Principles and Applications of the Slow Slide Servo

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Abstract

Slow Slide Servo is a novel machining process capable of generating freeform optical surfaces or rotationally non-symmetric surfaces at high levels of accuracy. In able to achieve good results with this technology some key parameters need to be satisfied. These parameters include tool path generation, tool radius correction, machine set-up, servo system performance, and the CNC (Computer Numerical Control) computing capabilities. This paper will discuss some of the parameters that allow for good slow slide servo results and include recent experimental form and finish results on several different freeform surfaces.

Introduction/Background

With advances in optical design and the advent of advanced ultra precision machining systems freeform optical surfaces are now a practical solution to many problems. These freeform surfaces are today used in many applications including eyewear, electro-optics, defense, automotive, and others. Although these surfaces are referred to as freeform most of them in fact are mathematically determinant. These non-symmetrical surfaces include torics, biconics or bi-ashperics, phase masks, NURBS defined surfaces, F-theta lenses, progressive lenses, lens arrays, and lenses that require off-axis machining.

Several techniques exist for the manufacturing of freeform optical surfaces. These techniques include micro-milling, raster-cutting or fly-cutting, profile and form grinding and the fast tool servo. The proposed machining technique in this work is similar to the Fast Tool Servo but utilizes the existing machine Z-axis slide (Axis parallel to spindle rotation) as the oscillating axis. This method of manufacturing has proven to be as accurate and faster than most other methods. In this presentation we will discuss the steps required to manufacture parts using slow slide. This will include a machine description, the tool path generation and several examples of machined parts.
Slow Slide Servo

A typical diamond turning lathe consists of two linear axes and a spindle or rotary axis. Both linear axes, X and Z, are position controlled. The rotary axis is velocity controlled but in the case of the slow slide the rotary axis, or spindle axis, is position controlled. All three axes are then commanded by a CNC program to continuously contour in 3D. In typical machine tools 3D machining is performed using 3 linear axes, X, Y and Z (Cartesian Co-ordinate System). In slow slide we are performing 3D machining in Polar or Cylindrical co-ordinates. The XYZ are translated into R, Z and θ.

In slow slide servo as well as fast tool servo the z position is a function of not only x-axis but also the work spindle position or c-axis. A diamond tool is mounted along the z-axis of a lathe and the part with the freeform surface or non-symmetric surface is mounted on the work spindle. As the part rotates, the z-axis carrying the diamond tool oscillates in and out in a sinewave type motion to generate the surface. In a FTS the diamond tool is mounted on an auxiliary axis that is optimised to perform sinewave type oscillations, typically a piezo-electric stack or a voice coil motor, drives this auxiliary axis. The slow slide servo does not require any additional or auxiliary axes utilising only the existing diamond turning lathe’s z-axis, as the oscillating axis. The z-axis is driven in translation by a linear motor optimised to drive the z-axis and diamond tool in a sinewave type motion varying in amplitude and frequency. Depending on the amplitude of the sinewave, frequencies up to 60 Hz can be obtained. The c-axis is simply an additional axis in the machine co-ordinate system. This axis rotates the work piece about the z-axis, and is position controlled to very high accuracy. The position loop bandwidth of the c-axis, which is a measure of system performance, is typically above 120Hz.
Machine Description

- X-Axis
- Spindle C-Axis
- Z-Axis (Oscillation)
- Workpiece
- Tool-Holder/Tool
Several steps have to be completed to produce a freeform optical surface using slow slide servo. The block diagram below show these steps. The optical design engineer usually provides a drawing of the surface along with an optical equation that describes the surface. In some cases the design is based on NURBS (Non-Uniform Rational B-Splines) so a 3D CAD model is required for these surfaces. The first step is to analyze the surface and decide whether it is possible to generate it using slow slide servo. That includes checking the surface slopes; extremely steep parts are not possible to machine due to the interface between the cutting edge of the diamond tool and the work piece surface. In addition it is important to determine the tool sweep required and the maximum allowable tool radius. The second step is to design the fixture to mount the part on the work spindle or c-axis. During fixture design it is important to keep in mind that in most cases a rotationally symmetric work piece must first be machined utilising the same fixture to establish the correct tool height, tool center and tool radius. The third step is tool path generation.
The Moore Nanotechnology 350UPL was used for this work. This diamond turning lathe has a T-shape configuration with the spindle mounted on the X-axis and the diamond tool on the Z-axis. The spindle can operate in two different modes, velocity mode or position mode. The spindle is used in velocity mode for typical axisymmetric diamond turning work with a maximum speed of 10,000 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.
Axes Performance

A PID loop with feedforward compensation is used to control all the machine axes. The feedforward assists in eliminating most of the time delay between commanded and actual position. In other words it reduces the phase lag in the system.

C-axis
Bearing Type: Groove compensated air bearing
Motor: Rotary brushless DC motor
Travel: 360 degrees
Feedback: Rotary optical encoder
Resolution: 0.063 arc-sec (20,480,000 cts/rev)
Position Loop Bandwidth: >100Hz
Feedback Loop: P-I-D with feedforward

X-axis/Z-axis
Bearing Type: Fully constrained hydrostatic bearing
Motor: Linear brushless DC motor
Travel: 350mm/300mm
Feedback: Holographic linear scale
Resolution: 0.034nm (34 pico-meters)
Position Loop Bandwidth: >100Hz
Feedback Loop: P-I-D with feedforward

Control Loop Strategy

PID Loop with Feedforward Compensation

Rotary axis Closed position Loop Bandwidth
Tool Path Generation

Tool path generation for freeform surface is probably the most complex step in the slow slide servo process. As mentioned earlier, the surface is usually defined by an optical equation. This equation must be specified as a function in cylindrical coordinates $Z = \text{function}(r, \phi)$ where $r$ is the radius or the machine's x-axis and $\phi$ is the work spindle angle or c-axis position. Therefore, equations defined in Cartesian coordinates as $Z = \text{function}(X, Y)$ need to be converted to cylindrical coordinates. There are multiple ways to create the $r$ and $\phi$ points before solving for $z$. The $c$ points or $\phi$ can be made from equally spaced chords or equally spaced angles. Usually equally spaced angles yield better results. After the $r$ and $\phi$ points are determined they are used to solve the function for each of the $z$ points. The next step in tool path generation is the tool radius compensation. The surface slopes of the non-rotationally symmetric surfaces are not only dependent on changes in the radius $r$ but also on changes in the angle $\phi$. Slope calculations are required at every $z$ point. The slopes can be computed using two methods; the first method is the differentiation of the data points and the second method is the differentiation of the equation, $Z = \text{function}(r, \phi)$. The equation differentiation has been proven to be the more accurate solution, however it is the more difficult one to compute. If the optical surface is generated using NURBS the tool path is better computed using an off the shelf CAM (Computer Aided Manufacturing) software. CAM systems usually don't provide the same level of accuracy as obtained by solving an optical design equation, because they try to fit non-uniform splines to the surfaces and there are errors associated with these fitting functions.

Once the $z$, $x$, and $\phi$ data points are generated they are written to the NC file (The machine input file). The NC file is then executed. Unlike regular machining it is been found that to produce more accurate parts it is better to machine the part in inverse time G93 rather than mm/min G94. The reason behind this is inverse time allows the program to run with a variable velocity or axis feed rather than a fixed velocity. This variable velocity programming generates more accurate sine waves, while fixed velocity distorts the sine waves the machine is trying to perform.
Experimental Results

Several freeform surfaces are described below to illustrate the slow slide servo capabilities. The results of these surfaces are shown on the following pages.

• **Surface #1: De-centred sphere.** The part is an aluminium sphere with a 75mm diameter and a 75mm concave radius it 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 finish cycle on this part is about 30 minutes. A Zygo GPI laser interferometer is utilized to qualify the form accuracy of the surface.

• **Surface #2: Toric.** The two radii of the toric are 25mm and 75mm. A standard toric equation is used to calculate the Z points for the surface and the tool compensation was generated by differentiating the data points. The surface is machined in electroless-nickel with a 1.0mm radius tool and a spiral infeed of 2.5 microns per revolution. A Taylor Hobson Form Talysurf instrument was used to qualify the form accuracy of the surface. The surface is measured in two meridians 0 and 90 degrees, which correspond to the 25mm and the 75mm radii of the toric surface.

• **Surface #3: Cubic Phase Plate.** This part was machined in Zinc Sulfide. The diamond tool radius is 0.6mm and the rake angle of the tool is negative 25 degrees. The sag of the surface is 100µm PV. The part was machined in about 25 minutes. The form accuracy of the part was qualified using a Panasonic UA3P profilometer.

• **Surface #4: Zernike defined Surface.** This surface was designed using a Zernike equation. The same equation is then used to generate the tool path for slow slide servo. The surface was then machined in plastic (PMMA) using a 0.5mm radius diamond tool. Because the surface sag is small the form accuracy was measured using a laser interferometer with a reference flat. Although it was possible to measure this surface it was very difficult to analyze the surface for form accuracy from the laser interferometer measurement.

• **Surface #5: Sinewave Surface.** This surface was generated using a mathematical equation. The same equation is then used to generate the tool path and cut the part in electroless-nickel. The form was measured using a laser interferometer, but analysis of the form was not performed.
Surface #1: De-Centered Concave Sphere

Diameter: 75mm, Off-axis Distance: 19.4mm, Finish Machining Cycle: 30 minutes

Concave Radius: 75mm, Sag: 10mm PV

Form Accuracy:
PV-error 0.342 µm

Surface Finish:
5.696nm Ra
Surface #2: Toric Surface

Form Accuracy: (at 0 degrees) 0.088\(\mu\)m PV

Form Accuracy: (90 degrees) 0.086\(\mu\)m PV

Surface Finish: 3.530 nm Ra
Surface #3: Cubic Phase Plate

Surface Equation: \( Z = 0.025 \left( \frac{X}{10} \right)^3 + \left( \frac{Y}{10} \right)^3 \)

Material: ZnS (Zinc Sulfide)
Tool: 
- Material: Diamond
- Rake Angle: -25º
- Tool Radius: 0.6 mm
Feedrate: 7 mm/rev

Form Accuracy: 0.263 \( \mu \)m PV

Mathematical representation of the surface

Surface Finish: 4.756 nm Ra
Surface #4: Zernike described Surface

Zernike Design

Tool Path Generator

Laser Interferometer Measurement

Laser Interferometer 3D map

Surface Finish: 4.803 nm Ra
Surface #5: Sinewave Surface

Mathematically Generated Sinewave in the X and Y direction. The PV of waves is 8 µm

The surface imported in the Tool Path Generator

Measured on a Laser Interferometer

Photograph of the Surface
Conclusion

We have briefly described the processes required to, and illustrated the capability of, the slow slide servo to produce freeform optical surfaces. In general good form accuracy can be achieved on most freeform surfaces using slow slide servo technology. Qualifying the form accuracy of freeform surfaces is a difficult task. This is primarily due to the fact that there is no cost-effective commercially available metrology equipment capable of freeform measurement.