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

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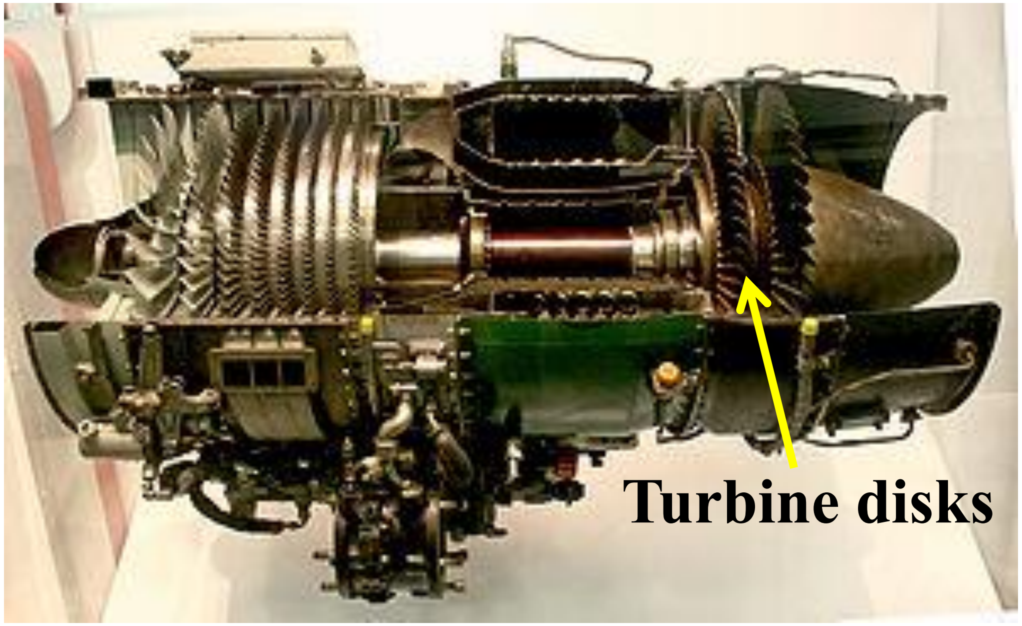
Outline

- 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
  - Setup, Pattern development, results
- Implementation onto simulated turbine disk
  - Analysis
  - 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

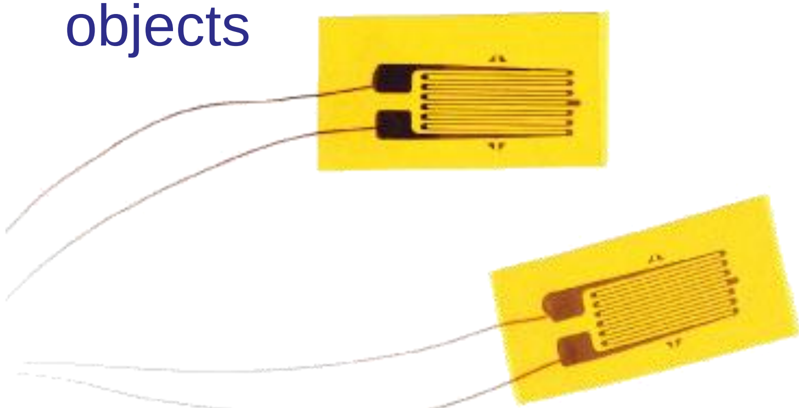
Motivation - Strain

- Definition: Deformation per unit length of an object

$$\varepsilon = \frac{L' - L}{L} = \frac{\Delta L}{L}$$

ε = *normal strain*
L = *original length*
L' = *new length*
ΔL = *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-correlate 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_o, 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

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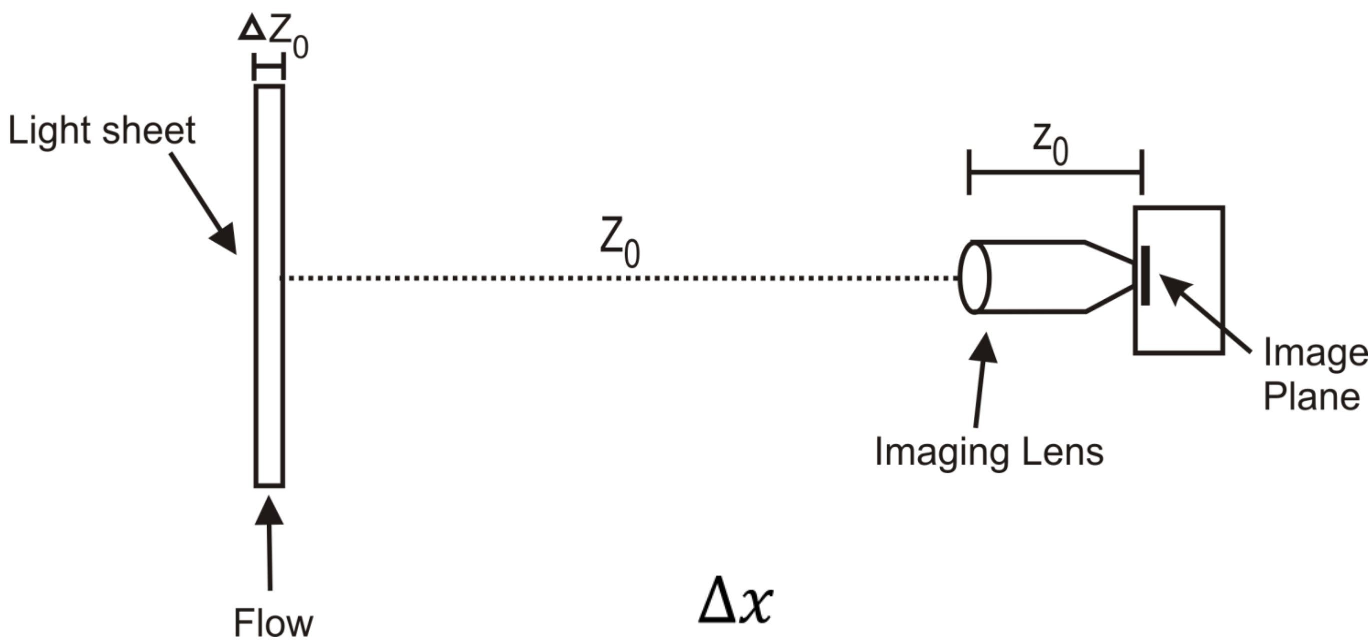
Theory – Particle Image Velocimetry (PIV)

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

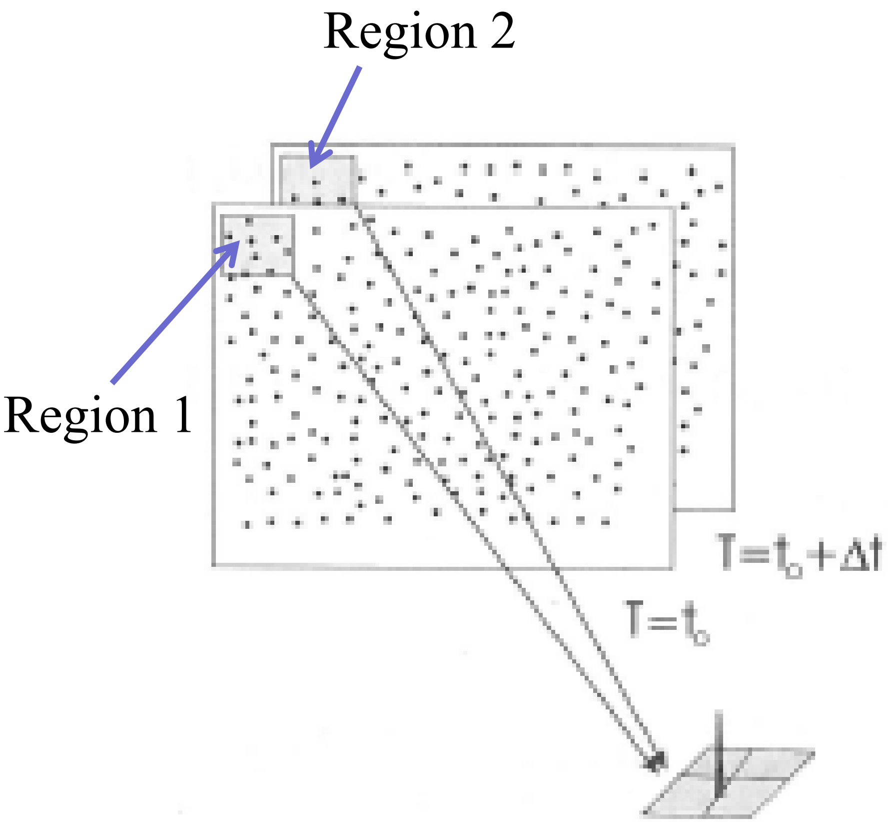


$$v = \frac{\Delta x}{M(\Delta t)}$$

Cross-correlation algorithms are used to calculate particle displacement Δx 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, Δx
- Process is repeated over the entire image
- Results in spatially averaged displacement vectors

Theory – PIV Optimization

3 guidelines to follow to optimize correlation peak results:

1. Nominally 10 particles per sub-region
2. Maximum expected displacement Δx_{max} < 1/4th sub-region size
3. Imaged particle diameter d_e spans 1-2 pixels

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

Correlation peak estimation error

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

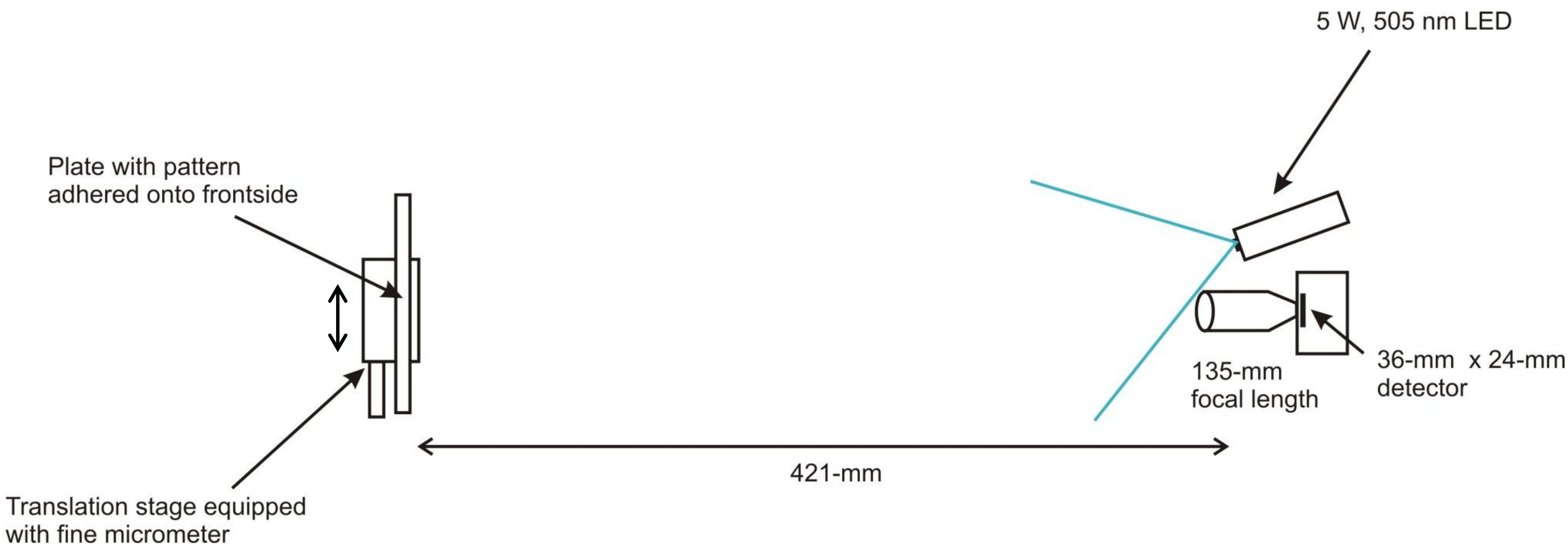
Nominally $\sigma_{\Delta x}$ = 0.1 pixel

Full scale error

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

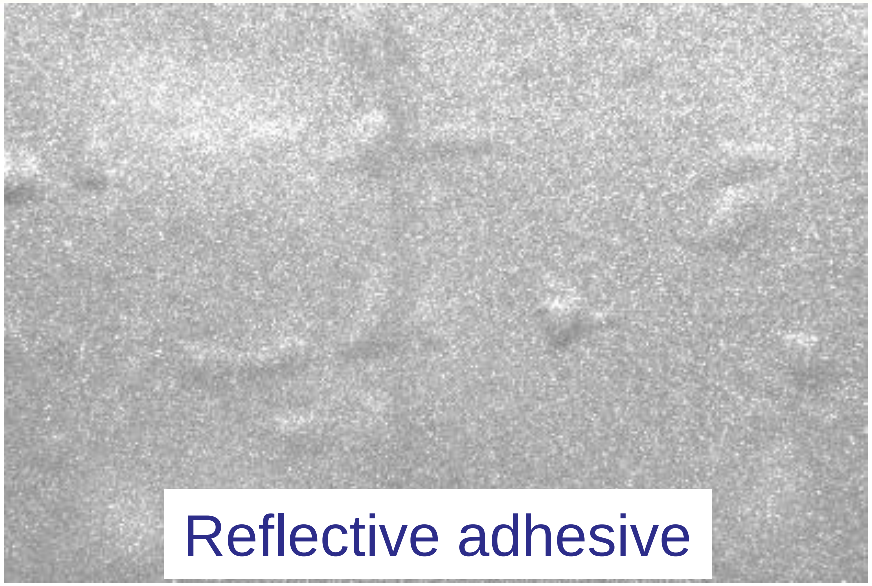
Nominally σ_u = 1%

Experimental Setup – Proof-of-Concept Study

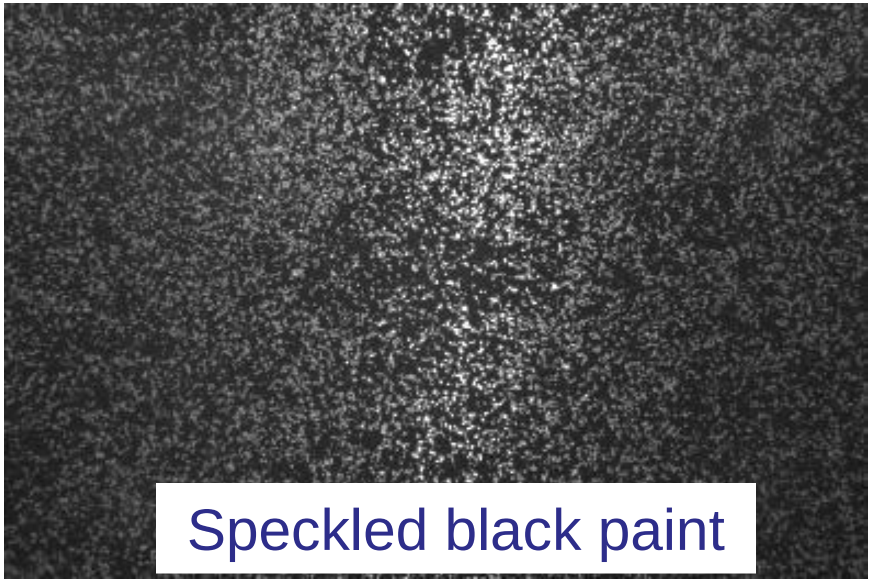


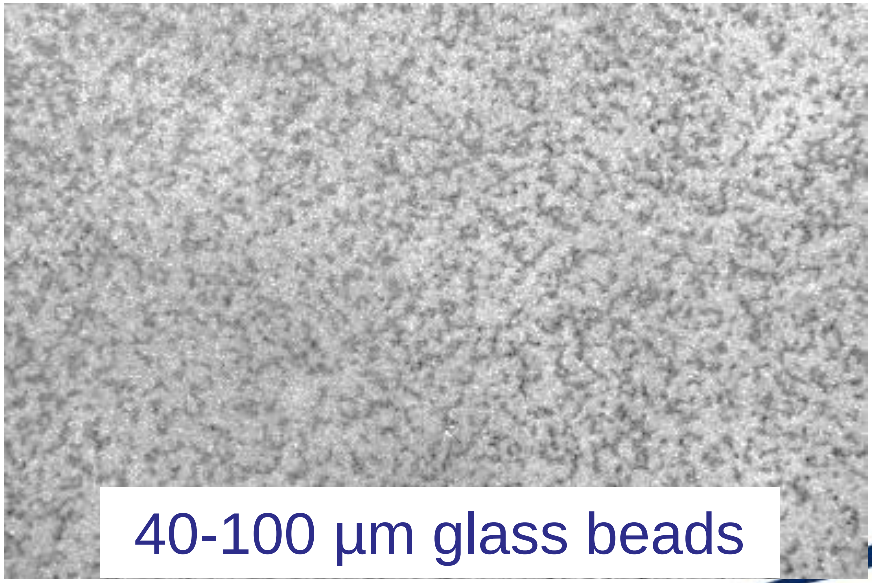
- Induce known shifts of 50 µm, 20 µm, and 10 µm
- Images acquired before and after shift
- Measure image displacement via PIV software
- Process repeated 5x for each pattern test

Background Patterns



FOV ~ 74 mm

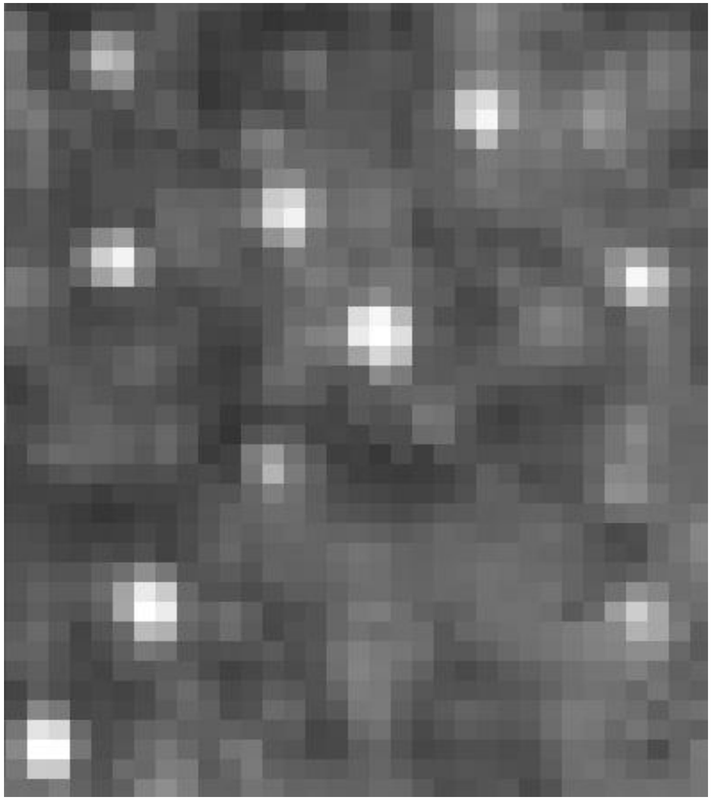




Results: Pattern Development

Rule: Imaged particle diameter d_e spans 1-2 pixels

1-2 pixels ⟶ 18.2 - 36.5 µm



Glass bead image

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

$d_{diff} = 29.4$ µm ⟶ $d_{e_{min}} = 1.6$ pixels

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

$d_e < 2$ pixels ⟶ $d_p <\sim 45$ µm

$d_p = 40 – 100$ µm ⟶ $d_e \sim 2 - 3$ pixels

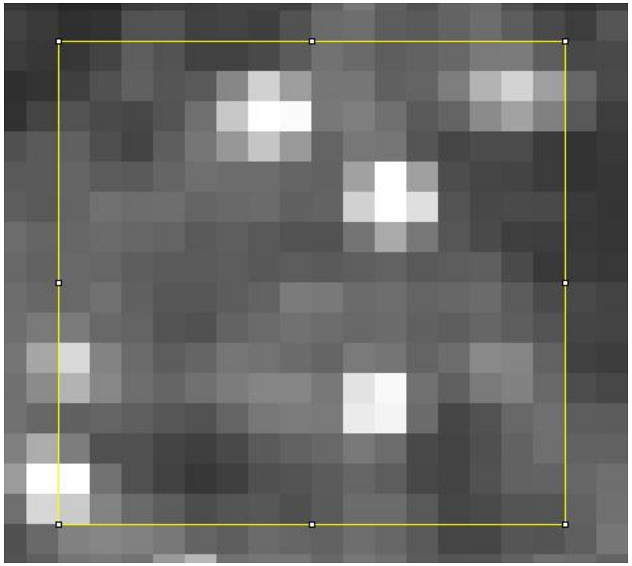
Results: Pattern Development

Rule: Particle displacement < 1/4th sub-region size *N*

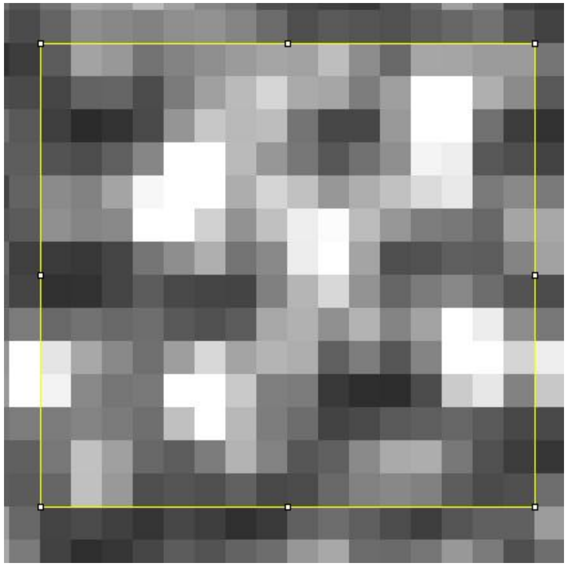
$$\text{Expected } \Delta x_{max} = 50\ \mu\text{m} = 2.78 \text{ pixels}$$

$$N = 16$$

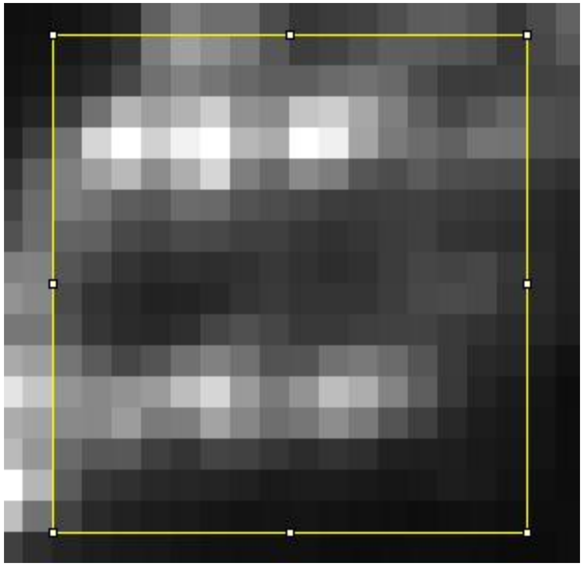
Rule: Nominally 10 particles per sub-region



Glass beads



Reflective adhesive



Black speckled paint

Results: Induced Shift

Experimental Error

Horizontal Shift

Shift (μm)	Reflective Adhesive Detected Shift (μm)	Glass Beads Detected Shift (μm)	Black Speckles Detected Shift (μm)
50.0	46.86 ± 3.01	46.56 ± 2.47	43.14 ± 6.89
10.0	6.37 ± 1.43	6.69 ± 2.01	5.77 ± 3.89

Vertical Shift

Shift (μm)	Reflective Adhesive Detected Shift (μm)	Glass Beads Detected Shift (μm)	Black Speckles Detected Shift (μm)
0.0	0.17± 2.72	0.38 ± 2.14	0.58 ± 2.89
0.0	0.13 ± 2.61	0.15 ± 2.14	0.44 ± 2.41

σ_{Δ_x} = 0.17 - 0.44 pixel ⟶ $3.22\mu m - 8.08\mu m$

Black speckle offset (50.0-μm) ~ 2x reflective adhesive and glass bead offset

Results: Simulated Shift

Lower Bound Error

Horizontal Shift

Shift (µm)	Reflective Adhesive Detected Shift (µm)	Glass Beads Detected Shift (µm)	Black Speckles Shift (µm)
36.54	36.54 ± 0.24	36.51 ± 0.58	34.54 ± 4.72

Vertical Shift

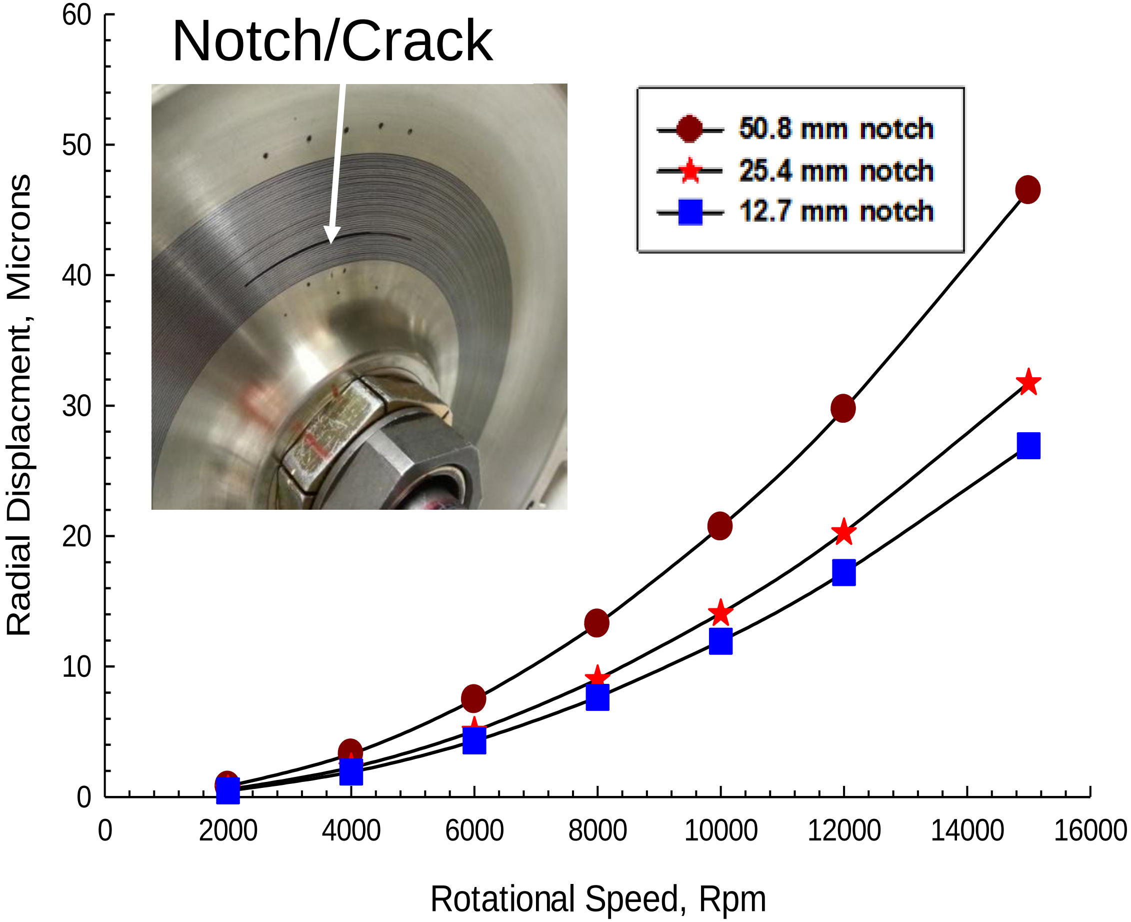
Shift (µm)	Reflective Adhesive Detected Shift (µm)	Glass Beads Detected Shift (µm)	Black Speckles Detected Shift (µm)
36.54	36.54 ± 0.16	36.51 ± 0.67	34.74 ± 4.61

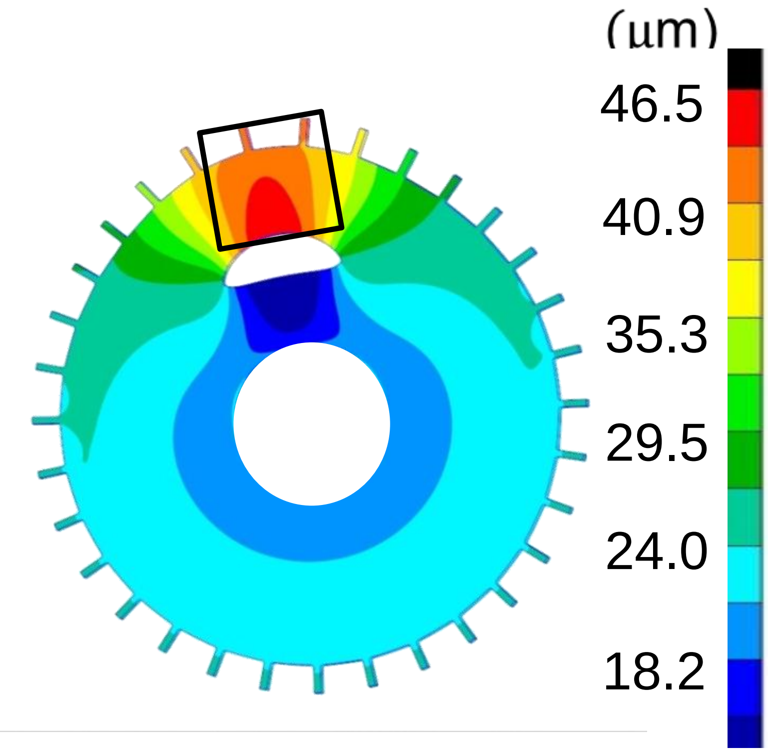
Black speckle error ~6.5% of full scale
Glass bead error ~0.79% of full scale
Reflective adhesive error ~0.32% of full scale

Can detect shift regardless of direction
Radial shift will be a vector

Implementation-
Rotating Disk Analysis

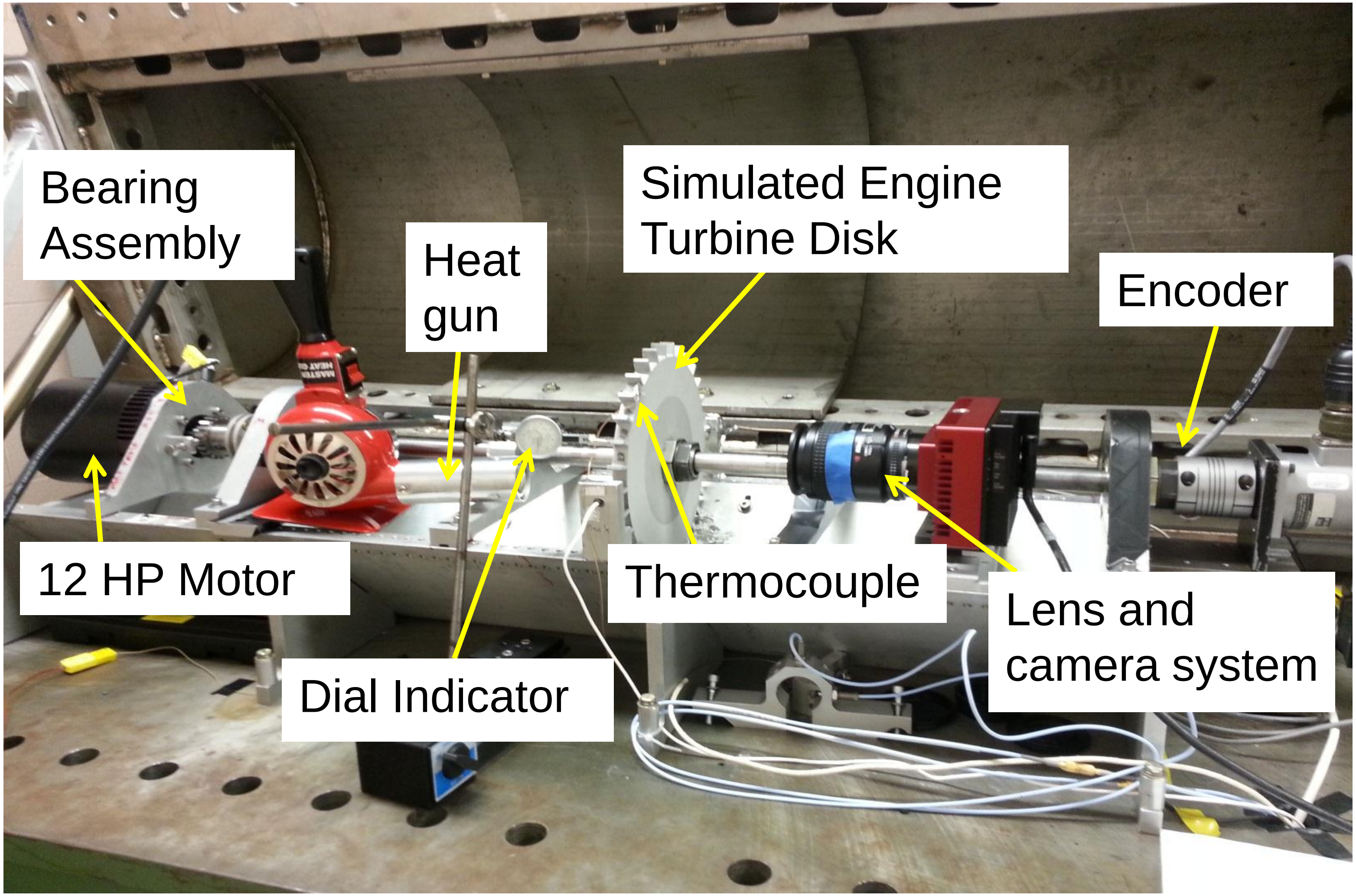
FEA was performed to estimate expected radial growth for different size notches on a 12.7 mm thick, 254 mm diameter Al disk



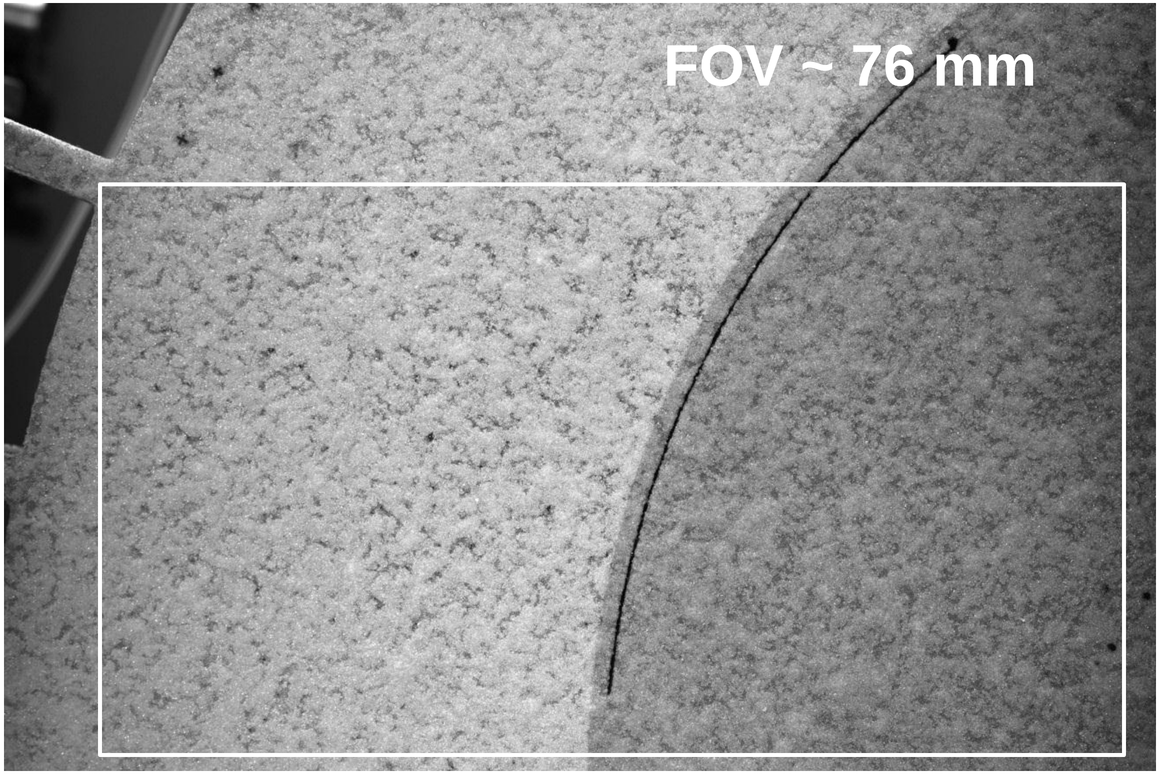


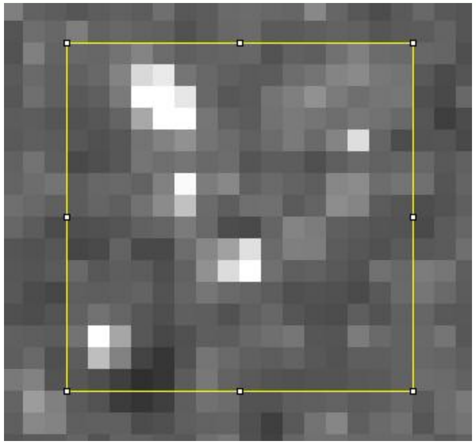
Implementation-
Rotating Disk Experimental Setup

NASA Glenn Research Center's High Precision Rotordynamics Laboratory

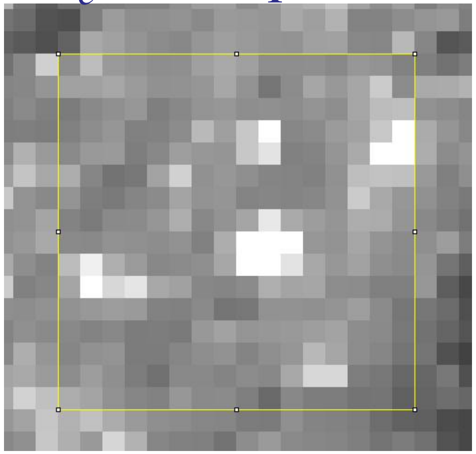


Implementation- Rotating Disk Preliminary Results





d_e ~2 - 3 pixels



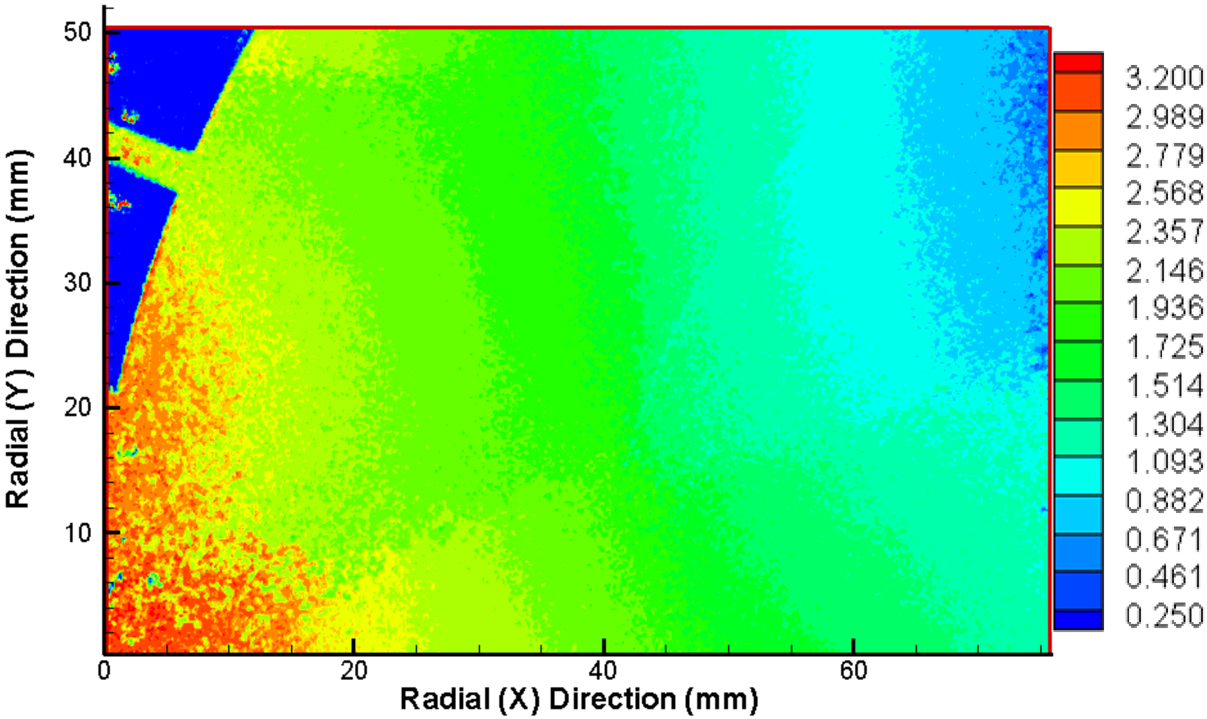
Lower bound error ~0.14% of full scale

- More uniform particle distribution
- Better focus ⟶ smaller d_e

Implementation-
Rotating Disk Preliminary Results

$\alpha = 23.6\times10^{-6}$ m/m ºC ΔT = 25.6 ºC   L = 0.0626 m

ΔL =0.0405 mm = 2.14 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 ⟶ smaller f/# ⟶ decrease blur circle

Acknowledgements

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