A lathe tool translator for form error reduction in diamond turning

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Summary

This paper presents the design of a fine motion controller for nanometer level control of a lathe tool during diamond turning. Fine motion of the tool in the direction of cutting is achieved by a piezoelectric stack actuator with relative motion between the tool and base being monitored using a capacitance gage. Motion constraint is provided by a leaf type flexure providing a relatively high stiffness in off-axis directions. Mounting the translation stage on a wedge facilitates tool height adjustment. A squeeze clamp is incorporated in the wedge to hold the tool at the correct height and increase the stiffness of the complete system. The current design provides a fine motion control with a maximum range of 3 μm, a step response settling time of 12 ms and tool height adjustment of ± 2.5 mm with repeatable positioning, with suitable feedback, to within a few micrometers.

1.0 Introduction

This abstract presents the design and manufacture of a fine tool controller for the machining of profiled mandrels using a diamond turning machine. Particular emphasis is the fabrication of surfaces for applications such as replicated mirror optics for x-ray reflectometry where nanometer geometrical tolerances are necessary. The motivation for this project is the precise manufacture using replication of single or nested grazing incidence x-ray optical elements.

This development is part of a larger program to increase the accuracy of replicated x-ray optics by adjusting the profile of diamond turned mandrels to compensate systematic errors introduced throughout the manufacturing process. Replication involves the manufacture of a shaped mandrel that is subsequently used as the master form for electro-deposition of a relatively thick metallic film. It is this deposited film that is used as the finished optic. Each manufacturing stage introduces errors. In this study, it is speculated that these errors may be removed by adjusting the profile of the replication mandrel. For this to be possible, it is necessary that these errors are repeatable and the profiles of mandrel and finished optic can be measured. Profile measurement, both in-situ in the diamond turning machine and of finished products, will form a future component of this study.

2.0 Instrumentation Design

In general, the servo tool provides a translation range of 3 μm with a resolution of 1 nm. Additionally, a contact based, long trace profiling system with sub nanometer resolution is envisioned for development[i]. Adapting a high precision servo tool and profilometer system into a diamond turning center is a challenging design task. Thermal instability in working environments is inherently a dominant factor effecting repeatability of machining and subsequent profiling. This key issue is currently being investigated at UNCC for high precision diamond turning. One key point is to maintain a thermal equilibrium between the tool and spindle post. To retain the same working zone, the spindle post should not expand at a faster rate than the tool post. For matching, the servo components are fabricated with stainless steel 303.

To position the cutting edge of the tool at the correct height (often coincident with the spindle axis), the tool stage incorporates a vertical adjustment in the base, figure 2.0.1. As shown, the vertical adjustment is achieved using a wedge guided by dovetail slides on each side. In general, the vertical stage consists of a base, wedge and platform. The base and platform are constrained in the *Z*-axis with respect to each other by two ‘wishbone’ flexure designs on the upper and lower sides. Side flexure systems generate high stiffness along the *Z*-axis and relatively low stiffness in the *Y*-axis direction. Thus, the base and wedge displace in the *Y*-axis as the wedge is displaced along the *Z*-axis using the micrometer. The wedge has a 5° taper on each side (a 10° wedge) and is separated in the middle of the *X* plane by a leaf type flexure. A bolt is then used to clamp the wedge to the dovetail slides once the tool height has been set. When the wedge is locked the three components of the tool carriage support are effectively a rigid body. The vertical stage assembly translates a total range of 5 mm and, with practice, a vertical resolution of 0.2 μm can be achieved.

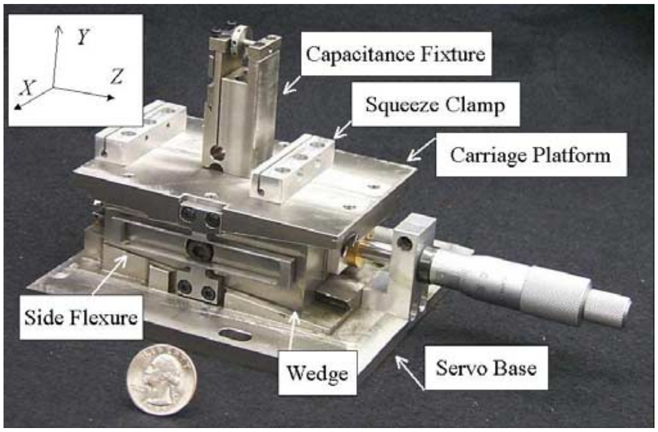

Figure 2.1: Servo tool capacitor fixture and vertical stage

A monolithic, tool translation flexure, figure 2.2, rigidly mounts to the top of the carriage platform, figure 2.1. Four leaf flexures are designed on each side of the tool mount to provide high axial stiffness and moderately high resonant frequency. Additionally, there are two further flexures underneath the carriage that are squeeze clamped to the platform. Consequently, the base flexures restrict the carriage from tilting about the *X* axis. A combination of conventional milling and wire EDM were used to produce the monolith. The tool carriage is designed with approximately 4 MN m^{-1} stiffness and a 400 Hz natural frequency.

A piezoelectric (PZT) stack actuator provides a single linear motion and uses capacitance gauging for closed loop control, figure 2.2. The PZT stack has a maximum range of 17 micrometers with an applied potential of 150 V. The use of capacitance sensor for closed loop control significantly reduces the hysteretic effects. In this design, the capacitance gage directly measures the local tool motion due to PZT expansion or contraction. The capacitive sensor consists of two aluminum coated glass slides. The base glass slide is approximately 1 mm in thickness and the central region is etched with a 20 μm step prior to coating of aluminum electrodes. A second slide bridges across the base plate and epoxy is applied to each corner. Glass slides of 0.2 mm

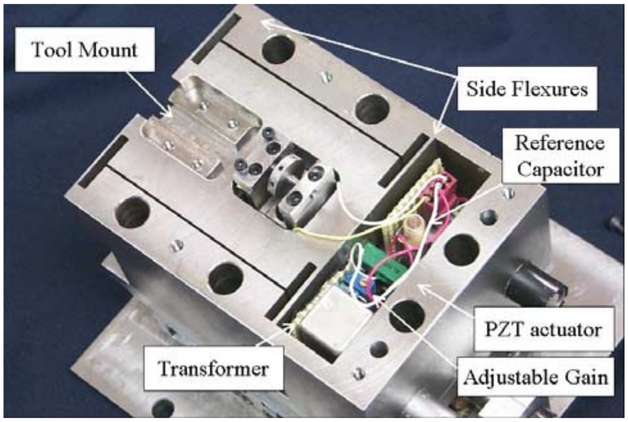

Figure 2.2: Tool translation flexure and capacitor electronics

thickness and aluminized on one face are chosen as the top slide to provide low stiffness. A ruby sphere is bonded with epoxy to the top slide to provide a contact point for transferring motion of the carriage to displacement of the thin glass slide electrode. The capacitance assembly mounts into a flexure tilt stage, figure 2.1. Maintaining low thermal drifts is mandatory for a 1 nm resolution metrology loop. Therefore, invar is chosen due to low thermal expansion properties for the fixture's components. A differential screw accommodates a fine adjustment mechanism and, with feedback, this can be controlled to better than 2 μm. The complete capacitor assembly and fixture is placed through a clearance hole in the tool carriage and bolts to the carriage platform. Fine differential adjustment is then utilized to bring the ruby sphere of the capacitance sensor into contact with the tool carriage. The contact is aligned with the diamond tool axis in order to minimize Abbe offset.

Servo electronics consist of a Thorlabs™ PZT amplifier, capacitance lock-in electronics and a PID controller. A separate circuit board is built to contain a variable gain preamplifier, adjustable reference capacitor and transformer. The reference capacitor and transformer circuit are used to null the measurement capacitor between a 1-10 μm contact range. Ideally, the reference and measurement capacitor should be mounted as close as possible to minimize added capacitance in the cabling. Thus, the electronic circuit board is designed to fit compactly in a pocket behind the tool carriage, figure 2.2. The gain potentiometer effectively changes the range of the servo while inversely affecting the resolution (i.e a higher resolution servo may be achieved by shortening the range). A commanded voltage is generated from LabView™ through a data acquisition board and transferred to the PID. The PID compares between the measurement capacitor signal and the command voltage to produce a corrective signal to the PZT controller.

Considering that the workpiece and servo tool may be doused with an oil or air bath, a thin walled environmental shell is utilized to prevent any oil from entering the carriage chamber and disrupting the electronics, figure 2.3. The shell is designed with a 1 mm wall thickness and made from aluminum 6061. Aluminum is chosen for the stress free properties and favorable high speed machining properties. Also, the shell is bolted directly to the tool carriage frame and moves with the platform when it is being adjusted for tool height. Lastly, the tool mounts in the carriage as shown and is rigidly clamped using an aluminum plate.

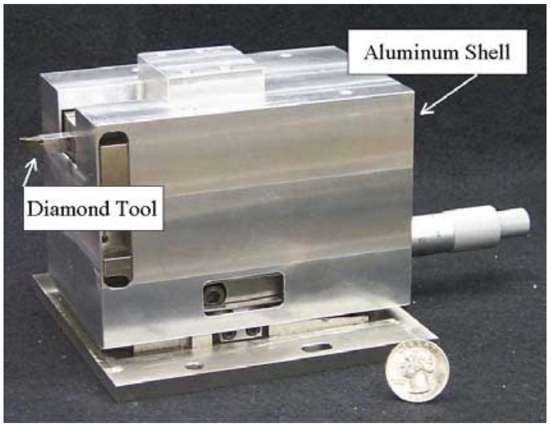

Figure 2.3: servo tool assembly

3.0 Performance Testing

Affectively, the servo tool is calibrated using a Hewlett Packard laser interferometer. During calibration, the demodulated capacitance voltage is compared to the laser displacement reading and a second order polynomial is used to fit the measured data. Next, the tool is tested to determine the fastest response time or limiting bandwidth. The response time is determined from the output from the capacitance gage when a step demand is fed into the PID controller. The servo's settling time is optimized by adjusting the three terms of the PID controller while monitoring the response in real time. Currently, the servo's optimal settling time is determined to be 12 ms.

Currently, research is underway to assess the servo tool's overall performance. Recent investigations include cutting step and sinusoidal profiles across the face of 4" diameter aluminum blanks. First, the tool servo is mounted into a Precitech diamond turning center with the PID controller and Capacitor lock-in located to the side of the Z-axis slide. These tests involve first facing the sample piece in several cutting passes until a P-V surface finish of between 50-100 Å is achieved. In the final pass, the *Z*-axis slide is translated towards the blank for a nominal depth of 0.5 μm and *X*-axis is slowed to 2 mm per minute. A sample is cut with a specified profile indenting every 0.3 cycles mm^{-1} and an increased 20 nm depth each cycle, figure 3.1. A Nanostep 2 is utilized to measure the subsequent surface profile. As shown, the steps increase approximately 20-25 nm each time. The surface roughness is determined to be 100-150 Å and, therefore, it is difficult to assess the servo's actual resolution from this early data. Typically, an approximate 50 Å surface finish is generated by a DTM. Initial performance testing revealed excessive tool tip wear. Future investigations aim to reduce tool tip wear for optimal servo performance. Additionally, current measurements indicate a rather large overshoot. This may be minimized by changing the settings in the PID controller. Initial results represent the first cutting tests generated by the servo. Thus, results shown are far from optimized and it is envisaged that more definitive performance measures will be presented in the near future.

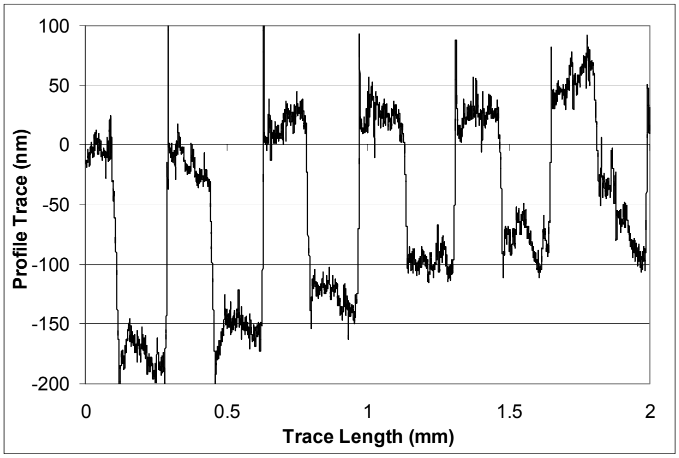

Figure 3.1: Steps machined into the face of an aluminum specimen

References

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[i] Lindsey K., Smith S.T. and Robbie C.J., 1988, Sub-nanometer surface texture and profile measurement with 'Nanosurf 2', *Annals of the CIRP*, **37**, 519-522

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