding environment after the sudden change
T_i = initial temperature of the item
τ = thermal time constant for the item

When $t = \tau$, $f(t) = (T_f - T_i)(1 - e^{-1}) = 0.632(T_f - T_i)$. This means that the item has experienced a change in temperature of 63.2% of the difference between its initial and final temperatures.

When $t = 3\tau$, the change in temperature has attained 95%. Similarly, $t = 5\tau$ represents a change in temperature of 99.3%. As time (t) increases beyond 5τ, the change in temperature approaches 100% of the original difference in temperature. For many practical applications, 4τ is used for the thermal soaking as the item will then be at greater than 98% of its steady-state temperature.

τ may be calculated from the following equation:

$$\tau = CV/hA \tag{1}$$

where
A = surface area, m^2
C = thermal capacitance, $J/°C \cdot m^3$
h = convective film coefficient, $W/m^2°C$
V = volume, m^3

In most cases, the fluid medium will be slowly moving air. For such a situation, assuming a value of 11.5 for the convective film coefficient is usually adequate. For additional information on estimating thermal time constants, thermal soak times, or fluid heat transfer properties, see ASME B89.6.2 or any textbook on heat transfer.

The following illustrates the calculation of a thermal soak time for the ball bar. The ball bar can be considered as being made up of three elements, two spheres and a cylinder. The spheres are 25 mm in diameter and the bar is 20 mm in diameter. The surface area and volume for the elements are shown in Table F-3.

The properties of the spheres will be constant regardless of the length of the bar. Substituting the value of r = 12.5 mm into the equations for the sphere gives the surface area as 1 964 mm^2 and a volume of 8 181 mm^3.

The length of the ball bar is from the center of one sphere to the center of the other. The length of the cylinder can then be found by subtracting 25 mm, i.e., two radii.

Table F-3 Sphere and Cylinder Surface Area and Volume

Element	Surface Area, mm^2	Volume, mm^3
Sphere	$4\pi r^2$	$\frac{4}{3}\pi r^3$
Cylinder	$2\pi rL$	$\pi r^2 L$

Table F-4 Ball Bar Area and Volume as a Function of Length

Length, mm	Length of Cylinder, mm	Surface Area, mm^2	Volume, mm^3
300	275	17 281	86 405
500	475	29 849	149 245
700	675	42 417	212 085
900	875	54 985	274 925
1 000	975	61 269	306 345
1 200	1 175	73 837	369 185

Ball bars are usually manufactured in millimeters. Table F-4 shows the surface area and volume for a number of different-length ball bars.

The total surface area and volume can now be found by simply adding the three elements together as shown in Table F-5.

As can be seen, the ratio is almost constant, as one would expect because the volume/area for the cylinder is constant at $r/2$ and the contribution of the spheres is very small.

From Eq. (1), using the values of volume/area from Table F-5, and taking the value of thermal capacitance, C, for steel as 990 $J/°C \cdot m^3$ and the convective film coefficient, h, as 11.5 $W/m^2°C$, the thermal time constant = $(990 \times 4.93)/11.5 = 0.38$ hr or 22 min.

The ball bar should be allowed to soak in a constant temperature environment for 4τ or about 1.6 hr prior to any measurements being taken.

Handling the ball bar also causes thermal errors. 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 one's 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.

The ball sphericity as defined in the Standard should be less than 20% of the AACMM repeatability.

Table F-5 Ratio of *V/A* for Ball Bars of Different Lengths

Length, mm	Surface Area	Volume	Ratio of *V/A*
300	(2)(1 964) + 17 281	(2)(8 181) + 86 405	4.85
500	(2)(1 964) + 29 849	(2)(8 181) + 149 245	4.90
700	(2)(1 964) + 42 417	(2)(8 181) + 212 085	4.93
900	(2)(1 964) + 54 985	(2)(8 181) + 274 925	4.94
1 000	(2)(1 964) + 61 269	(2)(8 181) + 306 345	4.95
1 200	(2)(1 964) + 73 837	(2)(8 181) + 369 185	4.96

Table F-6 Combinations of Length from a Commercially Available Invar Ball Bar Kit

Invar Bar Length	125 mm (Two Bars)	250 mm (Two Bars)	500 mm (Four Bars)	Total Number of Bars	Total Number of End Plugs	Total Length of Invar, mm	Total Length of Steel, mm	Total Length of Ball Bar, mm
125	1	0	0	1	2	100	25	125
250	2	0	0	2	4	200	50	250
250	0	1	0	1	2	225	25	250
375	1	1	0	2	4	325	50	375
500	0	0	1	1	2	475	25	500
500	0	2	0	2	4	450	50	500
500	2	1	0	3	6	425	75	500
625	1	0	1	2	4	575	50	625
625	1	2	0	3	6	550	75	625
750	0	1	1	2	4	700	50	750
750	2	2	0	4	8	650	100	750
750	2	0	1	3	6	675	75	750
875	1	1	1	3	6	800	75	875
1 000	0	0	2	2	4	950	50	1 000
1 000	0	2	1	3	6	925	75	1 000
1 000	2	1	1	4	8	900	100	1 000
1 125	1	0	2	3	6	1 050	75	1 125
1 125	1	2	1	4	8	1 025	100	1 125
1 250	0	1	2	3	6	1 175	75	1 250
1 250	2	0	2	4	8	1 150	100	1 250

Ignoring the thermal correction may not be the best strategy for ball bar kits that are screwed together to form longer lengths. Each bar typically has a threaded stainless steel plug in each end, usually approximately 12.5 mm in length. Typical lengths in commercially available kits are 125, 250, and 500 mm, although other lengths up to 1 500 mm are readily available. In a commercially available kit, all lengths are certified to ±0.003 mm or ±0.008 mm.

Table F-6 shows how different ball bar lengths can be obtained from a commercially available kit.

Table F-7 Natural Frequency of Ball Bars as a Function of Length

Case	Bar Dimensions	250	500	750	1 000	1 250
1	20 mm dia.	186	46	21	12	7
2	25 mm dia.	248	62	28	15	10
3	40 mm dia.	371	93	41	23	15
4	20 mm OD, 10 mm ID	224	56	25	14	9
5	25 mm OD, 20 mm ID	310	77	34	19	12
6	40 mm OD, 25 mm ID	447	112	50	28	18
7	20 mm dia.	154	38	17	10	6
8	25 mm dia.	205	51	23	13	8
9	40 mm dia.	307	77	34	19	12
10	20 mm OD, 10 mm ID	185	46	21	12	7
11	25 mm OD, 20 mm ID	256	64	28	16	10
12	40 mm OD, 25 mm ID	370	92	41	23	15

For example, for a change in temperature of 5°C, a nominal 1 250 mm long bar, made up of $(2 \times 125) + (2 \times 500)$ bars and treated purely as an invar bar, will expand by $(1\,250)\,(1.26 \times 10^{-6})\,(5) = 0.0079$ mm.

However, including the steel plugs will give an expansion of $(1\,150)\,(1.26 \times 10^{-6})\,(5) + (100)\,(11.7 \times 10^{-6})\,(5) = 0.0131$ mm, or a difference of about 60%.

F-7 HYSTERESIS ERRORS

Applying a force parallel to the ball bar in one direction and then applying it in the opposite direction can check these. The applied force should be twice the probing force. The test should then be repeated, but with the direction of the force perpendicular to the ball bar axis. The hysteresis in each direction should be less than 20% of the AACMM repeatability.

F-8 PROBING ERRORS

Probing forces may cause deflections in the ball bar and the fixture. Lateral deflections have a direct influence on determining the distance between ball centers, because symmetrical deflections cause the ball diameters, as fit to the data, to appear smaller and thus a longer ball bar length (center-to-center distance) is calculated.

Distortions due to gravity cause two effects, which can be combined for tilted bars: an overall shortening of the ball bar from compression along the vertical direction, and a shortening of the ball bar due to the sag of the bar when it is held horizontally. For ball bars as commonly built, the first effect is very small and the second is insignificant because it is a cosine error.

F-9 NATURAL FREQUENCY OF VIBRATION

Free-standing ball bar systems can be very susceptible to vibrations. For many designs, 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 sources or can be induced by the motion of the AACMM operator.

The natural frequency of vibration of the overhanging section can be found from

$$\omega_n = \frac{1}{2\pi} \sqrt{\frac{g}{\delta}} \text{ Hz}$$

The resultant values are shown in Table F-7. Cases 1 through 6 are for steel, while Cases 7 through 12 are for invar bars of the same cross section.

NONMANDATORY APPENDIX G
KINEMATIC, CONICAL SEAT, AND CHAMFERED HOLE DESIGN RECOMMENDATIONS

G-1 PURPOSE

Simply stated, the principle behind kinematic mounting is that a rigid body should be constrained by no more than the number of single points equal to the number of unwanted degrees of freedom of that body. Since a rigid body has six degrees of freedom (three translations and three rotations), this dictates that the number of point contacts be six or less. Constraining a rigid body in such a manner ensures that no stress is induced in the body as a result of the mounting. Under the right applications, this provides for a very stable and highly repeatable (depending on the choice of materials) mount. However, kinematic mounts are not ideal for all situations, due to the high local stresses that may result from point loading.

G-2 GENERAL

For the purposes of this Standard, kinematic mounting is used for locating precision spheres, either a reference ball or an AACMM probe tip. This is most effectively accomplished through the use of the trihedral socket. In this case, it will only be necessary to constrain the three translations of the sphere. Therefore, three point contacts are all that are required (the three rotations have no effect on the sphere, since it is symmetric about all three of its axes). Forms of the trihedral and guidance on how to make them are shown in Fig. G-1.

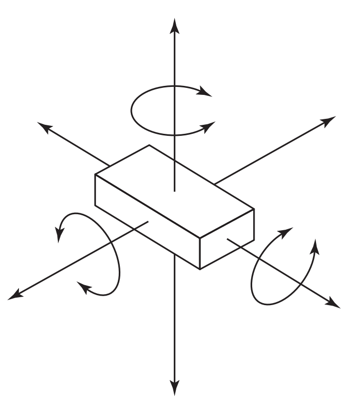


Fig. G-1 Degrees of Freedom for a Rigid Body

G-3 TRIHEDRAL SOCKET CONSIDERATIONS

There are several ways to construct the trihedral socket or "kinematic seat." Probably the easiest is to place three spheres (could be ball bearings) in a flat bottom hole or "cup" as shown schematically in Fig. G-2. The sizes of the spheres and the hole will depend on the size of the sphere that is to be constrained by the seat. Similarly, the depth of the hole will depend upon the degree of access required for the seated sphere. In order to maintain stable contact, the angle of contact as measured from the horizontal should be 45 deg. In this case, the relationship between the diameter of the three spheres forming the seat (d) and the diameter of the sphere that is to rest in the seat (D) will be

$$d \geq 1.58D$$

and the diameter of the cup (CD) can be found from

$$CD = 2.16d$$

Variations on this particular version of the trihedral socket use surface-mounted hemispheres that are spread out, i.e., not touching one another, which allows the use of smaller spheres to form the seat and allows the addition of a magnet, if so desired, to help keep the seated sphere in place. If possible, the hemispheres should be placed on a flat plane and spaced 120 deg apart (see Fig. G-3), as is inherent in the three spheres in a cup case. When designing this variation of mount, be sure that the sphere to be seated does not contact the hemisphere support surface before resting on the hemispheres. Again, assuming that the spheres contact at 45 deg, this leads to the relationship

$$d > 0.414D$$

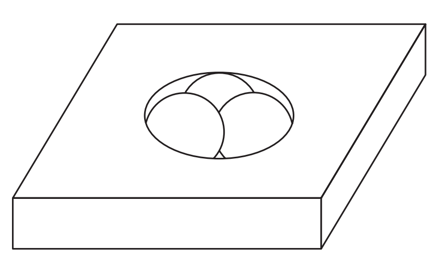


Fig. G-2 Three-Sphere Kinematic Seat

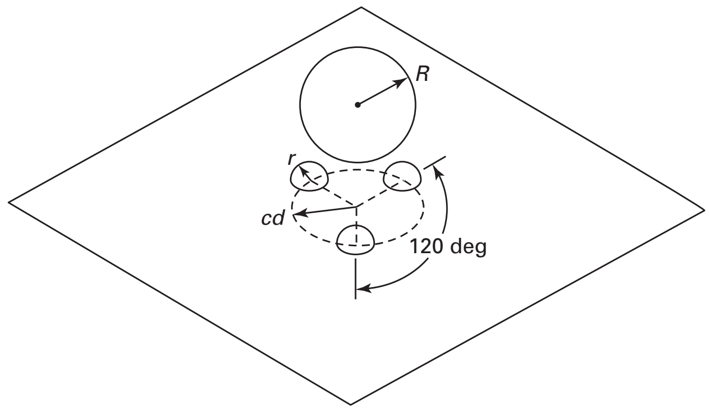


Fig. G-3 Three-Hemisphere Kinematic Seat

or requires that the hemisphere support surface be relieved to accommodate the seating sphere. A second useful relationship for this configuration gives the diameter of the circle (cd) that circumscribes the triangle formed by the center points of the three hemispheres:

$$cd = 0.707(D + d)$$

G-4 CONICAL SEAT CONSIDERATIONS

In less-demanding applications, an alternative to the kinematic seat is the conical socket. These sockets or seats can be easily constructed on a drill press, grinding machine, or milling machine using a tool with the proper included angle. It is recommended that the cone angle be within the range of 60 to 120 deg and that the depth of the conical socket be such that a minimum of one-third of the ball diameter lies inside the cone. If two or more conical sockets are used to define distance points on an artifact of length, reasonable care must be exercised to ensure that the axes of the cones are parallel. Burnishing an annulus of contact at the proper contact diameter can further refine the conical socket. This can be accomplished by placing a “sacrificial” hardened steel ball, of the same nominal diameter as the sphere that the conical socket is designed to locate, and hitting it with a hammer. Although this will destroy the ball, it will provide a more repeatable seat for locating spheres.

G-5 CHAMFERED HOLE SEAT CONSIDERATIONS

A number of material parameters and design considerations for a chamfered hole seat are discussed. Some of the important design requirements are hardness, surface roughness, wear, elastic modulus, yield strength, and mounting configuration, although each may have significantly different contributions depending on whether the chamfered hole is being used for performance acceptance or periodic recalibration. While many materials can be used, the following guidelines address the use of a steel seat or an anodized aluminum seat.

Hardness, or the resistance to permanent indentation, is denoted by a number of different scales. Commonly used scales for engineering metals are Brinell (HB), Rockwell (HR), and Vickers (HV), depending to a certain extent on the material being measured. The different tests involve pushing a ball, cone, or pyramid into the surface and expressing the hardness as a ratio of the load and the depth or surface area of the indentation. As such, for some of the scales, empirical relationships have been developed with other material properties, but careful attention should be paid to the units.

While wrought aluminum alloys are typically relatively soft, their use as a chamfered hole seat can be considered if they are anodized or, more specifically, hard anodized. Anodizing is an electrochemical conversion process that changes the outer structure of the metal. Aluminum, on exposure to air, naturally develops a thin oxide film that seals the surface from further oxidation. For most purposes, this thin oxide layer doesn’t enhance surface hardness, as the depth is quite shallow. Hard anodizing makes a much thicker oxide coating, up to 0.08 μm in thickness. The hardness of a correctly treated anodized aluminum oxide coating can approach that of diamond, making it very suitable for consideration in artifact design.

It is easy to recognize that a hole with a poor surface finish will change size and shape due to the continual insertion of the probe tip. A poorly machined surface with lots of chatter will change over a period of time. To minimize the effect, the surface finish of the chamfer should be 0.8 μm or better, paying attention to the material selection and manufacturing process. As a comparison, this is about the same finish as found on commercially available gear teeth.

Over the duration of a performance evaluation test, wear should not be a problem for a correctly selected combination of suitable materials. Although wear generally alters the surface topography and may result in surface damage, it also has a beneficial effect of reducing surface roughness by removing the peaks from asperities. Of the most common wear mechanisms, only adhesive and abrasive wear are discussed. Both are usually associated with sliding, which for this application may be considered minimal. For adhesion wear to occur, fragments of one material are detached from it and adhere to the other material. Abrasive wear will occur when the harder of the two materials slides into the softer material. This second process is highly dependent on the force applied to the material interface.

This is actually a measure of the interatomic bonding force, but in general engineering and metrology is more commonly associated with the linear relationship between stress and strain in materials. For many engineering alloys, the relationship that the yield strength equals 0.003 times the modulus of elasticity holds true. However, it should be noted that for alloy steels this is not always the case. Reference should be made to relevant handbooks for precise material specifications being used. One important use of the value of the modulus of elasticity is in the calculation of the elastic deformation. For many practical applications, for common engineering materials, this number is usually negligible.

This property is the ability of a material to resist plastic deformation and is usually considered the point that plastic deformation first takes place. For ferrous alloys, the yield point is very noticeable, but for other materials, including aluminum, there is no pronounced yield point. A question, of course, is if it was a global plastic deformation or a local plastic deformation due to a poor surface finish.

Many times in artifact design it is desirable to constrain the artifact with no more points of contact than one per degree of freedom that is to be constrained. Unfortunately, these point contacts may give rise to considerable stress levels in a very localized region. The resulting contact deformation can be a significant error in any subsequent measurements of the artifact. The term *Hertzian stress* is sometimes used to describe this contact stress/deformation phenomenon.

The formula shown below is a typical example for a spherical indentation on a flat surface, taken from a basic strength-of-materials textbook. While other factors are present, it gives a good approximation of the effects for many cases. Friction effects and form deviations will cause deviations from the Hertz equations.

The deformation can be approximated from Hertz's formula

$$\alpha_0 = \sqrt[3]{\frac{9P^2}{8D}\left(\frac{1-\nu_1{}^2}{E_1} + \frac{1-\nu_2{}^2}{E_2}\right)^2}$$

where

D = sphere diameter

E_i = modulus of elasticity

P = perpendicular measuring force

α_0 = depth of elastic compression

ν_i = Poisson's ratio

NONMANDATORY APPENDIX H DETERMINATION OF THERMAL ERROR INDEX

H-1 PURPOSE

The purpose of this Appendix is to introduce the user to the concept of the *thermal effect index (TEI)*, a means of assessing thermal influences on the AACMM performance tests and/or workpiece measurements. It is approximately the percent degradation of the performance test or measurement under consideration due to thermal effects. The thermal error index is composed of four parts: the nominal differential expansion (NDE) error, the uncertainty of nominal differential expansion (UNDE), the uncertainty due to temperature measurement (UTM), and the thermal variation error (ETVE). The methods used in this Appendix closely parallel those of the ISO Technical Report 16015, Geometric product specification (GPS) — Bias and uncertainty of dimensional measurements due to thermal influences, which is a modernization of ASME B89.6.2, Temperature and Humidity for Dimensional Measurement. The user is referred to these documents, along with the ISO Guide to the Expression of Uncertainty in Measurement (GUM), for a more thorough treatment of this and related subjects.

H-2 NDE, UNDE, UTM, AND ETVE

H-2.1 Nominal Differential Expansion Error (NDE)

All materials exhibit the property that they expand or contract when they undergo a change in temperature. This behavior is quantified by a parameter known as the coefficient of thermal expansion (COTE), which may be positive, negative, or very near zero. Typical values of COTE for some common engineering materials are listed in Table H-1. In a simple first-order model, the change in length of a body due to change in temperature is described by the equation

$$\Delta L = \alpha L \Delta T$$

where
- L = nominal length of the part
- T = ambient temperature during the test or measurement
- α = nominal material coefficient of thermal expansion
- ΔL = change in length
- ΔT = change in temperature ($T - 20$), °C

For measurement instruments, the thermal expansion manifests itself in two ways: the expansion of the workpiece and the expansion of the instruments' scale. The resultant of these two are known as differential thermal expansion or, when using a nominal value for the COTE, as the nominal differential expansion (NDE). This is calculated from the equation

$$\mathrm{NDE} = \alpha L_w - \alpha L_s = \alpha_w L_w \Delta T_w - \alpha_s L_s \Delta T_s$$

where
- s = subscript denoting scale
- w = subscript denoting workpiece

For the AACMM, the nominal length of the scale can be considered to be the length of the arm. If the AACMM has provisions for correcting for workpiece, scale, or both, then the corresponding values can be set to zero in the above equation. If the supplier does not provide an automated means to correct for the differential expansion between the AACMM and the workpiece, then this error must be calculated and included in the TEI.

Table H-1 Nominal Coefficient of Thermal Expansion for Various Materials

Material	COTE × 10^{-6}/°C	COTE × 10^{-6}/°F
Plain carbon steel	11.5	6.4
Stainless steel	17.0	9.4
Aluminum alloys	23.0	12.8
Carbon graphite	−0.9	−0.5
Plastics	80–200	44–110
Invar	1.0	0.6

H-2.2 Uncertainty of Nominal Differential Expansion (UNDE)

It is impossible to exactly know the coefficient of thermal expansion of either the AACMM or the artifact/workpiece under test. Consequently, any calculation of the differential thermal expansion will be in error. The UNDE attempts to account for this error by assigning an uncertainty to the nominal differential expansion calculation. For those cases where the COTE is not explicitly calibrated, the error in the COTE value is typically estimated to be $\pm 1.0 \times 10^{-6}/°C$ for both the scale and the workpiece. As this is assumed to be uniformly distributed, the standard uncertainty in the COTE then becomes

$$u(\alpha) = \frac{1 \times 10^{-6}/°\mathrm{C}}{\sqrt{3}} = 0.577/°\mathrm{C}$$

Using this, the length uncertainty due to uncertainty in the coefficient of thermal expansion can be calculated as

$$u_{\mathrm{NDE}}(L) = \sqrt{L_w^2 \cdot \Delta T_w^2 \cdot u^2(\alpha_w) + L_s^2 \cdot \Delta T_s^2 \cdot u^2(\alpha_s)}$$

For the case where $\Delta T_w = \Delta T_s = \Delta T$, this reduces to

$$u_{\mathrm{NDE}}(L) = \sqrt{\frac{(L_w^2 + L_s^2) \cdot \Delta T^2}{3}}$$

H-2.3 Uncertainty Due to Temperature Measurement (UTM)

Similar to the UNDE, this uncertainty source arises from the inability to measure the temperature of the AACMM and the workpiece without error. This again results in an error in the nominal differential expansion correction that depends on the accuracy of the thermometer. For calibrated thermometers, the standard uncertainty is calculated from the information given by the uncertainty of that calibration. For typical uncalibrated thermometers (e.g., thermistor, thermocouple),[1] an estimate of ±0.2°C (±0.4°F) can be used, resulting in a standard uncertainty for temperature measurement of

$$u(T) = \frac{0.2}{\sqrt{3}} = 0.12°\mathrm{C}$$

The uncertainty in temperature measurement can then be used to calculate the length uncertainty due to temperature measurement:

$$u_{\mathrm{TM}}(L) = \sqrt{\alpha_w^2 \cdot L_w^2 \cdot u^2(T_w) + \alpha_s^2 \cdot L_s^2 \cdot u^2(T_s)}$$

H-2.4 Environmental Temperature Variation Error (ETVE)

Environmental temperature variation error (ETVE) is determined by a drift test and is sometimes referred to by that name. Any drift test should be conducted for a period equal to the duration of the longest performance test/measurement task. 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.

H-2.4.1 ETVE Test: General. The procedure for measuring the ETVE of the AACMM requires monitoring the apparent drift of a fixed point in space. To accomplish this, a low thermal expansion artifact (e.g., invar, super invar, or steel with a known coefficient of thermal expansion) is used to generate a thermally stable point within the working volume of the machine at a distance of between 75% and 90% of the length of the arm. The thermal expansion coefficient of the artifact should be chosen such that the change in length of the artifact during the test, or the uncertainty in the change in the length, should be less than the single-point articulation test (SPAT) specification for the machine under test. This will be accomplished if

$$L\ \alpha\ \Delta T \leq \mathrm{SPAT}/2$$

where

L = length of the arm

α = thermal expansion coefficient of the artifact bar

ΔT = temperature deviation from 20°C that is expected during the test/measurement, °C

H-2.4.2 ETVE Test Methodology. The artifact is mounted between the AACMM base and the probe axis using a ball and magnetic trihedral socket arrangement. For more information on the construction of kinematic seats, see Appendix G. It does not matter whether the socket or the ball is substituted for the probe; however, if the socket is used to replace the probe, the artifact then becomes the familiar ball bar. If it is necessary to support the arm and/or artifact in order to perform this test, the artifact should be located in a horizontal plane at the height of the first machine axis. Additionally, the arm should be constrained only by its own weight and using the minimum number of contact points necessary in order to minimize external forces, both thermally induced and otherwise. The goal is to ensure that the metrology loop (i.e., the path through the structural components that can influence the measurement) is comprised entirely of the AACMM and the test artifact. While, for example, clamping the arm or test artifact in a fixture that is rigidly mounted to a surface plate might appear to be a good idea from a structural stability standpoint, what will actually be measured during the course of the test is the thermal drift of the arm, the artifact, the surface plate, and possibly the fixture.

Prior to conducting the ETVE test, the AACMM shall be maintained in the thermal environment under evaluation for a period of at least 8 hr (overnight is recommended) with the machine in its "resting" position. With the artifact securely positioned between the AACMM base and probe axis, measurements of the length of the bar are then conducted for a time period at least as long as the time required to conduct the longest performance test specified in this Standard. The test period shall be divided into intervals of approximately 1 min, during which three measurements of the bar length are made. In order to minimize the effect of nonrepeatability, the mean value of the three lengths for each interval shall be calculated and reported as a single value for that interval.

[1] This is a very conservative estimate of uncertainty for these types of temperature systems and does not reflect the level of uncertainty that could be achieved when these systems are properly calibrated.

H-2.4.3 ETVE Test Data Analysis. The range of variation of these mean length values shall be the ETVE. Unless otherwise stated, the ETVE will be assumed to be an uncertainty source that is uniformly distributed and of full width given by the range of value of the drift test, i.e., the ETVE. The resulting uncertainty in length measurement due to environmental temperature variation error is then:

$$u_{\text{ETVE}}(L) = \frac{\text{ETVE}}{2\sqrt{3}}$$

H-2.5 Calculation of TEI

In accordance with the Guide to the Expression of Uncertainty in Measurement, the above uncertainty sources (UNDE, UTM, and ETVE) can be combined in a root-sum-squares fashion to provide an estimate of the standard uncertainty of a length measurement due to thermal effects:

$$u_T(L) = \sqrt{u^2_{\text{ETVE}}(L) + u^2_{\text{TM}}(L) + u^2_{\text{NDE}}(L)}$$

This standard uncertainty can then be combined with the bias term (NDE), if applicable, to give the thermal error index. This represents the maximum thermal error contribution to a length measurement as a percentage of the desired artifact or workpiece tolerance (TOL). The TEI is given by the equation

$$\text{TEI} = 2\left[\frac{|\text{NDE}| + 2u_T(L)}{\text{TOL}}\right] \times 100\%$$

or in its complete form

$$\text{TEI} = 2\left[\frac{|\text{NDE}| + 2\sqrt{\frac{\text{ETVE}^2}{12} + L_w^2 \cdot \Delta T_w^2 \cdot u^2(\alpha_w) + L_s^2 \cdot \Delta T_s^2 \cdot u^2(\alpha_s) + \alpha_w^2 \cdot L_w^2 \cdot u^2(T_w) + \alpha_s^2 \cdot L_s^2 \cdot u^2(T_s)}}{\text{TOL}}\right] \times 100\%$$

The above formulation(s) of the thermal error index assumes a coverage factor of $k = 2$ for the thermal uncertainty term. Substituting the combined standard uncertainty of the length measurement for the artifact/workpiece tolerance gives an estimate of the uncertainty attributable to thermal effects.

NONMANDATORY APPENDIX I
STATISTICS USED IN SPECIFYING AACMM PERFORMANCE EVALUATION

I-1 PURPOSE

This Standard employs a variety of statistics to describe the performance of AACMMs. Typically these are the maximum deviation from a reference value (which is the calibrated value of an artifact if one is available), the range of deviations from a reference value, twice the root-mean-sum-of-squares (2 RMS) of the deviations, and, in the case of the single-point articulation test, twice the standard deviation of the point location. The rationale for the use of these statistics is described below.

I-2 EFFECTIVE DIAMETER TEST

This test is primarily concerned with detecting errors in the AACMM probe tip size. This is an important parameter, as an incorrect probe tip size will be transferred into all measured features of size, e.g., the diameter of a bore. The test uses a calibrated test sphere that is measured three times in accordance with para. 5.2 and the largest deviation (error) from the calibrated diameter is reported. The maximum deviation statistic is employed because

(*a*) it is the diameter error (not the range of errors) that concerns users, since it is this error that transfers additively into all features of size

(*b*) the probe tip size error is typically due to a systematic effect, e.g., a poorly calibrated artifact supplied with the AACMM, hence a systematic effect is best (and most clearly) reported as a diameter error and

(*c*) given the significance of this error, reporting the maximum error is prudent

I-3 SINGLE-POINT ARTICULATION PERFORMANCE TEST

The SPAT seeks to measure the variability in measuring a single physical point in space. Since a point in space does not have an associated calibrated value, the average point coordinates are taken to provide a reference location. The physical quantity of interest to the user is the distance [given by Eq. (1)] of each data point from the reference location. This represents how far away the measured point coordinate might be from the mean point coordinate.

Paragraph 5.3 reports two statistics about the magnitude of the point coordinate errors as measured by distances from the reference location. The maximum deviation represents the largest distance away from mean point coordinates that should occur with a well-functioning AACMM. This statistic has a simple physical interpretation, a simple calculation, and places an upper bound on the distance deviation one might expect from an AACMM.

The second statistic, $2s_{SPAT}$, is a measure of the variation of the ten point locations measured in accordance with para. 5.3.

This statistic is derived as follows. Compute the standard deviation of each point coordinate; for example, the X coordinate standard deviation, s_x, is given by

$$s_x = \sqrt{\frac{\sum_{i=1}^{n}(X_i - X_a)^2}{n-1}}$$

where X_a is the average X coordinate, and similarly for s_y and s_z.

Create the statistic s_{SPAT} from

$$s_{SPAT} = \sqrt{s_x^2 + s_y^2 + s_z^2}$$

which represents the radius of a spherical region, centered at the average point coordinate, in which the measured point coordinates are likely to be found (s_{SPAT} is the standard deviation of the point coordinate vector). Using the definition of s_x (from above) and δ_i [from Eq. (1)], we get

$$s_{SPAT} = \sqrt{\frac{\sum_{i=1}^{n}\delta_i^2}{n-1}}$$

which is equivalent to Eq. (2).

Twice the standard deviation of the point locations is reported ($2s_{SPAT}$), as is customary with the ISO Guide to the Expression of Uncertainty in Measurement (GUM), to provide a value that contains most (typically 95%) of the distance variation of a point location from its average value. The $2s_{SPAT}$ statistic is more robust than the maximum deviation, since it includes all the data and is not solely determined by one extreme value. Furthermore, the $2s_{SPAT}$ statistic is useful when performing an uncertainty evaluation, as it represents a Type A uncertainty contributor that is in a form that is utilized by the GUM.

I-4 VOLUMETRIC PERFORMANCE TEST

The volumetric performance test seeks to report information about the AACMM length measuring error between two points in space. Since we are detecting length errors, a calibrated length is required, typically the center-to-center distance of a ball bar. This test reports three statistics: the maximum length error, the range of length errors, and twice the RMS of the length errors.

The maximum length error is reported, as it has a simple physical interpretation, a simple calculation, and places an upper bound on the magnitude of the length error one might expect from an AACMM. Additionally, this statistic is similar to the performance value employed by the international standard on CMM performance evaluation (ISO 10360-2, GPS — Acceptance and reverification tests for coordinate measuring machines — Part 2 CMMs used for measuring size) and allows some comparison with CMMs specified to that standard.

The range of length errors is reported for comparison with ASME B89.4.1b-2001, Methods for Performance Evaluation of Coordinate Measuring Machines, volumetric performance specification for Cartesian CMMs.

Twice the RMS of the length measuring errors is also reported for the 20 length positions and orientations. This test uses a calibrated artifact and hence measurement errors are determined; thus the errors for both the short and long ball bar can be combined in this statistic. Since the artifacts are calibrated, we do not consume one degree of freedom in computing the mean error, but rather compute the RSS value about the true value, taken as the calibrated value of the artifact. Consequently, the denominator of the RSS calculation has the value of n (instead of $n - 1$) to reflect the fact we are using the calibrated, not mean, value.

Twice the RMS is reported, as is customary with the GUM (referenced above), to provide a value that contains most (typically 95%) of the length errors of the artifacts as measured using this test procedure. The RMS statistic is more robust than the maximum deviation, since it includes all the data and is not solely determined by one extreme value. Furthermore, the RMS statistic is useful when performing an uncertainty evaluation, as it represents a Type A uncertainty contributor that is in a form that is utilized by the GUM.

NONMANDATORY APPENDIX J
APPLICATION OF DECISION RULES

J-1 GENERAL

Most standards define a minimum set of performance tests with associated methods for data analysis and reduction. However, to optimize the benefits of standardization, a decision rule must also be applied to the testing results. For example, the decision rule applied to an articulated arm coordinate measuring machine may not be the same as used for a gage block or micrometer, but should be the same for all articulated arm coordinate measuring machines.

ISO 14253-1:1998, Geometrical Product Specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 1: Decision rules for proving conformance or non-conformance with specifications, defines the "default rule" as subtracting the expanded uncertainty from the specification limits. This is an easy rule to understand and apply, but can have a significant negative economic impact. As a result, ASME B89 standards have adopted the general statement, "B89 standards that adopt standards referencing ISO 14253-1 as a normative standard shall explicitly state a different default decision rule, where the 4:1 simple acceptance and rejection rule from B89.7.3.1 shall be the default rule unless a different rule is specified." Simple acceptance and rejection are defined in para. 4.1 of ASME B89.7.3.1-2001, Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications.

J-2 REQUIREMENTS FOR DECISION RULES

For AACMMs that are tested using the procedures described in this Standard, the simple 4:1 acceptance and rejection rule implies the following:

The acceptance zone includes all test results up to and including the manufacturer's specification value stated in Fig. 3 and the rejection zone is any value outside the acceptance zone.

The 4:1 ratio of uncertainty in the test result (due to the testing equipment) relative to the specification must conform to para. J-4.

Issues associated with the rejection of measurement values that comprise the performance tests and issues associated with repeated performance tests must conform to the relevant sections of paras. 5.2.3 and 5.4.3 in the Standard and to para. J-3 of this Appendix.

If all performance test results lie in their acceptance zones, the AACMM is considered acceptable with regard to the performance specifications. If any test result lies in a rejection zone, the AACMM is considered to be out of specification and may be rejected. (A rejected AACMM may be retested after appropriate adjustment by the manufacturer; however, the entire set of performance tests must be performed upon retesting.)

J-3 FURTHER DISCUSSIONS ON REPEATED MEASUREMENTS

In general, most performance tests will be conducted only once. If the output result is considerably outside the specified maximum permissible error, the decision that the supplier adjust the AACMM is clearly the most viable option, after which the entire set of tests will be repeated. Difficulties arise when the output results are only marginally outside of the specification limits. If the test result lies in the rejection zone by no more than 25% of the specification value, then the test may be repeated. The arithmetic mean of the two test results shall be taken as the test result.

J-4 TEST UNCERTAINTY EVALUATION ISSUES

When the simple acceptance decision rule is used, the issue of evaluating uncertainty components needs to be addressed. For the purposes of this Standard, the uncertainty under consideration includes all sources associated with the testing equipment under the conditions that prevail at the time of testing. It is the test uncertainty that must be one-fourth the specification. Since a test may involve multiple measurements, the uncertainty of the test may be different from the uncertainty of the individual measurements involved in the test. The reproducibility of the test value is not one of the uncertainty sources of test uncertainty; the test value, including its reproducibility, is controlled by the stated test specification value.

J-4.1 Single-Point Articulation Performance Test

The only test uncertainty associated with this equipment is the rigidity of the artifact and its geometrical perfection. Typically, these uncertainties will be negligible relative to the SPAT specification values. However, if it is desired to evaluate the test uncertainty, proceed as follows: Place a precision indicator, having an uncertainty no larger than one-tenth the specification value against the kinematic seat (or sphere). Insert the AACMM probe into the seat (or against the sphere). Using a typical AACMM probing force, probe toward and away from the indicator and record the deflection, including its sign, for each of the two probing directions, i.e., both positive and negative deflections. Repeat this for a total of five different probing directions, yielding a total of ten readings; this should include three directions that are approximately mutually orthogonal. Analyze the ten readings in a manner identical to the data analysis for the performance test to obtain the uncertainty associated with the rigidity of the kinematic seat (or sphere). That is, the maximum deflection observed is the test uncertainty associated with $\delta_{\max}$, and twice the standard deviation of the deflections is the test uncertainty associated with $2s_{SPAT}$.

The preceding analysis assumes that the contribution of a geometrically imperfect seat (or sphere) is negligible. This is usually a good assumption, as the form error of a seat or sphere is typically a factor of 50 less than the performance specification. If the geometry of the kinematic seat is not negligible, then this uncertainty contribution needs to be combined (in an RSS manner) with that due to the rigidity issue. If F is the (peak to valley) form error of the test sphere, or the maximum range that a perfect sphere can move in the kinematic seat, then the test uncertainty associated with $\delta_{\max}$ is $0.5F$ and with $2s_{SPAT}$ is $0.58F$.

J-4.2 Effective Diameter Test Uncertainty

The uncertainty sources that contribute to this test uncertainty include the uncertainty in the calibrated diameter of the sphere (as stated on its calibration certificate), the size uncertainty in the sphere diameter due to the uncertainty in the CTE and the temperature prevailing at the time of testing (this is usually a small contributor), and the uncertainty associated with the lack of rigidity of the test sphere mount. (It is assumed that the effect of the sphere's form error on its diameter has already been included in the uncertainty associated with the sphere diameter calibration.) The standard uncertainty associated with the rigidity of the mounting is identical to the uncertainty associated with $\delta_{\max}$ found in the single-point articulation performance test and can be evaluated in the same manner.

Since these uncertainty sources can be considered uncorrelated, the test uncertainty is

$$U = 2\sqrt{u^2_{\text{artifact Cal}} + u^2_{\text{CTE}} + u^2_{\text{fixturing}}}$$

J-4.3 Volumetric Performance Test Uncertainty

J-4.3.1 Uncertainty of a Single Length Measurement. The uncertainty of a length measurement will include the uncertainty of the calibrated artifact as stated on the calibration certificate, the length uncertainty resulting from the uncertainty of the coefficient of thermal expansion at the temperature that prevails at the testing time, and the added uncertainty due to the fixturing. This last source can be minimized by using the best practices as discussed in Appendix F.

Assuming that all of the input quantities are uncorrelated with sensitivity coefficients equal to unity, then the expanded uncertainty for a single length measurement performed with the testing equipment can be found from

$$U = 2\sqrt{u^2_{\text{artifact Cal}} + u^2_{\text{CTE}} + u^2_{\text{fixturing}}}$$

where the internationally accepted default coverage factor of 2 is used.

J-4.3.2 Volumetric Test Uncertainty. For this test, the data is gathered using short and long calibrated ball bars. In general, although not always, the uncertainty is length dependent, i.e., typically the uncertainty in the calibrated length of the short ball bar will be less than the uncertainty in the calibrated length of the long ball bar. Since the volumetric performance test involves two calibrated lengths, the test uncertainty involves both of these uncertainty sources. However, since this Standard uses simple acceptance and rejection as the decision rule, and consequently the magnitude of the test uncertainty does not affect the size of the acceptance zone (as it does using the default rule of ISO 14253-1), it is usually sufficient to determine the volumetric test uncertainty based on the uncertainty of the larger of the two lengths, as given below.

Compute the uncertainty of a single measurement as described in para. J-4.3.1 for both length standards and select the larger of the two; denote this value as U. (Usually this will be expanded uncertainty of the longer of the two length standards.)

For the volumetric performance test, the following uncertainties are associated with the performance values:

Performance Parameter	Expanded Test Uncertainty
Maximum deviation	U
Range of deviations	$2U$
2 RMS of deviations	$2U$

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ASME B89.4.22-2004

ISBN 0-7918-2940-5

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L08004