Machining of Freeform Optical Surfaces by Slow Slide Servo Method

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Motivation

- Provide a simple cost effective method to produce freeform optical surfaces
- Minimize the amount of axes and equipment
- Simple tool set-up
- Simple part set-up
- Simple CNC programming
- Improve surface finish
- Improve form accuracy
- Reduce machining cycle time
Examples of Freeform Surfaces

Grinding Application

Automotive Heads-Up Displays
Finish Cycle: 50hrs. (Large lens)
Finish Cycle: 30hrs. (Small lens)
Courtesy: B-con Engineering

Fly Cutting Application
F-Theta Lenses
Finish Cycle: 20hrs
Manufacturing of Freeform Optics

- **Grinding**
  - Slow machining cycle
  - Un-deterministic process (Wheel Wear)

- **Fly Cutting or Raster Cutting**
  - Slow machining cycle
  - Difficult to set-up
  - Limited by tool swing diameter

- **Fast Tool Servo**
  - Fast machining cycle
  - Limited travel
Slow Slide Servo

- X-Axis
- Spindle
- C-Axis
- Z-Axis (Oscillation)
- Workpiece
- Tool-Holder/Tool

Diagram showing the movement and components of the slow slide servo system.
Key Requirements for Slow Slide

- Two linear axes X and Z
- Position controlled spindle or C-axis
- Direct drive motors on all axes
- Friction free bearings on all axes
- Low heat generation from motors and bearings (Air or liquid cooling)
- High resolution feedback systems
- High bandwidth closed position loops

CNC requirements
- High speed data processing
- Look ahead capabilities
- High order trajectory generation
Diamond Turning Lathe

- Two Linear axes
  - Hydrostatic bearings
  - Air cooled linear motors
  - 8.6nm feedback resolution
  - 100 Hz position loop bandwidth

- Open Architecture CNC
  - Look ahead capabilities
  - High order trajectory generation
  - High speed servo loop
  - Unlimited file size
Spindle / C-axis

- Groove compensated air bearing (Liquid cooled)
- Integrated motor (Liquid cooled)
- Integrated encoder: 20,480,000 counts/rev (0.06 arc-sec)
- Max. speed in position mode 2000 RPM
- No structural dynamics between command and response below 1000 Hz
C-axis Block Diagram

\[
\begin{align*}
\frac{B(s)}{A(s)} & : \text{Open Loop Transfer Function} \\
\text{Where -- } & \quad K_P: \text{Proportional Gain} \quad K_{vff}: \text{Velocity Feedforward Gain} \\
& \quad K_i: \text{Integral Gain} \quad K_{aff}: \text{Acceleration Feedforward Gain} \\
& \quad K_D: \text{Derivative Gain} \quad \text{ZOH: Zero-Order-Hold} \\
\end{align*}
\]
Closed Loop Transfer Function

- 170 Hz Closed position loop bandwidth
- No phase shift up to 10Hz
C-axis Compliance

- 1 arc-sec/in-lb from 0 to 10 Hz
- 2.25 arc-sec/in-lb
1/4 Arc-Second Step Moves

![Graph showing position over time for 1/4 Arc-Second Step Moves. The x-axis represents time in seconds, ranging from 0 to 6, and the y-axis represents position in Arc-Seconds, ranging from -0.2 to 1.4. The graph displays a series of steps, each representing a movement of 1/4 Arc-Second, with noise visible.]
Cutting Tests

- **De-Centered Concave Sphere (6061 Al)**
  - Diameter: 75mm, Concave Radius: 75mm
  - Off-axis Distance: 19.4mm, Sag: 10mm PV
  - Finish Machining Cycle: 30 minutes

- **On-axis Tilted Flat (6061 Al)**
  - Diameter 50mm, Tilt Angle 2.25 Degrees
  - Sag: 2mm PV
  - Finish Machining Cycle: 30 minutes

- **Cubic Phase Plate (ZnS)**
  - Size: 20mm X 20mm
  - Sag: \(\sim 100 \, \mu m\) PV
  - Finish Machining Cycle: 21 minutes
De-Centered Sphere - Form Results

PV-error 0.342 μm
De-Centered Sphere - Finish Results

Actual Ra: 5.696nm, Theoretical Ra: 4.6nm
Tilted Flat - Form Results

PV-error 0.259 µm
Tilted Flat - Finish Results

Actual Ra: 2.711 nm, Theoretical Ra: 2.0 nm
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: -25°
  - Tool Radius: 0.6 mm
Feedrate: 7 \( \mu \text{m/rev} \)

Mathematical Representation of the Cubic Phase Plate Surface

Interferometric Representation of the Cubic Phase Plate Surface
Cubic Phase Plate - Form Results

Form Error: 0.263 μm
Cubic Phase Plate - Finish Results

Slow Slide Servo Results
Ra: 4.756nm

Typical Polishing Results
Ra: 4.278nm
Future Work/Questions

- Improve form accuracy to less than 0.2 \( \mu \text{m} \)
- Machine different surfaces
- Understand cutting mechanics

Questions?