

A COMPARATIVE STUDY OF PART ERROR CONTRIBUTORS IN HIGH-SPEED MACHINING

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INTRODUCTION

The accuracy of parts produced by machining operations has been studied extensively over the past decades. It is known that machined part accuracy has four major contributors: machine geometric errors, thermally induced errors, trajectory following errors caused by controller/structural dynamics, and errors due to the cutting forces. In computer numerical control (CNC) machining, the desired spatial trajectory of the cutting tool is ideally defined by the part program. The purpose of the part program is to place the tool tip at particular coordinates relative to the part at every instant in time, leaving behind newly created surfaces which form a workpiece of the proper dimensions. Errors in the final dimensions of the machined part are determined by the accuracy with which the commanded tool trajectory is followed, combined with any deflections of the tool, part, or machine caused by the cutting forces.

Prior research has shown that the part dimensional errors associated with the cutting force cannot be properly modeled and understood unless the vibrational dynamics of the tool-holder-spindle-machine-workpiece system are considered; and that in high-speed machining (HSM), the errors associated with cutting forces can be as large, or larger, than the errors typically associated with geometric, thermal, and controller effects for modern machine tools. Most importantly, small variations in the tool point dynamics and/or small changes in spindle speed can result in part errors which are much larger than typical tolerances. This is referred to as surface location error (SLE).

This paper reports preliminary results of a study designed to quantify the contributions of geometric, thermal, controller, and cutting force errors to the accuracy of parts produced on a modern CNC high-speed milling machine. All data reported here was collected on a Mikron UCP-600 Vario CNC 5-axis milling machine with x, y, and z axis travels of {600, 450, and 450} mm, respectively. The vertical Step Tec spindle

accepts HSK-63A tool holders and is capable of speeds up to 20000 rpm with cutting power up to 16 kW. This machine was purchased new in 2005 and measurements undertaken soon after installation. For the purposes of this study, the machine was operated as a three-axis machine and, therefore, error motions of the B and C rotary axes are not included.

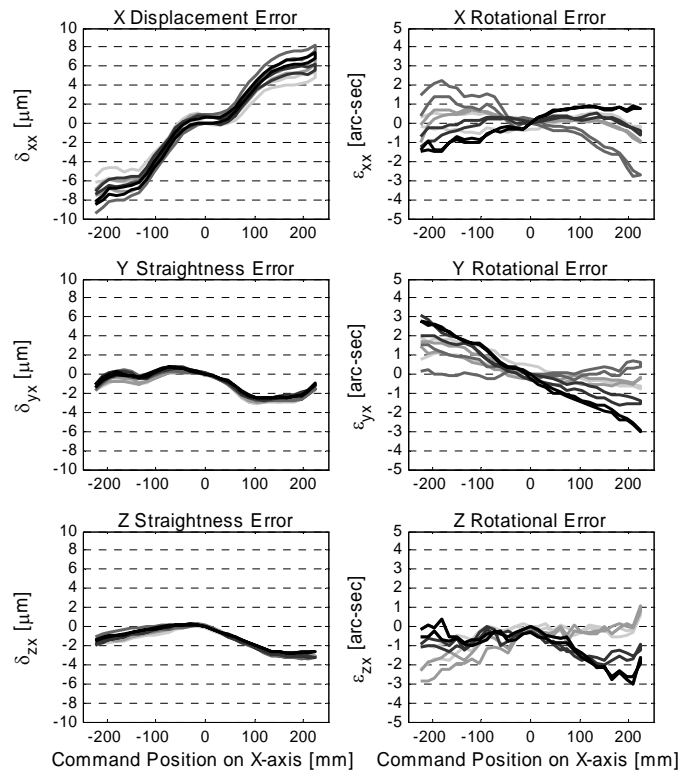


Figure 1: Error motions for the x-axis.

GEOMETRIC ERRORS

The geometric errors for the x, y, and z axes of the machine were measured using the Laser Ball Bar [1,2]. Six degree-of-freedom error motions (3 displacements and 3 rotations) were measured for each axis at 15 mm intervals for both the forward and reverse directions of motion. Axis orthogonality errors were also measured. All errors were measured with the machine in a cold state and were repeated five

times. Figure 1 shows measurement results for the x-axis. Comparable results were obtained for y and z Orthogonality errors are reported in Table 1.

Table 1: Axis orthogonality errors.

Axes	Angle (deg)	Error (arc-sec)
xy	89.99977	-0.8182
yz	89.99934	-2.3744
xz	89.99860	-5.0591

A homogeneous transformation matrix (HTM) model of the machine geometry errors was created and used to predict tool point positioning errors in a coordinate system attached to the workpiece at points along the machining tool path. An example for the x-axis transformation error matrices is provided in Eq. 1. The matrices for the y- and z-axes are constructed similarly. Note that orthogonality errors between the axes are included as linear terms in the appropriate straightness error functions of the axis.

$${}^{part}\vec{P}_{tool} = {}^{part}T_x E_x X T_y E_y Y T_z E_z Z \vec{P}_{tool}, \text{ where} \quad (1)$$

$${}^{part}T_x = \begin{bmatrix} 1 & 0 & 0 & x_{command} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} E_x = \begin{bmatrix} 1 & \varepsilon_z(x) & -\varepsilon_y(x) & \delta_x(x) \\ -\varepsilon_z(x) & 1 & \varepsilon_x(x) & \delta_y(x) \\ \varepsilon_y(x) & -\varepsilon_x(x) & 1 & \delta_z(x) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

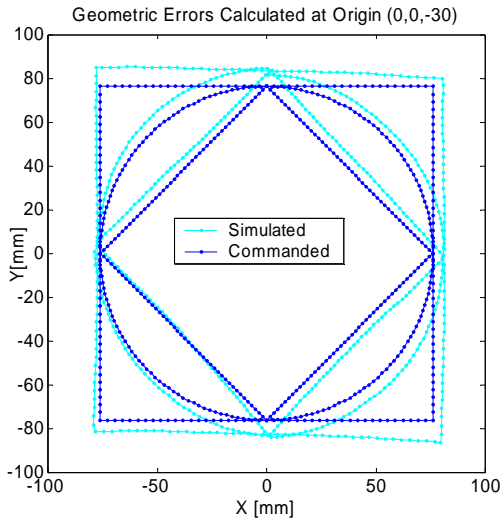


Figure 2: Part errors due to machine geometry (2000x error magnification).

The geometric errors were used in conjunction with the HTM error model to predict part errors using a Monte Carlo approach. At two to five mm increments along the part features, a value

for each of the 18 machine geometric error components was selected from the distribution of the measured values at the appropriate axis location. The normal distance from the resulting tool point location to the surface of the feature being machined was then computed and saved. After a large number of iterations, statistics on the feature error at points along the surface were computed. The mean results are shown in Fig. 2 (with 2000x error magnification) for the NAS 979 test part. The points in the simulation all lie within an xy plane located at z = -30 mm. This is the minimum value of z for which geometric error measurements were recorded with the Laser Ball Bar.

THERMAL ERRORS

Significant heat is generated during machining, both during chip generation and from the axis and spindle motors and bearings. This heat serves to distort the machine geometry and causes errors in machined parts. Thermal errors associated with spindle thermal growth were measured using a nest of five capacitance probes reading against a cylindrical tool blank held in the rotating spindle. The capacitance probes were sampled at one minute intervals as the spindle was exercised from a cold state at speeds of 5000 rpm and 15000 rpm. Results are shown in Fig. 3.

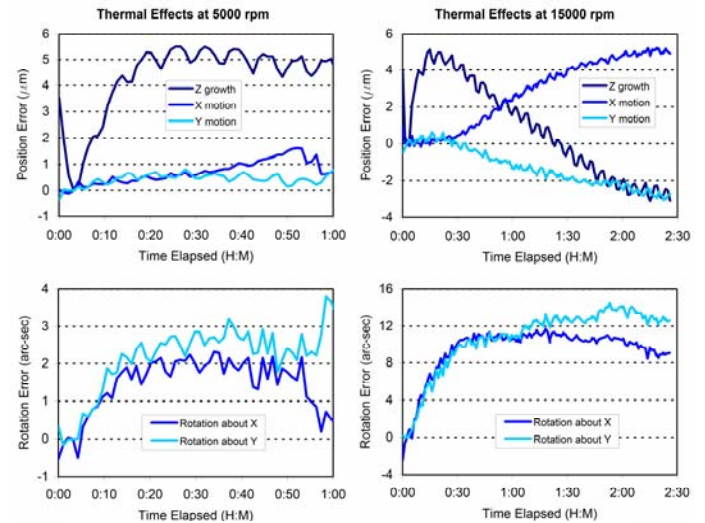


Figure 3: Spindle thermal growth errors.

CONTROLLER TRACKING ERRORS

CNC motion controllers may introduce tool path trajectory errors under high-speed motions, such as those typically encountered during HSM. These error motions were measured on the test machine using a Heidenhain grid plate encoder.

This instrument is capable of dynamic measurement of the two-dimensional trajectory of a read head held in the (non-rotating) machine spindle relative to a grid encoder plate fixed to the machine worktable. For these tests, the NAS 979 part program was modified to remove the z-axis motions associated with the different heights of the square, circle, and diamond features on the part. However, it is not expected that the small z-axis motions introduce significant geometric errors into the tool trajectory, allowing a comparison between the tool path recorded by the grid plate and the path predicted by the geometric machine model.

Figure 4 shows the tool paths measured by the grid plate at two different feed rates. A comparison between Figs. 3 and 4 shows significant similarities. Because the increase in feed rate between the two grid encoder experiments did not show significant differences, we conclude that the controller tracking errors are negligible in comparison to the geometric errors on this CNC machine.

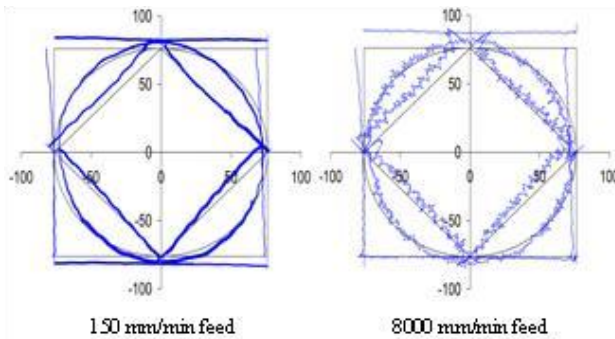


Figure 4: Grid plate measurements at two feed rates (2000x error magnification).

SURFACE LOCATION ERRORS

As noted, dynamic deflections of the cutter during stable machining can lead to significant errors in the actual location of the machined surface. Because SLE occurs due to forced vibrations, the dominant control parameter (for fixed system dynamics) is spindle speed which defines the excitation frequency (i.e., the tooth passing frequency). Previous researchers have demonstrated time-domain and semi-analytical predictions of SLE coupled with experimental comparisons [3-6]. In this study, we apply a new frequency-domain, analytical solution to SLE prediction [7]. In this approach, the tool-holder-spindle-machine dynamics as reflected at the tool point (i.e., the tool point frequency response

function, or FRF) are used directly to determine the machined surface location.

To evaluate the analytical solution method, a four flute, 19.05 mm diameter carbide endmill was selected for cutting tests. It was inserted in a collet holder with an overhang length of 57 mm. The non-rotating tool point FRF (Fig. 5) was measured and cutting tests were performed to identify the force model coefficients; this data was used to make SLE predictions for a large range of spindle speeds using a 50% radial immersion (radial depth equal to tool radius).

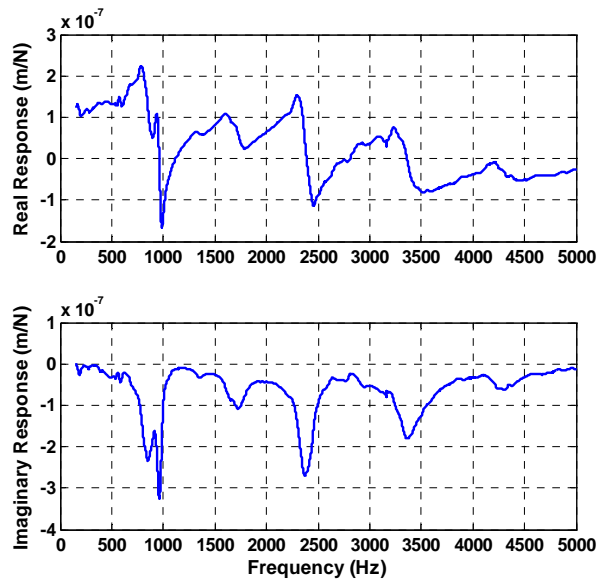


Figure 5: Tool point FRF for the 19.05 mm diameter endmill.

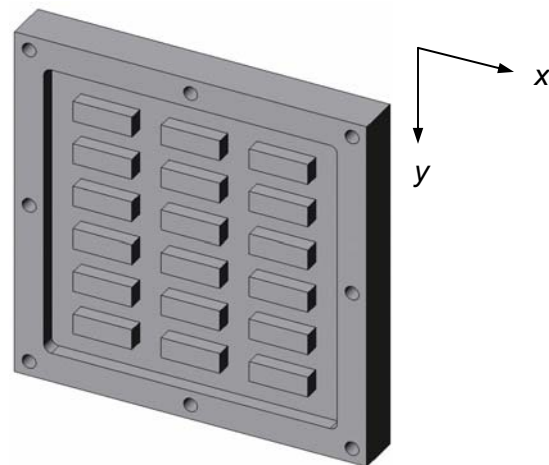


Figure 6: Diagram of the test part. Each raised boss was 50.8 mm x 17.8 mm x 12.7 mm.

The selected parameters for the cutting tests were: {7500 to 17500} rpm spindle speed range,

6 mm axial depth, 50% radial immersion, and 0.15 mm/tooth feed per tooth value. This spindle speed range was divided into 102 individual test cuts performed on 304.8 mm x 304.8 mm x 38.1 mm 6061-T6 aluminum blocks; see Fig. 6. Each block was initially machined to leave 18 evenly spaced rectangular bosses (50.8 mm long x 17.8 mm wide x 12.7 mm high) of nominally the same dimensions on each side.

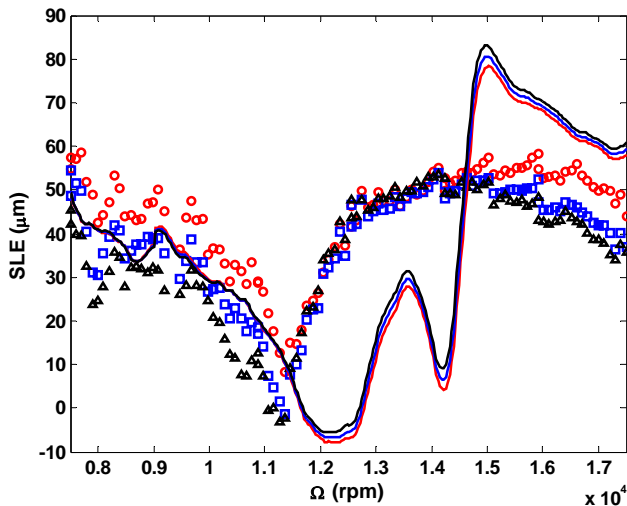


Figure 7: SLE vs. spindle speed (Ω) for experiments and prediction (lines).

These bosses were then finished machined at different spindle speeds to determine the resulting SLE. The feed direction during cutting (along the boss length, Fig. 6) was aligned with the x-axis of the machine to avoid any gain mismatch contouring errors. The test cuts were performed along the length of the bosses to remove roughly one-half of their width, leaving an uncut portion on the bottom as a reference. The width of the remaining top section was measured using a touch trigger probe CMM and then compared to the width of the bottom uncut portion to determine the amount of material that was removed. Surface location error was computed by comparing the amount of material removed to the commanded value. Further, measurements of the cut width were completed at three axial locations: {2 (circle), 3 (square), and 4 (triangle)} mm from the top of the boss. See Fig. 7. Reasonable agreement is observed. Discrepancies have been shown to be the result of changes in the spindle response at speed relative to the non-rotating response.

CONCLUSIONS

A comparison between the measured error sources is given in Fig. 8. For the selected tool-

holder-workpiece material combination, SLE is the dominate contributor. As HSM becomes more widely accepted, it is critical that the relative contribution to part inaccuracy of all error sources, including SLE, be well understood and strategies for either avoidance or compensation be developed.

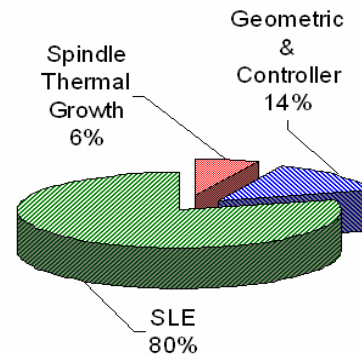


Figure 8: Relative contributions of machining error sources.

ACKNOWLEDGEMENTS

This work was supported by BWXT Y-12, Oak Ridge, TN.

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