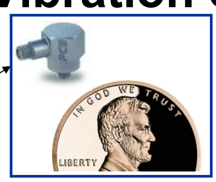
ME/EMA 540

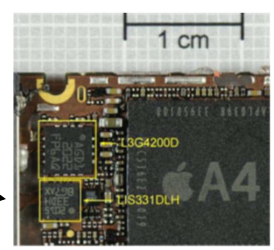
Experimental Vibrations & Dynamic System Analysis

Overview of Vibration Sensors

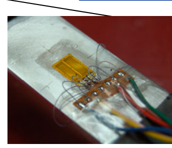
(Common) Vibration Sensors

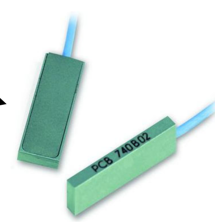
- Accelerometers
  - Piezoelectric***
  - MEMS
- Strain Gauges
  - Foil**
  - Piezoelectric (high output)
- Laser Doppler Vibrometer*
- Other Laser Methods*
- Digital Image Correlation





Accelerometer in Apple iPhone 4S





* Most Common in Industry

How does a Piezoelectric Accelerometer Work?

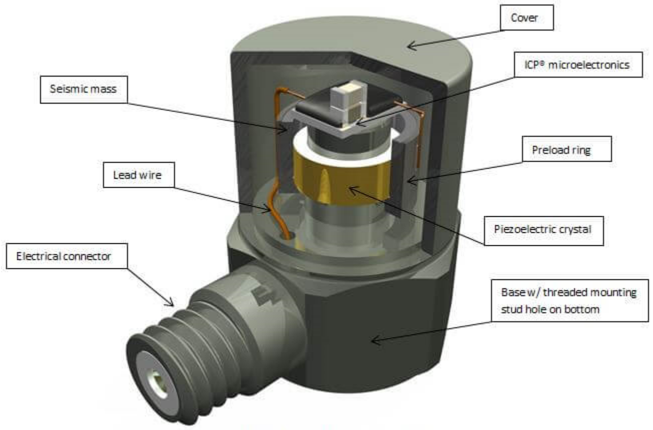


Figure 1: Typical ICP® Accelerometer

- Image: https://www.pcb.com/resources/technical-information/introduction-to-accelerometers
- Derivation (live)

Piezoelectric Accelerometer

Click to zoom

Model: 353B11

High frequency, quartz shear ICP® accelerometer, 5 mV/g, 1 to 10k Hz, 5-44 side connector

Price: Call for pricing
Quantity in stock: Call for stock

Product Manual (PDF)
Specifications (PDF)
Drawing (PDF)

Product Specifications

	ENGLISH	SI	
Performance			
Sensitivity (±10 %)	5 mV/g	0.51 mV/(m/s²)	
Measurement Range	±1000 g pk	±9810 m/s² pk	
Frequency Range (±5 %)	1 to 10000 Hz	1 to 10000 Hz	
Frequency Range (±10 %)	0.7 to 18000 Hz	0.7 to 18000 Hz	
Frequency Range (±3 dB)	0.35 to 30000 Hz	0.35 to 30000 Hz	
Resonant Frequency	≥70 kHz	≥70 kHz	
Broadband Resolution (1)	0.01 g rms	0.1 m/s² rms	[1]
Non-Linearity	≤1 %	≤1 %	[2]
Transverse Sensitivity	≤5 %	≤5 %	[3]
Environmental			
Overload Limit (Shock)	±10000 g pk	±98100 m/s² pk	
Temperature Range (Operating)	-65 to +250 °F	-54 to +121 °C	
Base Strain Sensitivity	≤0.005 g/με	≤0.05 (m/s²)/με	[1]
Physical			
Size - Height	0.43 in	10.9 mm	
Weight	0.07 oz	2.0 gm	[1]
Sensing Element	Quartz	Quartz	
Size - Hex	0.31 in	7.9 mm	
Sensing Geometry	Shear	Shear	
Housing Material	Titanium	Titanium	

- As of 9/28/2017
  - **Model: 353B15 (platinum stock products)**
  - **$320.00 USD**

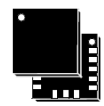
MEMS Accelerometer LIS331DLH

MEMS digital output motion sensor
ultra low-power high performance 3-axes "nano" accelerometer

Features

- Wide supply voltage, 2.16 V to 3.6 V
- Low voltage compatible IOs, 1.8 V
- Ultra low-power mode consumption down to 10 μA
- $\pm 2g/\pm 4g/\pm 8g$ dynamically selectable full-scale
- I²C/SPI digital output interface
- 16 bit data output
- 2 independent programmable interrupt generators for free-fall and motion detection
- Sleep to wake-up function
- 6D orientation detection
- Embedded self-test
- 10000 g high shock survivability
- ECOPACK® RoHS and "Green" compliant (see Section 8)

Applications



LGA 16 (3x3x1 mm)

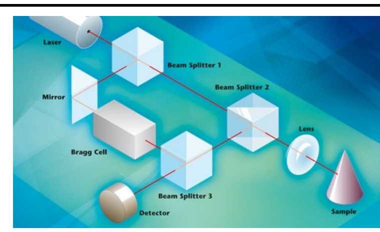
Description

The LIS331DLH is an ultra low-power high performance three axes linear accelerometer belonging to the "nano" family, with digital I²C/SPI serial interface standard output.

The device features ultra low-power operational modes that allow advanced power saving and smart sleep to wake-up functions.

The LIS331DLH has dynamically user selectable full scales of $\pm 2g/\pm 4g/\pm 8g$ and it is capable of measuring accelerations with output data rates from 0.5 Hz to 1 kHz.

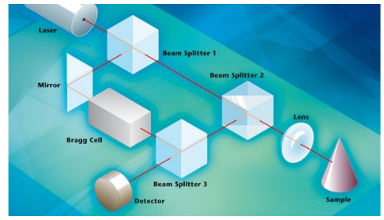
Laser Vibrometer



http://www.polytec.com/us/solutions/vibration-measurement/basic-principles-of-vibrometry/

- Use the Doppler effect, or constructive/destructive interference in a beam of light, to measure motion.
- How does it work?
  1. Split a beam of light
     1. Send one beam to the structure
     2. Shift the frequency of the other beam by ~10s of MHz.
  2. Collect the light that is scattered from the structure (often requires retro-reflective tape)
  3. Mix the two beams (incoming and outgoing) of light.
     1. The frequency shift, which is initially 100's of THz, reduces to 10's of MHz.
  4. Use a demodulator circuit (PLL or digital) to estimate frequency as a function of time. (Similar to an FM radio!)
  5. Surface velocity is then proportional to frequency

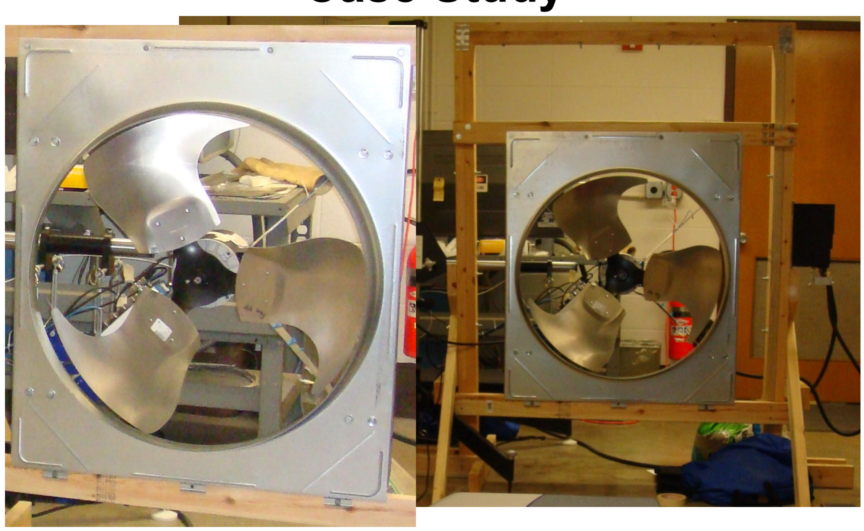
Laser Vibrometer



http://www.polytec.com/us/solutions/vibration-measurement/basic-principles-of-vibrometry/

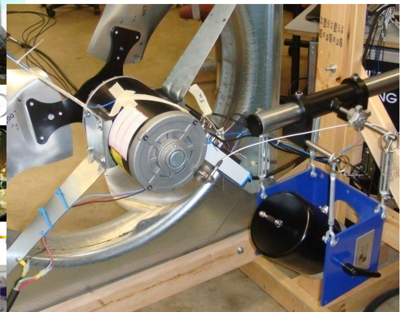
- Use the Doppler effect, or constructive/destructive interference in a beam of light, to measure motion.
- Advantages:
  - No mechanical connection to the structure!
  - Very high bandwidth (MHz to GHz)
  - Automation
- Disadvantages:
  - Noise tends to be higher than accelerometers
  - Need line of sight to measurement point
  - Measurement point moves if the structure moves (problem for freely suspended structures).
- Leading Manufacturer: Polytec Inc.
  - http://www.polytec.com/

Case Study

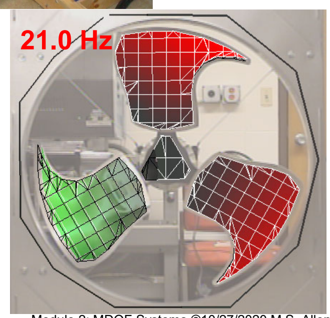


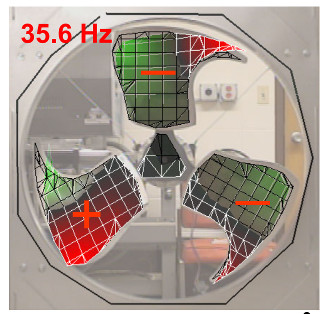
- LDV applied to condenser fane from commercial Trane air conditioning unit.

Conventional SLDV Approach



- Attached an electromagnetic shaker to perform sine-dwell tests with the Polytec system.
  - Shaker setup: 2-4 hours
  - Fastscan® to acquire ODS: 30 min–2 hours for each.





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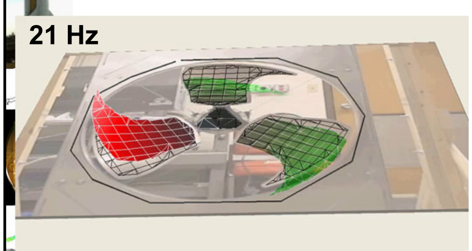
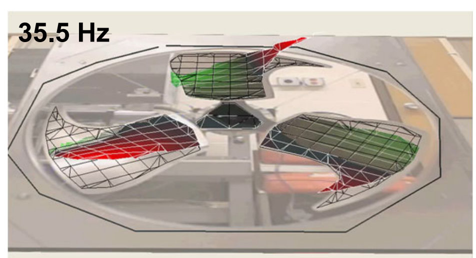
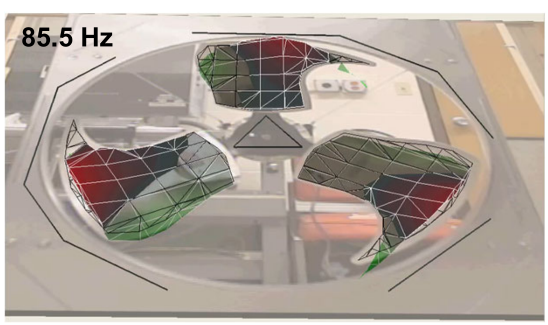
Sample SLDV Mode Animations







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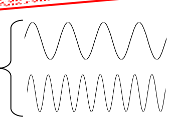
Application to Wind Turbine

- Test Challenges:
  - Most common sensors must be attached to the structure.
  - Cables must be run from the sensors to data acquisition hardware.
- Laser Doppler Vibrometer:
  - **Advantages:**
    - Non-contact laser measurement simplifies setup
    - Impact excitation is challenging – use the natural excitation from the wind.
  - **Disadvantage**:
    - Captures the response at only one point
    - Too expensive to use many lasers in parallel

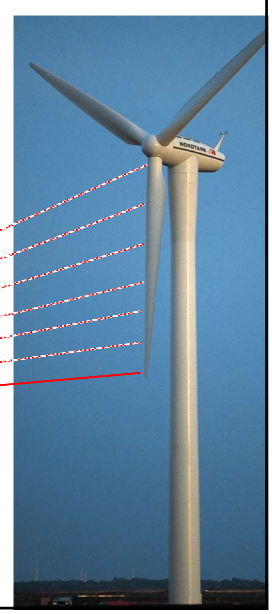
UW-Madison Research: CSLDV Solution

- Continuous-Scan Laser Doppler Vibrometry (CSLDV): Velocity is measured as the laser spot sweeps continuously over the structure.
  - First presented by Sriram & Hanagud (1990)
  - Later extended by Stanbridge, Martarelli & Ewins
    - Sinusoidal Excitation
    - Transient (Impact) Excitation
  - CSLDV with Lifting for Transient Response: Allen & Sracic 2010, Yang, Allen & Sracic 2010

LDV with scanning mirrors



drive signal for scanning mirrors



Movie: link1

A Useful Laser Show?

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OMA-CSLDV on Wind Turbine Blade

- Renewegy LLC in Oshkosh, WI: 20kW wind turbine with ~10m diameter rotor, ~30m tower height.
- Rotor parked (brake applied) during the test.
- Blade tilted so that the LDV measures in the flapwise direction.
- The blade was excited by only the ambient wind (3.5 m/s average wind speed) as both conventional and CSLDV measurements were acquired.
- Retro-reflective tape used, 66.4 meter standoff distance.

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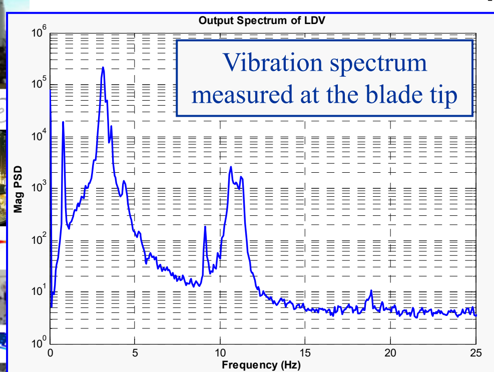
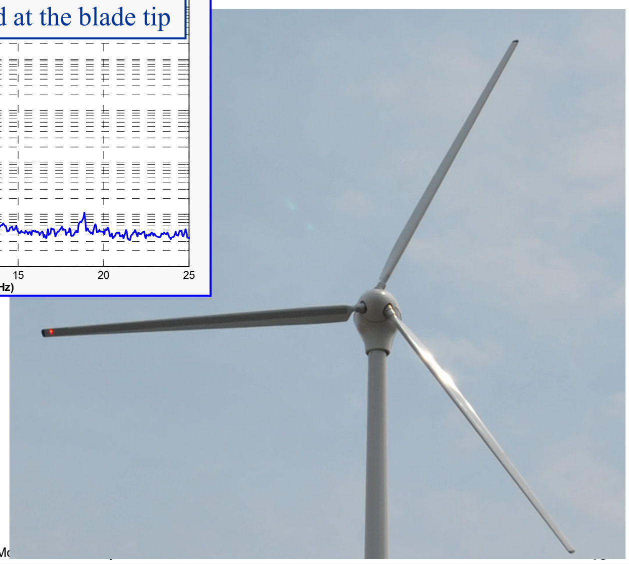
Conventional OMA (Tip Measurement)





- Laser positioned at a fixed point at the tip of the blade as shown.
- Power spectrum shows several peaks.

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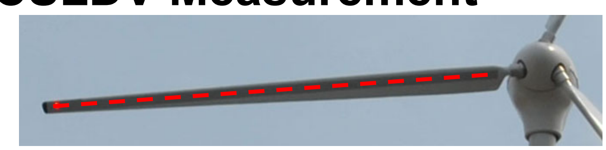
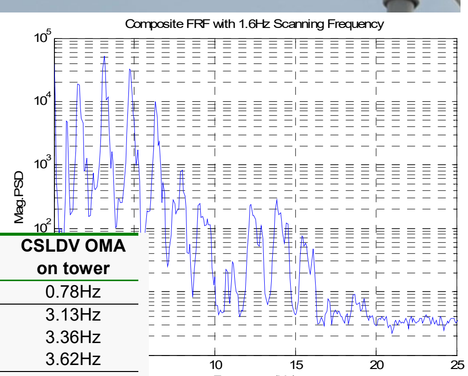
OMA-CSLDV Measurement



- Laser scanned along the length of the blade for CSLDV measurement.
- Several modes identified in the harmonic power spectrum.



Mode	Conventional test in stiff fixture	Fixed point OMA on tower	CSLDV OMA on tower
-	-	0.81Hz	0.78Hz
Flap Wise Bending 1	3.36Hz	3.13Hz 3.37Hz 3.63Hz	3.13Hz 3.36Hz 3.62Hz
Edge Wise Bending 1	5.24Hz	4.38Hz	-
-	-	9.13Hz	-
Flap Wise Bending 2	11.40Hz	10.63Hz 10.94Hz 11.25Hz	10.62Hz 10.86Hz 11.29Hz

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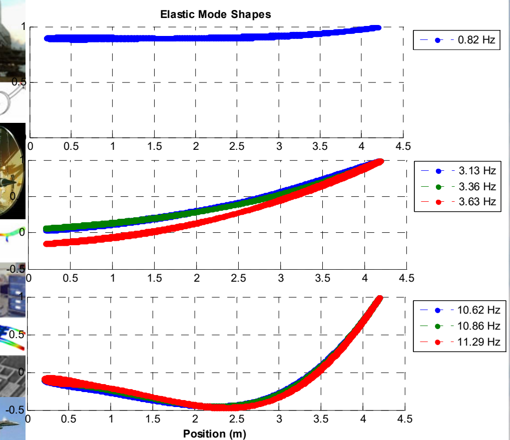
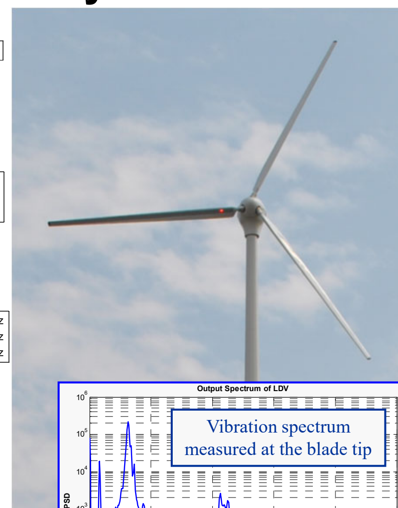
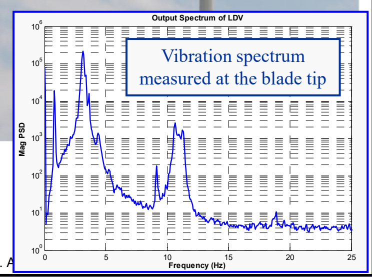
Mode Shapes Identified by OMA CSLDV







- CSLDV reveals the deformation shape of the structure associated with each frequency.

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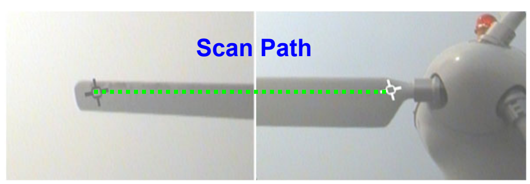
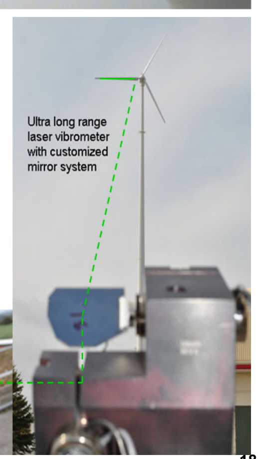
New Remote Sensing Vibrometer

- Field test at Renewegy LLC in Oshkosh, WI:
  - 20kW wind turbine with 9.4m diameter rotor and 30m tower height.
  - 77 m standoff from laser head to target.
  - Rotor was parked (brake applied)
  - The blade was excited by only the ambient wind with 9 m/s max wind speed
- Remote Sensing Vibrometer
  - Prototype from Polytec®
  - 1550nm wavelength
  - Higher power (10mW)
  - Designed for long range measurements, improved signal.



Standoff distance	77m
Blade length	4.5m
Max wind speed	9m/s
Scan Frequency	36Hz



Video of CSLDV with RSV

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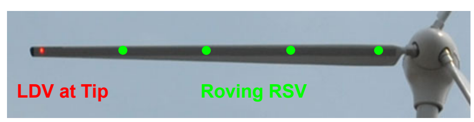
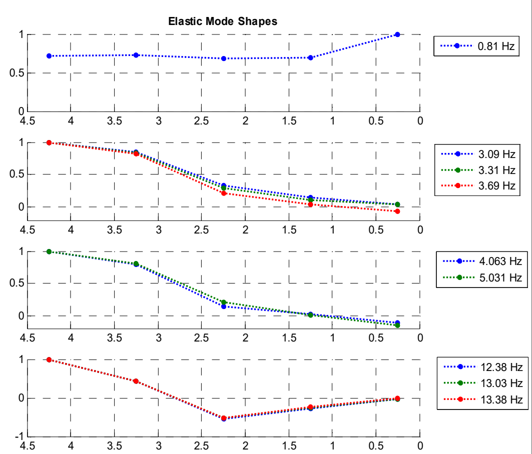
Validation with Traditional SLDV

- Laser position determined by measuring the angle of the RSV Laser head
- Measurements agree fairly well with those obtained by CSLDV
  - Two additional peaks could be identified around 4Hz and 5Hz due to lower speckle noise
- There are several points which appear to be questionable
  - Due to changing wind conditions?
- SLDV used 5.3 min long measurements at each of the 5 points = total 26.5min
  - OMA-CSLDV achieves far higher resolution with a single 6.7 min measurement!



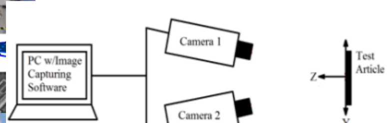


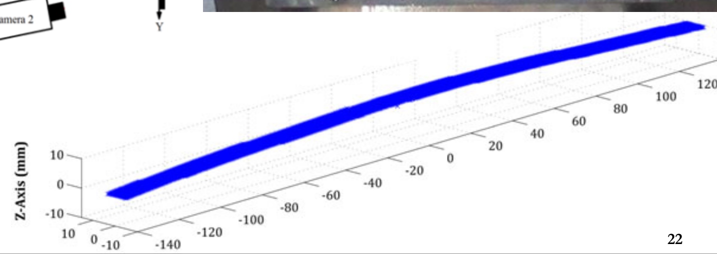
Comparison with Conventional Methods

- Conventional Test Methods:
  - OMA with accelerometers (fixed sensors)
    - Requires attaching sensors to the points of interest and running cables to data acquisition (or wireless transmitters).
- OMA with conventional scanning LDV
  - At least two measurement points needed to obtain mode shapes.
  - Cost per LDV: $80,000+
  - Each pair of points must be observed for at least 10 minutes.
- The results presented here were acquired with one ground based laser and two 10-min time records!

3D Digital Image Correlation (3D-DIC): Definition

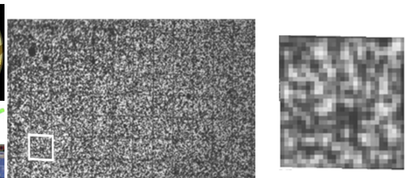
- Non-contact full-field deformation measuring technique
  - in- and out- of plane displacements
  - Static and dynamic measurements
- Uses two digital cameras to record surface
  - Full view of surface
  - Random speckle pattern
- Post process images to obtain displacements
  - For example, 64 GB of images may be captured in 10-30s. Then ~15-30 minutes are needed to offload the images and hours for image processing.



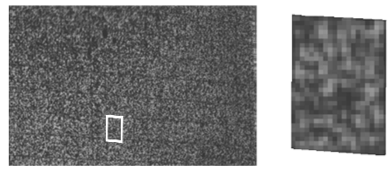


3D-DIC Example: X-, Y-, and Z – Displacement Calculation for Static Out-of-Plane Rotation

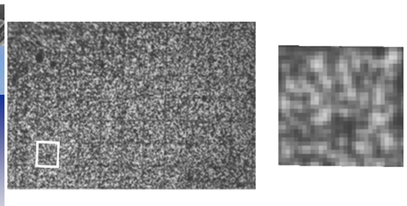
- Un-deformed Images
- Deformed Images



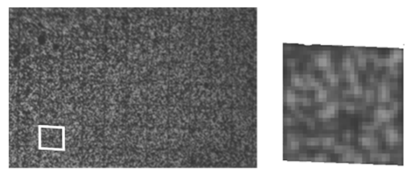
Camera 1



Camera 1



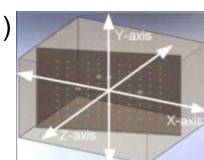
Camera 2

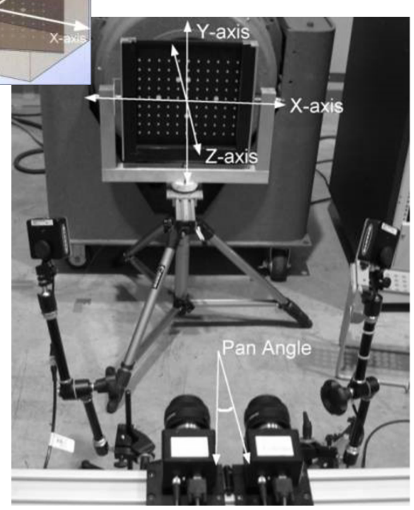


Camera 2

Areas of Potential Measurement Variation

- Calibration (Static 2011)
  - Cal Parameters
    - +/- Z distance
    - Tilt
  - Camera angle
- Experimental Setup (Dynamic)
  - Lighting
    - Frame rate
    - Shutter speed
    - Light Source
  - Camera Angle
  - Camera Cooling Fans
  - Speckle Pattern
- DIC Software
  - Correlation algorithm

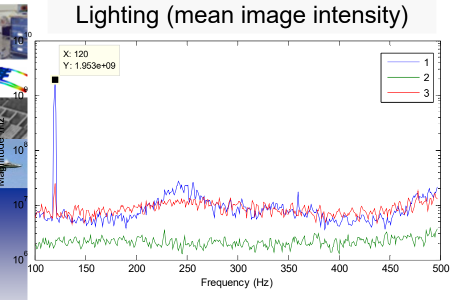




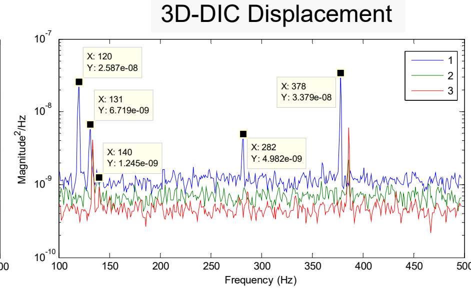
Static 3D-DIC System Noise - Lighting

- Lighting
  - Overhead Lights (120 Hz)
  - Fluorescent (120 Hz)
  - LEDs (none observable)

Lighting (mean image intensity)



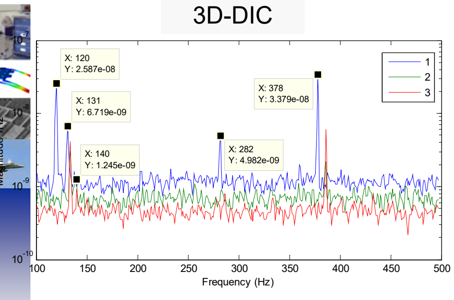
3D-DIC Displacement



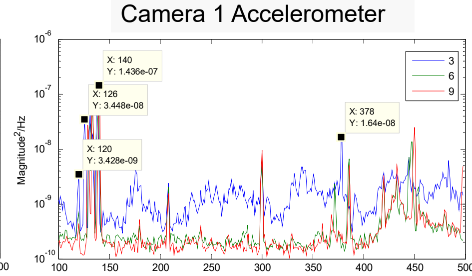
Static 3D-DIC System Noise - Camera Vibrations

- Camera Vibration
  - Peaks between 130 Hz & 140 Hz
  - Peak near 378 Hz
  - Peak near 282 Hz
    - Due to camera startup

3D-DIC

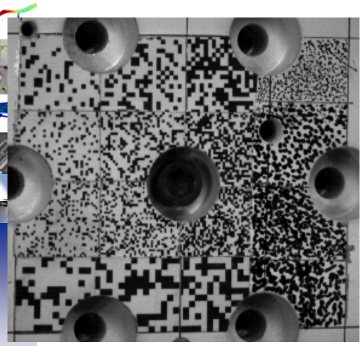


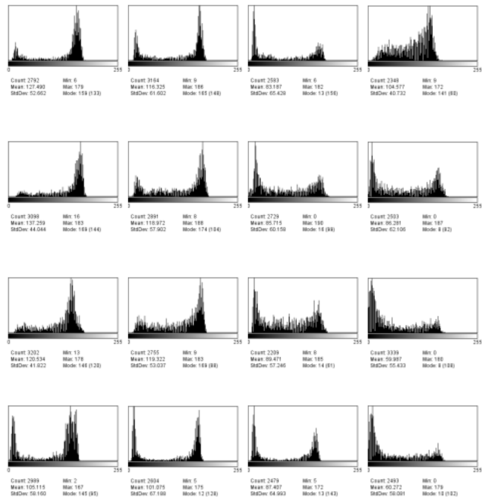
Camera 1 Accelerometer



Noise Results: Speckle Pattern Histograms

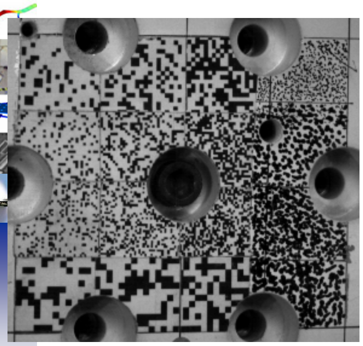
- Histogram
  - Distribution of grey levels
  - Use all available

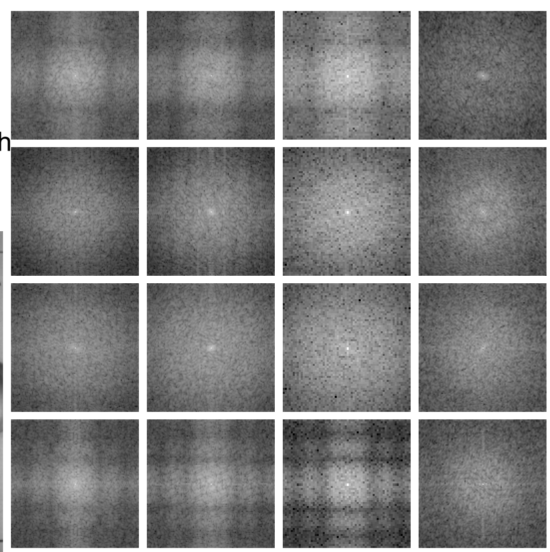


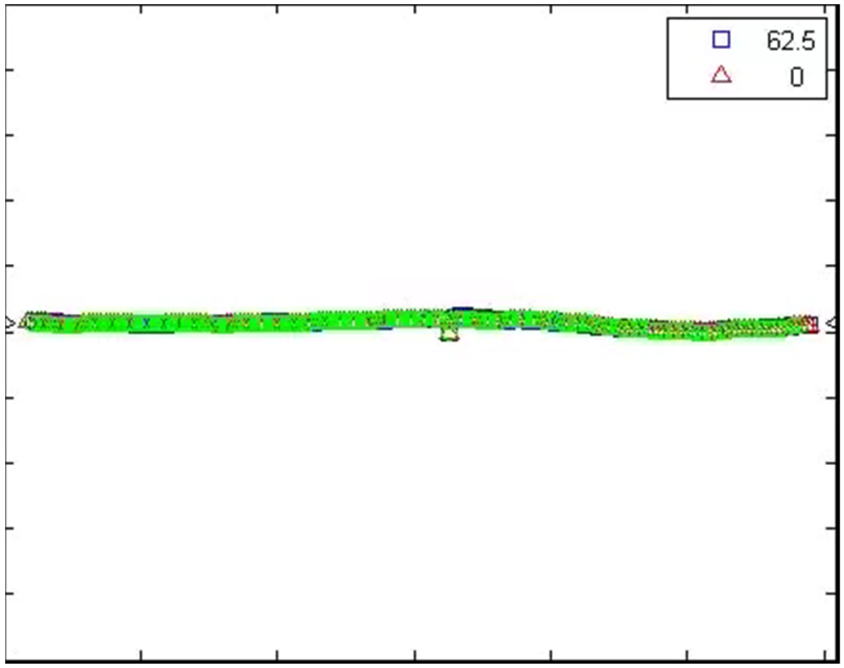


Noise Results: Speckle Randomness (DFT)

- Fourier Transform
  - Even distribution of grey levels
  - Good signal strength
  - Crammond et al. [1]







B1 DFT Waterfall (9g Sweep 60–120 Hz) -- Abanto-Bueno and Ehrhardt (2010)