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

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Outline

• Introduction
• Motivation for novel strain measurement techniques
  – Strain, current techniques, impact of strain
• Overview of optical strain measurement technique
• 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

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

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

• 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.
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-correlate before & after shift images using PIV algorithms
- Results give image displacements, i.e. total growth of the disk
Motivation / Key Benefits:

- Rotating disk adds complexity and additional error sources
- Mimic rotating disk exp. requirements, i.e. FOV, \( x_o \), camera, light source
- FEA predicts radial growth of \(~50\mu m\) 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

Proof-of-Concept Study
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.
Theory – PIV Processing

• 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 $\Delta x_{\text{max}} < \frac{1}{4}\text{th sub-region size}$
3. Imaged particle diameter $d_e$ spans 1-2 pixels

$$d_{\text{diff}} = (2.44(1 + M)\lambda f \#)^2$$

$$d_e = \sqrt{(d_p M)^2 + (2.44(1 + M)\lambda f \#)^2}$$

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 $\sigma_u = 1\%$
Experimental Setup – Proof-of-Concept Study

- 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
Results: Pattern Development

Rule: Imaged particle diameter $d_e$ spans 1-2 pixels

1-2 pixels $\rightarrow$ 18.2 - 36.5 µm

\[ d_{diff} = (2.44(1 + M)\lambda f\#)^2 \]
\[ d_{diff} = 29.4 \text{ µm} \quad \rightarrow \quad d_{e_{\text{min}}} = 1.6 \text{ pixels} \]

\[ d_e = \sqrt{(d_pM)^2 + (2.44(1 + M)\lambda f\#)^2} \]
\[ d_e < 2 \text{ pixels} \quad \rightarrow \quad d_p < \sim 45 \text{ µm} \]

\[ d_p = 40 – 100 \text{ µm} \quad \rightarrow \quad d_e \sim 2 - 3 \text{ pixels} \]
Results: Pattern Development

Rule: Particle displacement < $1/4^{th}$ 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>

$\sigma_{\Delta_x} = 0.17 - 0.44 \text{ pixel} \rightarrow 3.22 \mu\text{m} - 8.08 \mu\text{m}$

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

### Lower Bound Error

<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 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 ± 0.24</td>
<td>36.51 ± 0.58</td>
<td>34.54 ± 4.72</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**
Implementation - Rotating Disk Analysis

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
Implementation - Rotating Disk Preliminary Results

- More uniform particle distribution
- Better focus $\rightarrow$ smaller $d_e$

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

FOV $\sim 76$ mm

$d_e \sim 2 - 3$ pixels
Implementation - Rotating Disk Preliminary Results

\[ \alpha = 23.6 \times 10^{-6} \text{ m/m } ^\circ\text{C} \quad \Delta T = 25.6 \, ^\circ\text{C} \quad L = 0.0626 \text{ m} \]

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

- 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 $\rightarrow$ smaller f/# $\rightarrow$ decrease blur circle
Acknowledgements

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