METHODS FOR PERFORMANCE EVALUATION OF SINGLE AXIS POSITIONING SYSTEMS: INCREMENTAL STEP TEST

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INTRODUCTION

Many new ultra-precision linear and angular positioning systems are finding their way into emerging technologies. Applications such as semiconductor wafer inspection, laser micromachining, medical device fabrication, and micro assembly all are requiring tighter tolerances and improved positioning performance over previous generations of tools and processes. Measuring and certifying the performance of these types of systems with existing test methods, instrumentation, and standards is challenging at best [1, 2].

Many of these applications rely on a linear or rotary positioning axis to make small incremental moves to perform a task in a process. Currently, no standard test method exists that defines pass/fail criteria for determining the ability of the positioning system to perform these small commanded motions. Furthermore, no standard tests exist that helps quantify the smallest (or minimum) incremental move that a positioning axis is capable of performing. ASME B5.54-2005 outlines a *Least Increment Test* where small steps are performed to illustrate a machine tool's ability to make small incremental moves [3]. However, a quantitative treatment of what constitutes the smallest positioning increment is lacking.

As a result, many suppliers and users of positioning systems have developed their own internal methods and standards for characterizing the smallest increment of movement. In order to address the widespread use of "internal test methods" and "vendor-specific test methods and vocabulary", an effort is underway by members of government, industry, and academia to develop a new positioning standard [4].

This paper will discuss one test that is being proposed as part of this new standards effort – the *Incremental Step Test*. In addition, a proposed procedure for measuring and calculating the *Minimum Incremental Motion* performance parameter or smallest increment that a positioning axis is capable of achieving is also described.

INCREMENTAL STEP TEST

The proposed *Incremental Step Test* is designed to characterize a single axis positioning system's ability to reliably perform a commanded step. The step size is normally relatively small (e.g., 10 nm) and usually reflects the requirements of the precision application in which the axis is intended to be used. During the test, the axis is commanded to perform a series of either unidirectional or bidirectional steps. Based on a given set of criteria (described herein), the axis either passes or fails the test.

General Measurement Setup

An example measurement setup for a linear positioning axis is shown in Figure 1. In this setup, a fixed linear displacement sensor is used to measure the displacement of a target that is rigidly attached to the moving element of the positioning system. The measurement point, ideally, should occur at a point that corresponds to the functional point [5] or location of work of the intended application. The displacement sensor (e.g., laser interferometer, capacitance sensor, etc.) should be chosen to have adequate resolution, accuracy/linearity, and bandwidth to measure the expected displacements with a low measurement uncertainty. Measurement fixturing should be designed to have a natural frequency (lowest mode) higher than the desired measurement bandwidth.

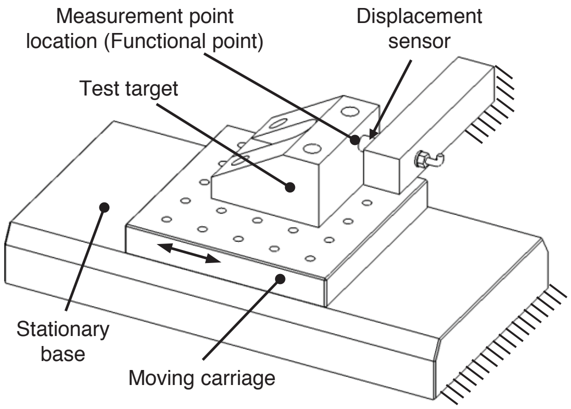

FIGURE 1. Example measurement setup for a linear axis step test showing the measurement of displacement at the functional point.

Incremental Step Test Procedure

As a default, the positioning axis is commanded to perform a minimum of ten positive (forward) and then ten negative (reverse) steps with a constant dwell period at each step. Additional steps may be commanded if deemed necessary to better reflect the end application. Measurements should be performed at a minimum of three locations within the travel range of the positioning axis (e.g., the two extremes of travel and the middle of travel for a linear positioning axis). An example displacement versus time plot for an *Incremental Step Test* performed on a linear positioning axis with a 2.5 nm commanded step size is shown in Figure 2.

Incremental Step Test Analysis

Quantitative step analysis uses performance parameters and variables determined from additional performance tests being developed as part of this standard development effort. These tests include the *In-position Jitter Test* and the *Move and Settle Test* [6]. For the purposes of this paper, these tests and parameters will be briefly described to help aid in the explanation of Incremental Step performance.

In-position Jitter

The proposed definition of *In-position Jitter* is the amount of motion, measured at the functional point, of a positioning axis when no motion is commanded to the axis. The ability of a positioning axis to perform steps that are smaller than the axis *jitter* is of little value to most applications. As a result, the *In-position Jitter* of a positioning axis under servo control must be considered when quantifying the small-step capability. The measurement is performed in the direction of travel while under servo control and employs the same measurement setup as the incremental step test (see Figure 1).

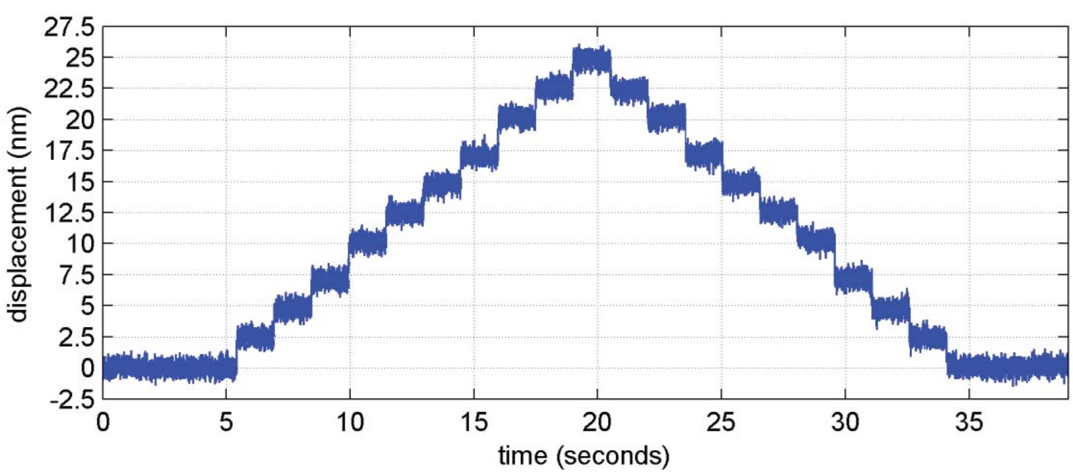

Figure 2. Example time verses displacement plot for an Incremental Step Test performed on a direct-drive linear positioning axis with a 2.5 nm commanded step size.

An example of the results obtained for an *In-position Jitter* measurement of a direct-drive linear stage is shown in Figure 3. The top plot shows the displacement versus time and the bottom shows the cumulative root-mean-square (RMS) value versus frequency of the measured data. In this example, the cumulative RMS value increases rapidly near 500 Hz due to a mechanical resonance present in the positioning axis.

In-position Jitter is reported as a standard deviation, s_{InPos}, over a given time period and measurement bandwidth. The selection of the measurement bandwidth is critical to ensure that the desired dynamics of the positioning axis are adequately captured in the measurement. Also, most measurement and feedback sensor noise increase with increasing measurement bandwidth. Therefore, it is necessary to use only as high as a bandwidth as necessary to capture critical application-specific process dynamics and to keep sensor noise to a minimum.

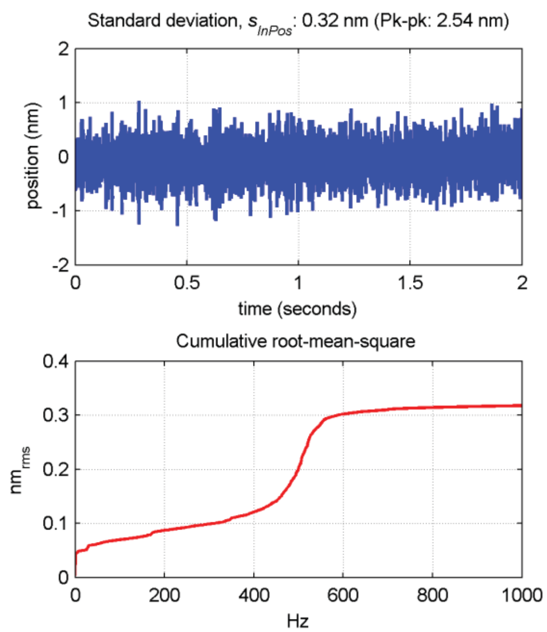

FIGURE 3. Example In-position jitter measurement results for a direct-drive, linear positioning axis.

Because applications can be vastly different, we propose that no single default measurement bandwidth be defined as part of this standard. Instead, it is recommended that the user of the positioning equipment determine and specify a measurement bandwidth based on the sensitivity of the application to motion over a specified spectral range. If the application is unknown or not specified, a measurement bandwidth that adequately captures the dynamics of the stage under test should be used. Such information should be provided by the manufacturer.

In addition, we recommend that the same measurement bandwidth be used for both the *Incremental Step Test* and the *In-position Jitter Test*. The exact details for how the *In-position Jitter* results are used in determining the step capability is defined later in this paper.

Move and Settle Variables

Two temporal variables, the move-and-settle time, t_{ms}, and the average time, t_{ave}, must be defined in order to perform data analysis. The move-and-settle time, t_{ms}, is the amount of time the positioning axis takes to make the commanded step and settle to within a predefined window. Definition of standard move and settle test criteria is currently underway as part of this standards effort [5]. Work performed as part of that effort will be used to define t_{ms}.

An illustration of these two test variables is shown in Figure 4. In order to obtain adequate data at each incremental step, the average time, t_{ave}, shall be at least two times larger than the move-and-settle time, t_{ms}.

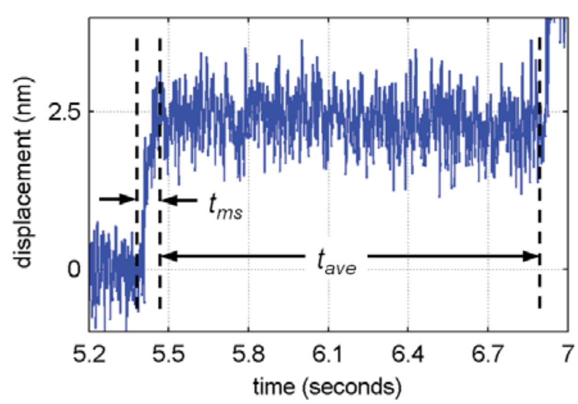

Figure 4. Illustration of the move-and-settle time, t_{ms}, and the average time, t_{ave}.

Incremental Step Test Calculations

In order to analyze the measurement data obtained from the *Incremental Step Test*, a few variables first need to be defined.

The incremental step size, $X_{inc,i}$, is defined as follows:

$$X_{inc,i} = \bar{X}_i - \bar{X}_{i-1} \quad (1)$$

where

$\bar{X}_i$ = mean step position of the i^{th} step, $\bar{X}_{i-1}$ = mean step position of the *(i-1)*th step.

The mean step positions are obtained by averaging the data over time period, t_{ave}. The sample mean, $\bar{X}_{inc}$, and sample standard deviation, s_{inc}, of the incremental step sizes are calculated for the forward (↑) and reverse (↓) directions as follows:

$$\bar{X}_{inc} \uparrow = \frac{1}{N}\sum_1^N X_{inc,i} \uparrow \quad (2)$$

$$\bar{X}_{inc} \downarrow = \frac{1}{N}\sum_1^N X_{inc,i} \downarrow \quad (3)$$

$$s_{inc} \uparrow = \sqrt{\frac{1}{N-1}\sum_1^N \left(X_{inc,i} \uparrow - \bar{X}_{inc} \uparrow\right)^2} \quad (4)$$

$$s_{inc} \downarrow = \sqrt{\frac{1}{N-1}\sum_1^N \left(X_{inc,i} \downarrow - \bar{X}_{inc} \downarrow\right)^2} \quad (5)$$

where

N = number of steps performed in each direction = 10 as default

The sample mean and sample standard deviation of the combined forward and reverse steps are calculated as follows:

$$\bar{X}_{inc} = \frac{1}{N_T}\sum_1^{N_T} X_{inc,i} \quad (6)$$

$$s_{inc} = \sqrt{\frac{1}{N_T-1}\sum_1^{N_T} \left(X_{inc,i} - \bar{X}_{inc}\right)^2} \quad (7)$$

where

N_T = total number of steps performed in the test, $N_T = N \uparrow + N \downarrow$

The calculated incremental step sizes, X_{inc}, for the 2.5 nm Incremental Step Test data example (shown in Figure 3) are shown in Figure 5. Other variables used in the analysis for the 2.5 nm step example are shown in Table 1.

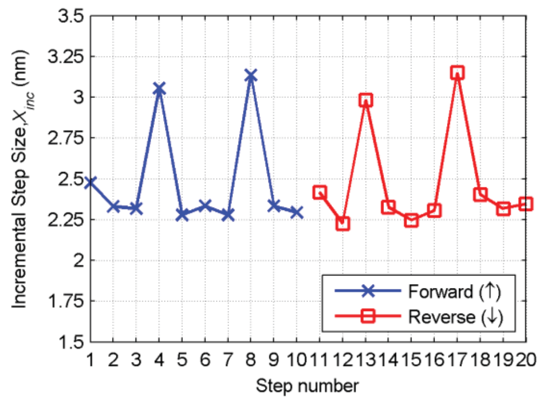

Figure 5. Incremental step sizes, $\boldsymbol{X_{inc}}$*, calculated from the 2.5 nm commanded incremental step test example.*

TABLE 1. Step variables calculated from the 2.5 nm incremental step data shown in Figure 3.

s_{InPos}	0.41 nm
$\bar{X}_{inc} \uparrow$	2.48 nm
$s_{inc} \uparrow$	0.33 nm
$\bar{X}_{inc} \downarrow$	2.48 nm
$s_{inc} \downarrow$	0.32 nm
$\bar{X}_{inc}$	2.48 nm
s_{inc}	0.32 nm

Unidirectional Incremental Step Criteria

In order to determine if the axis is capable of performing the commanded step in a unidirectional manner, the following pass/fail criteria is proposed:

Criterion A1 – Four times the standard deviation of the In-position Jitter must be less than the commanded incremental step size:

$$4 \cdot s_{InPos} < X_{CS} \quad (8)$$

where X_{CS} is the incremental commanded step size. For this test criterion, the In-position Jitter is measured for a minimum of 250 msec and a maximum of 2 seconds.

Criterion A2 – The difference between the sample mean of the forward direction incremental step sizes and the incremental commanded step size must be less than 5% of the incremental commanded step size:

$$\frac{|X_{CS} - \bar{X}_{inc}\uparrow|}{X_{CS}} < 0.05 \quad (9)$$

Criterion A2 ensures that the average of all steps taken is reasonably close to the commanded step size.

Criterion A3 – Four times the standard deviation of the forward direction incremental step size must be less than the incremental commanded step:

$$4 \cdot s_{inc} \uparrow < X_{CS} \quad (10)$$

Criterion A3 ensures that the measured incremental step sizes are bounded. Figure 6 shows a generic illustration of a unidirectional incremental step test that passes both Criteria A2 and A3.

Bidirectional Incremental Step Criteria

In order to determine if the axis is capable of performing the commanded step in a bidirectional manner, the following pass/fail criteria is proposed:

Criterion B1 – Same as Criterion A1.

Criterion B2 – The maximum sample mean of the forward and reverse direction incremental step sizes compared to the incremental commanded step size must be less than 5% of the incremental commanded step:

$$max\left[\left(\frac{|X_{CS}-\bar{X}_{inc}\uparrow|}{X_{CS}}\right),\left(\frac{|X_{CS}-\bar{X}_{inc}\downarrow|}{X_{CS}}\right)\right] < 0.05 \quad (11)$$

Criterion B3 – Four times the maximum standard deviation of the forward and reverse direction incremental step sizes must be less than the incremental commanded step:

$$4 \cdot max(s_{inc}\uparrow, s_{inc}\downarrow) < X_{CS} \quad (12)$$

If the measured results meet the unidirectional criteria and do not meet the bidirectional criteria, an additional unidirectional test is performed in the opposite direction as the first test to ensure that the unidirectional criteria are met in both directions when the axis is free from any backlash or machine hysteresis.

One likely cause of failure to meet the bidirectional criteria is the presence of a reversal error caused by backlash or hysteresis in the drive mechanism. This reversal error can be very large compared to the commanded step size and would require many steps in the reverse direction to completely eliminate the error. Therefore, a test is proposed that will attempt to quantify this reversal error. This test is proposed as the Incremental Step Reversal Error Test.

<u>Incremental Step Reversal Error Test</u>

To determine the Incremental Step Reversal Error, alternating successive steps starting at a step size much larger than the commanded incremental step are performed as illustrated in Figure 7.

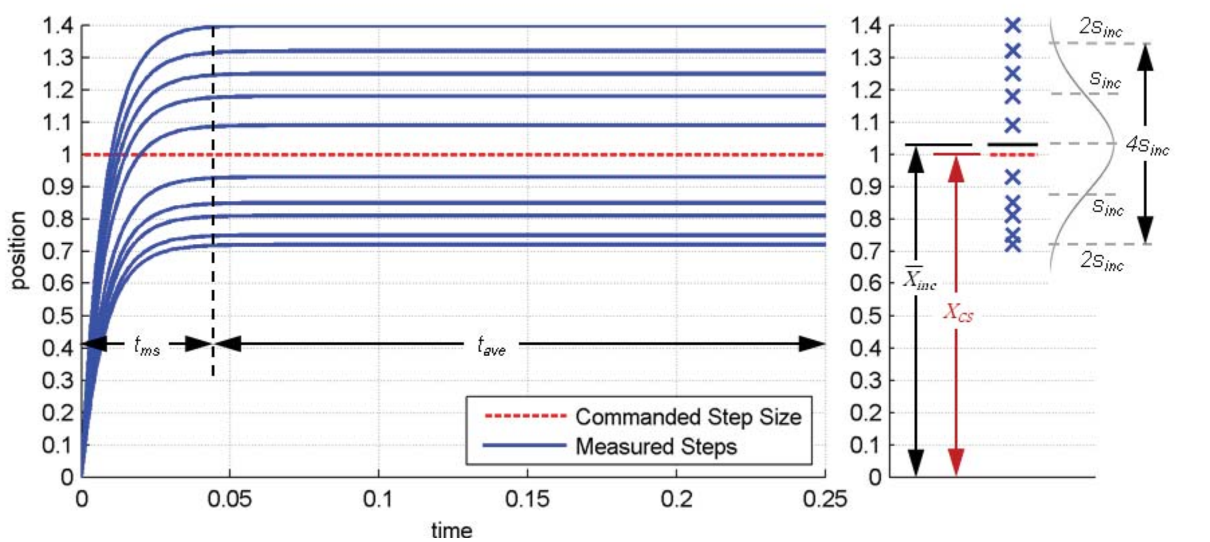

Figure 6. Illustration of Criterion A2 and A3 for determining if a positioning axis passes or fails an Incremental Step test.

Theoretically, the measured position will differ from the commanded position by the reversal error value. However, due to hysteresis and other nonlinearities that could be present at these small step amplitudes, the reversal error must be carefully defined. In order to deal with these other error sources, the Incremental Step Reversal Error, B_{inc}, is proposed as ½ of the commanded incremental step size for which the step error equals 50% of the commanded incremental step size:

$$B_{inc} = \frac{X_{CS,i}}{2} \text{ when } \frac{|X_{CS,i} - X_{inc,i}|}{X_{CS,i}} = 0.5 \qquad (13)$$

where $X_{CS,i}$ is the commanded incremental step at the i^{th} step.

Upon analysis of the results of this test, if the relative step error is greater than 50% for all steps taken, then the starting step size chosen was not large enough. The starting step size is increased and the test repeated until a step error of 50% of the step size is achieved.

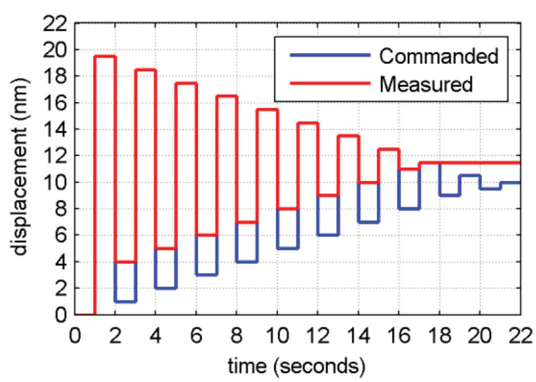

Figure 7. Successively alternating, decreasing steps used to measure the Incremental Step Reversal Error.

MINIMUM INCREMENTAL MOTION

The proposed definition for *Minimum Incremental Motion* is "the smallest mechanical incremental step that a positioning axis is capable of reliably performing" and is determined using the same criteria outlined earlier in this paper (A1-A3, B1-B3). Bidirectional Incremental Step tests are performed starting at the machine resolution or $2 \cdot s_{InPos}$, whichever is greater. The step size is increased until the Unidirectional Criteria (A1-A3), at a minimum, are met.

The results of the test are reported as one of the two following scenarios:

1. Unidirectional Minimum Incremental Motion of XX units with an Incremental Step Reversal Error of YY units (where units are the positioning axis units of nm, um, arc-seconds, etc.)

2. Bidirectional Minimum Incremental Motion of XX units (where units are the positioning axis units of nm, um, arc-seconds, etc.)

CONCLUSIONS

This paper presents proposed test methods for quantifying the small step capability of a positioning axis in order to encourage feedback from interested parties.

FUTURE WORK

An effort is underway to test a variety of positioning axes using the methods described in this paper. Future work consists of continued testing to support the methods and criteria presented.

In addition, detailed uncertainty analysis methods are being developed for this test to aid the users and suppliers of positioning equipment in quantifying the measurement uncertainty.

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