

Foundation for Dynamic Metrology of Machine Tools

Jimmie A. Miller, Robert Hocken, Vignesh Ramanan, Qibo Feng
Center for Precision Metrology (CPM)
University of North Carolina at Charlotte, Charlotte NC 28223

1. Introduction

The surge in demand for tighter tolerance machined parts has led to an increasing requirement that machining centers be specified with close accuracies measured according to accepted standards¹ and subsequently certified at regular time intervals. These standards typically specify measuring the positioning accuracy in the static state. As the tolerances are squeezed and machining techniques are developed for eliminating finishing processes, required machine performance will necessitate more detailed specifications for machines including the dynamic state.

Some data presented was acquired using a CPM designed and built, high speed (300 kHz) metrology acquisition system. Certain geometric error terms of two different machines were investigated both statically and dynamically. This presentation focuses on the observed dynamic errors with a brief description of the acquisition system mentioned later. Additionally, further dynamic error consideration is given which should affect non-axial machining along with some recommendations which should be included in any standard that includes dynamic measurement.

2. Dynamic Errors Observed

The inherent forces and moments of dynamic systems affect the characteristic positioning errors of a machine tool. The extent of these effects determines the necessity of measuring and/or compensating for them. Consider a table that is moving along a way. The orientation of this table may change by several arcseconds as it shifts from a static to dynamic state. Similarly, straightness errors have been observed to offset by many micrometers during the static to dynamic transition. Additionally, velocity errors along an axial direction may result in positioning errors as the machine contours along paths that are not along an axial direction.

2.1 Dynamic Observations with Commercial Instruments²

Dynamic measurement methods [interferometer based dynamic calibrators and telescoping ball bars (1 dimensional) and grid plates (2 dimensional)] are sensitive to motion induced errors. **Figures 1-3** show dynamic errors observed with a commercially available grid plate and ball bar on a machine having linear scale encoders which provide positional feedback information. **Figure 1** reveals one dimensional normal (perpendicular) error data taken with an telescopic ball bar while contouring along a circle at 1000 mm/min. Notice the error pattern along the circle. As the contour changes direction from an axial direction an oscillating error appears which increases in amplitude and spatial frequency as you approach a 45 degree contouring angle with respect to the axial directions. These errors are also visible when using a grid plate (two dimensional instrument), as shown in **Figure 2** for circular contouring at two different feedrates. The same pattern is observed along with a reduction in radial dimension. Using a grid plate to measure while contouring along a linear diagonal also reveals errors that have a definite spatial frequency as shown in **Figure 3** which also shows two sets of data taken using different machining parameters. One shows higher amplitudes at a specific frequency while the other shows a greater deviation from the commanded

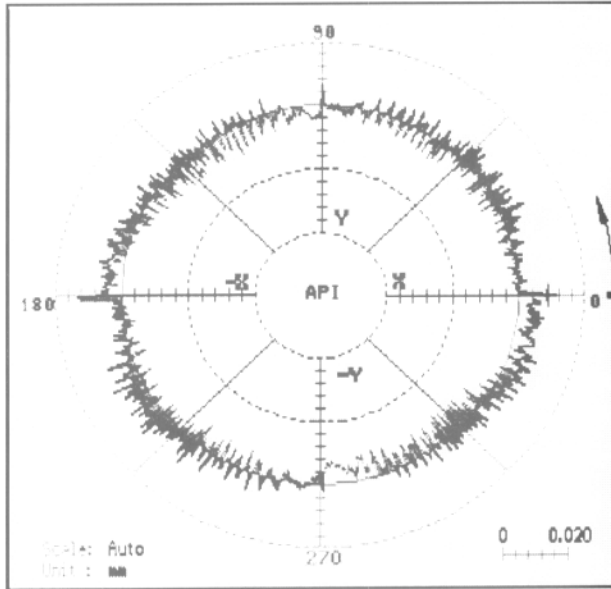


Figure 1. Data from extensible ball-bar revealing dynamic errors for 1.0 m/min feedrate.

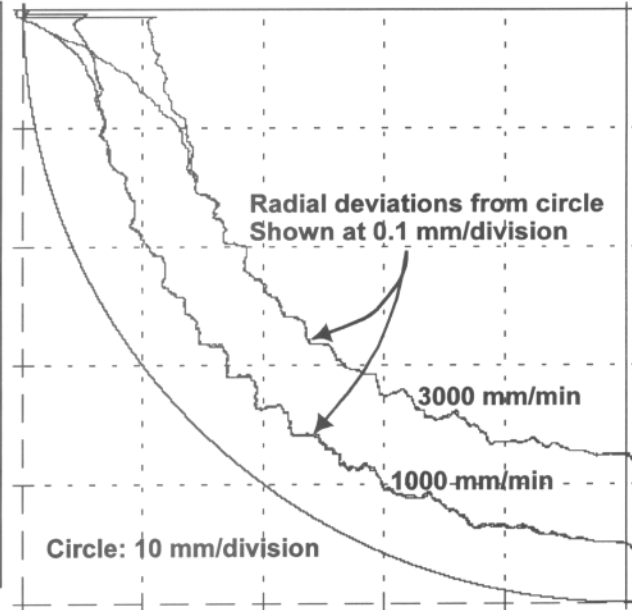


Figure 2. Grid plate measurement of circular contours with varied parameters.

path. Thus, the machining parameters of choice may be related to form and finish tolerances. The source of this error will be discussed later.

2.2 CPM Metrology Acquisition System Description

The present configuration of the acquisition system interfaces the digital servo port of a Zygo Axiom 2/20 laser system with two quadrature counters which employ the signals taken from either linear or rotary encoders which provide the reference to machine coordinates. The laser interface provided the capability of measuring either dynamic displacement accuracy, straightness error or angular error. The timing capabilities of the system provide for simultaneous ($< 1\mu\text{sec}$) triggering of individual components. Also capable of burst collection modes and FFT time analysis, the system provided comparison of the three input data types as a function of each other or time.

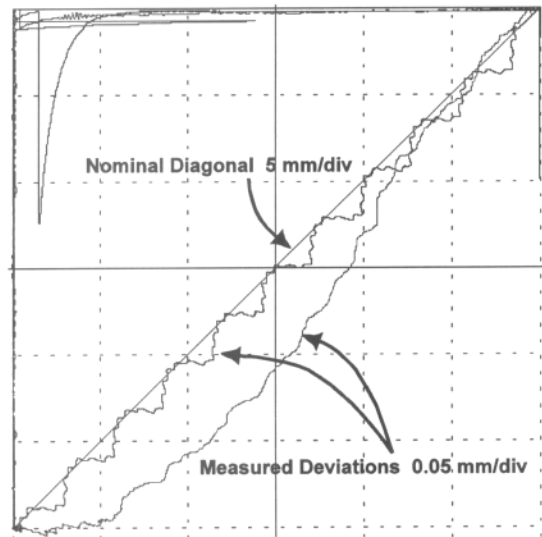


Figure 3. Grid plate measurement along a linear diagonal with varied parameters.

2.2 Dynamic Observations using CPM Metrology Acquisition System

Measurements utilized two vertical spindle machines, one with rotary encoders on the ballscrews and the other with linear scales. **Figure 4** is derived from data taken using the direct x and y

encoder readings as a function of time while contouring a circle at two different feedrates. The machine used has linear scale based encoders. Similar errors revealed by the ball bar and grid plate are shown with a component that changes in amplitude and spatial frequency while contouring in a non-axial mode. This is enough evidence to state that this error component is not a result of geometrical way errors. This is not enough evidence, however, to totally attribute this error to the control system. Since the spatial frequency does not seem to be dependent on the feedrate (and thus time related), other sources must be considered which may produce the error. This error component may be due to the linear displacement accuracy of the ball screw. Even if the motor turns the ballscrew at a constant velocity, the minute pitch changes in the ballscrew will cause velocity and acceleration errors in the associated carriage. Since the velocity (and thus position) changes, the vector sum of two independent carriages can produce an error component that is perpendicular to the direction of the contour. For a linear multi-axis operation, such as contouring along a diagonal, this effect can have minima and maxima amplitudes depending on the phase of the errors of the associated ballscrews. It has also been suggested by others³ that the recirculation of the balls in the nuts may produce the same effect.

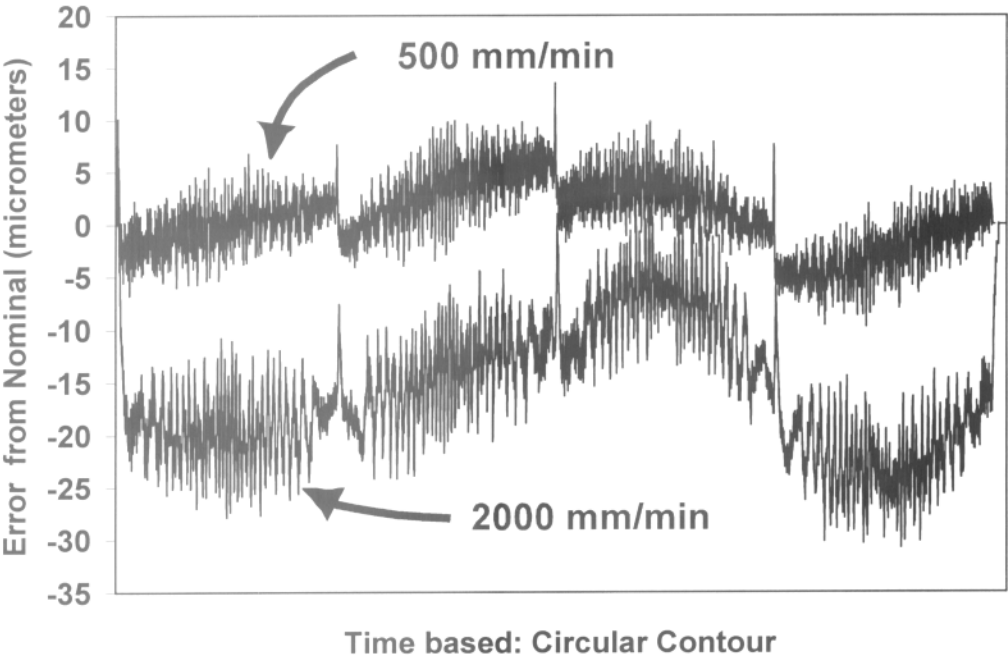


Figure 4. Time based data of encoder radial error from circular contour for two feedrates.

Additional analysis of data taken from a machine with angular encoders attached to the ballscrews revealed an offset between dynamic and static measurements such as those of **Figure 5** which shows an angular orientation jump of 2 arcseconds as the stage begins to move. This type of error has also been observed for straightness measurement where the effect has been observed to be as great as 25 micrometers. The question arises as to whether these errors are related to the

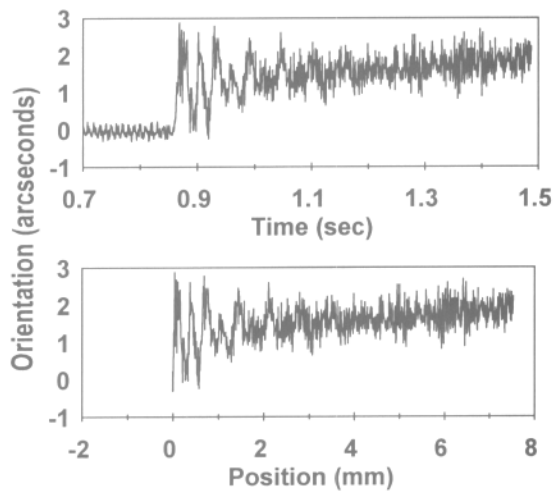


Figure 5. Angular reorientation of a table as it shifts from a static to a dynamic state.

4. Recommendations.

The following are recommended for precision manufacturing machines.

1. In addition to grid plate and telescoping ballbar techniques, additional dynamic specifications should be developed to ascertain contouring errors and static to dynamic transitions. This should be done along axes as well as along a diagonal to determine contouring capabilities.
2. Instruments should be built which allow for capturing machine encoder information in addition to other measurements. From this information, contouring correction of machines may be possible.
- 3. Machine tool builders should include an interface to each of their machine axes to facilitate dynamic measurements with commercial instruments that could relate external data with internal position and control. Machines could also be built which compare their desired positions with actual positions and update the process to account for current machine errors.**

References

1. Such as: ANSI/ASME B5.54-1992 "Methods for performance evaluation of computer numerically controlled machining centers", ASME 1992.
2. Instruments used and similar ones available from the following suppliers:
Automated Precision, Renishaw, Heidenhain, and Hewlett-Packard.
3. Private communication with Dr. Steve Patterson, UNC-Charlotte.
4. Ramanan, Vignesh, "High Speed Machine Tool Error Measurements", Masters Thesis, University of North Carolina at Charlotte, 1998.

carriage-way rigidity or the differences in servo control for each individual axis. An analysis was made of axis positions taken from direct encoder readings as the carriage began a diagonal displacement⁴. Although the position of the axes should be the same, comparison revealed a difference in encoder readings corresponding to a positioning error of about 24 micrometers between the axes. The particular error (believed to be servo driven) could result in a 17 micrometer form error in a production part within 1 mm of the beginning of a diagonal cut and an error in edge placement of about 9 micrometers.