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Further Investigation of a Moiré Based Crack Detection Technique on a Simulated Turbine Engine Disk

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Introduction

- Investigate if Moiré patterns can be used to optically measure radial growth due to defects such as a crack in a rotating disk

- On-going research at NASA GRC to develop and validate instrumentation and new fault detection techniques for the in-situ health monitoring of gas turbine engines
  - NASA 's Aviation Safety Program (AvSP), Vehicle Systems Safety Technologies Project (VSST)

NASA Turbofan Simulator – Sensor Evaluation Tests, 2009

- **A series of tests were conducted on a spin rig using a subscale turbine engine disk to demonstrate this potential fault detection technique**
  - **Initial validation tests in 2011 were inconclusive[1-2]**
  - **Currently in the process of the next phase of validation tests**

Theory Behind the Moiré Concept

- Moiré patterns result from the overlap of figures with periodic spacing[3-4]:

- Let p = spacing of initial pattern
- Let q = spacing of second pattern, where

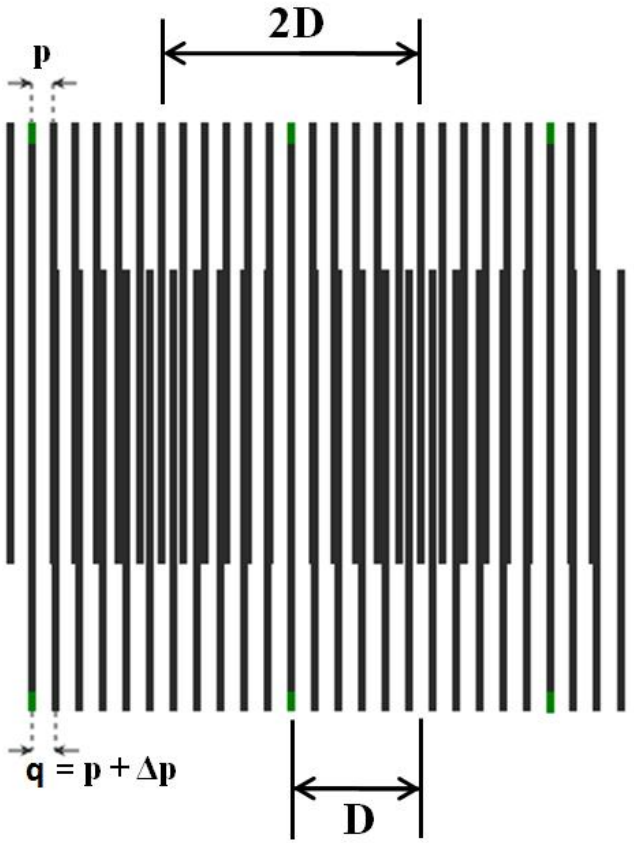
  $q = p + \Delta p,\ 0<\Delta<1.$ (1)

- Where the patterns coincide is a “light zone”
- After a given # of lines, n, the second pattern’s lines fall between the lines of the first pattern…this is “dark zone”

- The middle of a dark zone is when the shift ($n \cdot \Delta p$) is p/2

  $n \cdot \Delta p = p/2$, or $n = p/(2\Delta p)$ (2 & 3)

- Where n is the number of lines on the second pattern to get to the middle of a dark zone



Theory Behind the Moiré Concept

- D, is the distance between the point where the patterns coincide; the middle of a “light zone” and the point where they overlap; the middle of a “dark zone”

$$D = n\,(p + \Delta p) \quad = p^2/(2\,\Delta p\,) + p/2 \qquad (4\ \&\ 5)$$

- Solving for **Δp**

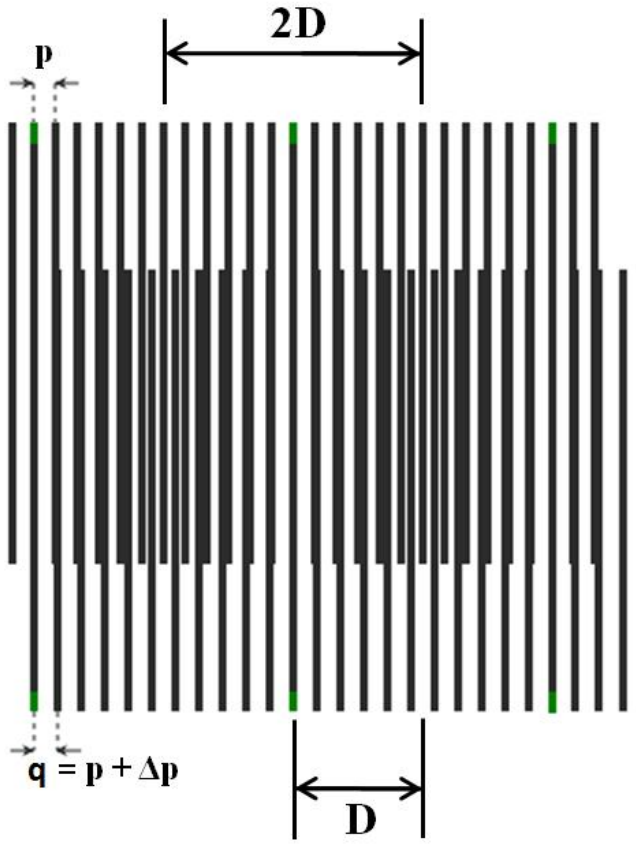
$$\mathbf{\Delta p = p^2 / (2D - p)} \qquad (6)$$

- This can relationship cab be related to strain

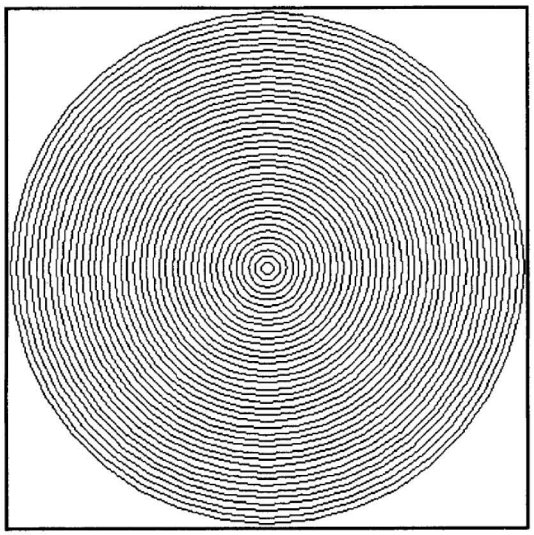
$$\varepsilon = \Delta p / p \qquad (7)$$

$$\mathbf{\varepsilon = p / (2D - p)} \qquad (8)$$

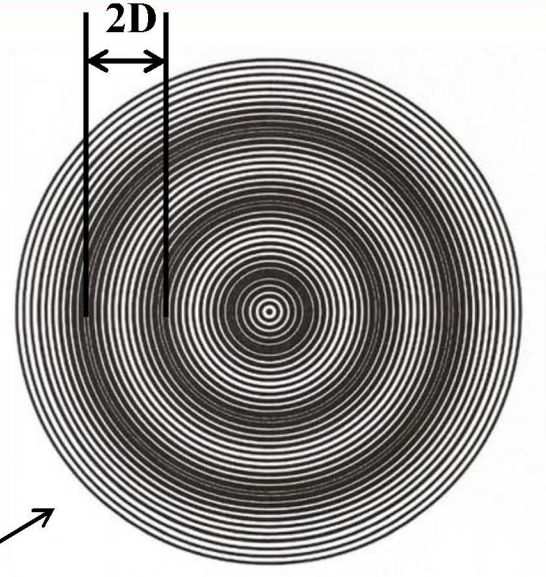
- **Hence, for a given spacing, p, and a measured distance, D or 2D, you can get strain or Δp**



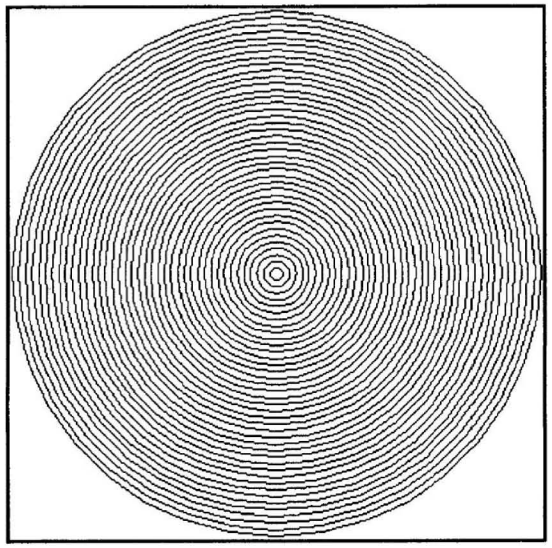
Technical Approach



Spacing = p



Reference Image Acquired at Static Conditions (0 RPM)



Spacing = p + Δp

Overlay of "On Condition" image on "Reference" image to get disk growth

Image Acquired On Condition (10 to 12KRPM)

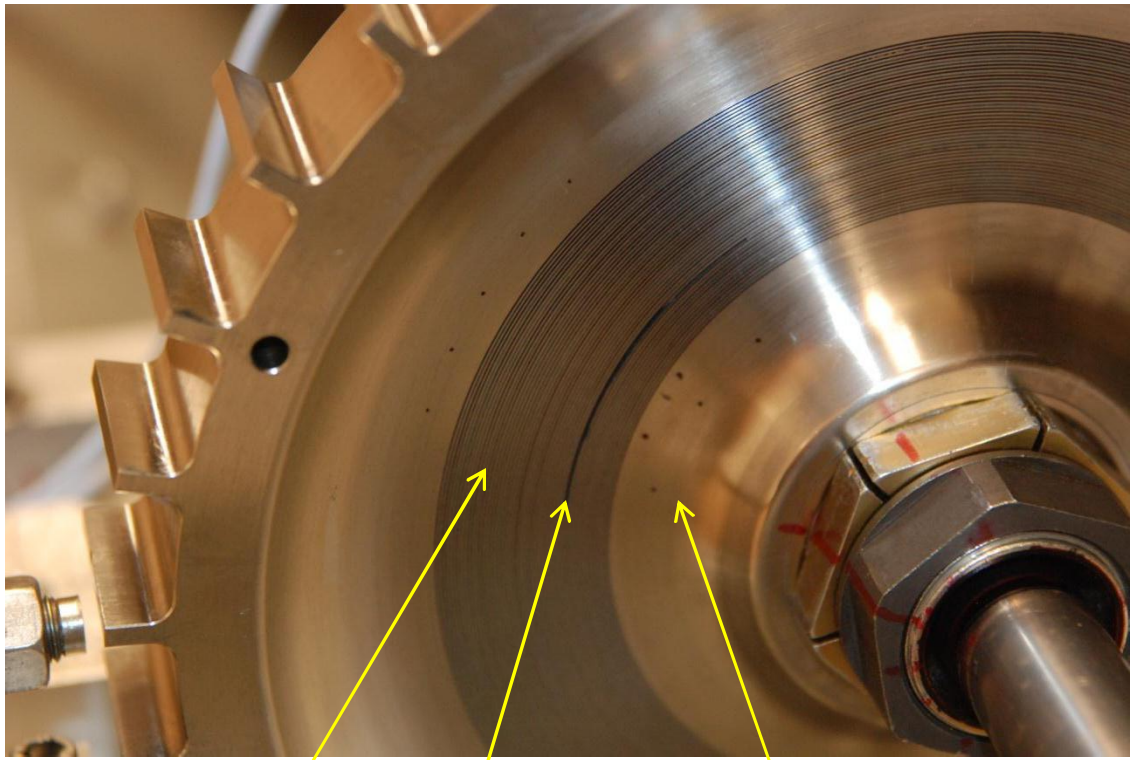
$$\Delta p = p^2 / (2D - p)$$

$$\varepsilon = p / (2D - p)$$

Initial Test Disk - 2011

- Introduced a notch on the disk to imitate a crack
  - Located mid-span r = 2.14” (54.4mm)
  - 2.00” (50.8mm) long
  - ~0.10” (2.54mm) deep
  - 0.015” (0.38mm) wide
- Machined a pattern consisting of concentric circles onto the test disk
  - 0.010” (0.25mm) wide
  - 0.020” (0.50mm) spacing
- Could not cover entire disk with pattern due to its curvature
  - Begins r = 1.86” (47.24mm)
  - Ends r = 2.82” (71.63mm)
- Sensitivity of the technique to optically detect radial growth & strain was limited due to the coverage area & spacing

Disk with Defect

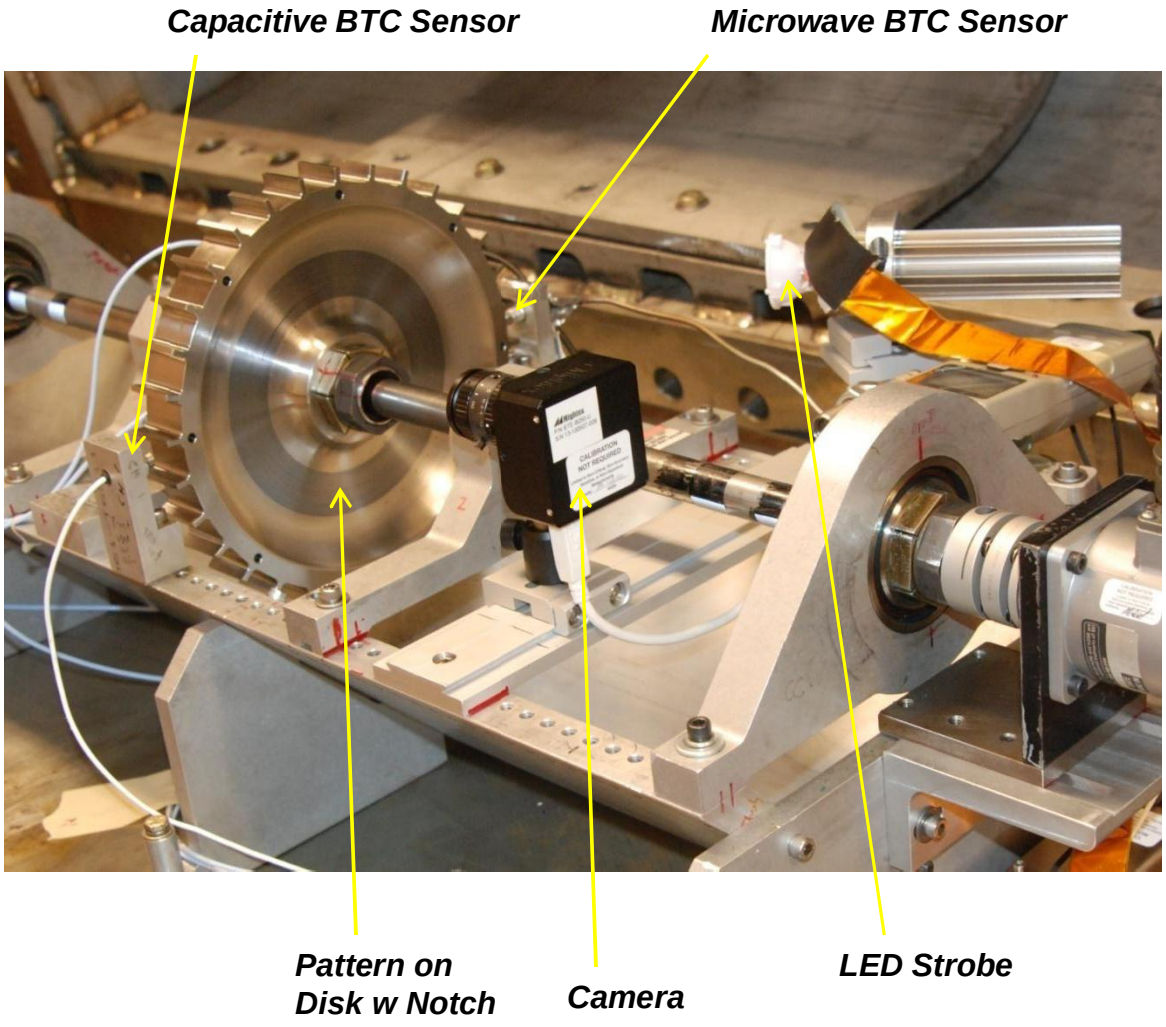


Circular Patterns ***2” Long Notch*** ***Registration Marks***

Rig Setup for Moiré Test - 2011

- 5 Megapixel miniature digital camera w/ 12 & 25 mm lens
- 10W White LED used as a strobe
- Laser 1/rev for strobe signal
- In-house designed & fabricated pulse delay & pulse width circuitry used to control strobe
  - Capture “crack” region in cameras field of view
  - Control pulse width to obtain a near static image
- Additional instrumentation
  - (x1) Microwave blade tip clearance (BTC) sensor
  - (x1) Capacitive blade tip clearance (BTC) sensor
  - (x2) Eddy current shaft displacement sensors

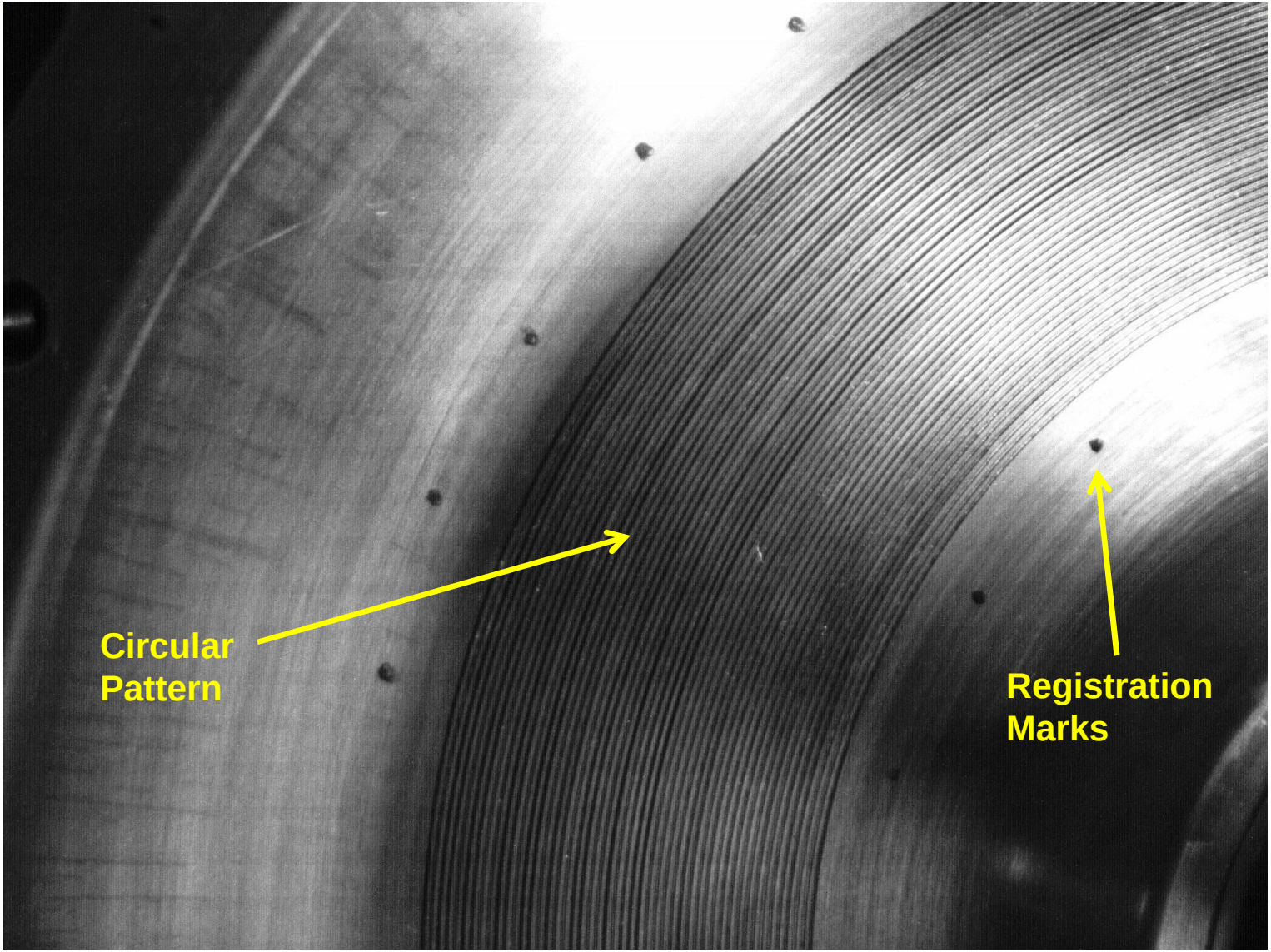
Setup for Moiré Disk Experiment



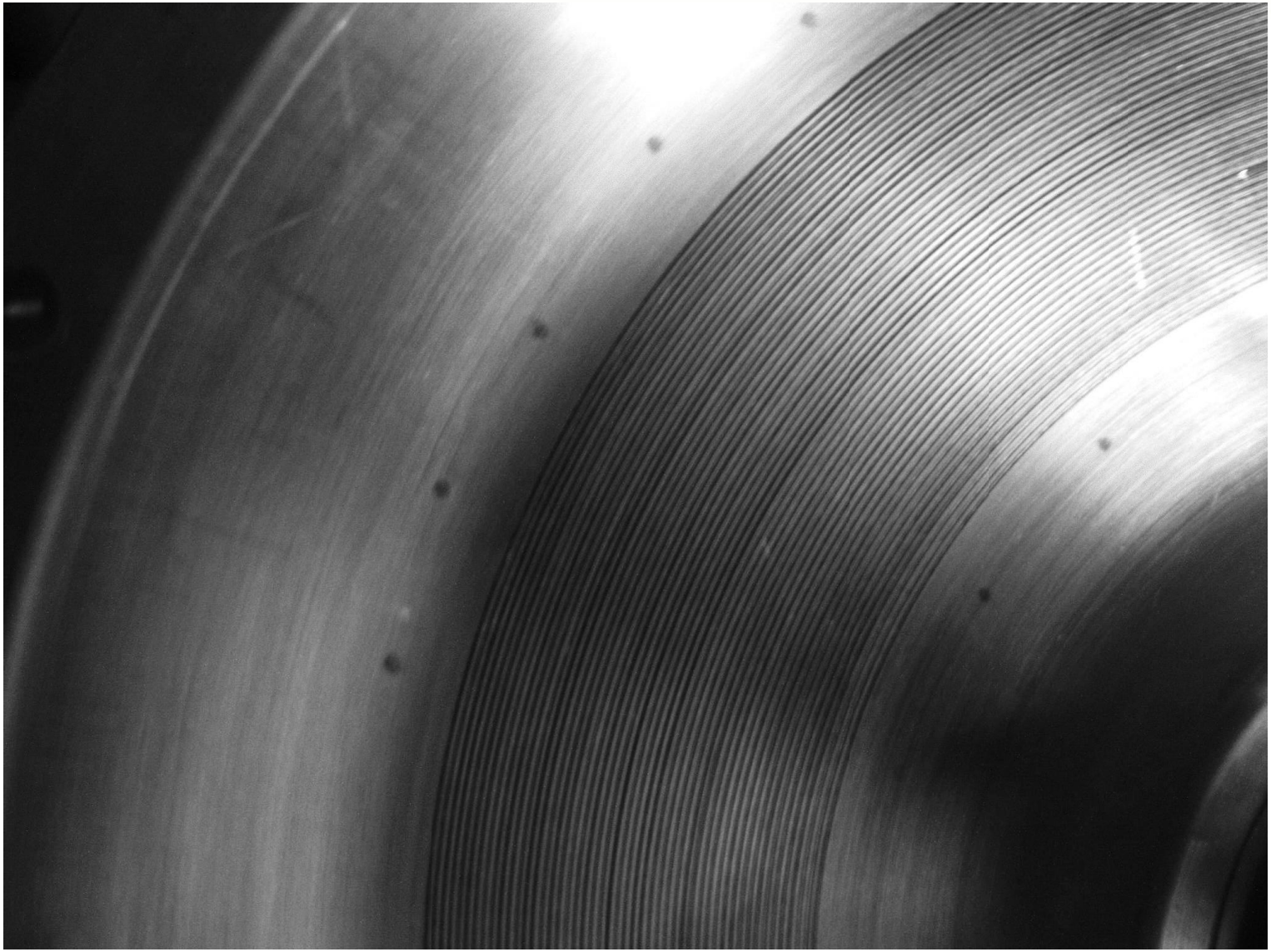
Data Acquisition Methodology

- Acquired reference image at 0 RPM
- Acquired on-condition image at 12,000 RPM
- Post-processed to get composite image
  - Images were first aligned using registration marks on inside radius of disk
  - Imaging processing software was used to get sub-pixel alignment
  - On-condition image was then overlaid on top of reference image using image processing software
- Composite image then analyzed for appearance of Moiré, light and dark zones due to radial growth of the disk….**optically measure D or 2D** to back out radial **growth** & **strain**
- Two portions of the disk were analyzed
  - Region with notch to study localized radial growth due to defect
  - Clean baseline region, 180 degrees from notch region

Disk – Baseline Section @ 0 RPM with 12mm Lens, Initial Validation Tests 2011

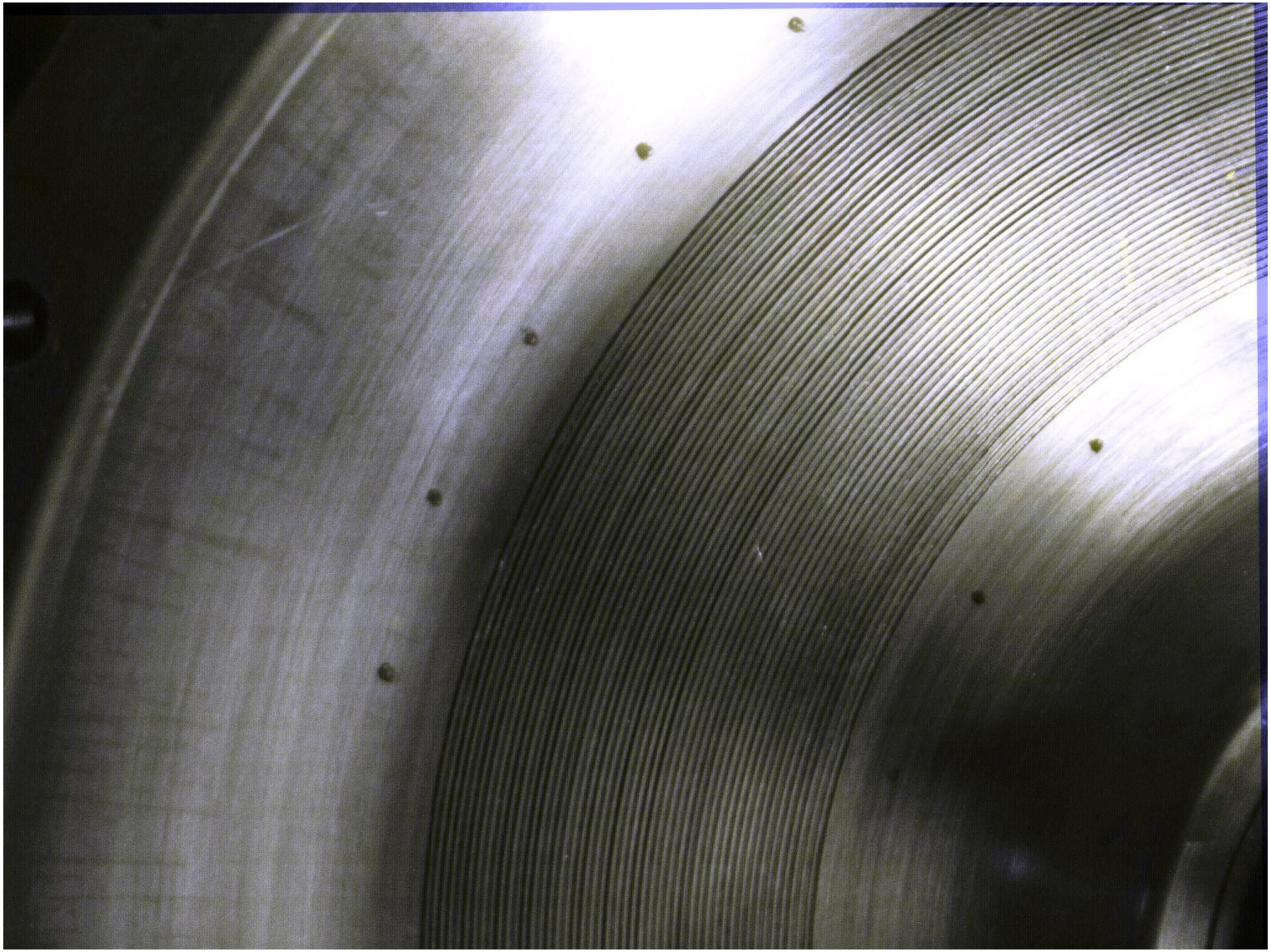


Disk – Baseline Section @ 12000RPM with 12mm Lens, Initial Validation Tests 2011



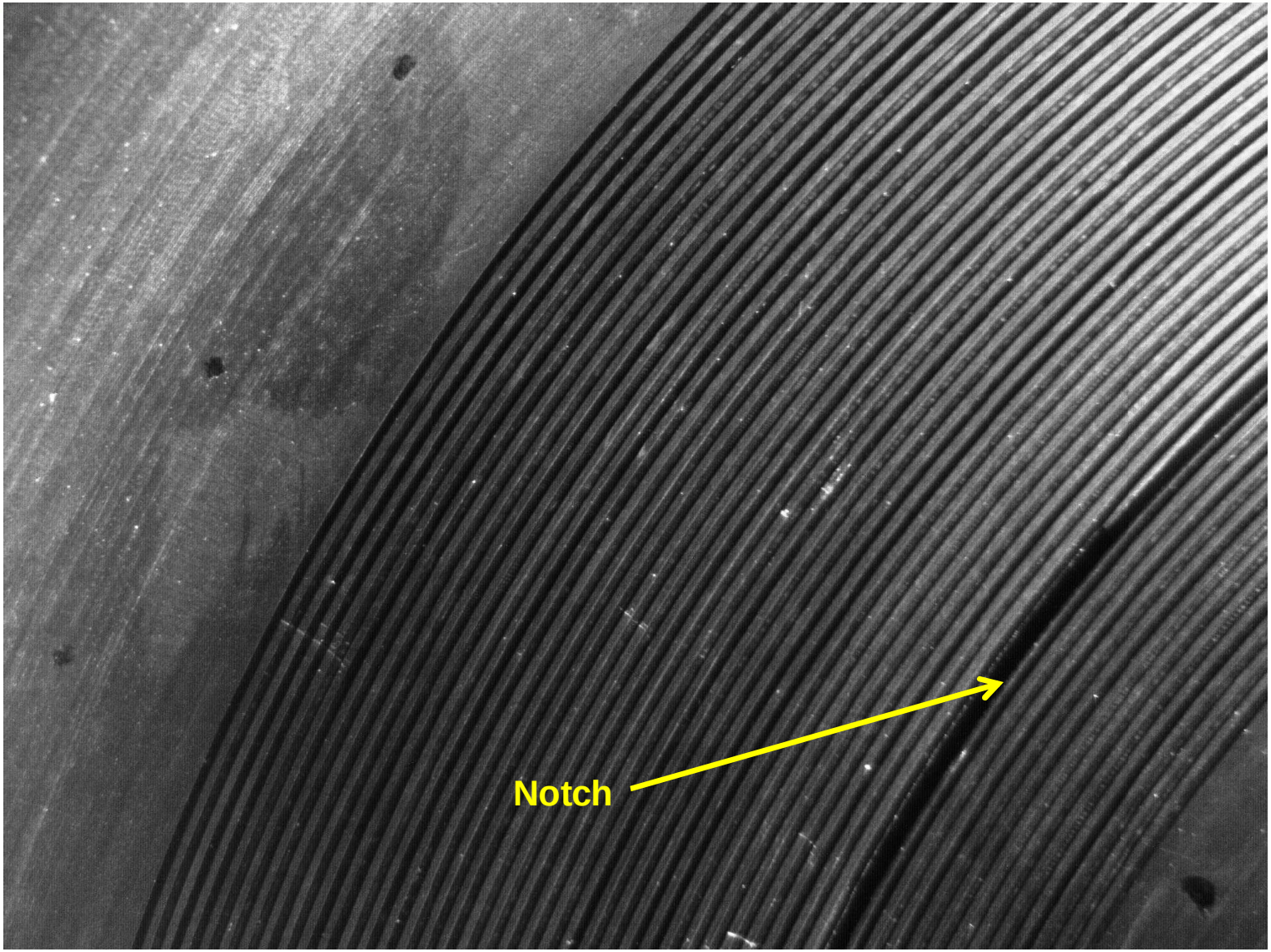
- Challenges in obtaining uniform lighting
- Some image smearing observed
- Image not in exact position as reference

Baseline Section Comparison, Initial Validation Tests 2011



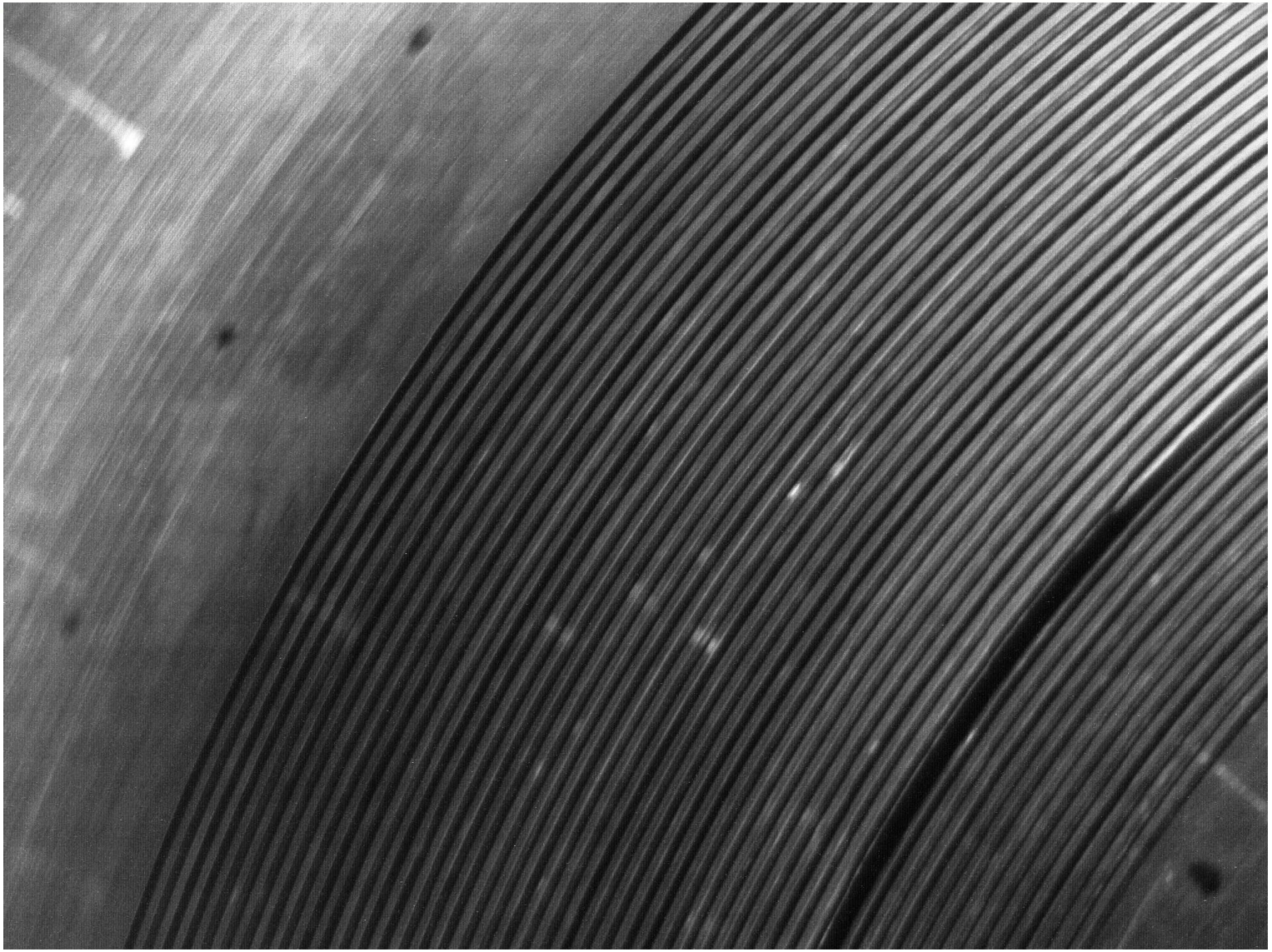
- Moiré was not observed
- The patterns on the two images matched
- Radial growth was not observed
- Expected for this side of disk

Disk – Notch Section @ 0 RPM with 25mm Lens, Initial Validation Tests 2011



- Used 25 mm lens to magnify region of interest
- Repeated experiment

Disk – Notch Section @ 12000RPM with 25mm Lens, Initial Validation Tests 2011

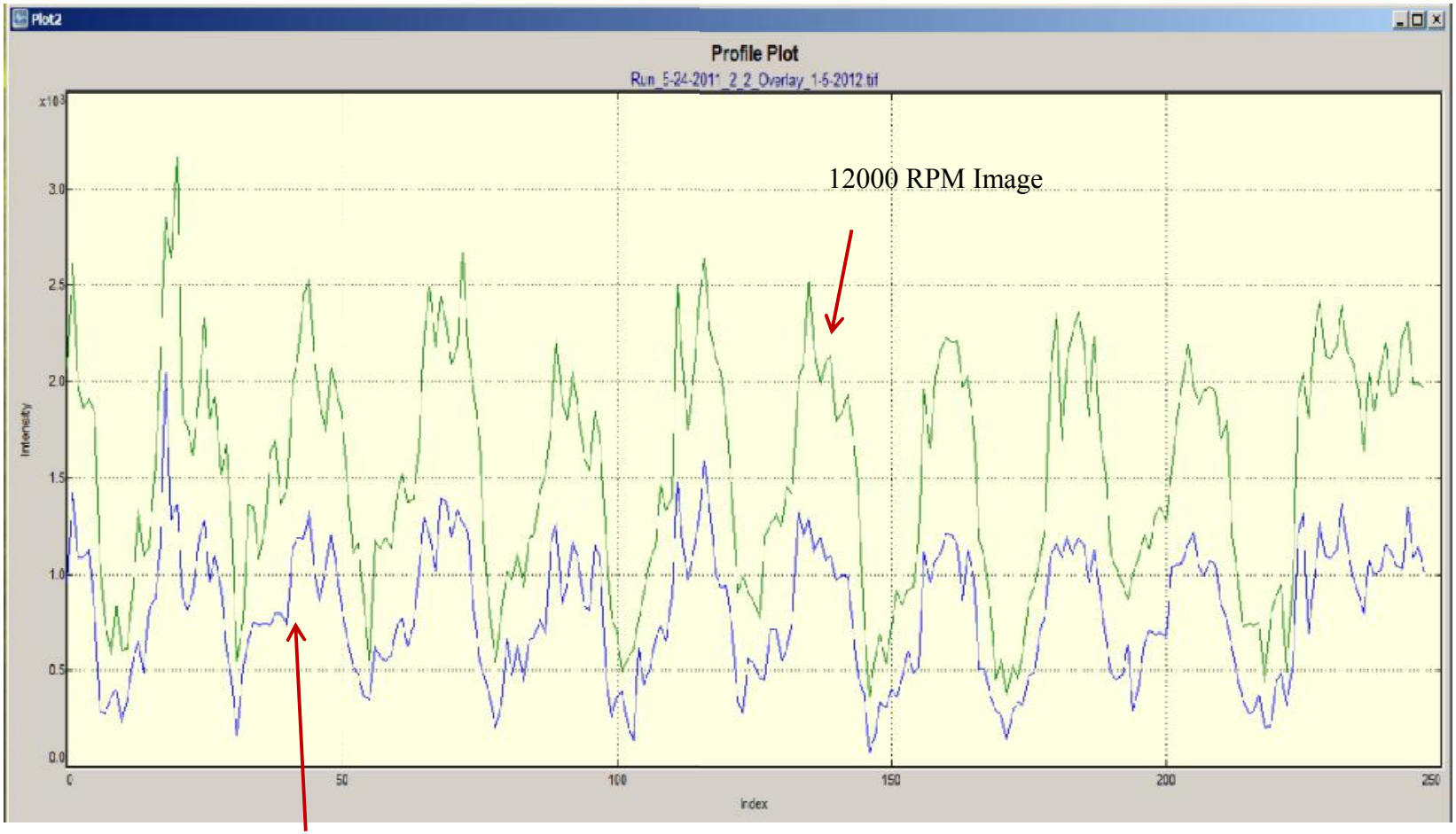


- Same challenges as previously observed previously in acquiring "snapshot" at 12000 RPM

Notch Section Comparison, Initial Validation Tests 2011

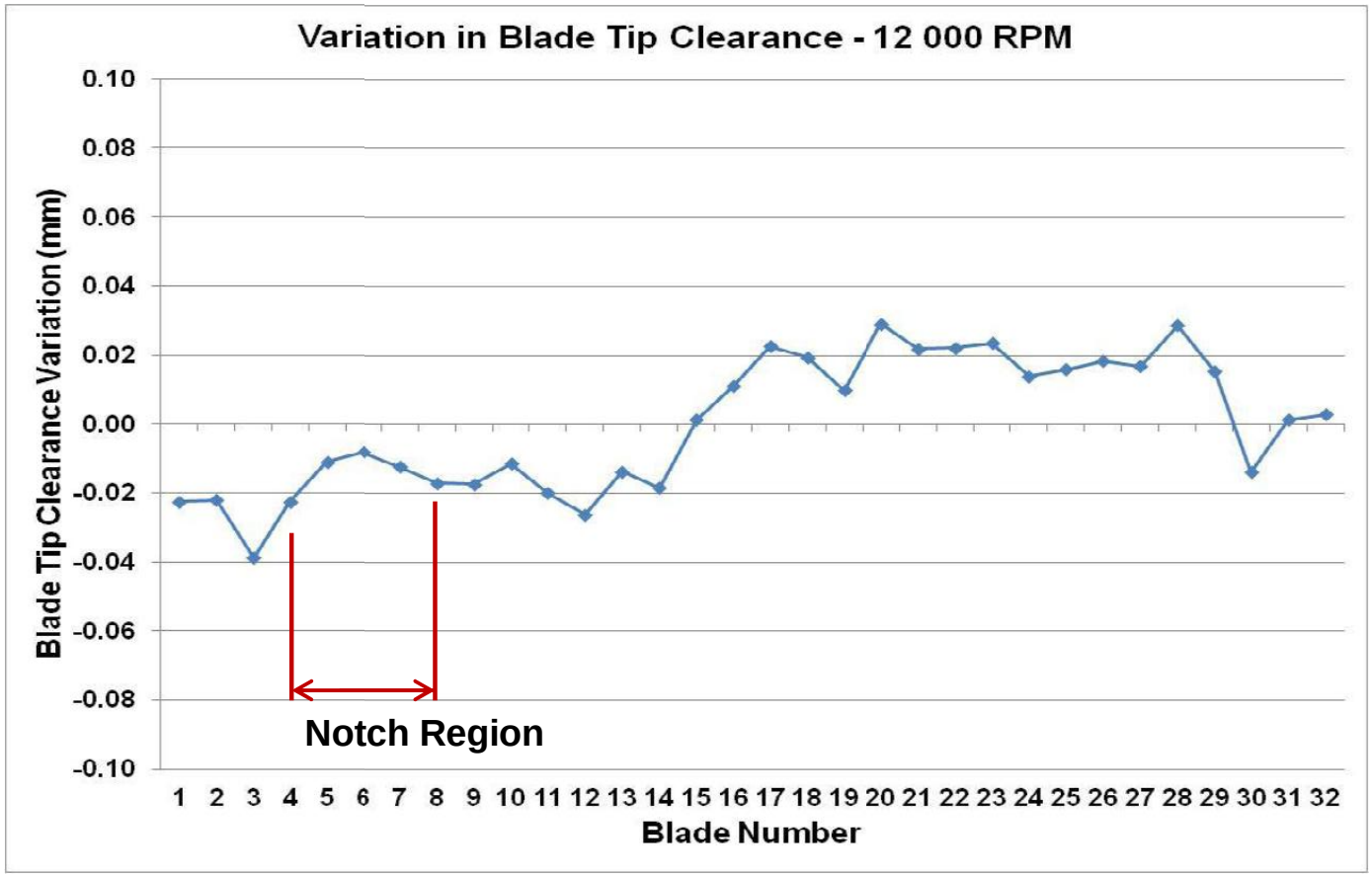
- Overlay of on-condition image onto the reference image
- Moiré was still not observed
- The patterns lined up on each other
- Again very little to no radial growth was observed
- Expected to at least observe the initiation of a pattern shift

Intensity Profile Analysis, Initial Validation Tests 2011



- Analysis verified that a shift, hence radial growth was not observed.

Blade Tip Clearance Results, Initial Validation Tests 2011



- Analyzed data acquired from microwave blade tip clearance sensor
- Showed a +/- 0.03 mm (+/- 0.001”) variation in tip clearance
- Due to shaft wobble previously observed with rig, not radial growth
- Corroborated lack of growth that was observed optically

Findings from Initial Validation Test in 2011

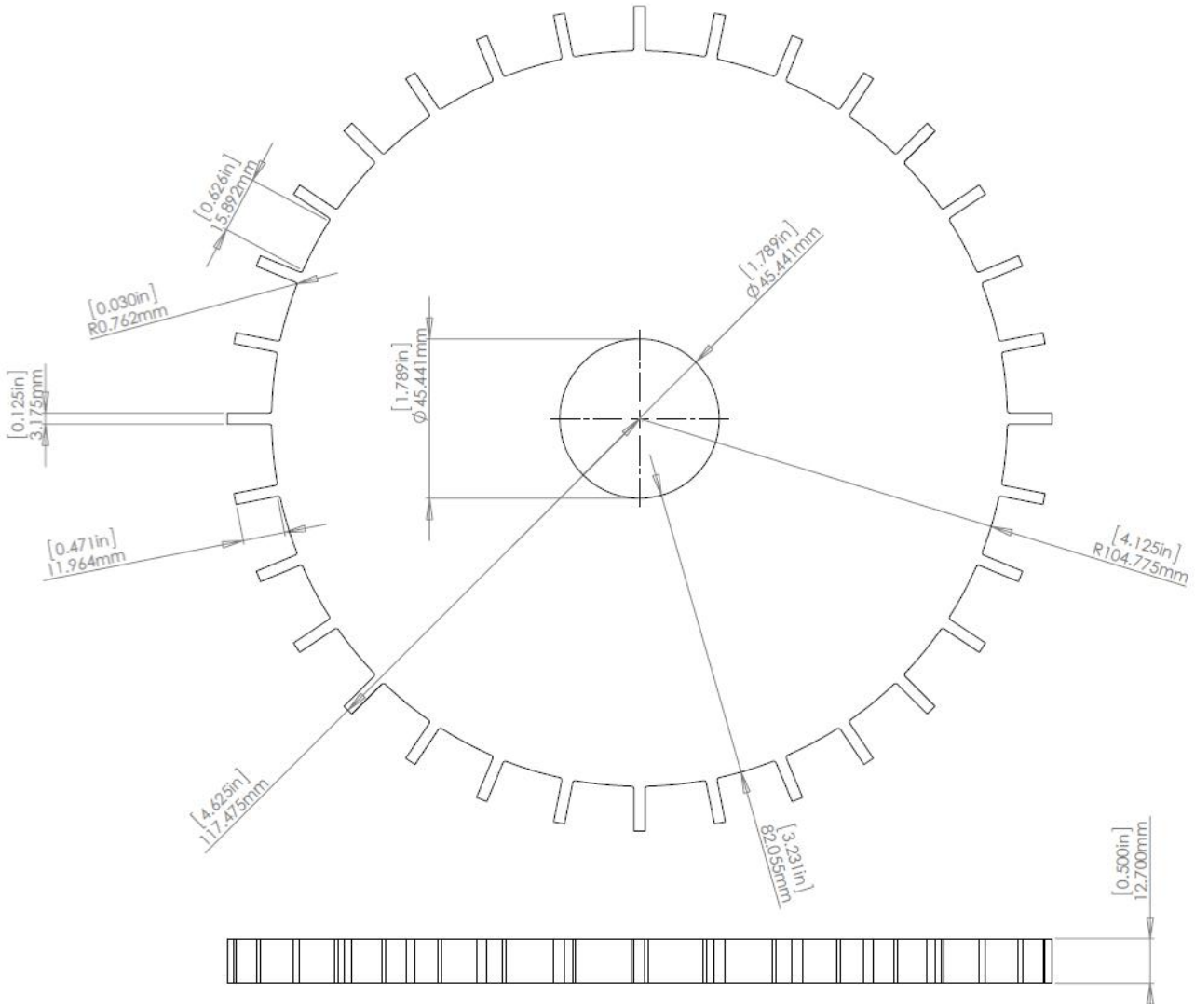
- The experiment did not yield the expected results
  - The disk did not experience the radial growth that was expected in the notched area of the disk as predicted by the analysis.
  - This finding was confirmed by both the optical and external sensor data
  - Lack of radial growth prevented successful demonstration of the Moiré based crack detection technique.

- Positive outcomes
  - This test entry was a “learning” experience
  - Our first attempt at acquiring optical data real time inside the spin rig during operation
  - Were able to successfully acquire images on condition and develop testing and image processing methodologies required for this technique

Experiment Improvements 2012

- Improvements for next phase of testing 2012
  - Refined FEA model to better predict growth, disk material ,crack size
  - Investigated alternate crack initiation techniques to get radial growth (…..this is still in process)
  - Investigated and used alternate technique of etching pattern on disk
    - Pattern was laser etched on to disk surface
  - Improved LED lighting to get more uniform coverage of disk and crisper images
    - Decreased LED pulse duration down to 2us to minimize image blur
  - Fabricated new test disk out of Aluminum
  - Simultaneously acquire external sensor data to validate other techniques
    - Center of mass variation, vibration based crack detection techniques
    - Data driven anomaly fault detection algorithms

New Subscale Disk

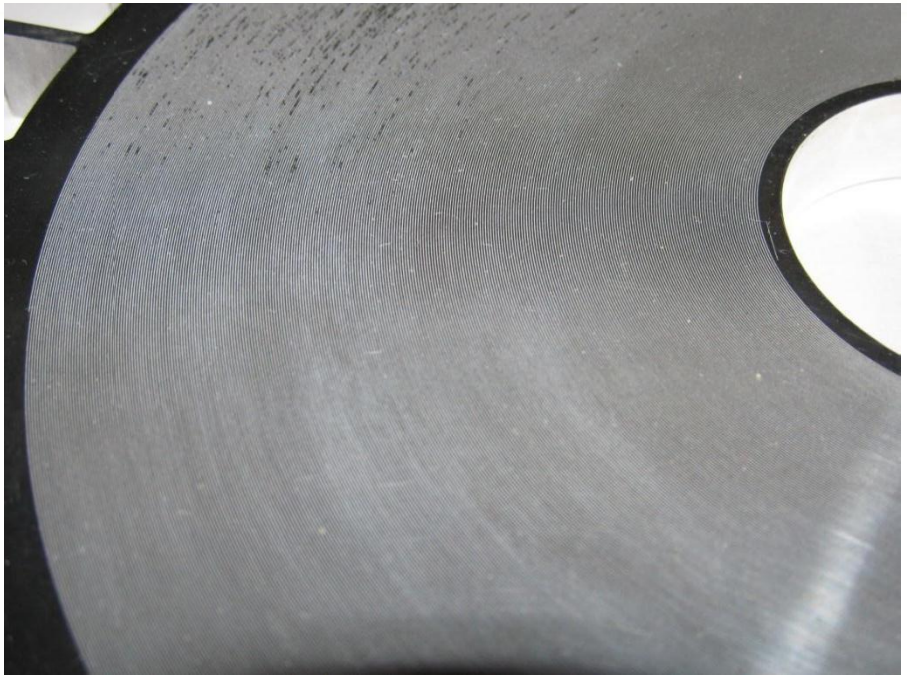


New Aluminum Disk Dimensions

New Aluminum Disk

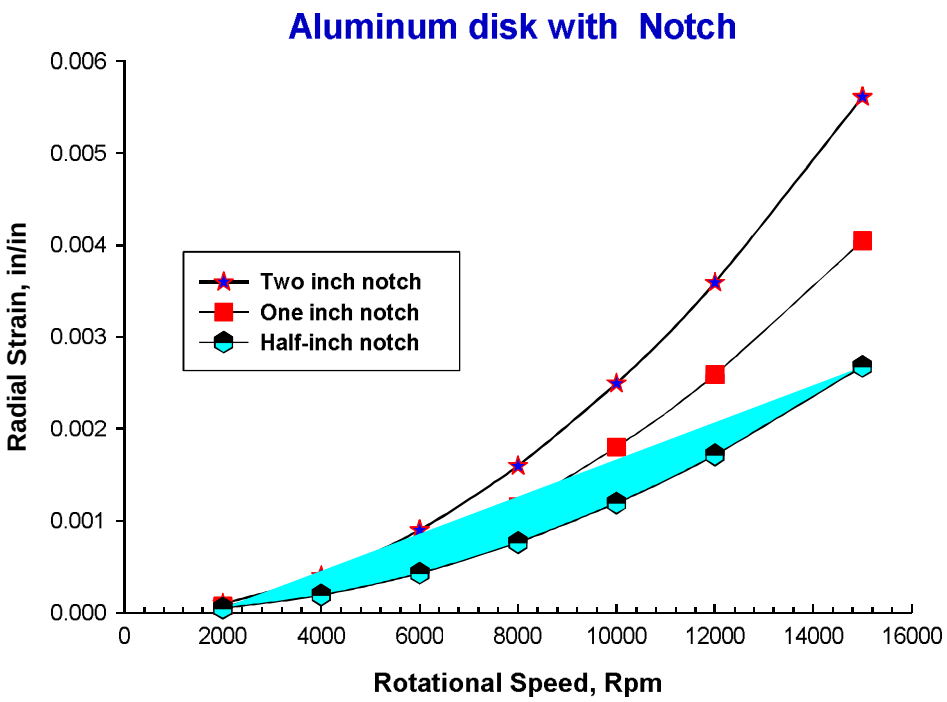
- Flat simplified geometry
  - Inexpensive
  - Easier to work with
- Softer material will experience greater radial growth to better demonstrate the concept
- Once validated, the technique will be refined for further use on more realistic materials and geometries

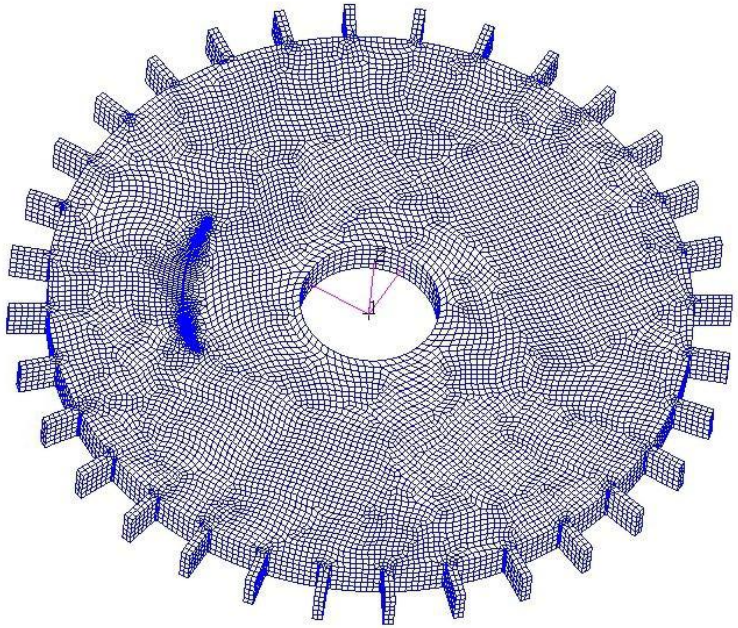
New Subscale Disk – Moiré Pattern



- Pattern of concentric circles was laser etched on to the surface of the disk
- p= 0.010” (0.25mm) pattern spacing
- Applied over most of disk area from radius = ~0.98” (24.9mm) to ~3.76” (95.5mm)
- Coverage will allow optical measurement (observance of “D” or “2D”) for measurements of radial strain down to a level of ~0.0017 in./in.
  - Measurements limited by spacing and area covered
  - For ε = ~0.0017 in./in. the first & only dark band is expected to occur at the outer edge of disk

New Disk - Analysis

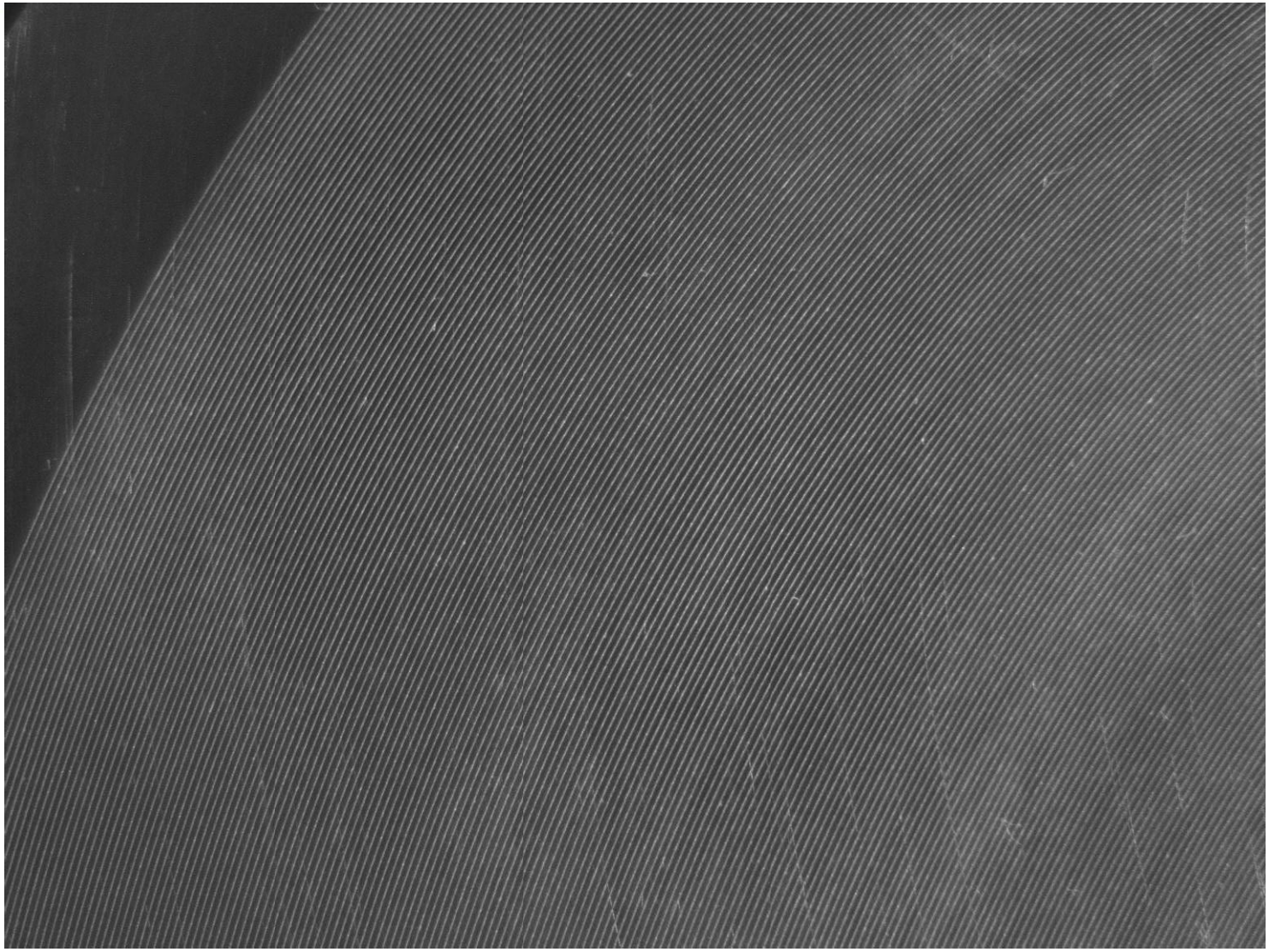




Finite Element Model of the Aluminum Disk with 2 inch Notch

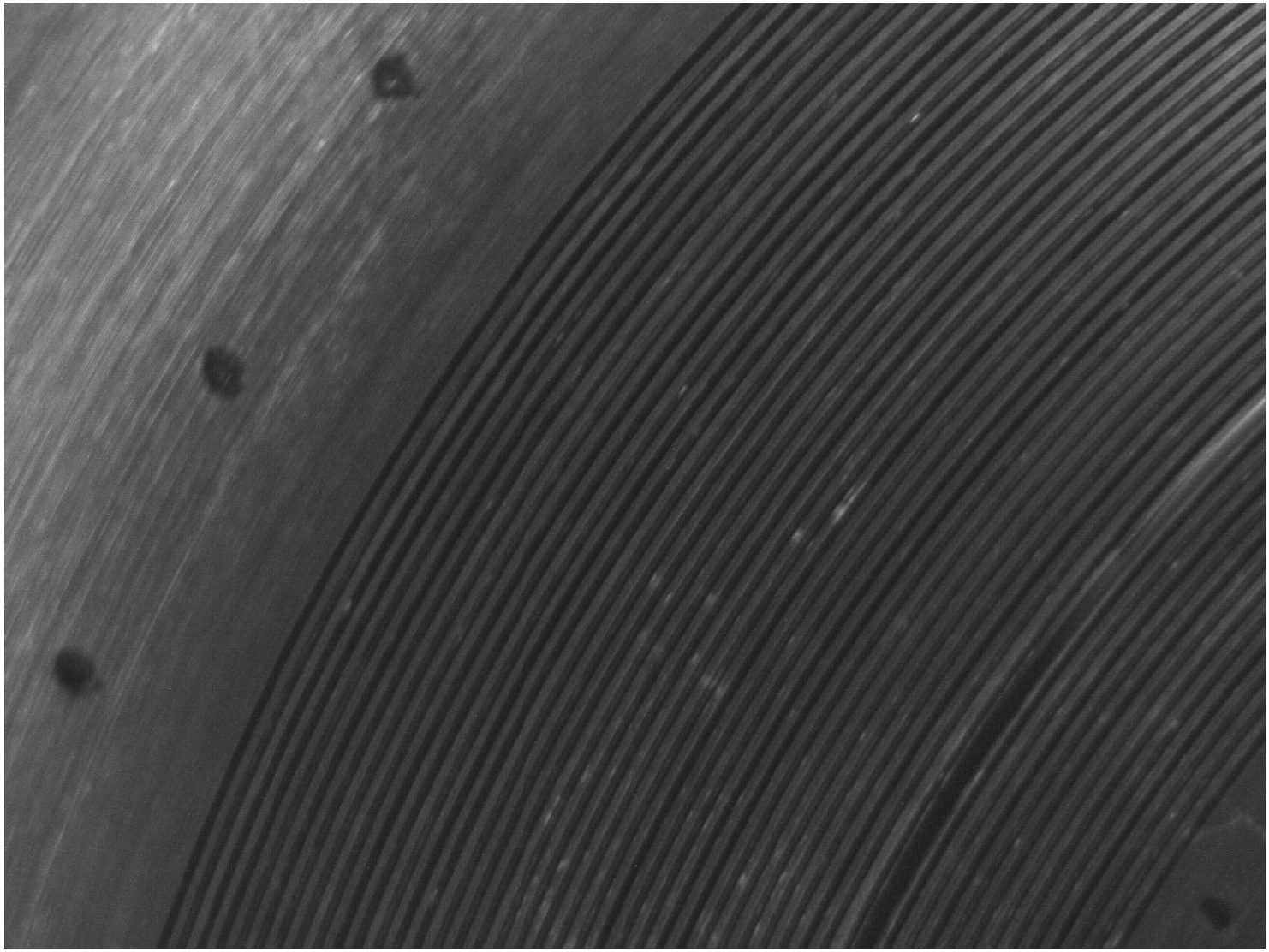
- Analysis shows radial strains up to ~0.0030 in./in. over the range and crack sizes we plan on introducing
- Expect to observe at least one dark zone set up on the pattern during operation at high end of range

New Disk – Static Image



- Same field of view as previous disk
- Improved lighting
- Better defined & more uniform coverage with circular patterns
- ***Have not yet spun new disk up***
- ***In the process of resolving mechanical connection issues with the spin rig's shaft***

Old Disk at 12000 RPM



- Re-ran original disk from previous 2011 tests
- Operating LED strobe at pulse width of 2 µs
- Have obtained near static image, significantly reduced image “blur”

Current Status 2012

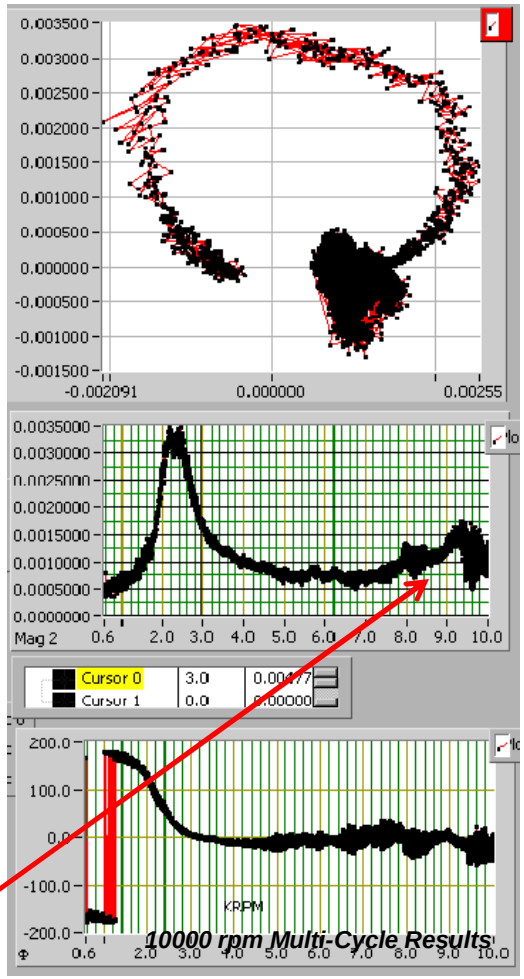
- Repeated testing on original disk used in 2011 experiments to check out improvements in set-up
  - Pulsing strobe at 2 us significantly reduced image blur
  - More uniform lighting coverage
  - Analysis yielded same results….no radial growth observed on original disk

- New Aluminum test disk has been fabricated
  - 0.010” (0.25 mm) spacing achieved on applying circular patterns
  - Expect to see the initiation of a Moiré pattern with up to 1 dark zone observable at the high speed test conditions
  - In the process of resolving mechanical issues with mounting the disk onto the High Precision Spin Rig’s shaft
  - Plans are to run the validation experiment once these issues have been resolved…will also piggyback two other techniques onto experiment

Vibration Based Crack Detection Technique

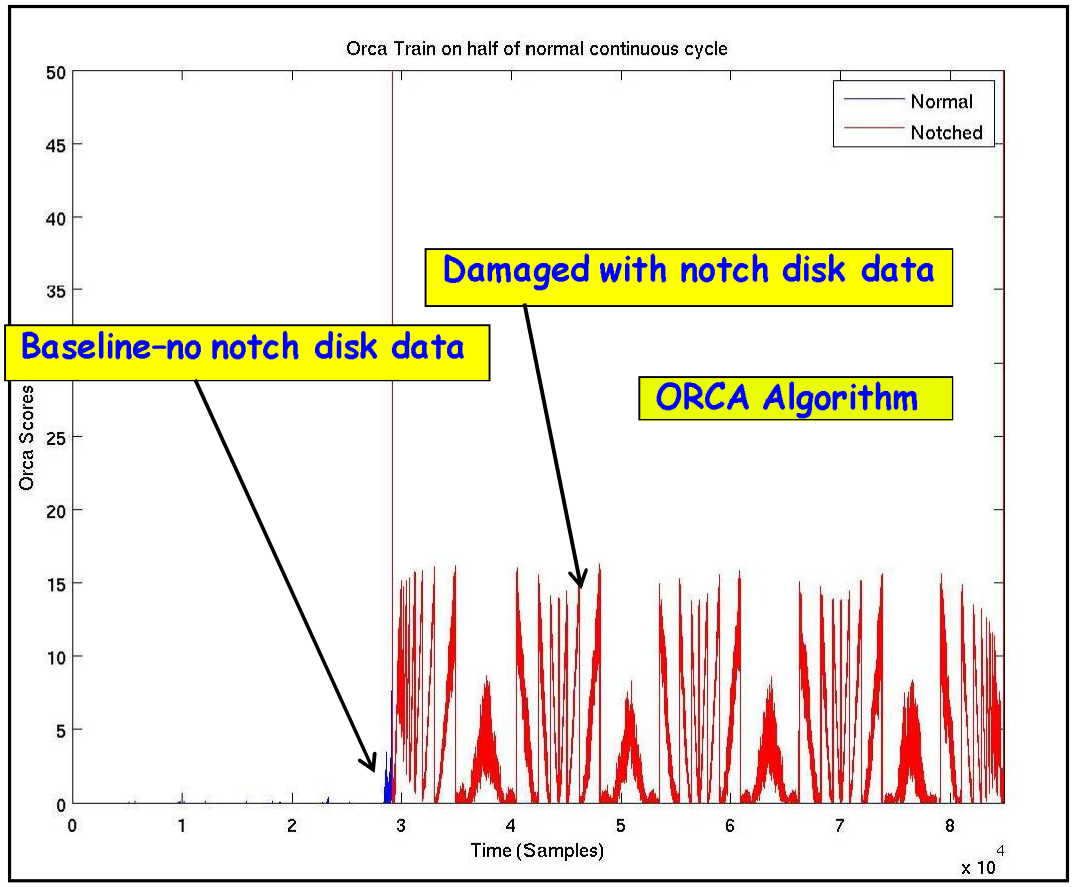
- A defect such as a crack creates minute deformations in the disk as it is being rotated
  - Crack opens up due to centrifugal loading
- This deformation creates a speed dependent shift in the disks center of mass
- This shift can be detected by analyzing the vibration response (radial motion) of the combined disk-rotor system as it is operated over a range of speeds[5-9]
  - Synchronous whirl disk-rotor system as measured by the external blade tip clearance and shaft displacement instrumentation
  - In the post-critical region the crack induced shift in the disks center of mass grows and starts to dominate the overall vibration response
  - Expect speed dependent change in amplitude in the post critical speed region {f (ω^2)}..was observed in 2009

Notched Disk (2009 data)



Data Driven Anomaly Detection Techniques

- Data mining using external blade tip clearance & shaft displacement sensor data
- Techniques developed by Ames Research Center
- Three methods investigated 2009-2011[10-11]
  - Orca
  - Inductive Monitoring System (IMS)
  - One-Class Support Vector Machines (OCSVM)
- Validation results looked promising
- Will continue validation as part of this experiment



Orca data analysis results (2009)

Conclusion

- Expect to start testing using new disk once mechanical issues have been resolved

- Plan on validating three techniques
  - Moiré based crack detection technique
  - Vibration based crack detection technique
  - Data driven anomaly detection techniques

- Will report on results at next conference

Acknowledgements

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  - Timothy Bencic of the NASA GRC Optical Instrumentation and NDE Branch for the high power LED and associated conditioning electronics used in the experiment to acquire the images

  - Timothy Heineke of the NASA GRC Machining Branch for fabrication and machining required for the test disks

  - The NASA Aviation Safety Program's Vehicle Systems Safety Technologies Project for supporting this effort

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