DIAMOND TURNING OF TEXTURED SURFACES USING FAST TOOL SERVO SYSTEM

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Outlines

- Background of diamond turning using FTS
- Aims of this work
- Design and evaluation of FTS
- Machining test using FTS
- Conclusions
Background of diamond turning with FTS

- **Fast Tool Servo (FTS)**
  - An auxiliary servo module of the tool holder with an actuator that oscillates the tool at a particular bandwidth.
  - FTS System is used in a variety of the diamond turning applications.
Background : Motivation

✓ Technological trends of micro machining using FTS

- Rising luminance of display as concentrating light through diffuser sheet vertically with light condensing function of prism and micro lens. (LMS Co., LTD)

  • light condensing of micro lens => luminance up

✓ Technologies ;
  ▪ How to manufacture master roll using FTS, **efficiently**.
    - High bandwidth FTS actuated with the effective stroke
  ▪ How to get high machining **accuracy** (form accuracy, surface roughness)
    - FTS errors ; hysteresis, frequency response, etc.
    - Cutting conditions ; tool design, cutting path (CAD/CAM)
Aims

**Purposes of this work**

- Developing FTS System for improving machining accuracy in diamond turning
  - Reducing dynamic errors of FTS (hysteresis, frequency response etc.)
- Finding machining conditions to perform high bandwidth FTS cutting
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Developing fast tool servo (FTS) system for diamond turning

- Designing the various leaf springs of FTS actuated by PZT.
- Investigating the hysteresis and the stroke of FTS for designed models.

<table>
<thead>
<tr>
<th>Type</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>895Hz</td>
<td>1150Hz</td>
<td>2074Hz</td>
<td>12179Hz</td>
</tr>
<tr>
<td>B</td>
<td>1873Hz</td>
<td>2615Hz</td>
<td>2703Hz</td>
<td>14483Hz</td>
</tr>
<tr>
<td>C</td>
<td>2489Hz</td>
<td>3592Hz</td>
<td>3669Hz</td>
<td>20033Hz</td>
</tr>
</tbody>
</table>

- Natural frequency: type C > type B > type A
Experimental Setup for testing performances of FTS

✓ The waveforms which was generated in a PC with Lab VIEW S/W were amplified by power Amp. to supply to the PZT actuator.

✓ The corresponding displacement of FTS stroke was measured by a capacitive sensor.

<table>
<thead>
<tr>
<th>Amp - Models</th>
<th>E-472.20(PI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channels</td>
<td>2</td>
</tr>
<tr>
<td>Average output power</td>
<td>110 W</td>
</tr>
<tr>
<td>Voltage gain</td>
<td>100±1</td>
</tr>
<tr>
<td>Output voltage</td>
<td>3 to 1100 V</td>
</tr>
</tbody>
</table>
Peak to peak strokes according to actuating frequencies of FTS

✓ Compared three types of FTS

400V Input (Sinusoidal wave)

Displacement (μm)

Frequency (Hz)
Comparing hysteresis for three types of FTS

![Graph comparing hysteresis for three types of FTS](image)

- **Type A**
- **Type B**
- **Type C**

Displacement (μm) vs. Voltage (V)

1.5μm
Comparison of profile errors between input and output signals of FTS(type C)

Actuating frequency : 10Hz
Input voltage : 400V(Sine wave)

Actuating frequency : 300Hz
Input voltage : 400V(Sine wave)

1.5μm
Comparison of profile errors in triangular and square wave input (type C)

Actuating frequency : 10Hz, Input voltage : 400V

Triangular wave

square wave
Design FTS actuated by dual PZT

✓ Comparing two types of FTS actuated by single and dual PZT
✓ Using lever mechanism to amplify the output stroke of FTS

FTS actuated by single PZT : SFTS
FTS actuated by dual PZT : DFTS

<Schematic diagrams of two types PZT>

Specifications of piezoelectric actuator

<table>
<thead>
<tr>
<th>PZT</th>
<th>Displacement</th>
<th>Blocking force</th>
<th>Stiffness</th>
<th>Capacitance</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-010.40 (PI)</td>
<td>60 μm</td>
<td>2200 N</td>
<td>38 N/μm</td>
<td>260 nF</td>
</tr>
</tbody>
</table>

<Experimental Setup>
Comparison of response characteristics between single and dual PZT actuators

- **Frequency response and step response**

  DFTS: FTS actuated by dual PZT;  
  SFTS: FTS actuated by single PZT

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**Step responses**

- Single PZT
- Dual PZT

500V input

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**Frequency responses**

- Dual PZT
- Single PZT
Response characteristics in new DFTS designed for roll machining

✓ Comparing two types of FTS actuated by single and dual PZT

DFTS

Output stroke of FTS (10 Hz)
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Machining test of mold roll using FTS

Experimental Setup

<table>
<thead>
<tr>
<th>Feed rate 100 μm/rev</th>
<th>f = 1000 Hz</th>
<th>n = 48 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f = 1500 Hz</td>
<td>n = 72 rpm</td>
</tr>
<tr>
<td></td>
<td>f = 2000 Hz</td>
<td>n = 96 rpm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Feed rate 20 μm/rev</th>
<th>f = 1000 Hz</th>
<th>n = 48 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f = 1500 Hz</td>
<td>n = 72 rpm</td>
</tr>
<tr>
<td></td>
<td>f = 2000 Hz</td>
<td>n = 96 rpm</td>
</tr>
</tbody>
</table>

Cutting conditions

<table>
<thead>
<tr>
<th>Wave length(L)</th>
<th>440 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000Hz, 48 rpm</td>
<td></td>
</tr>
<tr>
<td>1500Hz, 72 rpm</td>
<td></td>
</tr>
<tr>
<td>2000Hz, 96 rpm</td>
<td></td>
</tr>
</tbody>
</table>
Results of micro patterning on mold roll surfaces (Type A)

- Patterns machined by various cutting conditions

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>48</td>
</tr>
<tr>
<td>1500</td>
<td>72</td>
</tr>
<tr>
<td>2000</td>
<td>96</td>
</tr>
</tbody>
</table>

Feed rate:
- 100μm/rev
- 20μm/rev
Evaluating of pattern profiles machined on mold roll surfaces

✔ UV-casting process

Patterned film by imprinting process

Conditions of UV-casting

<table>
<thead>
<tr>
<th>Resin</th>
<th>UV resin</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Film</strong></td>
<td>290 x 210 mm Thickness: 100 μm</td>
</tr>
<tr>
<td><strong>Time (UV light applied)</strong></td>
<td>5 min</td>
</tr>
</tbody>
</table>
Pattern profiles transferred by UV film casting

- Input Voltage 500V, FTS 1500 Hz, spindle speed 72rpm, feed rate 100μm/rev
- Wavelength 440 μm, Depth of cut 14 μm

![Profile Comparison Image]

- Measured profile
- Sine wave (given input profile)
- Profile errors
Evaluating machined patterns at each actuating frequency

Input voltage 400V (Sinusoidal wave)
-●- FTS, type C (disk leaf spring)

- Irregular patterns at near 2kHz and 4kHz due to uncontrollable vibration.
Deformed profiles caused by conditions of FTS cutting

✓ Selection of tool clearance angle

- \( \theta > \theta_c , \theta_c = \arctan \left( \frac{2H}{L} \right) \)

\( \theta \): the clearance angle of tool
\( \theta_c \): the tangential angle of input wave
\( H \): the amplitude of profile; depth of cut
\( L \): the wavelength of profile

✓ Ex.) Height, \( H = 5\, \mu m \), Wavelength, \( L = 100\, \mu m \).
Clearance angle of tool, \( \theta \geq 6 \) degrees.

Specifications of diamond tool

- Tool material: Diamond
- Clearance angle: 5 degrees
- Nose angle: 90 degrees

Microscope imagine

<table>
<thead>
<tr>
<th>Line</th>
<th>Min((\mu m))</th>
<th>Max((\mu m))</th>
<th>Mid((\mu m))</th>
<th>Mean((\mu m))</th>
<th>Ra((\mu m))</th>
<th>Rz((\mu m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>0.003</td>
<td>1.553</td>
<td>0.778</td>
<td>0.700</td>
<td>0.292</td>
<td>0.059</td>
</tr>
</tbody>
</table>

Extrapolated profile
Machining test to investigate deformed profiles

✓ Deformed profiles according to the variation of wavelengths

- L = 33.3 μm
- L = 25 μm
- L = 20 μm
- L = 10 μm
Bur formation due to plastic deformation of machined structure

<Cutting conditions>
FTS: 100Hz
Wave length, L=25μm
Clearance angle of tool, θ=5 degrees
Depth of cut, H= 5μm

✓ Machining region: without bur
Plastic deform region: bur formation

L=10μm
Conclusions

- A prototype of FTS system with PZT actuator was developed for diamond turning applications.
  - Experiments to describe the hysteresis behaviors of FTS were performed.
  - The hysteresis nonlinearity of FTS must be compensated by feed back control in low bandwidth of FTS.
  - DFTS with dual PZT actuators showed better tracking performances and longer travel range than SFTS with single PZT actuator.
- Microstructures on mold roll surfaces were manufactured in diamond turning using FTS system.
  - It is necessary to select suitable tool shape according to given cutting conditions (especially, clearance angle of tool) in order to fabricate desired profiles.
Thank you for your attention !!!