Progress of a cross-correlation based optical strain measurement technique for detecting radial growth on a rotating disk

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Outline

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• Motivation for novel strain measurement techniques
  – Strain, current techniques, impact of strain
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• Motivation for proof-of-concept study
• Brief PIV basics
  – Setup, Processing, Optimization
• Proof-of-concept Experiment
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• Implementation onto simulated turbine disk
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  – Setup
  – Preliminary results of thermal growth detection
• Conclusions & Future Work
• Acknowledgements
Introduction

- NASA is interested in the development non-intrusive strain measurement technologies for gas turbine engines and their components.
- Optical surface measurements for internal parts of a flow, such as engine turbine disk.
- Rotating turbine engine disks operate in harsh environmental conditions and are exposed to repeated thermal and mechanical loads.
- Cumulative effects of these external forces lead to high strains.
Motivation - Strain

- Definition: Deformation per unit length of an object

\[ \varepsilon = \frac{L' - L}{L} = \frac{\Delta L}{L} \]

\( \varepsilon = \) normal strain
\( L = \) original length
\( L' = \) new length
\( \Delta L = \) change in length

- Typically measured with strain gages
- Intrusive, not easily implemented on rotating objects
Motivation – Impact of Strain

Strain on an engine turbine disk can lead to a fault, such as a crack, which can lead to catastrophic failure.

Present study investigates a potential optical strain measurement technique that may eventually lead to in situ health monitoring.
Overview – Optical Strain Measurement Technique

• Optical strain measurement technique being investigated offers potential to measure radial growth of a cracked engine turbine disk

• Basic concepts of how the technique works:
  – A high-contrast random speckle pattern applied to the disk
  – Image pattern using CCD camera under static and loaded conditions
  – Under loaded conditions, cracked disk will experience strain causing the disk to grow in radial direction
  – Disk grows thus pattern will “shift”
  – Cross-corrlate before & after shift images using PIV algorithms
  – Results give image displacements, i.e. total growth of the disk
Proof-of-Concept Study

• Motivation / Key Benefits:
  – Rotating disk adds complexity and additional error sources
  – Mimic rotating disk exp. requirements, i.e. FOV, $x_0$, camera, light source
  – FEA predicts radial growth of ~50µm for proposed disk
  – Growth of disk not yet been verified using other experimental techniques
  – Can the technique detect a shift this small? What are it’s resolution limits?
  – Investigate range of resolvable shifts technique can detect
  – Induce a range of known shifts on the pattern
  – Acquire images before and after the induced shift
  – Cross-correlate images in PIV software to measure shift
  – Test multiple patterns for optimization purposes in order to choose most effective pattern
Theory – Particle Image Velocimetry (PIV)

PIV is a technique for measuring the in-plane velocity field of a flow seeded with tracer particles.

Cross-correlation algorithms are used to calculate particle displacement $\Delta x$ between the two closely spaced images in time.
Each image is divided into small sub-regions (1 & 2).
Sub-region 1 is cross-correlated with corresponding sub-region 2.
- Correlation plane peak gives the resulting displacement vector, $\Delta x$.
- Process is repeated over the entire image.
- Results in spatially averaged displacement vectors.
3 guidelines to follow to optimize correlation peak results:

1. Nominally 10 particles per sub-region
2. Maximum expected displacement $\Delta x_{\text{max}} < \frac{1}{4}$th sub-region size
3. Imaged particle diameter $d_e$ spans 1-2 pixels

\[ d_{\text{diff}} = (2.44(1 + M)\lambda f \#)^2 \quad \rightarrow \quad d_e = \sqrt{(d_p M)^2 + (2.44(1 + M)\lambda f \#)^2} \]

**Correlation peak estimation error**

\[ \sigma_{\Delta x} = \frac{d}{N} = \frac{\sqrt{2}d_e}{N} \]

Nominally $\sigma_{\Delta x} = 0.1$ pixel

**Full scale error**

\[ \sigma_u = \frac{\sigma_{\Delta x}}{\frac{1}{4}N} \]

Nominally $\sigma_u = 1\%$
• Induce known shifts of 50 µm, 20 µm, and 10 µm
• Images acquired before and after shift
• Measure image displacement via PIV software
• Process repeated 5x for each pattern test
Background Patterns

Reflective adhesive

FOV ~ 74 mm

Speckled black paint

40-100 µm glass beads
Rule: Imaged particle diameter $d_e$ spans 1-2 pixels
1-2 pixels $\rightarrow$ 18.2 - 36.5 $\mu$m

$d_{diff} = (2.44(1 + M)\lambda f\#)^2$
$d_{diff} = 29.4\, \mu m \rightarrow d_{e_{min}} = 1.6$ pixels

$d_e = \sqrt{(d_p M)^2 + (2.44(1 + M)\lambda f\#)^2}$
d_e < 2 pixels $\rightarrow$ d_p < ~45 $\mu$m

$d_p = 40 - 100\, \mu m \rightarrow d_e \sim 2 - 3$ pixels

Glass bead image
Results: Pattern Development

Rule: Particle displacement < 1/4\textsuperscript{th} sub-region size $N$

Expected $\Delta x_{max} = 50 \, \mu m = 2.78$ pixels

$N = 16$

Rule: Nominally 10 particles per sub-region

Glass beads
Reflective adhesive
Black speckled paint
## Results: Induced Shift

### Experimental Error

<table>
<thead>
<tr>
<th>Shift (µm)</th>
<th>Reflective Adhesive Detected Shift (µm)</th>
<th>Glass Beads Detected Shift (µm)</th>
<th>Black Speckles Detected Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.0</td>
<td>46.86 ± 3.01</td>
<td>46.56 ± 2.47</td>
<td>43.14 ± 6.89</td>
</tr>
<tr>
<td>10.0</td>
<td>6.37 ± 1.43</td>
<td>6.69 ± 2.01</td>
<td>5.77 ± 3.89</td>
</tr>
</tbody>
</table>

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<th>Black Speckles Detected Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.17 ± 2.72</td>
<td>0.38 ± 2.14</td>
<td>0.58 ± 2.89</td>
</tr>
<tr>
<td>0.0</td>
<td>0.13 ± 2.61</td>
<td>0.15 ± 2.14</td>
<td>0.44 ± 2.41</td>
</tr>
</tbody>
</table>

\[ \sigma_{\Delta_x} = 0.17 \text{ - } 0.44 \text{ pixel} \quad \rightarrow \quad 3.22 \mu m \text{ – } 8.08 \mu m \]

Black speckle offset (50.0-µm) \~ 2x reflective adhesive and glass bead offset
## Results: Simulated Shift

### Lower Bound Error

<table>
<thead>
<tr>
<th>Shift (µm)</th>
<th>Reflective Adhesive Detected Shift (µm)</th>
<th>Glass Beads Detected Shift (µm)</th>
<th>Black Speckles Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.54</td>
<td>36.54 ± 0.24</td>
<td>36.51 ± 0.58</td>
<td>34.54 ± 4.72</td>
</tr>
</tbody>
</table>

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<tr>
<th>Shift (µm)</th>
<th>Reflective Adhesive Detected Shift (µm)</th>
<th>Glass Beads Detected Shift (µm)</th>
<th>Black Speckles Detected Shift (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.54</td>
<td>36.54 ± 0.16</td>
<td>36.51 ± 0.67</td>
<td>34.74 ± 4.61</td>
</tr>
</tbody>
</table>

**Black speckle error ~6.5% of full scale**  
**Glass bead error ~0.79% of full scale**  
**Reflective adhesive error ~0.32% of full scale**

**Can detect shift regardless of direction**  
**Radial shift will be a vector**
FEA was performed to estimate expected radial growth for different size notches on a 12.7 mm thick, 254 mm diameter Al disk.
Implementation - Rotating Disk Experimental Setup

NASA Glenn Research Center’s High Precision Rotordynamics Laboratory

- Bearing Assembly
- Heat gun
- Simulated Engine Turbine Disk
- Encoder
- 12 HP Motor
- Dial Indicator
- Thermocouple
- Lens and camera system
Implementation - Rotating Disk Preliminary Results

- More uniform particle distribution
- Better focus $\xrightarrow{}$ smaller $d_e$

Lower bound error $\sim 0.14\%$ of full scale

FOV $\sim 76$ mm

$d_e \sim 2 - 3$ pixels
ΔT = 25.6 ºC
α = 23.6 \times 10^{-6} \text{ m/m ºC}
L = 0.0626 \text{ m}

\[ \Delta L = 0.0405 \text{ mm} = 2.14 \text{ pixels} \]

- Challenge to obtain reliable reference of the thermal growth
- Discrepancy may be result of physical ref. measurement
- Thermocouple placed away from measurement/max growth region
- Higher resolution dial indicator
Conclusions and Future Work

• Proof-of-concept study
  • Validate optical strain measurement technique
  • 3 patterns were evaluated using PIV optimization guidelines
  • Images of each pattern acquired before and after induced shift
  • Particle displacement calculated using cross-correlation algorithms
  • Black speckles had highest error for both induced/simulated shifts
  • Reflective adhesive and glass beads both accurate to < 1% full scale

• Implementation onto rotating disk
  • Implemented glass beads onto cracked simulated turbine disk
  • Induced a shift to the beads via thermal growth of the disk
  • Preliminary results follow expected trend and appear to track growth

• Future Plans
  • Investigate ways to obtain a more reliable reference measurement
  • Develop/implement image registration routine using fiducial marks
  • Rotate disk (12k-15k rpm) and measure radial growth
  • Future refinement will include decreasing $d_e$ to achieve 1-2 pixels
    • Other light sources $\longrightarrow$ smaller f/# $\longrightarrow$ decrease blur circle
Acknowledgements

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