An Evaluation Of Ultra-Precise Machine Tool Contouring Performance: *The Low Amplitude Sine Tracking (LAST) Test*

Mark Craig Gerchman and David H. Youden

Rank Taylor Hobson Inc.
Keene, New Hampshire 03431 USA

Introduction

Micro-stepping position tests are often used to demonstrate the performance of ultra-precise machine tools. These tests record the ability of a machine tool to precisely move slides over very short distances. To optimize machine performance for these tests it is necessary to detune slide servo system characteristics from typical operating values. Therefore discreet micro-stepping tests are not representative of the dynamic contouring performance of ultra-precise machine tools.

The low amplitude sine tracking test measures the contouring performance of ultra-precise machine tools under typical slide servo conditions. The metrology instrumentation necessary to perform the test is available in many laboratories and the testing configuration is easy to align. Interpretations of the test results provide not only a measure of machine tool contouring performance but also information useful for the proper tuning of slide servo system characteristics. The test as described is not biased to a particular machine tool geometry and parameters that define the test are suitable to machine with various resolutions. Although this is a contouring performance test in two dimensions, generalizations of the test to three dimensional machines are straightforward.

Test Description

The low amplitude sine tracking test, or LAST test, measures the ability of a machine tool to execute a coordinated sequence of motions. The sine wave motions that make up the tracking sequence require low amplitude variations in slide speed that are typical of ultra-precise machine tools. In a thorough LAST test, several tracking sequences are performed in different orientations. Usually, for a two-axis machine tool with an orthogonal slide configuration, three tracking sequences are performed. These include orientations that are parallel, perpendicular, and at 45 degrees to the principal spindle axis. The use of these different orientations provides an evaluation of the motion of each slide including reversals and speed variations.

The tracking sequence of the LAST test, shown in figure 1, is a five part motion. Two axes can be defined in the plane of these motions. They are designated the fast and slow axes; because of the relative speed of coordinate slide motions in these directions. The five contouring motions consist of: (1) a straight move along the fast axis of one-quarter wavelength; (2) a half-wavelength sine wave motion; (3) a reversal in the fast direction and a one and one-half sine wave motion; (4) another reversal in the fast direction and a one-half sine wave motion; and (5) a straight move along the fast direction of one-quarter wavelength that returns to the starting position.

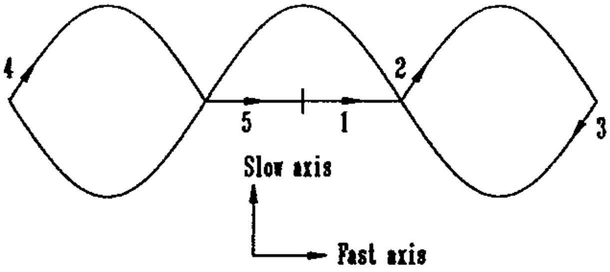

Figure 1. LAST Tracking Sequence

The choice for the sine wave's amplitude and wavelength are related to the machine tool's minimum programming increment and typical operating velocity. For the ultra-precise machine tool measured to date, the amplitude of the sine wave has been 25 minimum programming increments: yielding a total motion in the slow axis of 50 increments. The time to perform the LAST test tracking sequence has been standardized to three minutes. This has helped to reduce temporal drift in the metrology instrumentation and eliminate long term environmental considerations. Given the duration of the tracking sequence the wavelength is determined from a typical machining speed. As an example, a diamond turning lathe with 0.000,01 mm programmability operating at typically 2.5 mm/min has a LAST sine wave with a 250 nm amplitude and 2.5 mm wavelength.

The programming of the tracking sequence is defined using 100 constant speed linear moves per wavelength. These moves are equally spaced along the fast axis. Since the beginning and ending straight line motions are also divided into moves of the same size, this results in a program sequence 300 blocks long. The use of linear interpolation and this spacing provides a bench mark for the comparisons of different machine tools under identical conditions. The adequacy of these parameters for the description of the tracking sequence will be established later. A LAST evaluation using other interpolation schemes and curve fitting can be performed to evaluate and compare machine controller operations.

A preferred technique for measuring and recording the tracking sequence is capacitance gaging. Figure 2 show a typical configuration of the LAST test. By mounting a capacitance probe on one axis and a conductive straightness standard on the other, a measure of the slow axis position in time can be obtained. The measurement should be performed at cutting height in the vicinity of the typical tool-work interaction. Typically the frequency response of the recording system should be adequate to sample at 0.001 of the tracking sequence wavelength. For the example given, this corresponds to a 16.7 Hz filter.

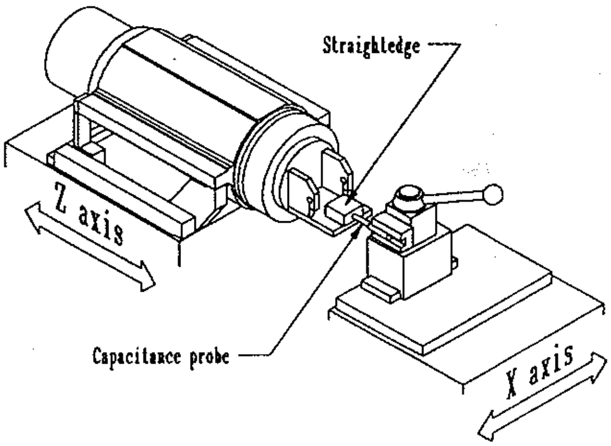

Figure 2. LAST Test Configuration

Plotting the slow axis position in time provides an easy way to evaluate a machine tool's contouring performance. It provides a valuable diagnostic tool for evaluating servo system performance and dynamic positioning accuracy. By digitizing the information an subtracting the desired sine wave motions, the residual errors can be quantified. The symmetry of the tracking sequence permits the effects of gaging electronic drift to be separated from out-of-squareness conditions in the test configuration. The resultant error plot can be analyzed using a number of techniques including harmonic analysis. A contouring position error can be expressed from a reduced trace as either a peak-to-valley or *rms* error.

Tracking Sequence Analysis

Although the representation of the tracking sequence is straightforward, it's description masks some inherent inaccuracies. These inaccuracies are caused by describing a tracking sequence that does not yield the expected sinusoidal output. The errors created are caused by three different factors. Fortunately, because of the large wavelength to amplitude ratio (10,000 to 1 in the example given), these errors can be shown to be below influencing levels.

The first effect is caused by the use of constant speed in the description of the side motions. To describe this effect consider the position along the fast axis as 'x' and the position along the slow axis as 'z'. The description of a portion of the tracking sequences sine wave is shown in equation 1. Where z is a function of x, the amplitude a, and wavelength lambda.

$$z=z(x)=A\cdot \sin\left(\frac{2\pi x}{\lambda}\right) \tag{1}$$

Because of the effects of maintaining constant speed in the contouring mode the output of z as a function of time is not a sine wave. The exact relationship between z and time is given by the differential equation shown in equation 2.

$$\frac{\partial z}{\partial t}=\frac{v}{\sqrt{1+\frac{\left(\frac{\lambda}{2\pi A}\right)^{2}}{\left(1-\left[\frac{z}{A}\right]^{2}\right)}}} \tag{2}$$

This effect causes variations in the speeds along both axes by the requirement to maintain a constant contouring speed. A computer simulation using Runge-Kutta techniques applied to the example given, shows this effect to produce maximum errors of less than 0.1 nm.

The second effect is caused by the use of straight line segments to approximate the smoothly varying sine wave. The choice of an appropriate number of segments to accurately represent the tracking sequence is also influenced by a third effect which is the requirement that the segment endpoints be integral multiples of the minimum programmable increment. Although a large choice of straight line segments may appear beneficial to better fitting the curve, once the curve fit is less than (plus or minus) one half the minimum programmable increment the total error in representing the curve increases with additional segments. An infinite number of straight line segments whose ends are forced to the nearest programmable increment results in a total error fit of one programmable increment. The selection of 100 line segments per wavelength was selected as a reasonable trade off between these two effects regardless of the tracking orientation used.

Example

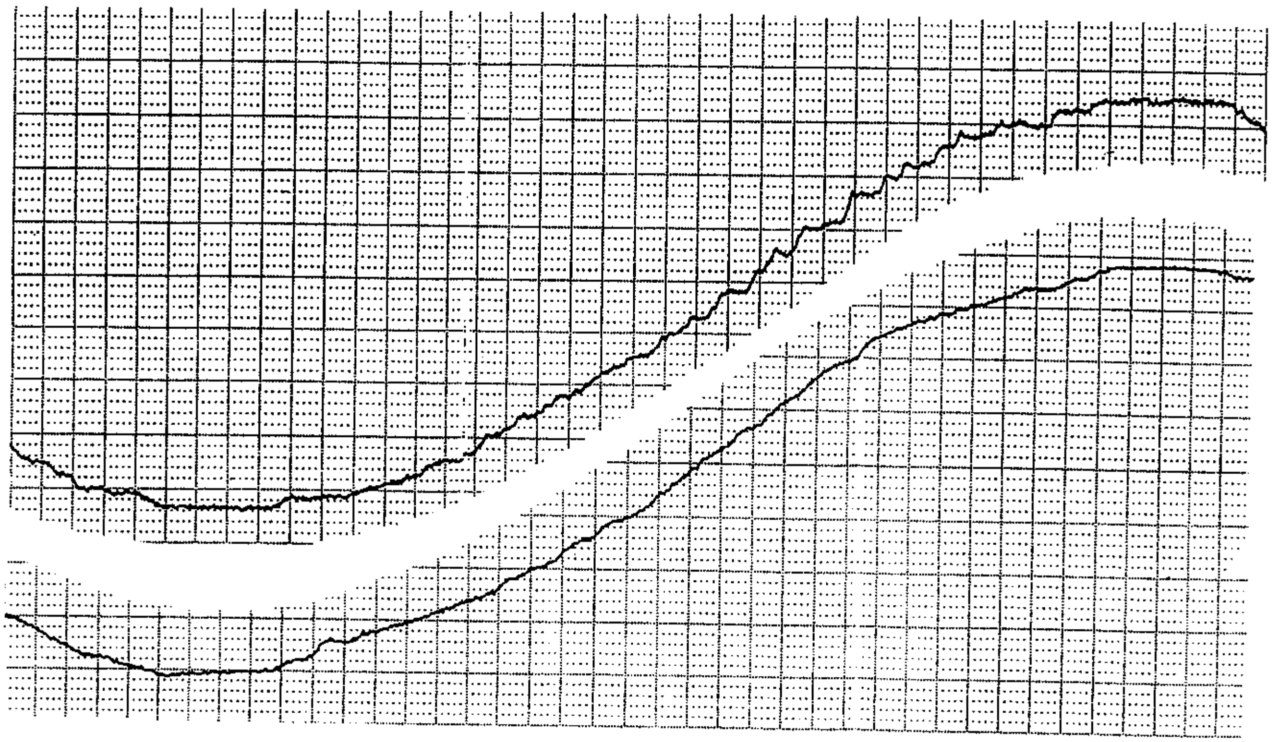

Figure 3. Illustrated here are segments of two traces from LAST tracking sequences. The upper trace shows the performance of a diamond turning lathe with a minimum programmable increment of 10 nm and a feedback resolution of 10 nm. The lower trace shows an identical machine, with the same programmable increment, operating at a feedback resolution of 2.5 nm. In this instance, the LAST test illustrates how the contouring performance of these machine tools has improved with increased feedback resolutions.