On-Machine Dimensional Measurement Technology for Prognostics and Health Monitoring for Precision Manufacturing Systems and Processes

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OMM: On-Machine Measurement
LAM: Laser-Assisted Machining
BRDF: Bidirectional Reflectance Distribution Function

OMM: Manufacturing Process Monitoring

- **Spindle metrology**
- **Machined surface OMM; BRDF meas.**
- **Cutting temp measurement**
- **Cutting tool wear monitoring**
- **LAM & its process monitoring**
- **Fast tool servo**

Grating interferometry, motion error, positioning control
Outlines

Part A. Introduction: On-Machine Measurement (OMM)

Part B. Current Research

a. Machined Surface Measurement #1
b. Machined Surface Measurement #2
b. Cutting Tool Wear Monitoring
c. Spindle Metrology
d. Conclusion
Part A. Introduction: OMM
Ultraprecision Technology: Machining

Automotive display

Aspheric lens

F-θ lens

Fresnel lens

Reflected to www.jtekt.co.jp
Cosine Error in Freeform Optics Metrology

Measurement results obtained by instruments: (a) nomarski microscope (Olympus), (b) laser scanning microscope (LSM, Keyence), (c) white light interferometry microscope (WLIM, Zygo), (d) scanning electron microscope (SEM, Hitachi) and (e) form talysurf (Taylor Hobson).
# Current Measurement: Postprocessing

<table>
<thead>
<tr>
<th>Measure</th>
<th>Contact</th>
<th>Non-contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantage</td>
<td>-High accuracy</td>
<td>-High speed, immune to measuring force</td>
</tr>
<tr>
<td>Disadvantage</td>
<td>-Easy to make the surface damage</td>
<td>-Difficulty to align the optical axis</td>
</tr>
<tr>
<td>Instrument</td>
<td>-LVDT, Stylus</td>
<td>-Interferometer, Confocal</td>
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</tbody>
</table>
Current Measurement: OMM

Spindle

Z-axis

X-axis

LVDT

Form error

Compensation Machining

Current Measurement: OMM
What to Measure by OMM Tools?

- Form error
- Cutting tool wear
- Cutting temperature
- Positioning or motion
- Spindle runout
- Machine vibration
- Cutting tool axis stiffness
- ...

OMM expensive?
Part B. Current Research

a. Machined Surface Measurement #1
Problem: Cosine Error in Measurement

Machining \leftrightarrow Measurement

NC-controlled trajectory

CMM Probe

Freeform surface

Lensed fiber

NC controlled path
Experiment

Autofocusing

Fizeau interferometry
Results

Autofocusing Method

Fizeau interferometry
Part B. Current Research

b. Machined Surface Measurement #2
Cosine Error Elimination by Using Spindle
Rotational and Spindle Error Separation

Artifact
Capacitive Sensor
Air Spindle

Radial Standard Deviation $\sigma_R = 0.217 \mu m$
Peak to Valley $PV_R = 0.786 \mu m$

Angular Standard Deviation $\sigma_S = 0.081 \mu m$
Peak to Valley $PV_S = 0.298 \mu m$
Concave/Convex Mirror Measurement

ΔR

R100 mm

87 mm

Z

Z=0

R=95 mm

87 mm
Bearing Inner/Outer Surface Profiles

Koyo 51211 Thrust Bearing

-70° R45 mm +70°

-70° R27.5 mm +70°
OMM System Integration for Freeform Surface Metrology
Part B. Current Research

c. Cutting Tool Wear Monitoring
Motivation

Roundness within 50 nm

How do we measure damage size?

[*] Frederick Winslow Taylor, On the Art of Cutting Metals, American Society of Mechanical Engineers, 1907.
Principle: Edge Diffraction

Interferogram

Displacement [μm]
Time [s]

I
F

Gaussian

Roughness \( \sigma \)

Transmitted field

Diffracted field

Detector

\( h \)

OKE

\( x_0 \)

\( y_0 \)

\( x_d \)

\( y_d \)

\( z_0 \)

\( z_d \)

16/27
Method: Cross-Correlation

\[ f(y) \otimes g(y) = \int f(\tau)g(y - \tau)d\tau \]

Hypothesis 1

Hypothesis 2
Cutting Tool Wear Calibration

(a) Normalized Output vs Time (s)

(b) Similarity R vs Number of machining

Sensitivity
5.62/wear(μm)

Sensitivity
1.14E-3/# of machining
Can we separate wheel wear from spindle runout?

Spindle motion + Roundness + Roughness

~0.3µm
Fringes: Cross-correlation

\[ [\text{lag}, r] = \text{CORR}(f, g) \]

**Hypothesis 1:** Attrition wear relates with lag.
**Hypothesis 2:** Abrasive wear relates with \( r \).

When do we need truing or dressing?
Wear Characteristics v.s. Edge Conditions

![Graph showing wear characteristics vs. edge conditions](image)

Scanning Length [μm]

APD Output [V]

- Ref.
- Attrition
  - +Abrasive
  - +Chipping

110 μm

(a) Ref., (b) Attrition + Abrasive, (c) Attrition + Abrasive + Chipping
Part B. Current Research

d. Spindle Metrology
Spindle Metrology

Reversal method: (a) measurement at $\theta=0^\circ$, (b) measurement at $\theta=180^\circ$, and (c) errors, $R(\theta)$ in red and $S_x(\theta)$ in purple.
Research Objective

Capacitive sensor for curved surface measurement?

(a) Conducting wires
Insulator
Guard electrode
Ground
Current path
Target
Measuring spot size

(b) Sensing electrode
Radius of Curvature [mm]
Sensitivity [mV/μm]
CS_Measured CS
Principle: Curved Edge Diffraction

Reflected wave

Transmitted wave

Plane wave

Spindle shaft

Interferogram

Detector

Diffracted wave

Ultraprecision-machined

Generally-machined

Normalized Output

Time (s)

Normalized Output

Time (s)
Sensor Characteristics

- Refracted wave
- Transmitted wave
- Interferogram
- Detector
- Plane wave
- Spindle shaft

Graphs showing displacement and scanning distance.
Experiment: Spindle Dynamic Char.

- Sensitivity: Z = 0.199, Y = 0.189
- Standard error: Z = 7.97E-4 (0.40%), Y = 6.72E-4 (0.35%)

Graphs showing CES output vs. CS displacement at 3000rpm and 9000rpm.

Diagram: Optical setup with components such as Prisms, BS, PDs, He-Ne laser, and electronic components like Amplifiers, Adders, Subtractors, and Dividers.
Dynamic System Identification

Stationary

(a) Displacement $r_1$ [µm]

(b) Displacement $r_{10}$ [µm]

3000 rpm

(a) detail

(b) detail

Displacement $r_1$ [µm]

Displacement $r_{10}$ [µm]

56Hz

680Hz

(a) Stiffness [N/µm]

(b) Damping ratio

Spindle Speed [rpm]

Spindle Speed [Hz]

(shaft+bearing) $M_s$

$F(t)$

$K_L$

$C_L$

$K_A$

$C_A$

$r$