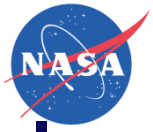

Progress of a cross-correlation based optical strain measurement technique for detecting radial growth on a rotating disk

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Biography

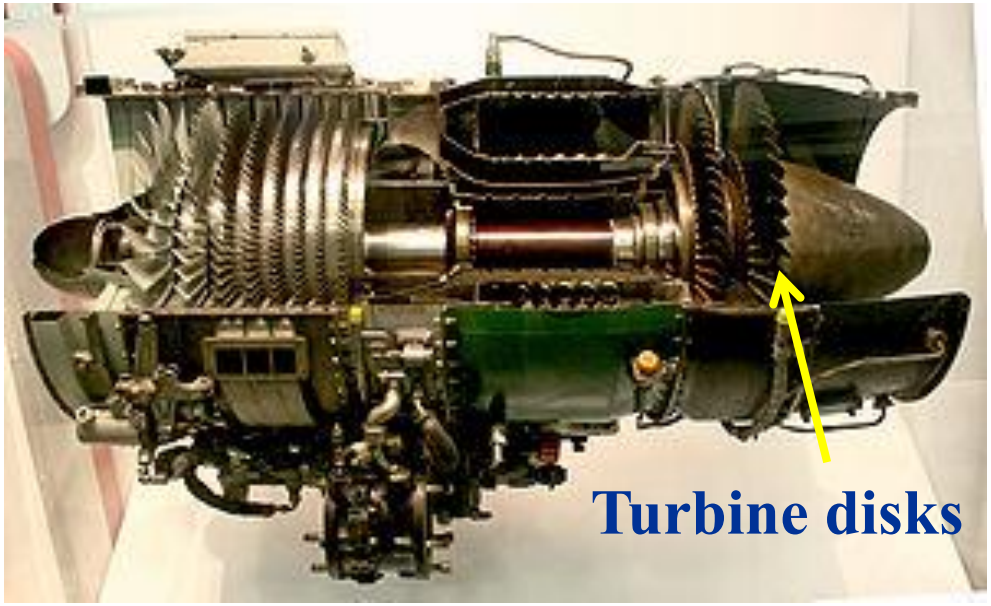
Mr. Fralick received an M. S. in Physics from John Carroll University in 1969, and did additional toward a Ph. D. in Physics from the University of Toledo. Mr. Fralick has been active in pursuing a variety of sensor technologies, primarily for aeronautics applications, although they have space applications as well. His areas of interest include measurement in harsh environments of gas and surface temperature, heat flux, and flow. He has published 25 technical papers, 10 of them in refereed journals, on a variety of topics, from Stimulated Raman Scattering to thermal analysis of heat flux gauges, and has 4 patents.

Outline

- Introduction & Motivation
  - Strain & Strain Impact
- Overview of the optical strain measurement technique
- Previous work
  - Expected results
  - Previous work
- Theory
- Scope of present study
- Pattern application
- Bench-top experiments for technique validation
- Technique implementation onto a spin rig
- Alternative pattern application
- Conclusions & Future work

Introduction & Motivation

- NASA is interested in the development non-intrusive strain measurement technologies for gas turbine engines and their components
- One such non-intrusive technology approach consists of a cross-correlation based optical surface measurements technique

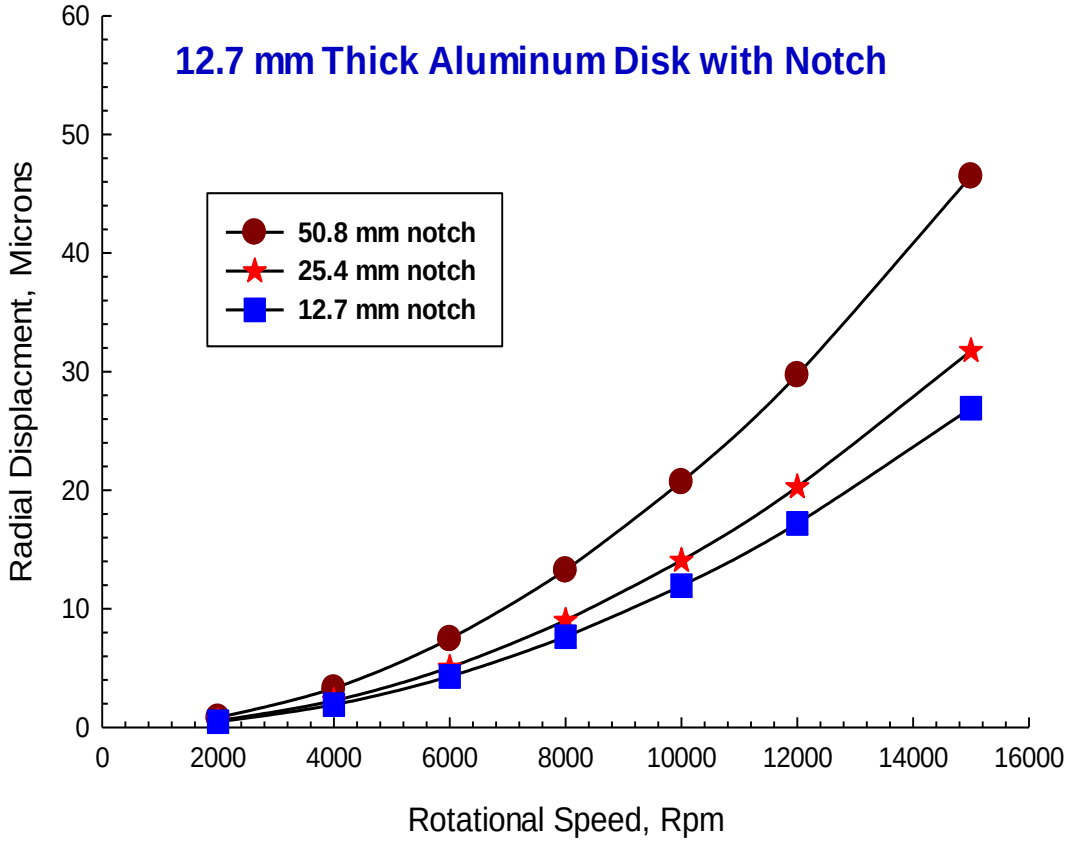


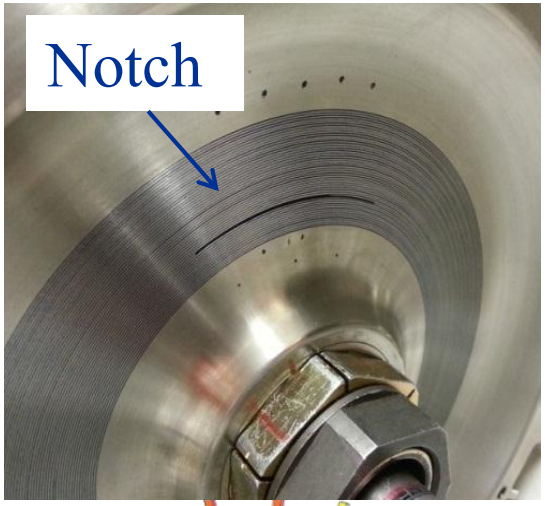
- This technique offers potential to measure radial growth (strain) of a rotating engine turbine disk
- For proof-of-concept of the optical surface measurement technique, experiments are performed on a pre-faulted (notched) turbine-like disk

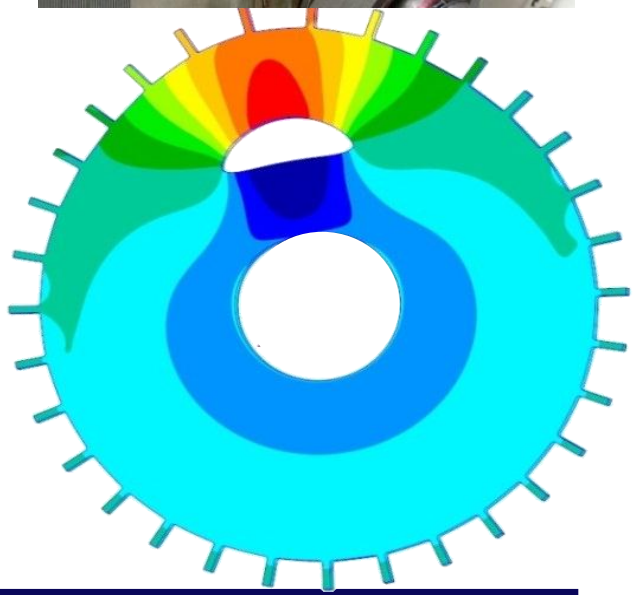
Overview:
Optical Strain Measurement Technique

- Basic concepts of how the technique works:
  - A high-contrast random particle pattern applied to cracked area
  - Image pattern using CCD camera under static and loaded conditions (rotating at 10k-15k rpm)
  - Under loaded conditions, cracked disk will experience strain causing the disk to grow in radial direction
  - Disk grows thus pattern will be “shifted” from static condition
  - Cross-correlate before shift & after shift images
  - Results give particle displacements, i.e. radial growth of the disk

Previous developmental work:
Expected radial growth of disk

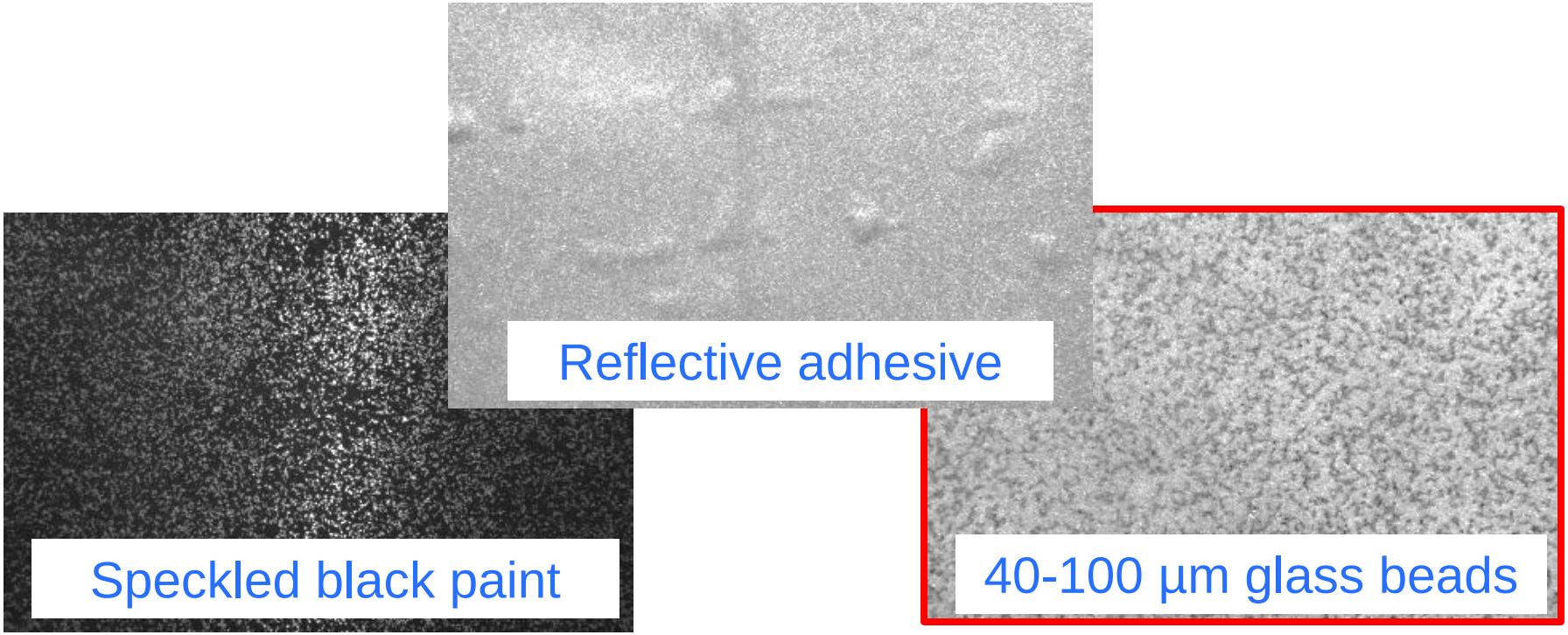






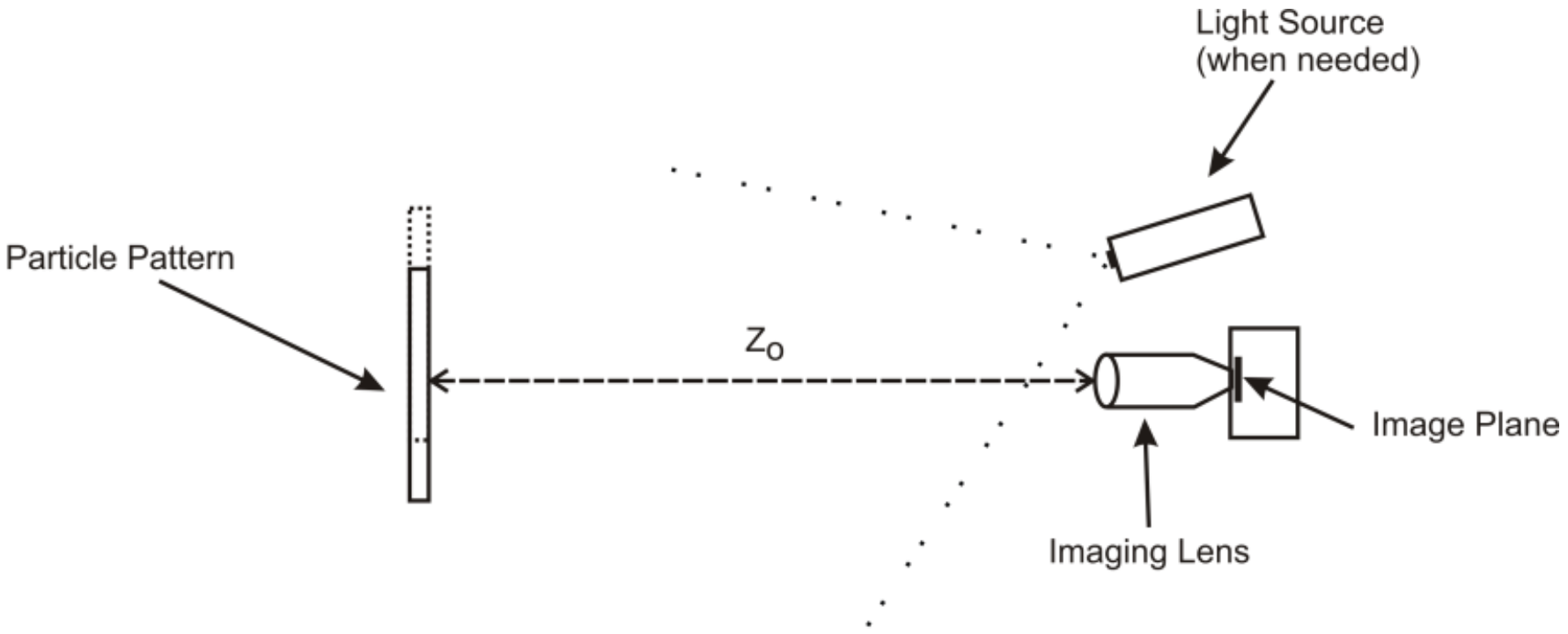
FEA predicts radial growth of ~50μm for proposed disk

Previous developmental work:
Initial Pattern Investigation



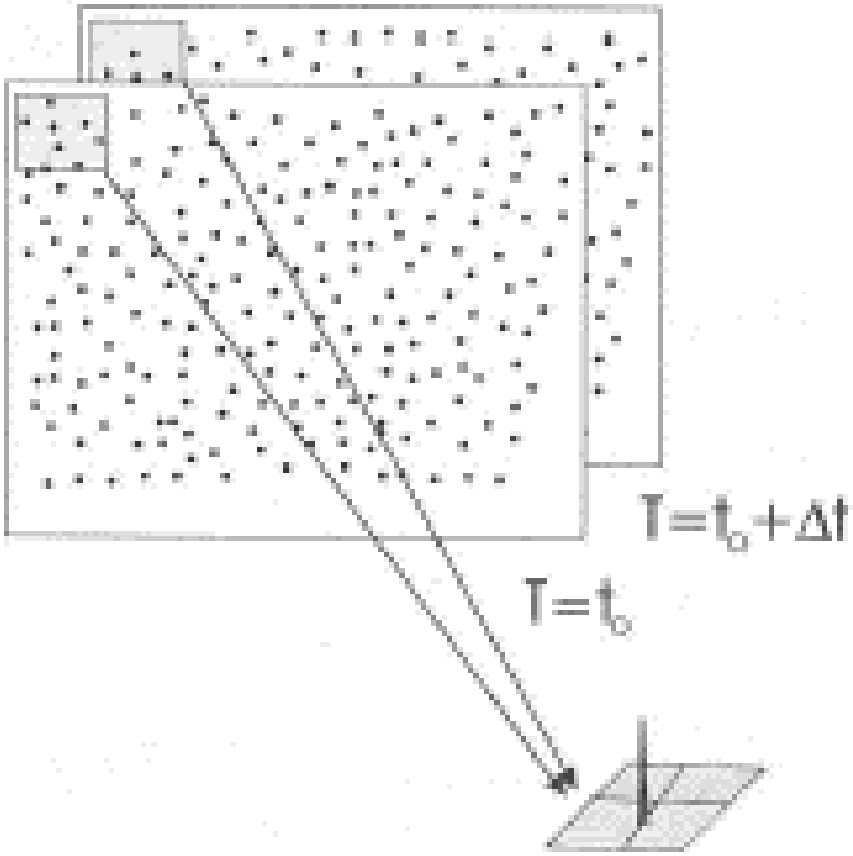
- To minimize measurement error of particle displacements (radial growth estimates), PIV optimization guidelines were followed for evaluation of the different patterns
- The micro-glass bead pattern adequately met the optimization guidelines and subsequently chosen to be used on the disk

Optical Strain Measurement Technique Theory



- A static reference image of the pattern is acquired
- 2nd image is acquired after the particle pattern experiences a displacement
- The two images are processed using cross-correlation algorithms (PIV software) to determine the particle displacements

Cross-Correlation Theory



- Each image is divided into small sub-regions (1 & 2)
- Sub-reg 1 is cross-correlated with corresponding sub-reg 2
- Correlation plane peak gives the resulting displacement vector
- Process is repeated over the entire image
- Results in spatially averaged displacement vectors
- Can use existing PIV algorithms

PIV Optimization Guidelines

1. Nominally 10 particles per sub-region
2. Particle displacement should be less than 1/4th sub-region size
3. Imaged particle diameter spans 1-2 pixels

Scope of Present Study

- Optimal micro-glass pattern applied onto disk and re-evaluated using PIV guidelines
- Two bench-top experiments are performed to induce shifts onto the disk (i.e. create particle displacements) in order to assess the technique's capability at detecting the displacements
  - Manually induced shift
  - Thermal expansion
- Implementation of technique onto a spin rig to assess under rotating conditions
- Test out alternative effective particle approach to mitigate issues that arose in micro-glass bead application

Micro-glass Bead Application onto Disk

- Disk composed of ***Aluminum 6061-T6***
- 32 blades, 12mm thick, ~190mm in diameter (not incl. blades)
- Pattern manually applied using spray adhesive
- Particle density hard to control
- Pattern re-verified to be optimal using PIV guidelines

Results:
Pattern Application onto Disk

Ensure pattern repeats/follows PIV optimization guidelines

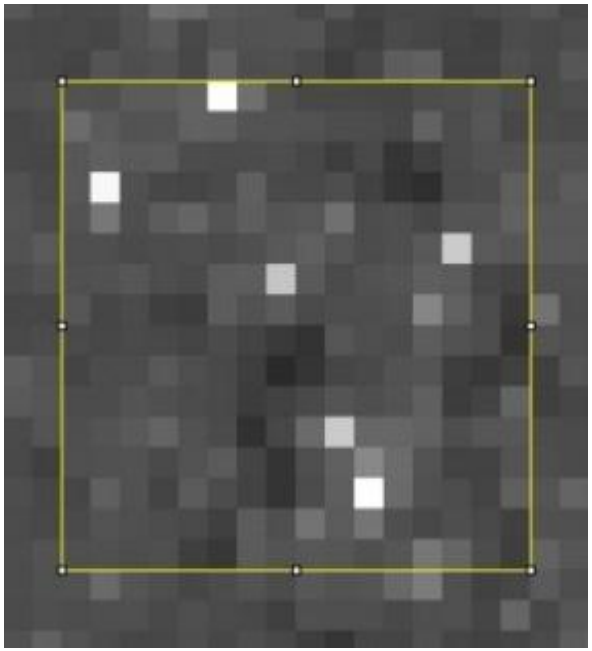
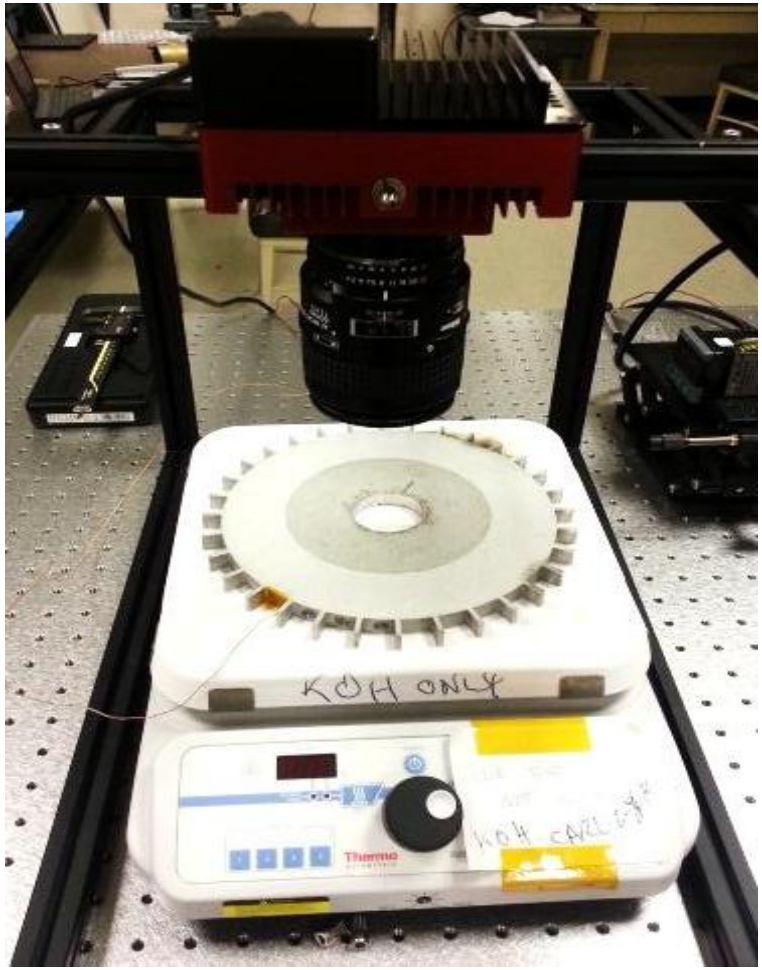


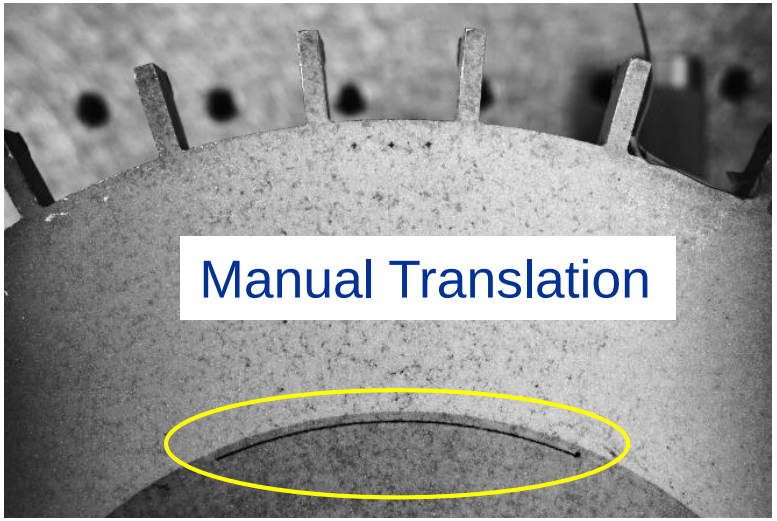
Image of micro-glass bead pattern adhered onto disk

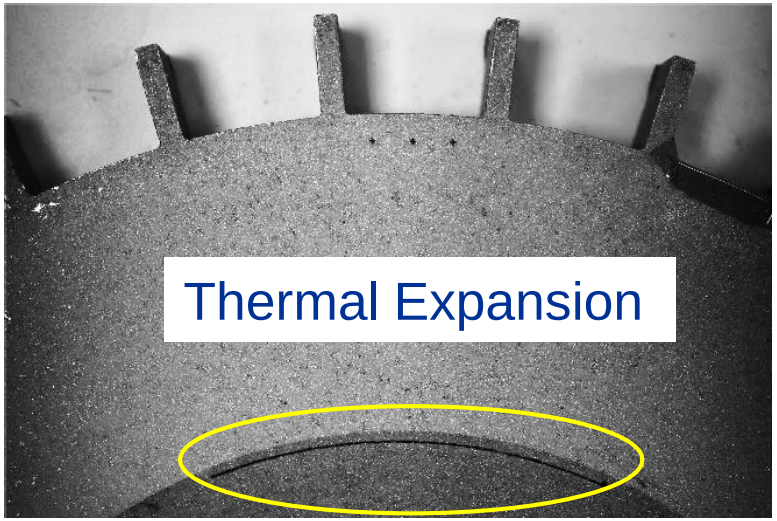
1. Imaged particle diameter spans 1-2 pixels
2. Nominally 10 particles per sub-region
3. Sub-region size chosen to be 16 pixels which is 4x larger than expected growth

Nominal value of
peak position error = 0.1pixel

Validation Tests Experimental Setup







Micro-glass Bead Results:
Induced Shift via Manual Translation

- Translate the disk 50-µm using a manual translation stage equipped with a fine micrometer
- Images acquired before shift and after shift and then cross-correlated

Horizontal Shift

Shift (µm)	Micro-glass Beads Detected Shift (µm)
50.0	49.7 ± 1.9

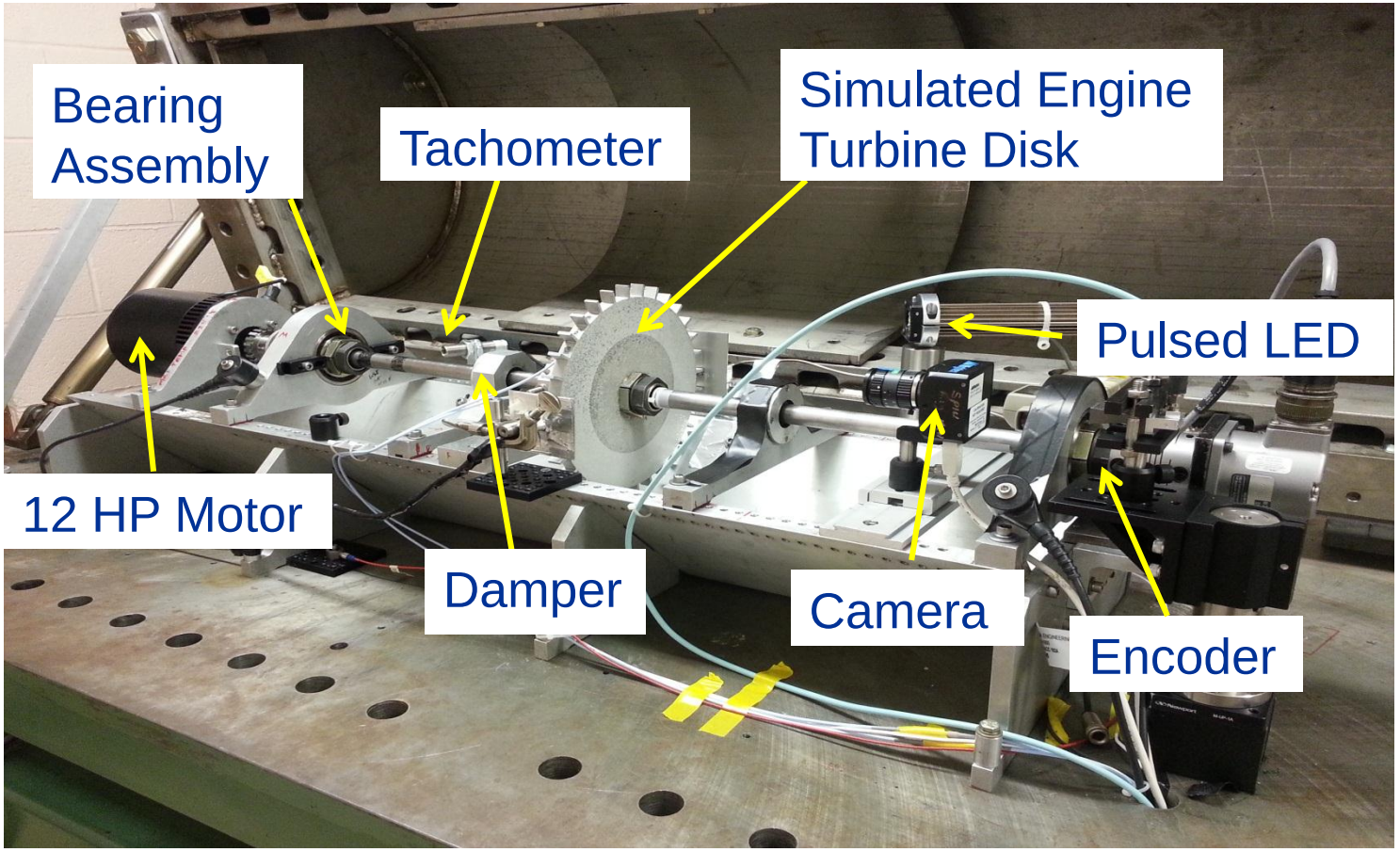
Vertical Shift

Shift (µm)	Micro-glass Beads Detected Shift (µm)
0.0	0.48 ± 0.68

Nominal value of displacement peak error = 0.1pixel (≈2.60µm)

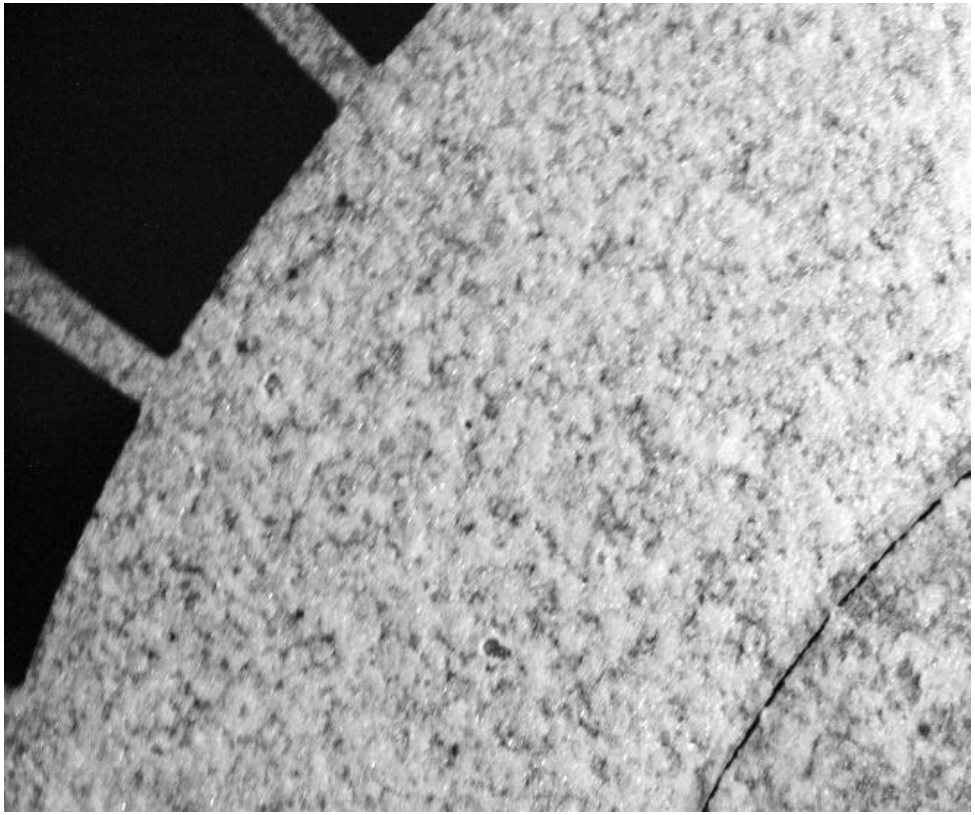
Results: Rotating Disk Implementation

NASA Glenn Research Center's High Precision Rotordynamics Laboratory



Results: Rotating Disk Implementation

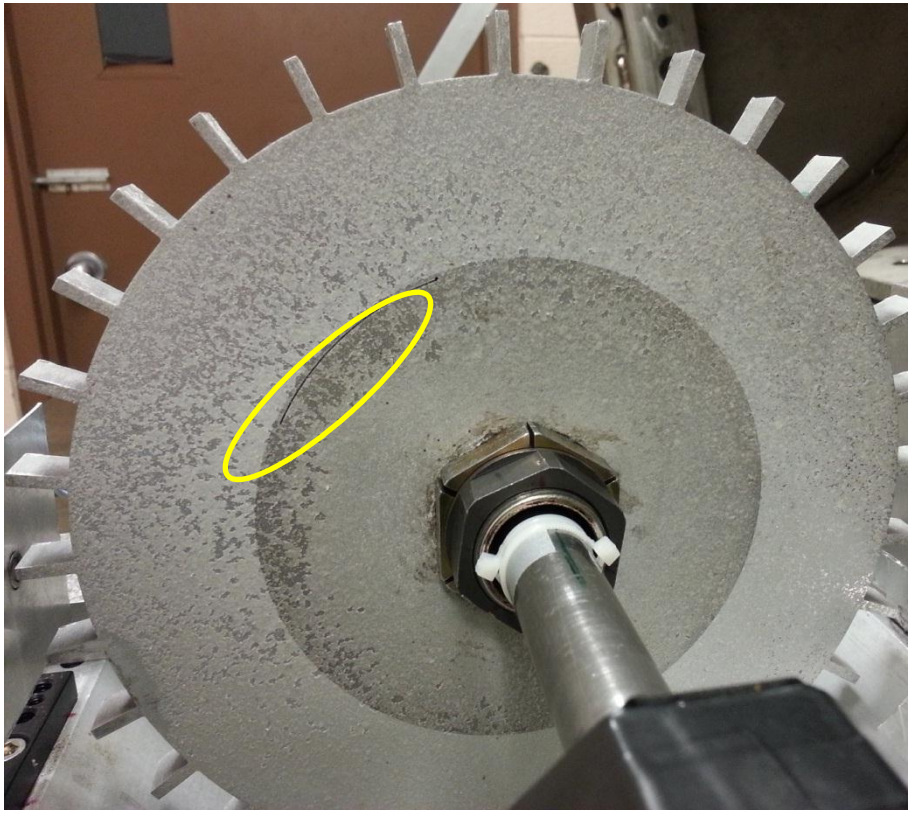
- Goal: “Freeze” motion of disk and capture cracked region in field-of-view
- Method: Pulse delay circuitry
  - Resulted in unstable and blurred images
- Method: Manually adjust once per rev signal
  - Required starting and stopping the rig several times to check field-of-view
  - Required running on condition to check stability
  - Obtained crisp images



Motion of disk “frozen” at 12k rpm

Preliminary data acquired during loaded conditions (10k & 12k rpm)

Results: Rotating Disk Implementation

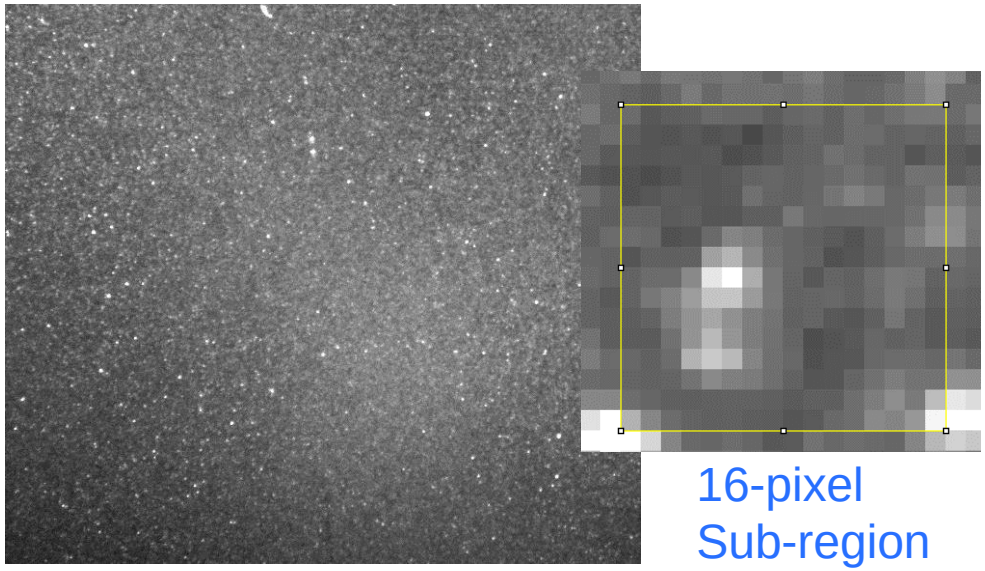


- Pattern disintegrated after operating several times at loaded conditions: 10k-12k rpm
- Physical evidence suggests that disk is expanding in cracked region
- Disk growth is weakening adhesive bonds is one possible explanation for pattern disintegration
- We expected this, just wanted to try it out to get prelim results spinning.

Alternative Approach: Vapor Blast

- An applied particle pattern is shown to have disadvantages; there is obviously a need for an intrinsic pattern
- Effective “particles” can be created on the surface via vapor blast, i.e. roughening up the surface
- This approach does not require physical particles or any adhesion

Al coupon after vapor blast



16-pixel Sub-region

Vapor blast coupon image acquired using optical system

Vapor Blast Results:

Induced Shift via Manual Translation

- Translate the coupon using a manual translation stage equipped with a fine micrometer
- Images acquired before shift and after shift and then cross-correlated

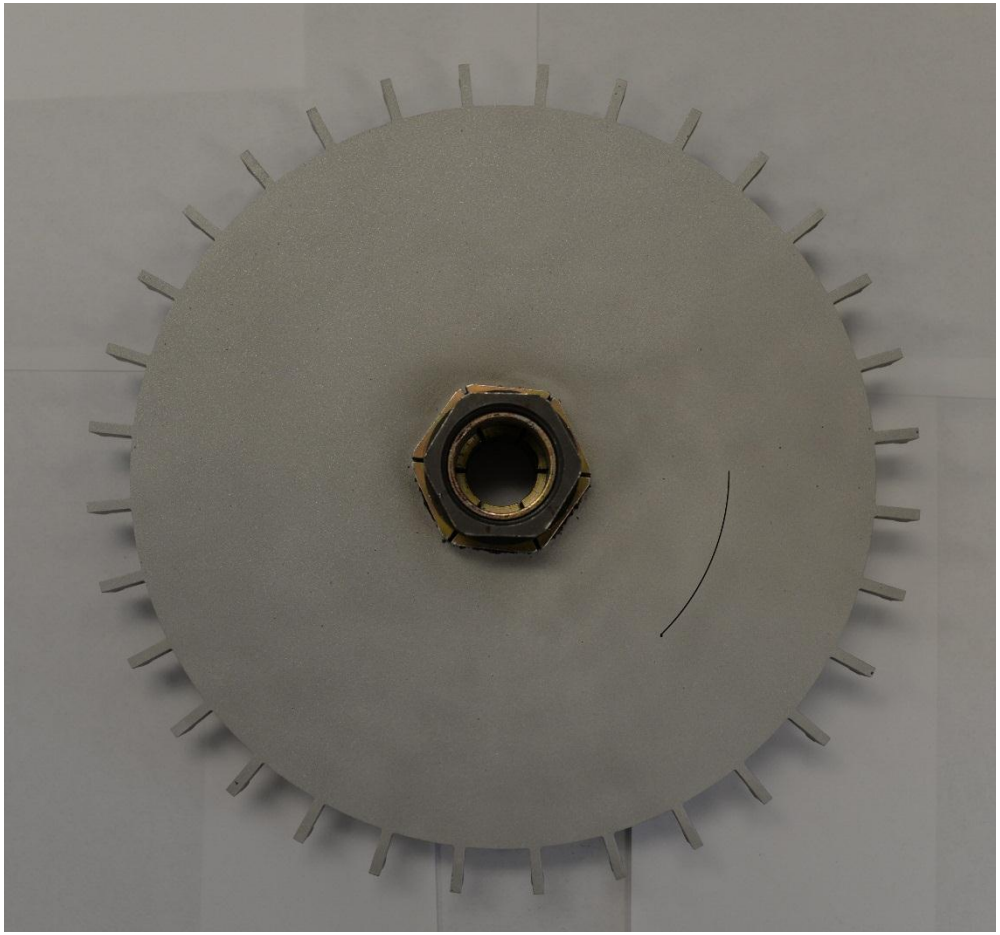
Horizontal Shift

Shift (µm)	Vapor Blast Detected Shift (µm)	Micro-glass Beads Detected Shift (µm)
50.0	45.3 ± 4.1	49.7 ± 1.9
100.0	93.6 ± 2.9	n/a

Accurate up to ~5-10% for preliminary test

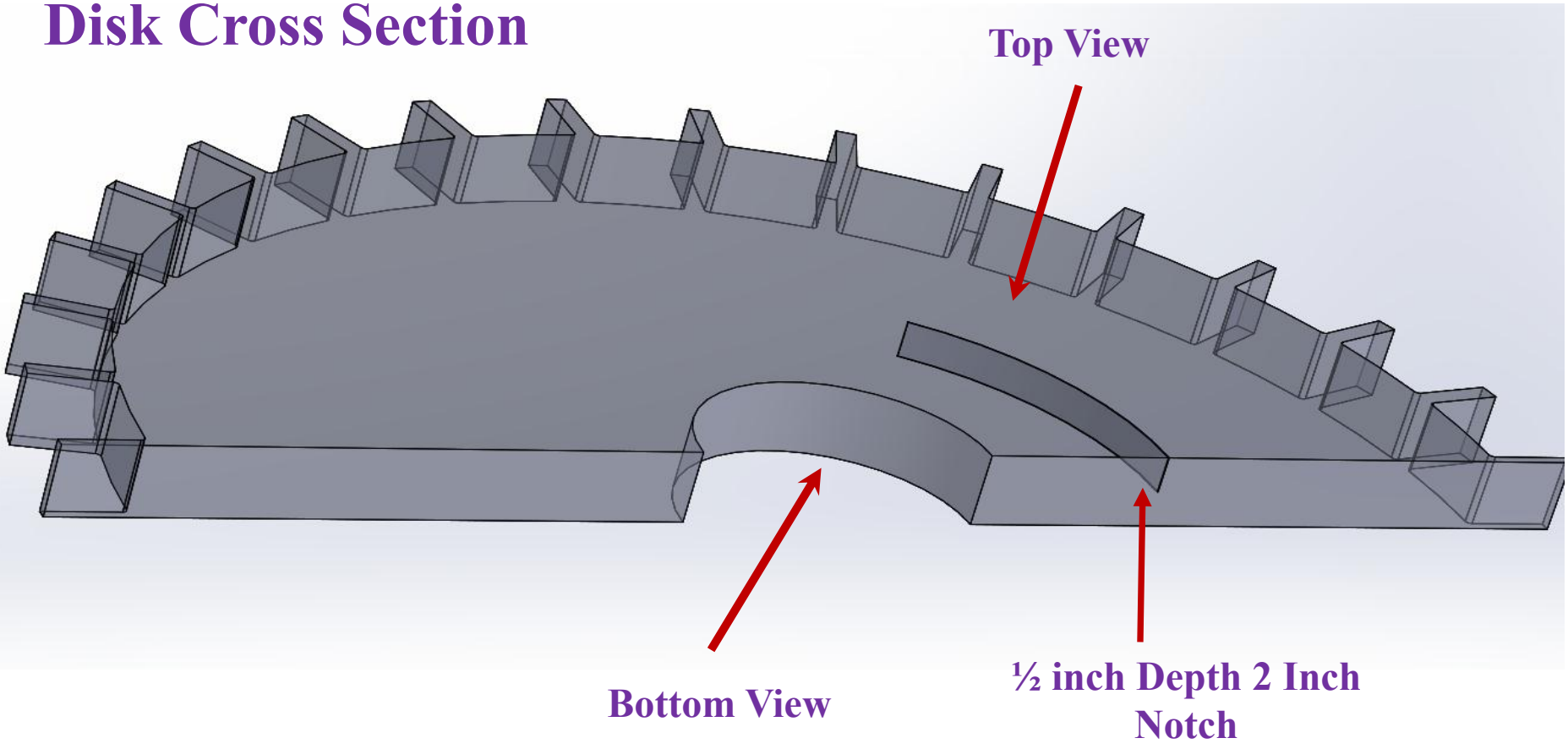
Nominal value of displacement peak error = 0.1pixel (≈5.0µm)

Vapor Blast Applied to Test Disk



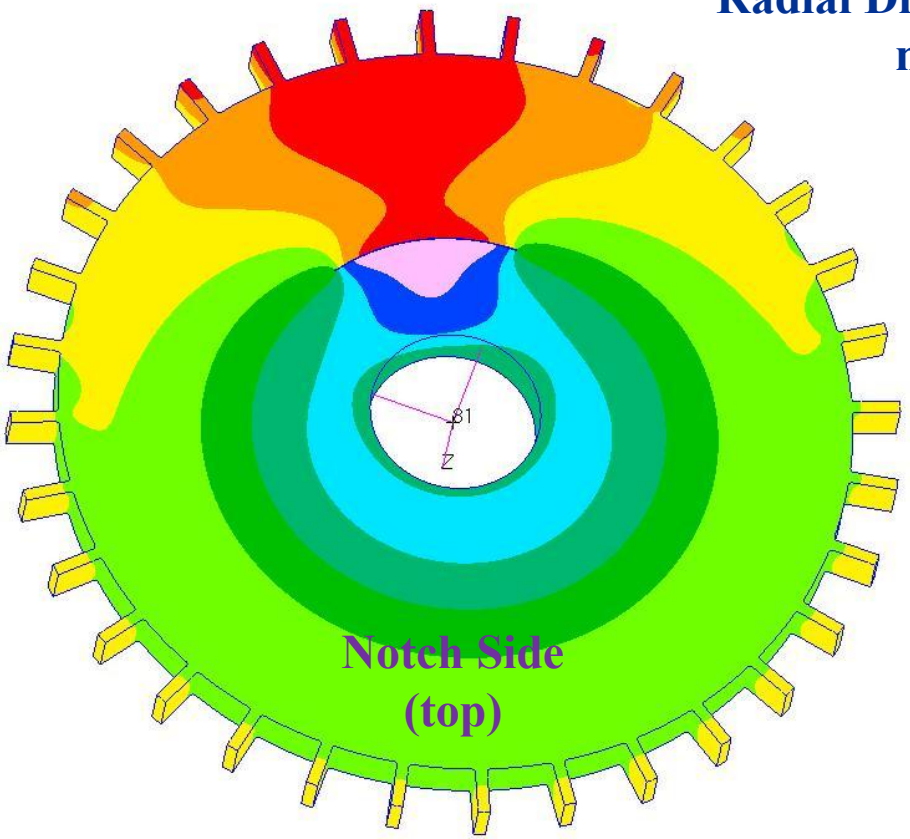
Test disk after vapor blast applied

Disk Cross Section



0.5 Inch Aluminum Disk with 2 inch (5.08 mm) long notch and 0.25 inch (0.635 mm) deep, (1/2 depth of disk)

Finite Element Results, Radial Displacement Contour profile at 15,000 Rpm Rotational Speed.



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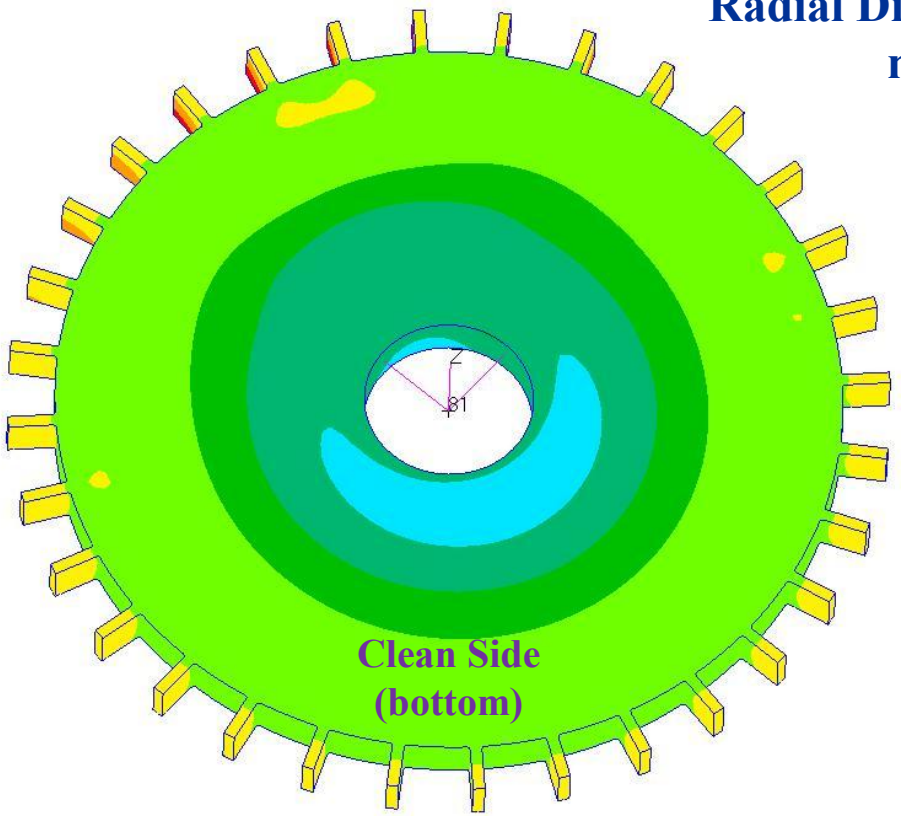
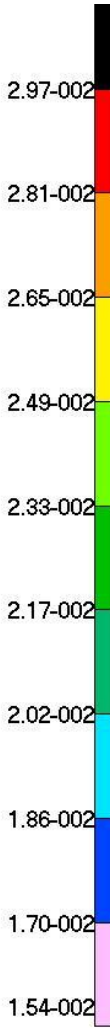
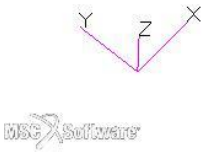


Radial Displacement, mm

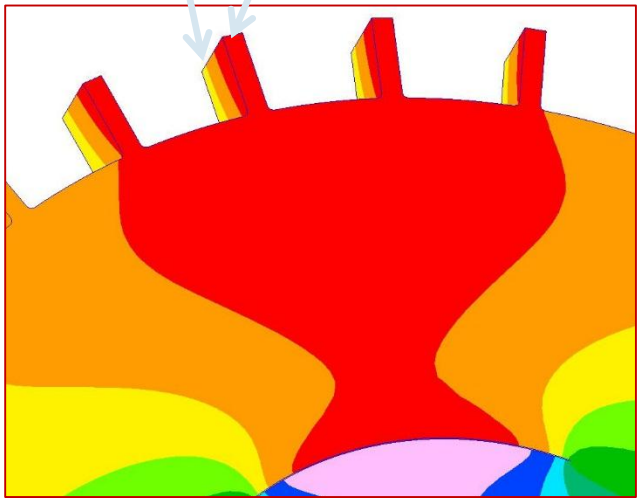


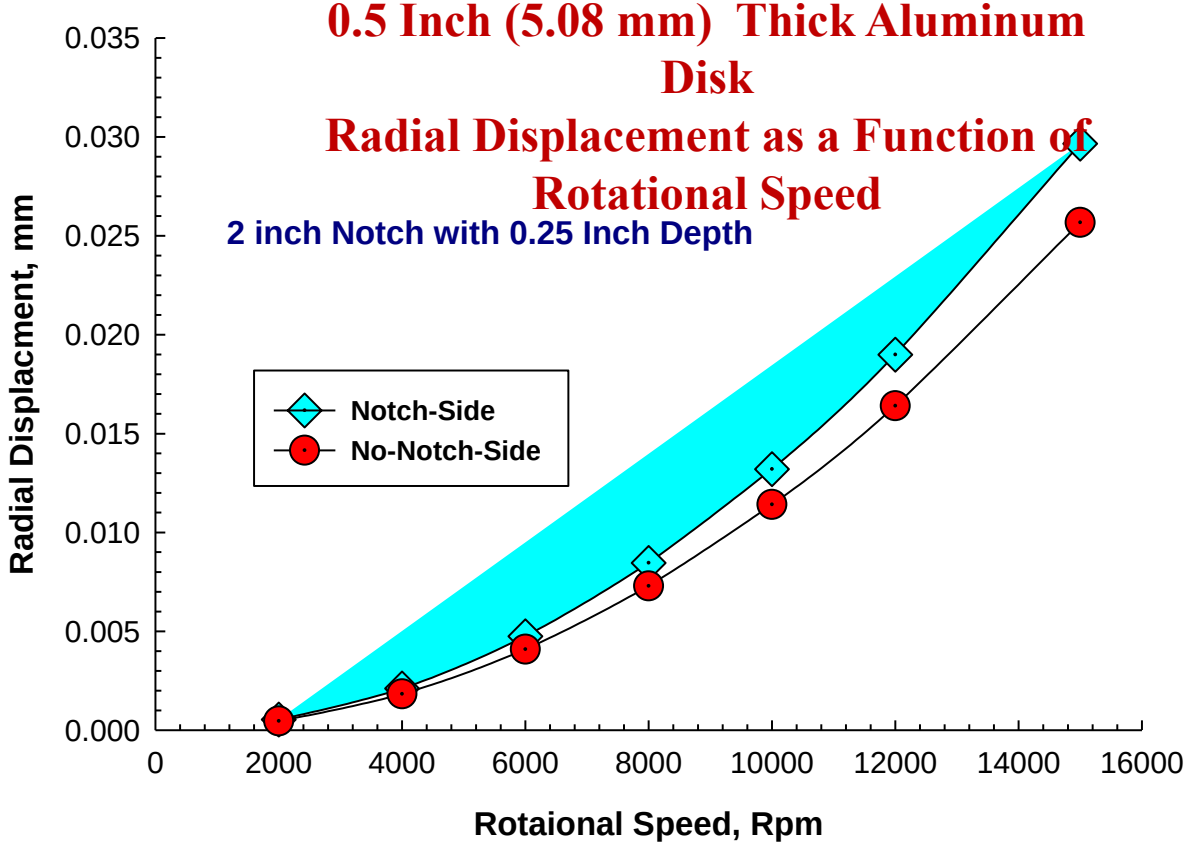


It is noted that the side where the notch exists experience higher displacement compared to the clean side. This is expected since a gap exists in the notch side due to material loss. A confirmation of a crack or a notch is then documented.

Clean Side Location

Notch Side Location





Conclusions & Future Work

- Micro-glass bead pattern applied onto an engine turbine-like disk
- Micro-glass bead pattern evaluated to ensure still optimal
- Two bench-top experiments performed to evaluate the detection of the particle displacements
  - Manually induced – accurate up to ~1.75% of full scale
- Disk with micro-glass bead adhered pattern is evaluated on the spin rig
- Micro-glass bead pattern deteriorated after running longer than anticipated
- Investigation of alternative method for particle pattern application that does not use the adhesion of physical particles
  - Vapor blasting created effective particles by roughening up surface
  - Initial results of a manual translation experiment show promise
- Future work to include investigation of effects of larger and additional effective particles using vapor blasting
- **Perform vapor blast on disk and test on spin rig - Pending**

Acknowledgements

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