EVALUATION OF PROPOSED TEST ARTIFACTS FOR FIVE-AXIS MACHINE TOOLS

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INTRODUCTION

In machine tool metrology, there are two primary ways to evaluate the performance of a machine tool: through a series of instrumented tests and through the manufacturing of test pieces. Advantages of test pieces are that machining parts is more akin to the actual purpose of the machine tool and that they do not require specialized measuring instruments. The disadvantages are that test pieces are composite tests—all errors present in the machine tool contribute to errors in the part—and part production is complicated by cutting forces and tool dynamics.

An early draft of an international standard [1] includes the introduction of two artifacts to test coordinated motion of 5-axis machine tools. The current work evaluates the production of these artifacts by discussing lessons learned and comparing axis trajectories and measurement results for each artifact. When possible, results are compared to analogous instrumented tests.

ARTIFACT DESCRIPTIONS

The most simple design that sufficiently tests the machine tool is desired to ease measurement, analysis, and correlation of part errors to machine error motions. A frustum (truncated cone) is the simplest geometry that can be produced using simultaneous 5-axis motion. The frustum artifact is already known to the machine tool community [2-5]. The frustum manufactured in this study is shown in Figure 1(a). The size differs from sizes prescribed in the draft standard because the current work was initiated before the release of the draft.

The second artifact is a truncated square pyramid (TSP), shown in Figure 1(b). This artifact is newer to the machine tool community.

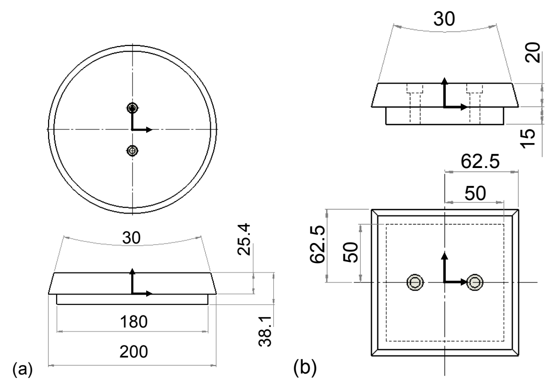

FIGURE 1. Engineering drawings of artifacts investigated in this study: (a) cone frustum, (b) truncated square pyramid. Length units are mm, *angle units are* degrees.

MACHINE

The machine used for the study is configured with a tilting-rotary table. The machine has a non-orthogonal B’-axis that is inclined from the Y-axis by 45°. The travel ranges are 800 mm for the X-axis, 700 mm for the Y-axis, and 550 mm for the Z-axis. The B’-axis ranges from 0° to 180° and the C’-axis has infinite rotation.

TOOL PATH

We chose similar cutting conditions to those prescribed by the draft standard: speed = 300 m/min, feedrate = 0.05 millimeters per tooth, tool = 12.7 mm diameter carbide cutter for Aluminum. The finish cut is made by side milling with a 0.1 mm radial depth of cut.

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Two stipulations must be made to ensure that all five axes are in simultaneous motion while machining. First, the artifacts are inclined about the Y-axis. Two frustum inclination angles are tested in this study: 10° and 15°. A 20° inclination angle is used for the TSP. Second, for the TSP, the tool path must be such that the vector describing the tool centerline must continually intersect the pyramid axis.

The tool paths were generated by commercially available computer aided manufacturing software. The machine controller allows programming using tool orientation vectors for the rotary axes and work coordinate system (WCS) positions for the linear axes.

SETUP

The frustum is mounted with the WCS origin offset from the C'-axis by a distance *R*, 50 mm in this study. The TSP is mounted such that the WCS origin lies on the C'-axis.

The machine tool utilized in this study is equipped with a touch trigger probe that is typically used to establish the position of the WCS origin and the orientation of the WCS with respect to the machine coordinate system. However, this proved problematic for these artifacts. Because the artifacts' work surfaces are not parallel to machine axes or WCS axes, the canned WCS cycles in the machine's controller could not be used directly on the artifacts. Custom fixtures were designed that had surfaces parallel to the machine axes, but uncertainty in mounting the artifact meant the part could not be cut with only one finish pass. User-written probing programs that contacted the actual work surfaces were written, but again excessive uncertainty prevented machining in one finish pass. These difficulties led to the decision to start with a part blank that was significantly oversized (5 mm), coarsely position the part in the desired programmed position, and use roughing passes before the final finish pass. The initial roughing pass may have variable depth of cut, but it trues the part for the finish pass.

AXIS TRAJECTORIES

The machine program was run through a computer model simulating the machine tool controller to generate the individual axis trajectories. The combination of the part's opening angle and the setup inclination angle determine the trajectories of the rotary axes. The trajectories of the linear axes are influenced not only by these same angles, but also by the position of the part within the machine's work volume (*i.e., R*). The axis trajectories for the setups explored in this study are shown in Figures 2, 3, and 4.

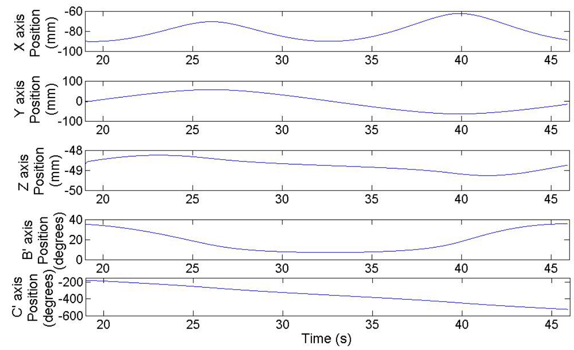

FIGURE 2. Axis trajectories for frustum with 10° inclination angle and setup offset from the C'-axis by 50 mm *in the x-direction.*

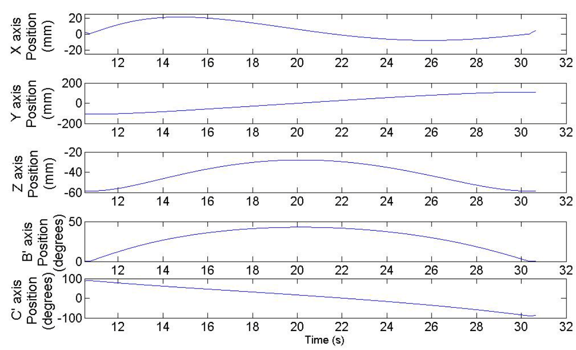

FIGURE 3. Axis trajectories for frustum with 15° inclination angle and setup offset from the C'-axis by 50 mm *in the x-direction.*

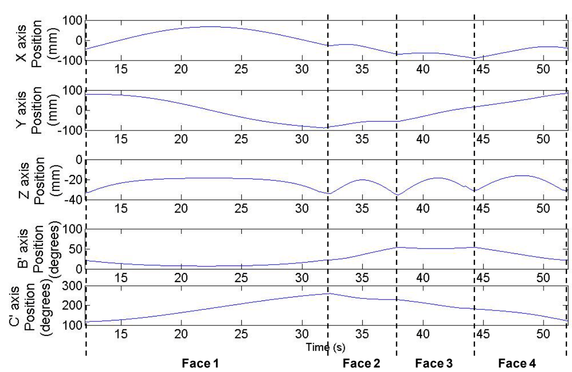

FIGURE 4. Axis trajectories for the TSP inclined by 20° and setup on the C'-axis.

The individual axis trajectories for the two frustum tests are very different (see Figures 2 and 3). For the 15° inclination angle, the B'-axis makes a relatively smooth transition from 0° to

≈ 43° and back to 0° to achieve the cone angle. The C'-axis rotates 180° at a near-constant velocity to trace the frustum surface. For the 10° inclination angle, the B'-axis ranges from ≈ 7° to ≈ 36° and back, but the C'-axis makes a full 360° rotation (from ≈ -193° to ≈ -553°). The trajectories of the linear axes are also quite different, but the ranges of these travels could be adjusted by selecting different positions for the test pieces within the work volume.

Also of note is that the axis trajectories for the 15° frustum test are different than the trajectories used to cut the same part with an orthogonal rotary axis configuration [3,4]. Specifically, on a machine with an orthogonal tilting-rotary table, the C'-axis travels 360°.

The trajectories for the TSP appear much more complex than those for the frustum tests. The trajectories for each face vary in range of motion and time. In fact, the trajectories for each face of the TSP can be thought of as four separate coordinated motion tests.

RESULTS

The draft standard prescribes what measurements should be taken, not the instruments that should be used to take them. As such, several possibilities for measurement are shown. For the frustum, the only measurement prescribed is the roundness of the machined surface. For the TSP, the straightness of each face is measured along with the perpendicularity of two faces to one reference face and parallelism of one face to the same reference face. Each part was measured at approximately its mid-height.

The frustum created using a 10° inclination angle was measured by a coordinate measuring machine (CMM) in two different ways: by contacting the work surface at 36 individual points and by scanning the CMM probe along the work surface. The results of the point-by-point measurement exhibit a non-circularity of 7 μm. The scanning measurement, shown in Figure 5a, appears slightly different. A notch or divot at 0° (the point of entry/exit for the tool) is quite apparent. Also, we noticed CMM probe hunting at the start of the measurement (the asterisk in Figure 5a). As such, the deviations immediately following the start of the measurement result from the measurement process, not from the artifact. If the notch and the hunting sections are ignored, the roundness is 6 μm. The expanded uncertainty in the CMM measurement is 3.4 μm over a travel of 450 mm.

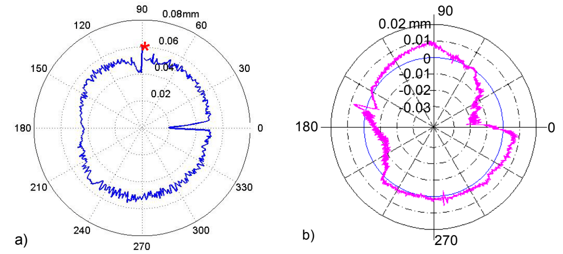

FIGURE 5. Results of measuring: a) 10° frustum test by scanning the CMM probe, and b) 15° frustum test by roundness tester.

The frustum created using the 15° inclination angle was measured on a roundness measuring machine with sub-micrometer expanded uncertainty. Figure 5b shows the results of this measurement, which reveals a different error profile. Again at the tool entry/exit point (*i.e.,* 0°), one can see a step of approximately 32 μm. The deviations on the opposite side of the part (from approximately 165° to 225°) are likely the result of chatter during the cutting process. Evidence of chatter was detected audibly during cutting and visibly on the part's surface.

The TSP was measured by scanning the CMM probe. The error profiles of each face, along with the best fit lines to those profiles, are shown in Figure 6. The straightness values for face 1 (facing toward the –X at setup), face 2 (facing toward +Y at setup), face 3 (facing toward +X at setup) and face 4 (facing toward –Y at setup) are 18 μm, 13 μm, 15 μm, and 7 μm, respectively. Face 1 was taken as the reference surface. The perpendicularity of faces 2 and 4 to face 1 are 136 μm and 139 μm, respectively, and the parallelism of face 3 to face 1 is 134 μm.

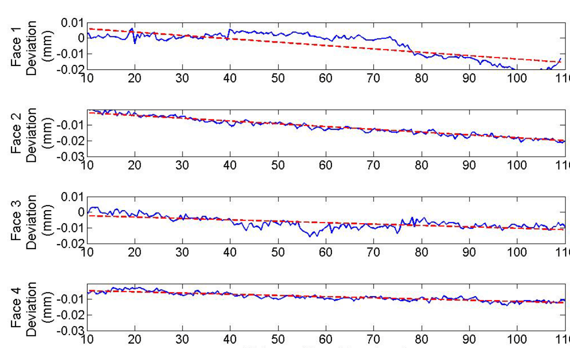

FIGURE 6. Results of measuring the TSP faces by scanning probe CMM.

BALLBAR TESTS

The TSP has no analogous instrumented test, but the frustum tool path can be checked using a telescoping ballbar. In fact, a draft international standard prescribes this as one of the tests for 5-axis coordinated motion [6]. The results of these tests are shown in Figures 7a and 7b for the frustum with the 10° inclination angle and the 15° inclination angle, respectively.

The profile in Figure 7b shows a step at the start/stop point similar to the one seen in Figure 5b, confirming that this step is indeed an error motion of the machine tool. The profile in Figure 7a shows a non-circularity of 6 μm, similar to the roundness observed in point-by-point CMM measurement, but the center of the entire ballbar profile is shifted by approximately 12 μm. This shift in the center is indicative of a location error in the rotary axis and any residual setup error after properly centering the ballbar spheres [7]. Also, the lack of a divot at the start/stop point indicates that this deviation in the artifact results from the cutting process, not from an error motion of the machine tool.

While the 10° and 15° results appear much different, closer examination reveals the similarity. The consistency in the plots appears if one compares the entire 15° ballbar plot with half of the 10° plot. If one takes the start point of the 10° test at 90° and the finish point at 270°, one notices a step of approximately 24 μm, very similar to the 25 μm step in the 15° plot. This comparison is valid because these are the portions of the plots over which the C'-axis positions are approximately equal to each other during cutting. In fact, previous measurements on this machine indicate a location error of the C'-axis in the machine's X-direction of approximately 10 μm [7].

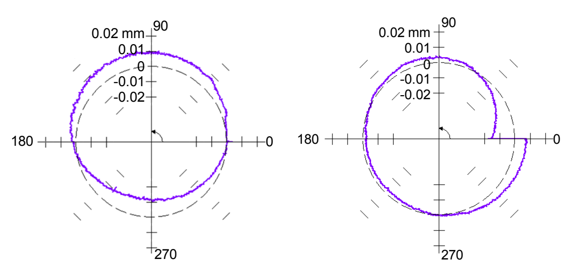

FIGURE 7. Results of measuring tool path deviation with a ballbar, a) in the 10° frustum test, and b) in the 15° frustum test. Expanded uncertainty (k=2) in ballbar measurement is 0.001 mm.

CONCLUSIONS

When machining test artifacts that do not offer paraxial surfaces, roughing passes may be necessary. When performing these roughing passes, one should take care to avoid unstable cutting conditions because chatter during roughing may be replicated in the finish pass.

The relative simplicity of the frustum and its associated axis trajectories along with an analogous instrumented test make it the preferred artifact to a truncated square pyramid. This simplicity is evidenced by the ability to link the observed test part error profile with a location error in the machine's C'-axis.

The cone frustum was tested at two different inclination angles that showed significantly different results. The result of the 10° frustum test is a deviation of 7 μm, while the result of the 15° frustum test on the same machine (with the same errors) is 32 μm. As such, care should be taken when judging the performance of a machine tool by machining only one artifact at one setup configuration.

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