Machining of Freeform Optical Surfaces by Slow Slide Servo Method
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Introduction
In recent years a significant amount of work has been accomplished in the area of freeform optical surface generation. Most of this work is driven by market demand for these types of surfaces, which currently includes eyewear, electro-optics, defense, automotive, and others. Presently there are several methods to manufacture such surfaces of which the most common ones are grinding and fly cutting. Both grinding and fly cutting rotate the tool and traverse either the tool or part in three linear axes to cut the surface. Grinding and fly cutting can produce very accurate surfaces but require long machining cycles and are difficult to set-up. Another method of fabrication is the fast tool servo (FTS), which is widely used in the contact lens industry. Some of the work on FTS dates back to 1980’s, Meinel [1] was able to successfully produce phase corrector plates, and Luttrell [2] produced off-axis conic surfaces and tilted flats with the FTS. However, the FTS system has travel limitations; most systems have a maximum travel range under 1mm.

This paper presents an alternative method of freeform optical surface fabrication, the Slow Slide Servo. The Slow Slide Servo is similar to the FTS in that, the part is mounted on the spindle and as it rotates the tool oscillates in and out to produce a surface. Unlike the FTS method this system does not use any additional axes to oscillate the tool; the Z-axis slide generates the oscillations. Another difference is the spindle position control or C-axis. In an FTS set-up the spindle has an encoder that feeds the position to the FTS unit without putting the spindle in position control. In a Slow Slide Servo all axes are under fully coordinated position control. The Slow Slide Servo can oscillate at ranges in excess of 25mm, it is easy to set-up, it is inexpensive, and it can produce very accurate parts.

System Specification
To implement the Slow Slide Servo method several key features must be available on the diamond turning lathe. Most of these features are the same for both the linear and the rotary axes. They include friction free bearings that generate little heat, direct drive motors with no mechanical compliance between the motor and the feedback system, high-resolution encoders, and minimal structural dynamics in the control loop. Another key feature is the control system or CNC. The CNC must have high-speed data processing, look-ahead capability, a high-resolution data acquisition system and high-order trajectory generation.

The Moore Nanotechnology 350UPL was used for the work presented in this paper. This diamond turning lathe has a T-shape configuration with the spindle mounted on the X-axis and the tool on the Z-axis. The spindle can operate in two separate modes, velocity mode and position mode. The spindle is used in velocity mode for typical axisymmetric diamond turning work with a maximum speed of 6,000 RPM. In the position mode the spindle uses an optical encoder to close the position loop. The same actuator motor and amplifier is used for both configurations. The resolution of the encoder and its electronics is 0.063 arc-seconds or 20,480,000 counts/rev. The C-axis positioning accuracy is +/- 2 arc-seconds. In this mode the spindle can operate at a maximum speed of 2,000 RPM. In order for the machine to operate as a Slow Slide Servo careful analysis of the position loops is required.

Axes Performance
A key requirement for the success of the Slow Slide Servo is the implementation of high closed position loop bandwidth on all axes. The bandwidth of a system is an indication of how well the system will respond in the time domain [3]. A system with low position loop bandwidth will have a sluggish response and will also exhibit a large time delay between the commanded position and the actual position. This time delay is an indication of phase shift. An ideal system would have zero phase shift.
A block diagram of the C-axis control loop is shown in Figure 1. The diagram shows a PID (Proportional-Integral-Derivative) loop with velocity and acceleration feedforward. The block containing \( \frac{B(s)}{A(s)} \) is the transfer function between the amplifier command and the encoder output.

\[
\frac{B(s)}{A(s)} = \frac{K_P (1-z^{-1})}{(1-z^{-1})} + K_I + K_vff (1-z^{-1}) - K_a (1-2z^{-1}+z^{-2}) - 2
\]

Where

- \( K_P \): Proportional Gain
- \( K_vff \): Velocity Feedforward Gain
- \( K_I \): Integral Gain
- \( K_a \): Acceleration Feedforward Gain
- \( ZOH \): Zero-Order-Hold
- \( \frac{B(s)}{A(s)} \): Open Loop Transfer Function

**Figure 1.** C-axis overall block diagram.

This transfer function includes motor and amplifier electrical dynamics and all associated structural dynamics in the spindle (shaft, encoder, and motor...). The PID loop is tuned for the highest gain values. Figure 2 shows the closed position loop transfer function of the system. The transfer function indicates that the system has a 170 Hz bandwidth (Measured at –3db crossing). Further, it shows that no significant modes exist in the spindle structure below 1000 Hz. The first destabilizing mode is at 1100 Hz, which is well attenuated with a second order low pass filter. Overall the transfer function shows that the system behaves like a second order system.

**Figure 2.** Closed position loop transfer function.

The phase plot shows that the system has zero phase up to a frequency of 10 Hz, after that the phase starts decreasing. Zeroing the phase across the entire bandwidth is a very challenging task, because
a causal system cannot have zero phase. To correct for the inherent phase lag, feedforward terms must be added (Figure 1). The feedforward terms will minimize the tracking error or the time delay between the commanded and actual position by altering the trajectory generation. The velocity and acceleration terms modifies the velocity and acceleration profile of the commanded trajectory. This reduces the tracking error to near zero.

Since the system is a direct drive without any mechanical advantage, all the stiffness has to come from the electrical dynamics. Measuring the static compliance of the system shows that it is infinitely stiff. This is due to the integral term in the PID loop. The integral gain corrects for any static error. The dynamic compliance in Figure 3 shows the system compliance at any particular frequency. The system stiffness is below 1 arc-sec/in-lbs. for up to 10 Hz. The worst stiffness occurs at the natural frequency and is less than 2.5 arc-sec/in-lbs.

Furthermore, the C-axis was commanded five step moves in both the negative and positive direction to show its response to small step commands. Figure 4 shows the response to quarter arc-second commands.

The X-axis and Z-axis of the machine have comparable performance to the C-axis. They both have a 100 Hz position loop bandwidth. In addition optimized acceleration and velocity feedforward gains are added to minimize tracking errors.

**Machining Results**
Several different freeform surfaces have been machined using the Slow Slide Servo to show the viability of this type of machining. One example of these surfaces is the cubic phase plate shown in Figure 5. This part was machined using Zinc Sulfide with a negative rake diamond tool. The sag of the surface is 100µm PV. The form results shown in Figure 6 indicate that the PV error is 0.26µm and the surface finish shown in Figure 7 averages a roughness of 4.6nm.

A second example is the machining of an off axis sphere. A 75mm diameter 6061 aluminum concave sphere with a 75mm radius is offset from the spindle center by 7.686mm. The sphere is then cut with a 1.5mm radius diamond tool. The maximum oscillation of the Z-axis is approximately 11mm. The form results of the sphere are shown in Figure 8. It shows that the sphere form accuracy is 0.33µm PV. The finish result shown in Figure 9 has a roughness average of 5.6nm. Several other surfaces have been machined including tilted flats, progressive lenses, cylinders, torics, and biconics in a variety of materials. They all showed comparable form and finish results to the above samples.

**Conclusions**
Most of the machining tests performed with the Slow Slide Servo indicates that it is a very viable method for producing freeform surfaces. Surface finish and form accuracy results are comparable to
axisymmetric diamond turning results. In addition, this method is inexpensive, does not have sag limitations, is very accurate, and is easy to set-up.

**Figure 5.** Surface of cubic phase plate.

**Figure 6.** Phase plate form accuracy results.

**Figure 7.** Phase plate surface finish results.

**Figure 8.** Off-axis sphere form results, PV-0.333µm, rms-0.047µm.

**Figure 9.** Off-axis sphere finish results, Ra-5.455nm, rms-6.753nm.

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**References**