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

Mark Woike, Gustave Fralick, Ali Abdul-Aziz, John Wrbanek, David Spry

NASA Glenn Research Center, Cleveland, Ohio
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)

- 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:
  - Let $p = \text{spacing of initial pattern}$
  - Let $q = \text{spacing of second pattern}$, 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 $p/2$
  \[ n \cdot \Delta p = p/2, \text{ or } n = \frac{p}{2\Delta p} \] (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”

\[
D = n (p + \Delta p) = \frac{p^2}{2 \Delta p} + p/2
\]  

(4 & 5)

- Solving for \( \Delta p \)

\[
\Delta p = \frac{p^2}{2D - p}
\]  

(6)

- This can relationship cab be related to strain

\[
\varepsilon = \frac{\Delta p}{p}
\]  

(7)

\[
\varepsilon = \frac{p}{2D - p}
\]  

(8)

- Hence, for a given spacing, \( p \), and a measured distance, \( D \) or \( 2D \), you can get strain or \( \Delta p \)
Technical Approach

Reference Image Acquired at Static Conditions (0 RPM)

Image Acquired On Condition (10 to 12K RPM)

Overlay of “On Condition” image on “Reference” image to get disk growth

\[ \Delta p = \frac{p^2}{2D - p} \]

\[ \varepsilon = \frac{p}{2D - p} \]
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
  - \( \sim0.10'' \) (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
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
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

Circular Pattern

Registration Marks
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
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

- 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 Aluminum Disk Dimensions
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 $\varepsilon = ~0.0017$ in./in. the first & only dark band is expected to occur at the outer edge of disk
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
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 \( f (\omega^2) \) was observed in 2009.
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
  - 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)](image)
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
The authors would like to acknowledge the following people for their contributions towards this effort:

- 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
References


