METHODS FOR PERFORMANCE EVALUATION OF SINGLE AXIS POSITIONING SYSTEMS: A NEW STANDARD

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INTRODUCTION

Many new high-precision linear and angular positioning systems with exceptionally long ranges of motion on the order of tens of millimeters and degrees with positioning resolutions on the order of a nanometer and a micro-radian, respectively, are finding their way into emerging global micro- and nanotechnology applications. Application areas include photovoltaic manufacturing, semiconductor manufacturing, life sciences, and telecommunications, which are four of many examples existing in a very broad positioning system industry. Some systems are designed and manufactured for specific applications while many others are modular in design to provide customers with the flexibility to integrate positioning systems with existing industrial applications and equipment.

Accurate knowledge of positioning performance is critical when selecting the appropriate positioning system(s) for an application. However, a dedicated standard for evaluating and certifying the performance of single axis positioning systems does not currently exist. Additionally, measuring and certifying the performance of high-precision systems with off-the-shelf instrumentation and test methods suggested by existing standards can be very challenging, specifically because the positioning performance of this class of positioning system is approaching the uncertainty of the measuring devices [1, 2]. Similarly, commonly used measurement methodologies and terminologies do not always account for or accurately represent error sources and uncertainties that contribute to positioning system performance as requirements become more precise. Many manufacturers and users of these systems are recognizing this challenge and have begun to develop their own internal methods and standards for characterizing these systems. Performance specifications based on these diverse and independent methods is leading to customer confusion and ambiguity. Members of industry (manufacturers and consumers), academia, and government have recognized this challenge and the need for a new standard for measurement methods that specifically address single axis positioning systems.

Performance standards provide a common infrastructure that improves communication, efficiency, innovation, and interoperability through the standardization of terminology, measurement methods, analyses, and data formats. The benefits of performance standards have been demonstrated over the past several decades by the advancements in the performance of computer numerically controlled (CNC) machine tools. Performance tests described by existing machine tool standards [3-5] have been used to characterize the performance of single axis positioning systems with success and limitations.

Recently, a group of volunteers from industry,

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academia, and government re-evaluated and thoroughly discussed the use of machine tool standards for characterizing single axis positioning systems having high-precision positioning performance. The group concluded that there is a need for a new standard that addresses the performance evaluation of single axis positioning systems. In addition to addressing static/quasi-static positioning performance, a new standard should also address dynamic positioning performance, test uncertainty, and the instrumentation and techniques required for low uncertainty measurements. With this in mind, a draft scope and outline for a new standard was generated and the American Society of Mechanical Engineers (ASME) B5 Technical Committee TC52 was chosen as the Standards Developing Organization [6].

In this abstract, we discuss factors affecting the accurate characterization and communication of positioning system performance. The scope for this new standard is presented and the new test methods being considered for inclusion in the standard are briefly described.

POSITIONING PERFORMANCE

There are many factors that contribute to the accurate characterization and communication of positioning system performance. Many users are not aware nor understand the importance of the contributors and select systems based on specifications (e.g., positioning resolution) that do not completely or accurately describe positioning performance. One goal for this standard is to emphasize and clearly describe these contributors and enhance communication.

Measurement Points and Coordinate System Location

Linear errors of positioning systems (e.g., linear positioning and straightness) are normally characterized by measuring the trajectory of a measured point (MP) that is rigidly attached to the moving element (e.g., linear axis carriage) of a positioning system, as seen in Figure 1. Furthermore, linear errors are affected by the angular error motions of a positioning system and thus, have different magnitudes along different point trajectories. The differences in magnitude are related by the offset distance (d) between points (Abbé Offset) and the angular error motions of the positioning system. These concepts are known as the *Abbé* and *Bryan Principles* [7].

Theoretically, the measured point can be located anywhere around the positioning system. To better understand the effects of the errors on the intended application, the measured point should, ideally, coincide with the functional point (FP) of the application [5], as seen in Figure 1. Unfortunately, spatial constraints may limit the ability to measure linear errors at the functional point and the reported errors may not truly represent the magnitudes of the errors affecting the application. However, if the location of the measured point with respect to the axis coordinate system is known (i.e., well documented). then the linear errors can be transformed to estimate the magnitude of the errors at any functional point in the work volume.

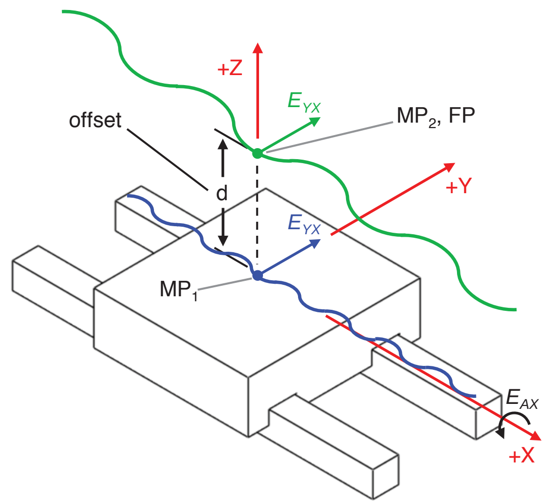

FIGURE 1. A schematic illustrating different straightness errors, E_{YX}, along different measurement points.

In current practices, the location of the measured point is usually not well documented or published and the methods for describing the location of the measured point are inconsistent between manufacturers, users, and metrologists. This makes it a challenge to perform direct comparisons of positioning system performance based on published performance data. Additionally, the locations of the axis coordinate systems vary between the various positioning systems available and the locations are usually vaguely described. Direct performance comparisons and error transformations can benefit from a well-defined and accurate method for describing the location and orientation of the axis coordinate frame and measured point.

To emphasize these principles and to enhance communication, the standard being developed will provide a method for identifying and describing the location and orientation of a positioning system's coordinate frame and the position of the measured point with respect to the coordinate frame. In addition, a guideline for estimating the error at different functional points by performing error transformations will be provided as an appendix. Standard nomenclature for representing the error motions of a positioning system will also be provided.

Static/Quasi-Static Performance

Many robust test methods for characterizing static/quasi-static positioning performance (e.g., linear positioning, straightness, and angular deviation) are well defined by existing machine tool standards [3-5] and have been thoroughly tested and implemented by industry. This standard will reference and describe many of these methods with appropriate examples and suggestions for implementation on single axis positioning systems. Both unloaded and loaded conditions will be considered, as well as rigid body and non-rigid body assumptions. In addition to existing methods, two new test methods for characterizing incremental positioning performance [8] and point repeatability [9] are also being considered for inclusion in this standard.

Dynamic Performance

During static/quasi-static conditions, the positioning errors are nominally the result of the geometric errors of the positioning system. During dynamic conditions, positioning errors are additionally affected by the forces and moments inherent in the dynamic system, e.g., drive forces occurring during acceleration and deceleration [10]. As a result, positioning errors can change and lower modes of vibration of the positioning system can be excited during static to dynamic transitions. Standard methods for characterizing the dynamic positioning performance do not currently exist. This standard seeks to establish a set of methods that can be used to characterize dynamic positioning error, dynamic straightness error, and dynamic angular deviation. In addition to these dynamic tests, this standard will also seek to develop standard methods for measuring the characteristics of the positioning system's servo control, e.g., dynamic response, settling times, etc.

Test Uncertainty and Test Uncertainty Ratio

Many users of high performing positioning systems (e.g., nano-positioners) are unaware of the challenge to accurately characterize their performance [11]. At a minimum, accurate characterization is limited by the uncertainty of the instrumentation and/or artifact(s) used during measurement. However, other influences associated with the test method affect the overall measurement uncertainty and the uncertainty of the calculated performance parameters. Examples include, but are not limited to, the influence of the metrologist, the test procedure, placement and alignment of the test equipment, the repeatability of setting up the test equipment, and the compensation of environmental effects on the measurement.

A measure of the quality of the test, taking into account all the influences, is known as *Test Uncertainty* [12]. An additional measure used to assess the ability of a particular test to evaluate a particular performance parameter is known as the *Test Uncertainty Ratio* (TUR) [12], which is the ratio of the specified performance parameter to test uncertainty. Historically, the general rule for an appropriate ratio was 10:1, but because of higher performing equipment, the current TUR suggested by ANSI Z540.3 is 4:1 [13]. Measuring and certifying the positioning performance of current nanopositioners with off-the-shelf instrumentation suggested by existing performance standards can be very challenging if the TUR is to be greater or equal to 4:1. In some instances the ratio is closer to 1:1 [2]. For this reason, it is important that this standard appropriately and clearly addresses test uncertainty and the TUR.

One goal for this standard is to provide a general guideline for formulating the test uncertainty for positioning performance measurements. This guideline will be similar to the guideline described by ISO 230-9 [14] and will be an essential tool for evaluating test setups and identifying areas of improvement. Examples of test uncertainty calculations for many of the test methods included in the standard will be provided, as well as a list of associated measurement technologies, uncertainty contributors, and limitations. Where necessary, uncertainty analyses for evaluating associated measuring technologies will be described, contributors to the measurement uncertainty listed, and uncertainty limits declared. When possible, existing guidelines for estimating measurement uncertainty (e.g., ASME B89.1.8-2011 [15]) will be referenced. Most importantly, the expectation is that the provided set of uncertainty tools will make the consumer/user aware of the level of uncertainty and setup scrutiny necessary to characterize precision positioning performance.

Environmental Conditions and Testing

Environmental conditions can affect the positioning systems' performance and the measuring instruments and setups used to characterize positioning system performance, especially as positioning performance specifications become tighter and approach the uncertainties of evaluation methods. Unfortunately, these effects are often misunderstood and contribute to uncertainty in the measurement. This standard will provide a set of guidelines for specifying acceptable environments for performance testing and for high-precision positioning system operation. Standard test methods for characterizing the environment and the thermal characteristics of positioning systems will also be provided. Additionally, methods for characterizing the uncertainty in environmental measurements and a list of the uncertainty limits due to traceability will be included.

Recording and Reporting Performance

When users of positioning systems go through the process of selecting off-the-shelf positioning systems for their application, they, in part, rely on published performance data for making decisions. Published data, however, may not truly represent the performance of the positioning system in the way in which it is intended to be used. Additionally, comparing the performance of similar positioning systems produced by different manufacturers can be challenging due to inconsistencies in the performance information published. Thorough and direct comparisons can be better achieved if a minimum set of test metadata, error results, and error parameters are provided. This data may then be used to predict the performance for a specific application. To help eliminate this challenge, this standard will provide suggested methods for reporting the performance determined by the standard test methods. The method of reporting will identify a minimum set of measurement parameters and encourage use of common units.

Performance data can have many purposes. It may be used for error compensation, vendor specification, customer acceptance, interim evaluation of the condition of a system, estimating performance at different functional points, and for simulating its effects on the performance of a larger machine [16] consisting of a collection of multiple positioning systems. Accurate implementation of data can be enhanced by standard electronic data formats and information models designed to facilitate the collection, archiving, and exchange of measurement and machine performance data [17, 18]. ASME B5.59-1 [17] and ASME B5.59-2 [18] provide such formats for machine tools. It is envisioned that this standard will support the format described by ASME B5.59 by providing additional elements used to describe the properties of single axis positioning systems and performance tests. These elements may be provided in an appendix and may include, but may not be limited to, the location and orientation of coordinate systems, the position of measurement points, the parameters used to describe motion/velocity profiles, and the contributors to test uncertainty.

STANDARD SCOPE

The planned scope for this new single axis positioning performance standard is as follows.

1) The standard will establish a methodology for specifying and testing the performance of precision positioning systems. It will address both single axis linear and angular (rotary) positioning systems with travels ranging from micrometers to meters and millidegrees to continuous rotation, respectively.

2) The standard will seek to highlight the importance of understanding measurement uncertainty, test uncertainty, and the test uncertainty ratio by providing methods for estimating the test uncertainty and the uncertainty of positioning performance parameters.

3) The standard will describe equivalent test methods and instrumentation described in existing machine tool standards [3-5] and additional methods and instrumentation used for the characterization of positioning systems having a relatively high positioning performance when compared to standard machine tool performance.

4) The standard will facilitate performance comparisons between systems by unifying terminology, general system classification, the treatment of environmental effects, the treatment of measurement uncertainty, and the treatment of performance data.

5) The intended use of the tests described by this standard will be for acceptance testing of new and reconditioned positioning systems and verifying continued capability of systems, already in operation, through periodic testing.

NEW TEST METHODS

In addition to describing equivalent test methods described in existing machine tool standards, this standard will also include additional tests for both static and dynamic conditions. Some of the additional tests being considered for inclusion are:

a) *Incremental Step Test*. A test that quantifies the ability of a positioning system to reliably perform a commanded step. The test will also provide a procedure to quantify *minimum incremental motion* (mechanical resolution) that a positioning system is capable of performing [8].

b) *Three Dimensional Point Repeatability*. A test that characterizes a positioning system's ability to repeatedly return to a defined target position(s) in three-dimensional space [9].

c) *Dynamic Positional Accuracy, Straightness [19], and Angular Deviation*. A series of tests designed to characterize the positional accuracy, straightness, and angular deviation of a linear axis for specified motion/velocity profiles.

d) *In-position Jitter*. A test that quantifies the motion of an axis at a functional point while no commanded motion is occurring [8].

e) *Move and Settle*. A test designed to quantify the time required for a servo-controlled axis to move a particular distance and settle to a predefined position error tolerance [20].

f) *Servo Characterization*. A test that uses frequency response techniques to quantify the performance and stability of closed-loop feedback control [21].

COMMENTS

An effort to draft a new standard for the performance evaluation of single axis positioning systems has been introduced and is under way. Members of the working group are actively working to evaluate the robustness of the new standard test methods by measuring the performance of various types of single axis positioning systems. It is expected that this standard will provide the foundation for an additional standard for the performance evaluation of multi-axis positioning systems.

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