Using Sampling Moiré to Extract Displacement Information from X-ray Images of Molten Salt Batteries

Phillip L. Reu, Enrico Quintana, Kevin Long

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Exceptional service in the national interest

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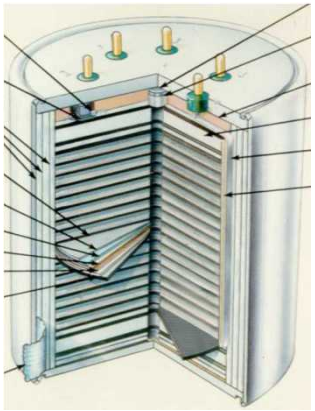

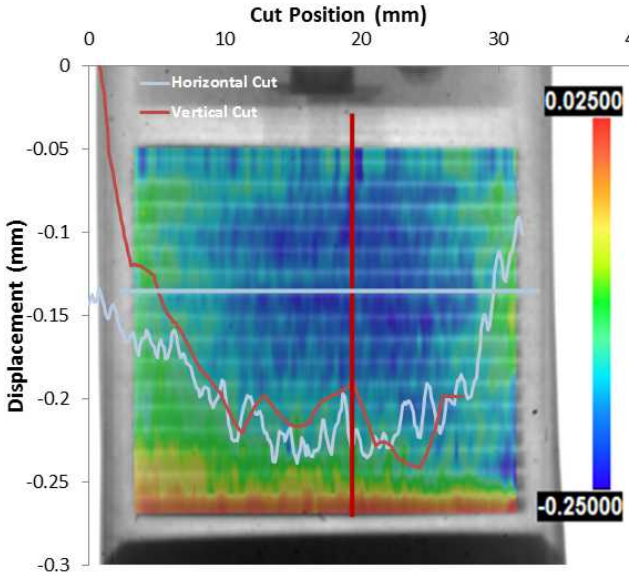

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National Nuclear Security Administration

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Why are molten salt batteries important?

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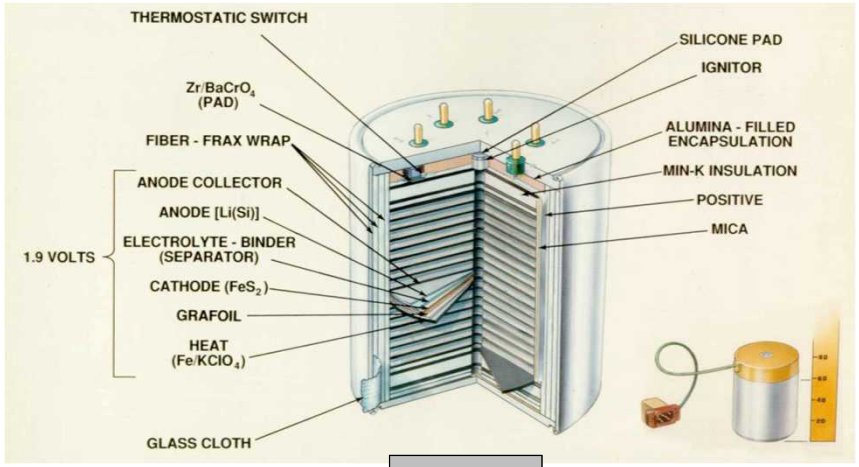
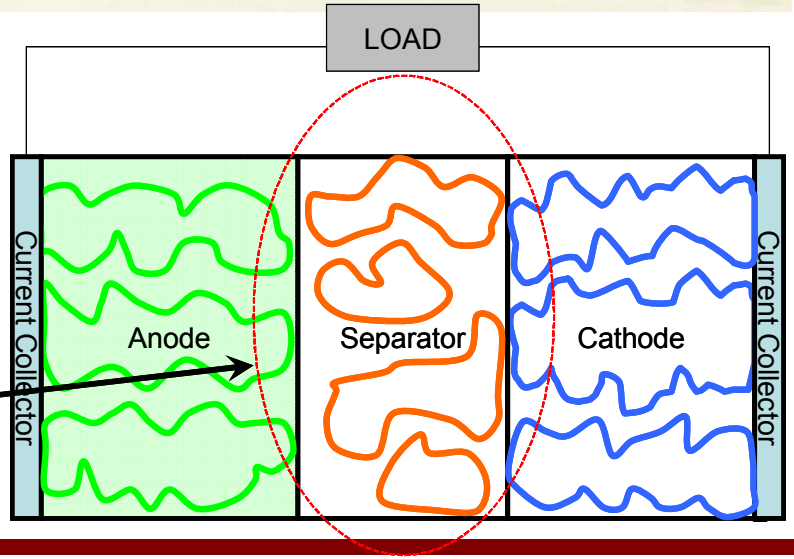
Many DOE & DoD systems use molten salt batteries due to their on-demand *reliability*, *long shelf life*, *and large specific power density*

Batteries Exist in Two States

- In the **cold state** (room temperature)
  - Electrolyte is Solid→No Conductivity
  - Open Circuit Battery
  - Inert Chemistry
- In the **hot state** (~400 C)
  - Liquid Electrolyte→High Conductivity
  - Closed Circuit→Battery Delivers or Takes in Power





Electrolyte Acts as a Thermal Switch

What Physics Are We Trying to Model?

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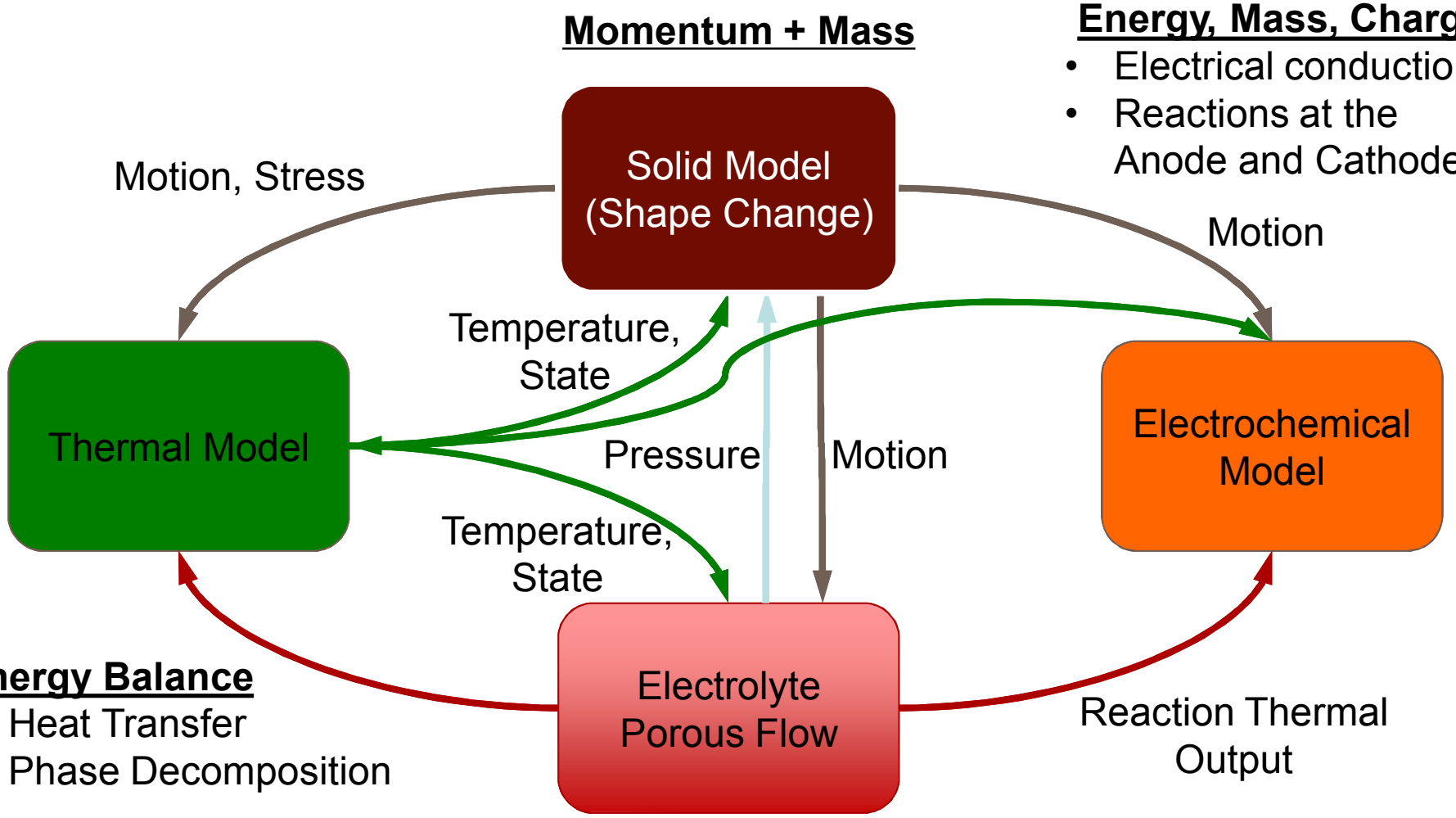
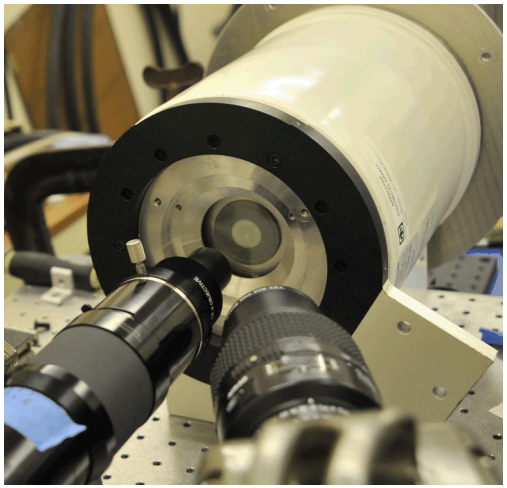
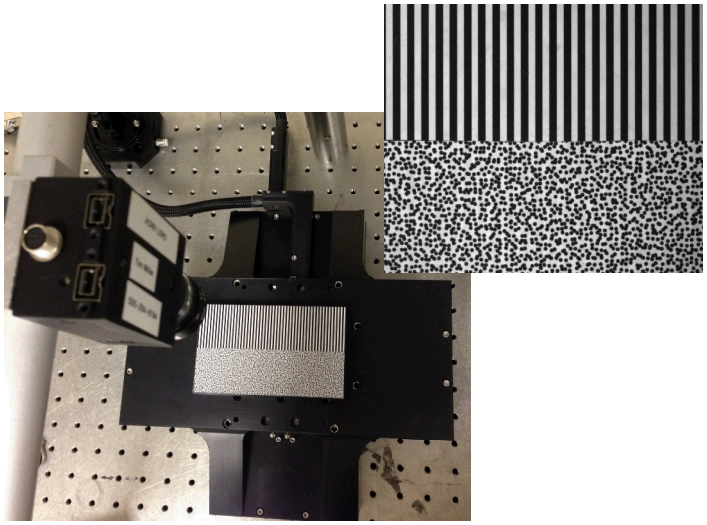


Voltage/Current Output depend on the thermal, mechanical, and electrolyte flow behavior through deforming porous media

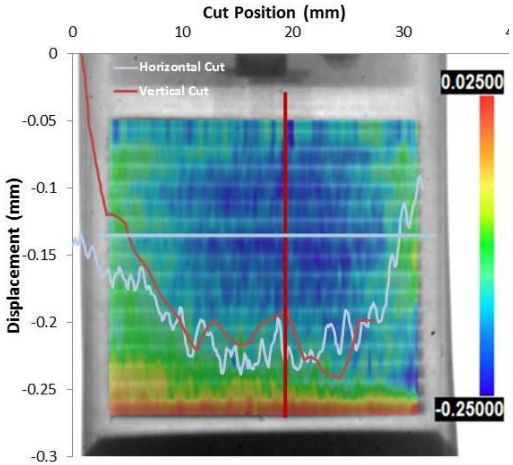
The experimental objective is to measure the layer displacement *in situ*



Experimental Setup



Technique Validation



Preliminary Results

Experimental setup was a collimated X-ray source, scintillator and high speed camera.

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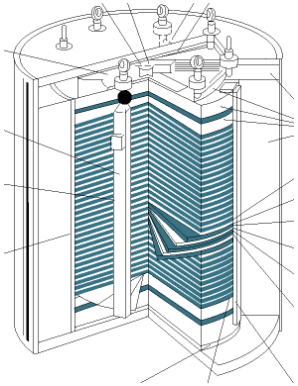
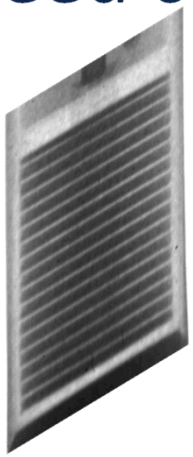
Collimated X-ray source

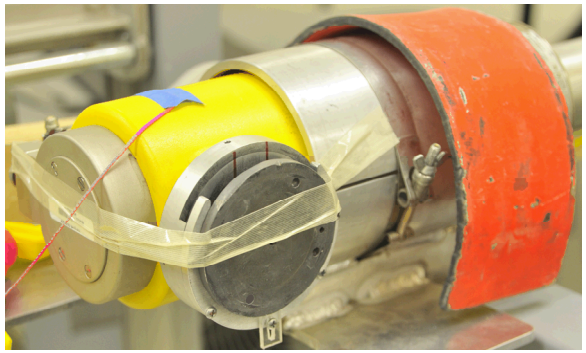


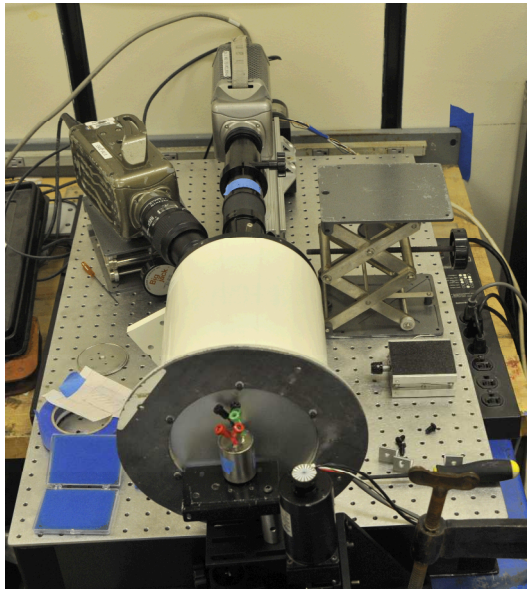
Molten-salt battery

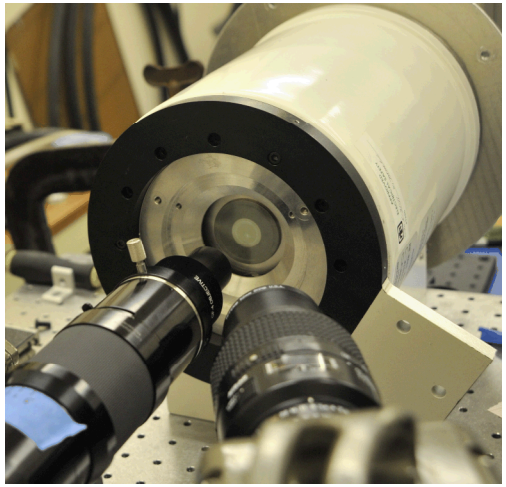


Intensified scintillator screen

High-speed camera







Sampling moiré method description.

Summary

The change in moiré interference fringe patterns between two (initially) periodic structures is measured and converted a displacement field

Thinning and Fringe Development

(a) Reference Pattern (Camera CCD Array)

(b) Initial Specimen Pattern (Battery Cells)
P = pitch of imaged pattern

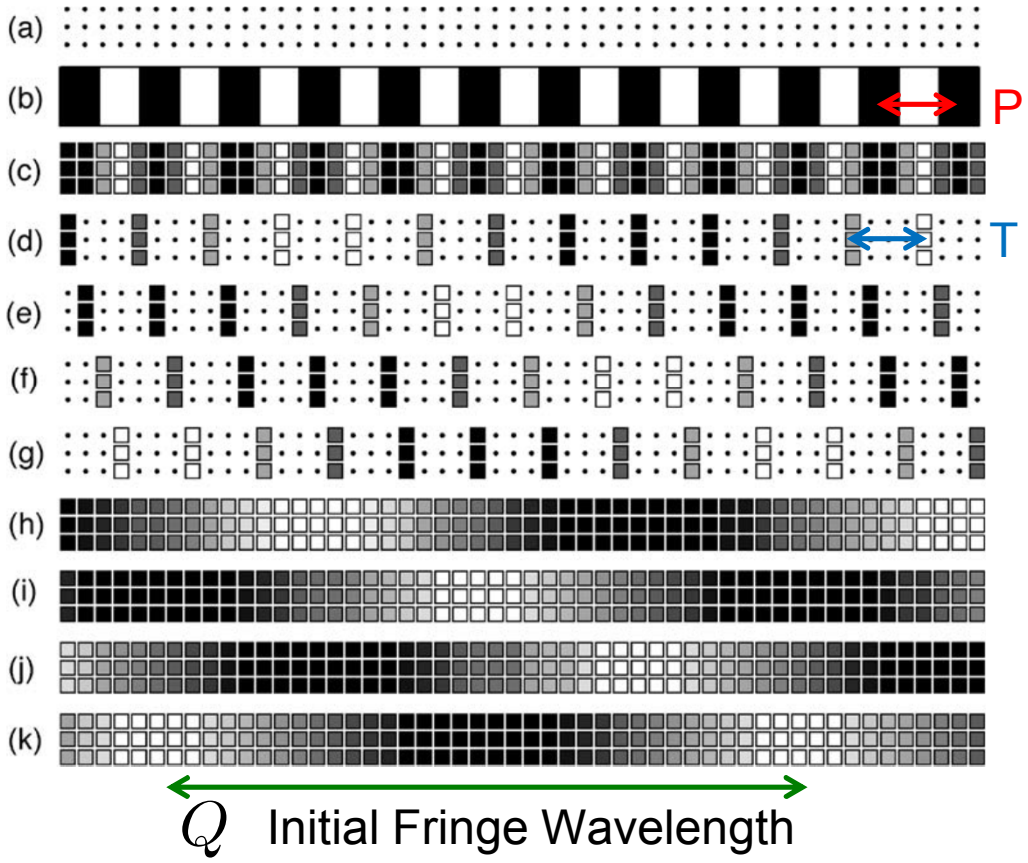
(c) Image Recorded on (a) from the pattern in (b)

(d) Thinning: Every T^{th} pixel is selected from (c) starting at location *k=1*

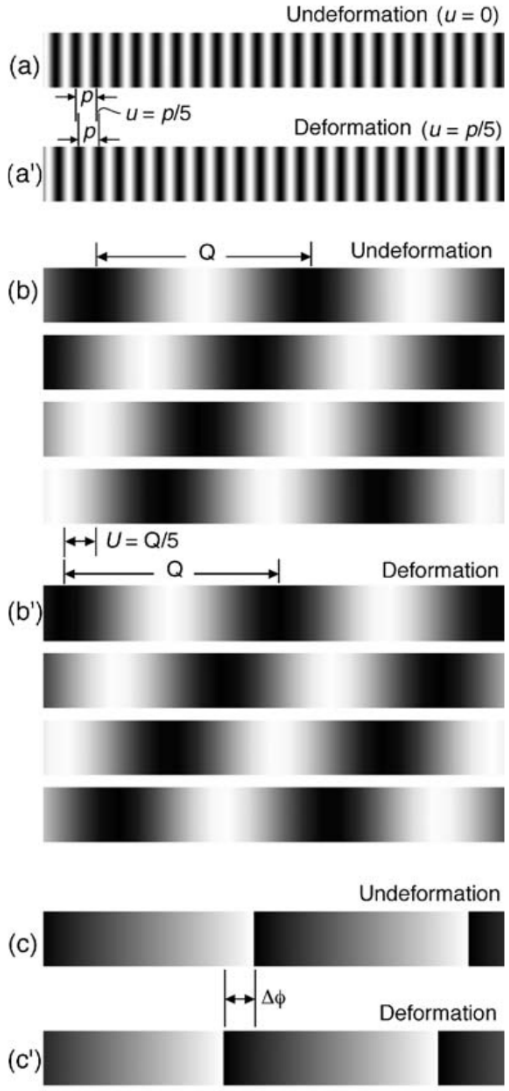
(e-g) Every T^{th} pixel is selected from (c) started *k=2, 3, … T*

(h-k) Linear spatial interpolation of (d-g)

For best results P ≈ T



Measuring the displacement is done by taking the difference between two states.



Deformation and Fringe Movement

(a) Initial Specimen Pattern (Battery Cells). NOTE: Reference image (CCD) is not shown

(a') Deformed Specimen Pattern (Battery Cells Uniformly Displaced)

(b) Undeformed four thinned moiré Fringe Patterns with (initial) fringe spacing *Q*

(b') Deformed four thinned Moire Fringe Patterns with fringe spacing *Q*. NOTE: With non-uniform deformation, *Q*, may change

(c) Phase Difference between (b) and (b')

$$\frac{u}{p} = \frac{U}{Q} = p\frac{\Delta\phi}{2\pi}$$

Ri *et al.* Experimental Mechanics, 2010

Image processing was done before conducting the moiré analysis

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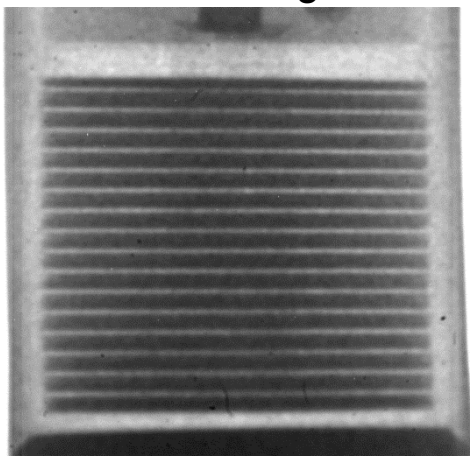
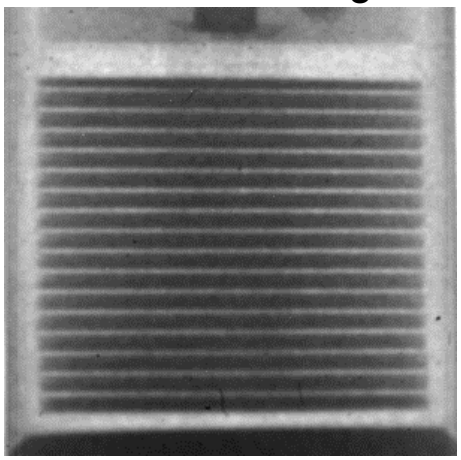
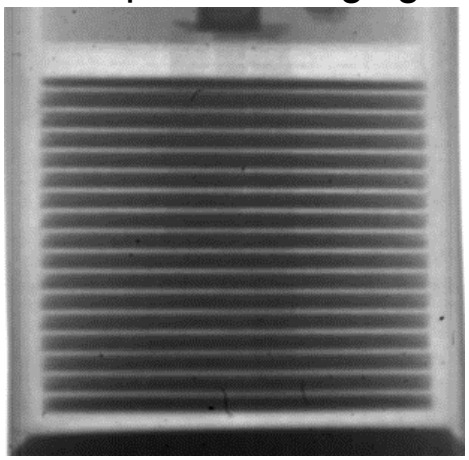
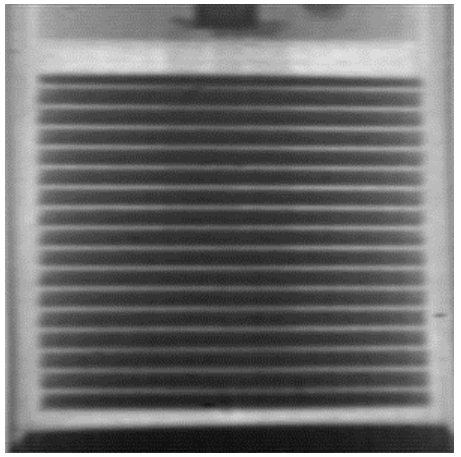
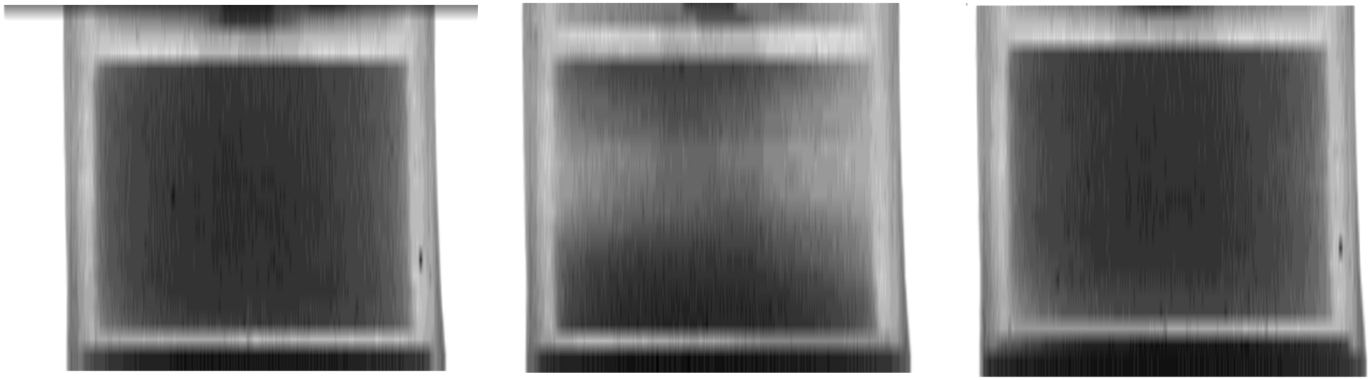
Raw Image	Decimated Image	Temporal Averaging	Fourier Spatial Filter
			
1632 × 1200 P = 53.2 pixels 2.5% Noise f_s = 500 fps	408 × 300 P = 13.3 pixels 1.73% Noise f_s = 500 fps	408 × 300 P = 13.3 pixels 0.69% Noise f_s = 50 fps	408 × 300 P = 13.3 pixels 0.53% Noise f_s = 50 fps

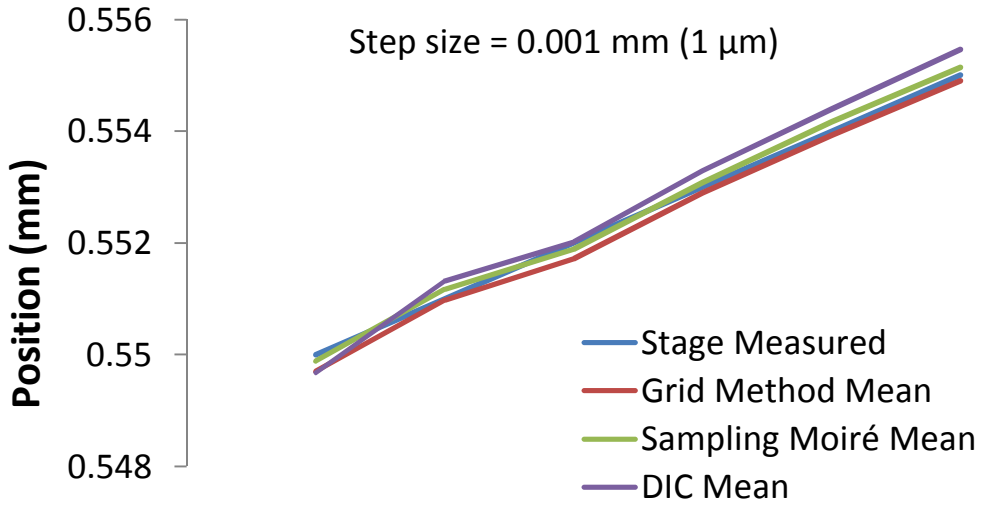


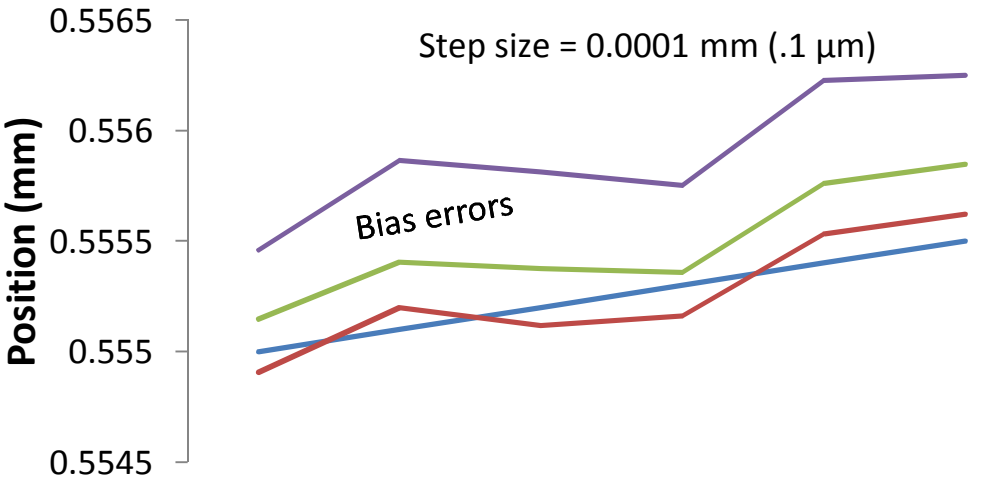
Phase Image = 1 ⋯ Phase Image = 7 ⋯ Phase Image = 13

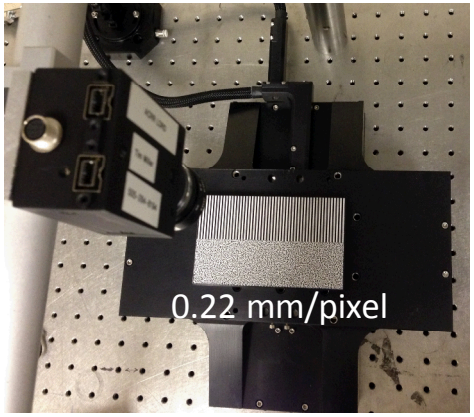
[a]Rossi, M., et al. (2014). Measurement Science and Technology **25(2): 025401.**

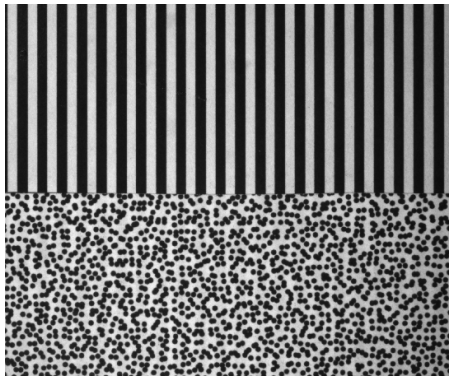
Remember: For best results P ≥ 4 and anecdotally P = 5 to 6 pixels

Experimental validation was done with a nanometer precision displacement stage.









Average StDev Results

(µm)	All Points	Step 1 µm	Step 0.1 µm
Stage	0.0051	0.0044	0.0068
Grid	6.27	7.18	7.21
Sampling	5.57	6.18	6.19
DIC	2.02	2.20	2.21

Without careful calibration bias = 12 µm

Devivier, C., et al. (2013). Composites Part A: Applied Science and Manufacturing **48(0): 201-218.**

Synthetic image moiré verification showed sub-pixel accuracy.

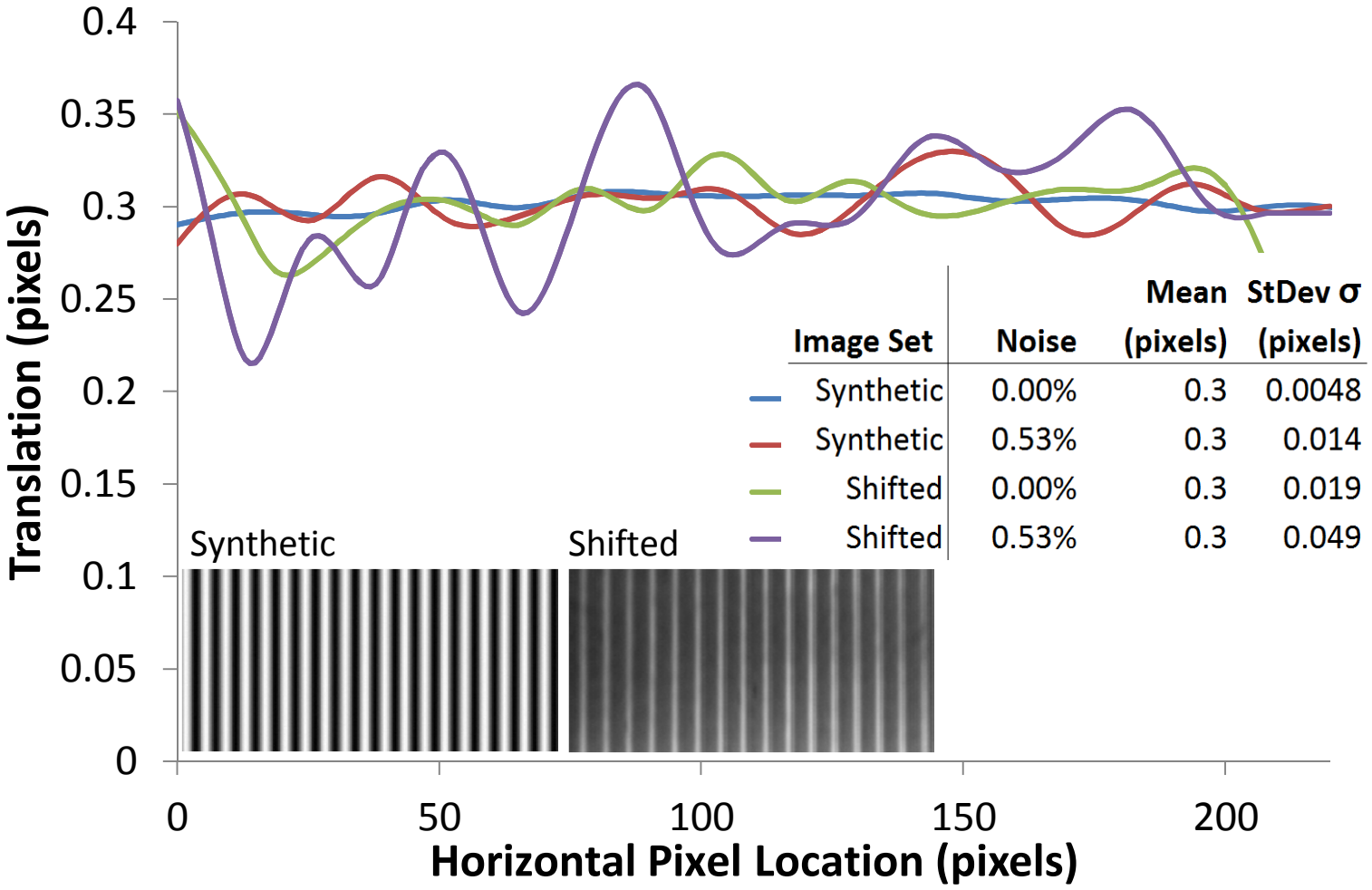
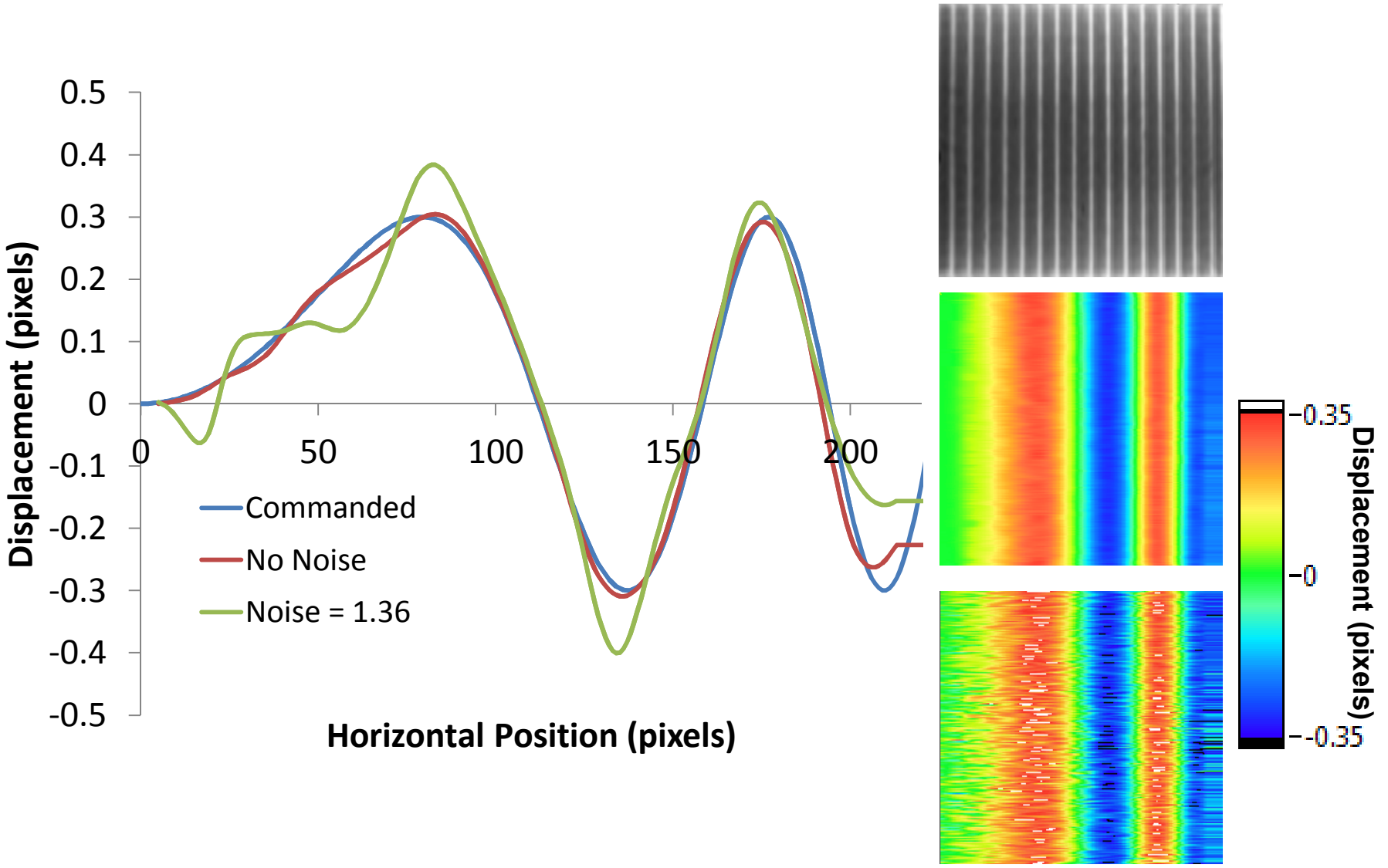
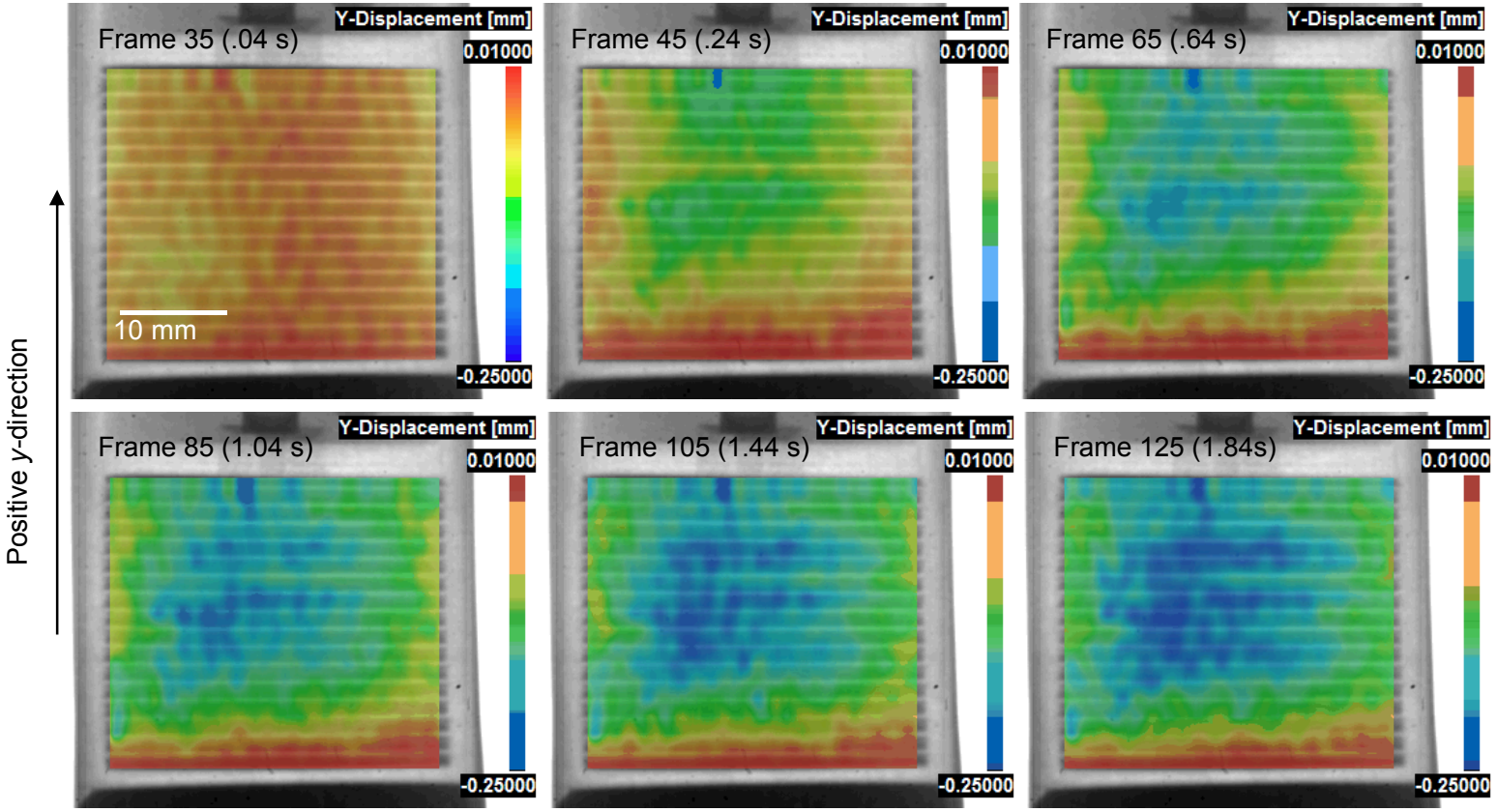


Image Set	Noise	Mean (pixels)	StDev σ (pixels)
Synthetic	0.00%	0.3	0.0048
Synthetic	0.53%	0.3	0.014
Shifted	0.00%	0.3	0.019
Shifted	0.53%	0.3	0.049

Synthetically created spatially varying displacement fields



Sampling moiré—results MC3246A



Time evolution of the displacement data. Positive deformation is up.

Sampling moiré—results MC3246A

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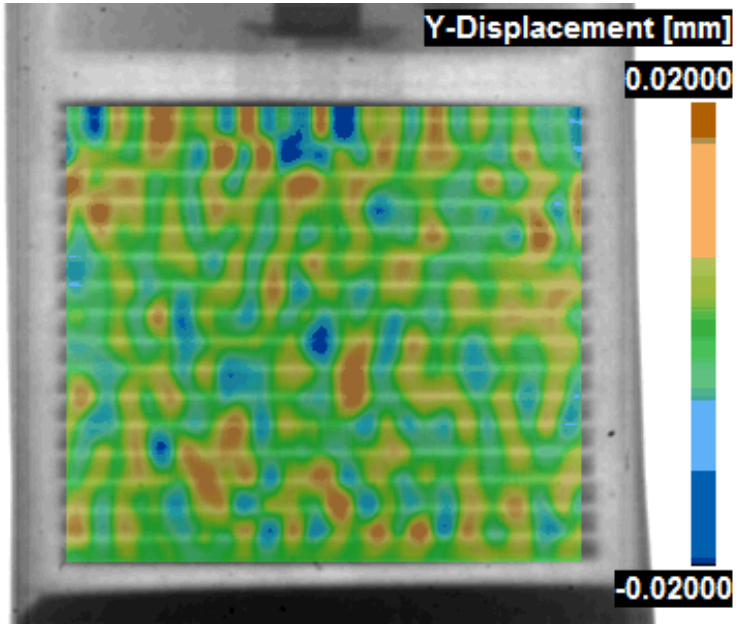
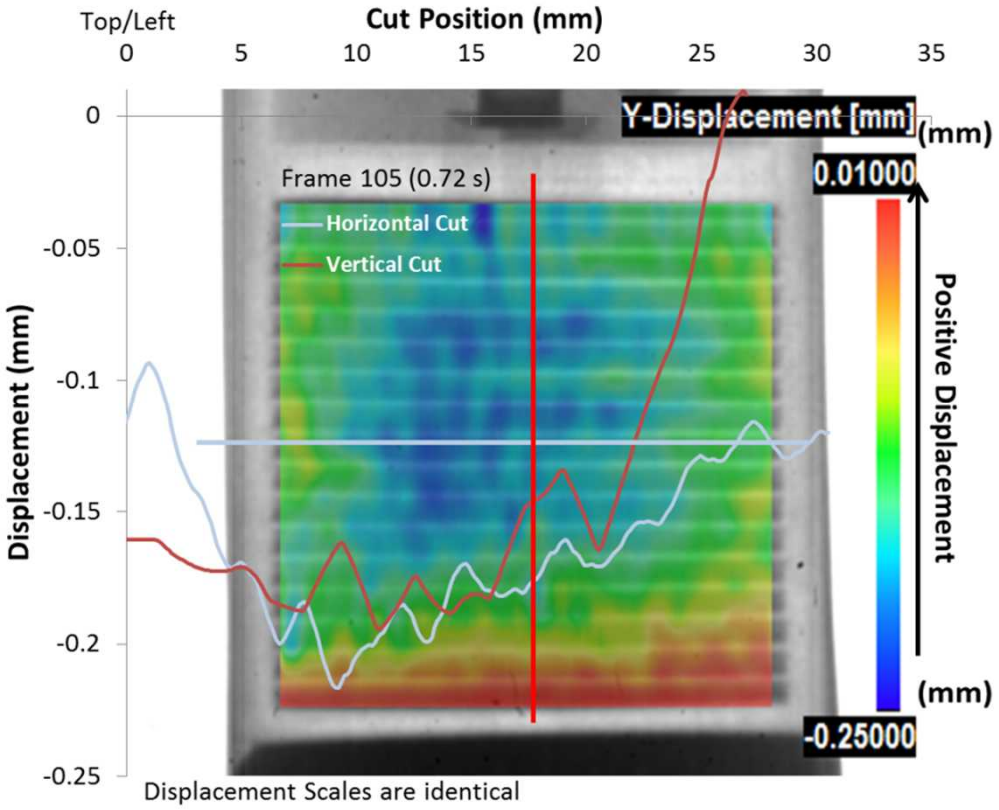
Displacement Noise Floor Measurement

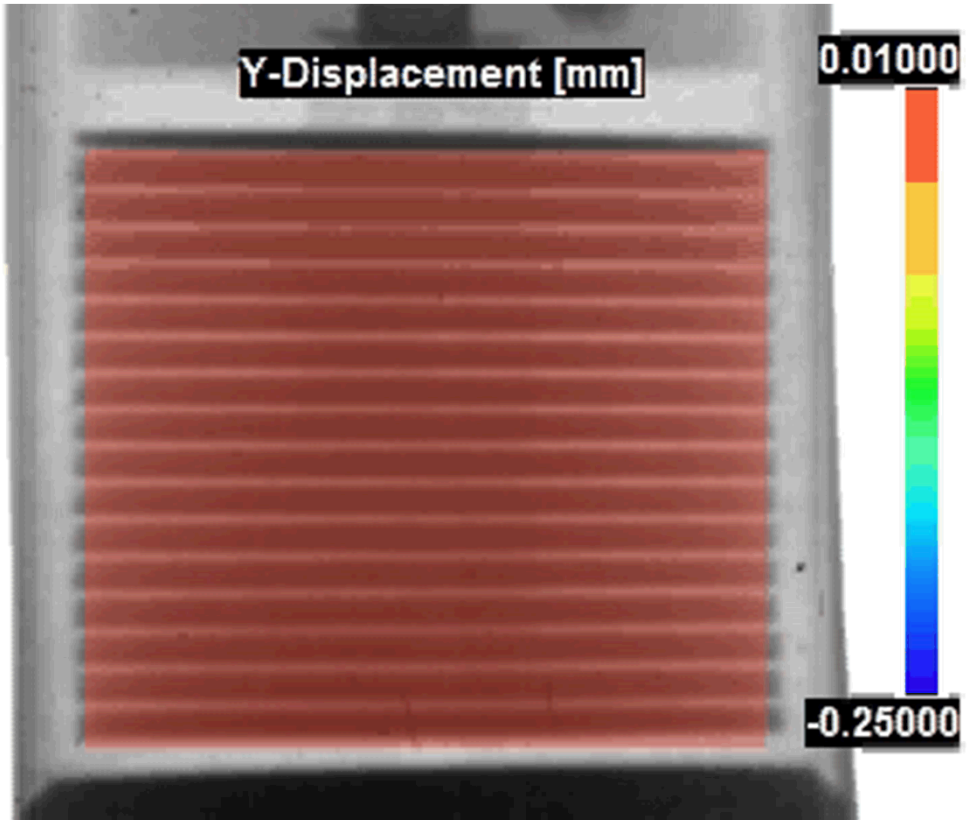


Displacement Measurements Post Rise Time



Sampling Moiré—Results MC3246A

- Video of the displacement along cut lines as a function of time



Sampling Moiré—Results MC3246A
Axial Displacement Time Histories at Collected Points

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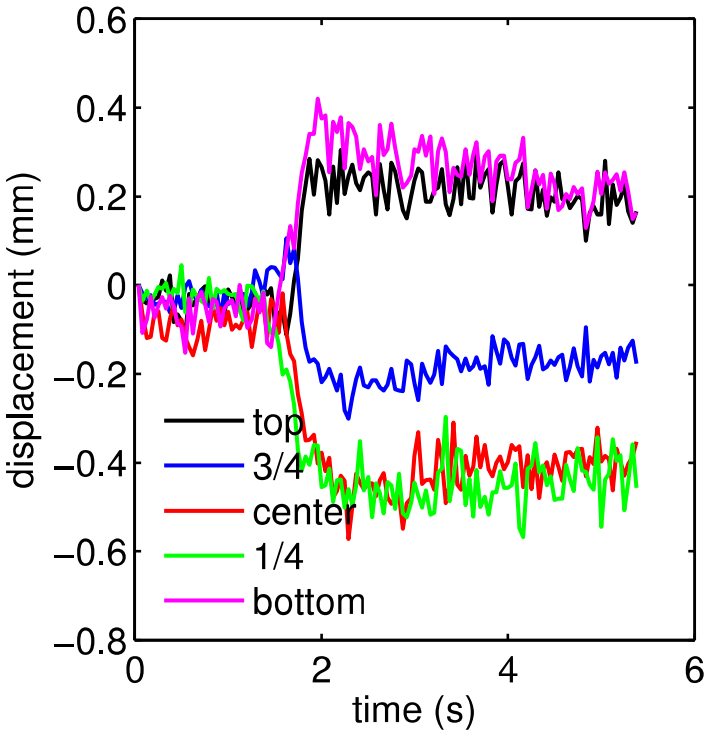
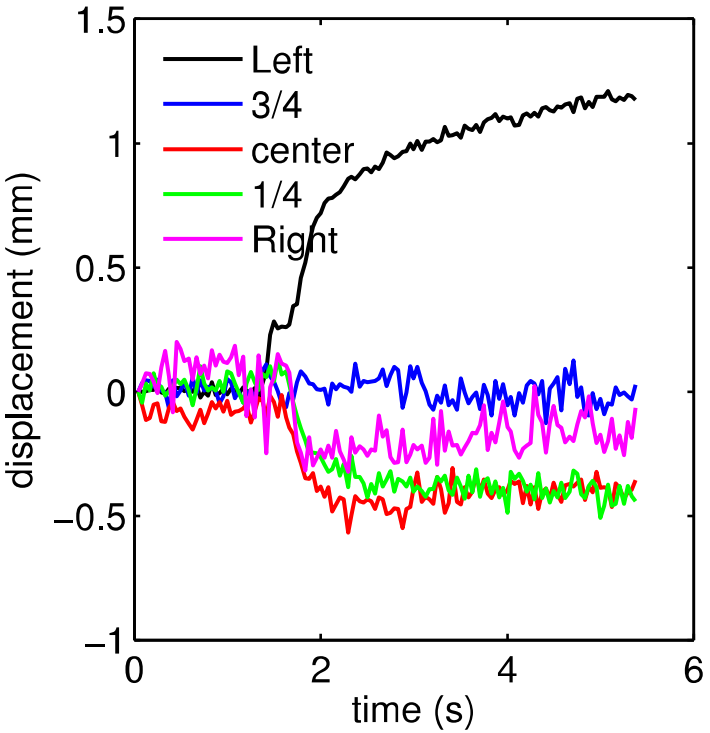
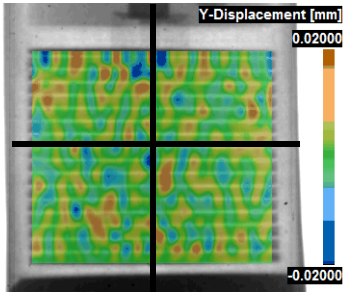
Vertical Cut at 5 evenly spaced Points Top-to-Bottom



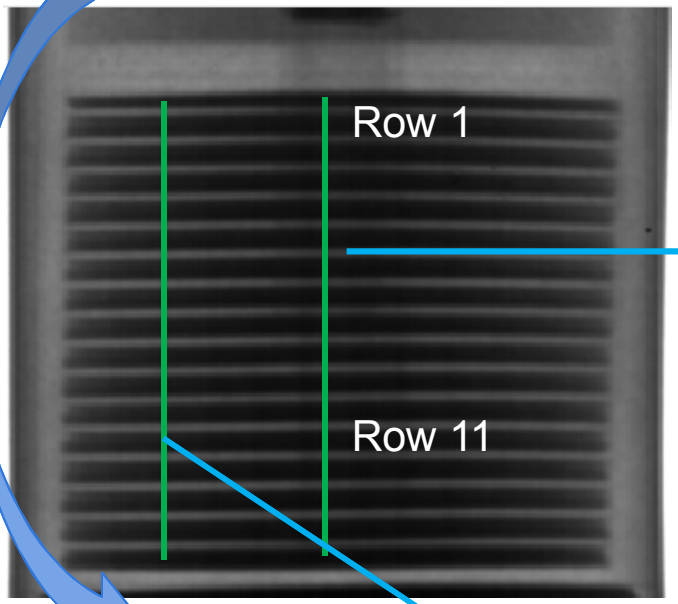
Horizontal Cut at 5 evenly spaced Points Top-to-Bottom

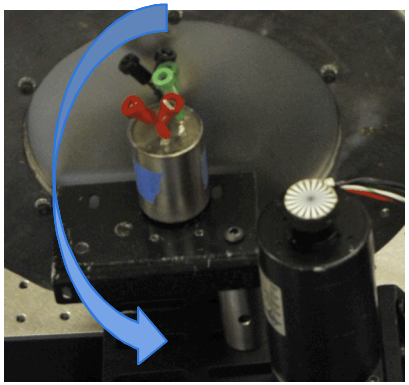


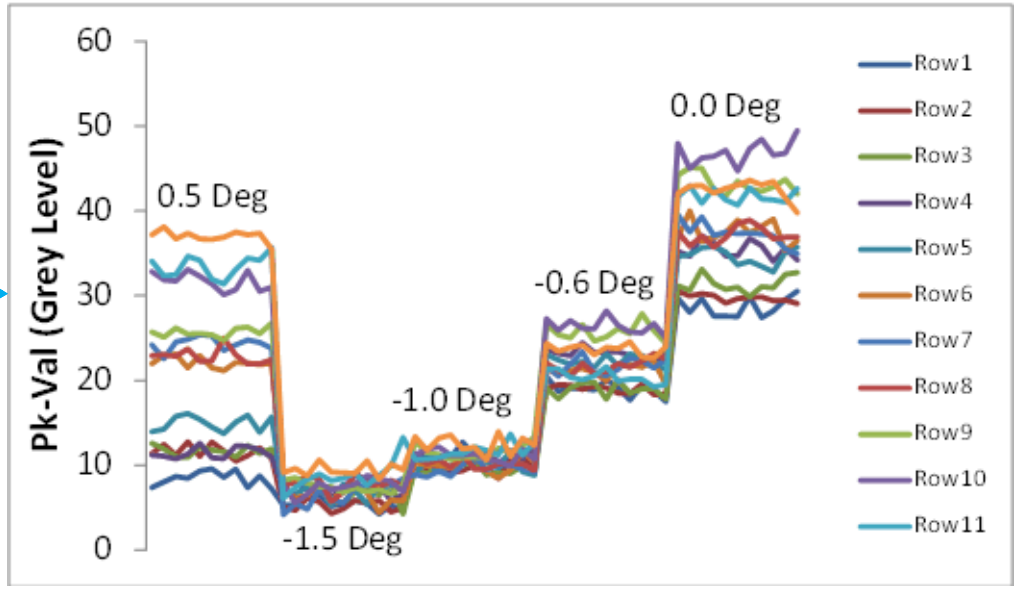
Time Histories Review Non-Trivial Displacement Field Spatial Variation

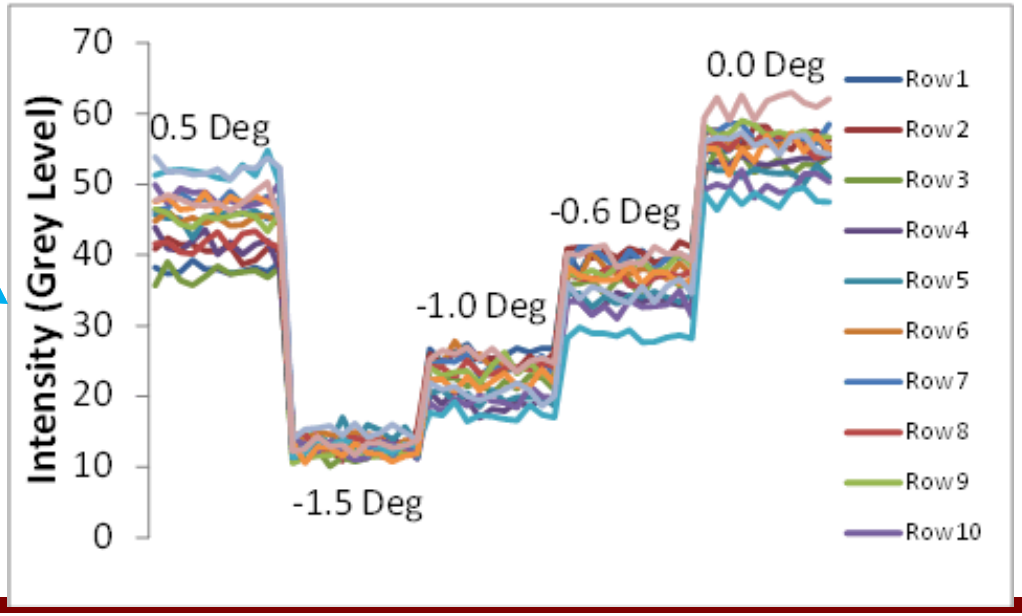


Sampling moiré—open issues

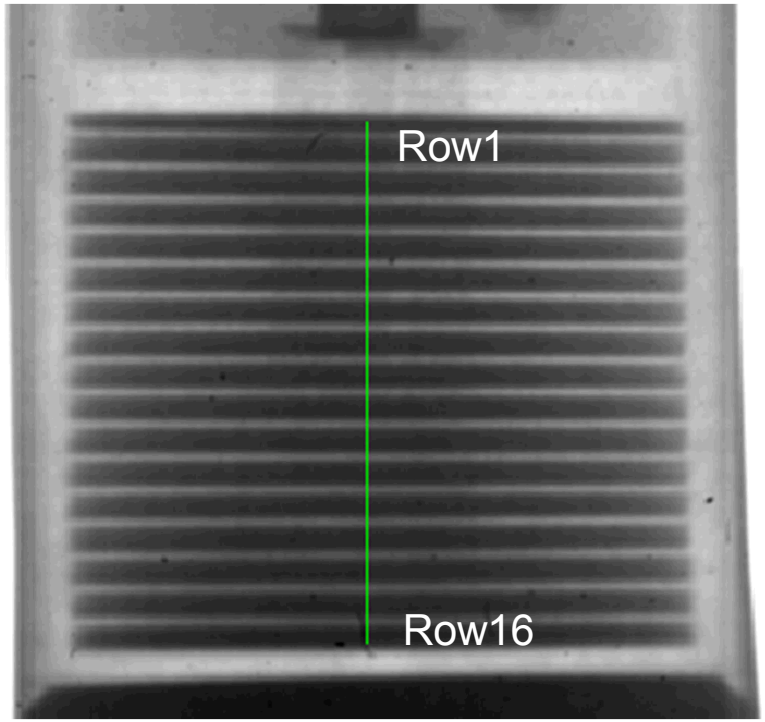


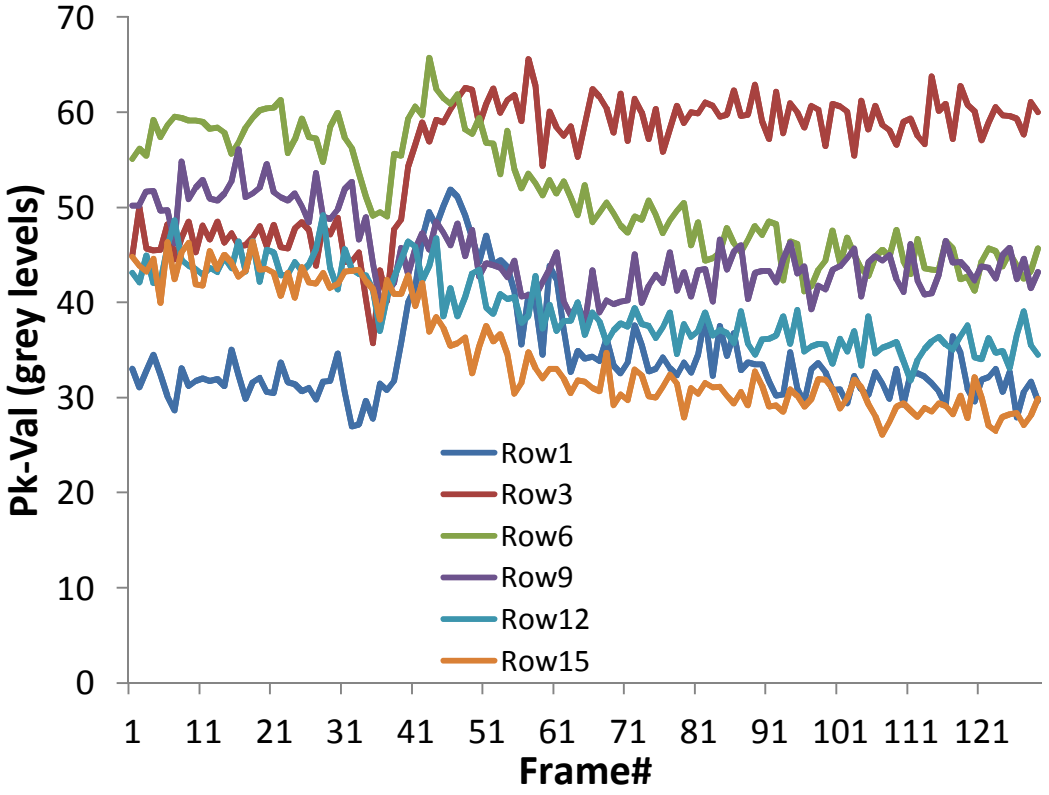






You can see this loss of contrast in the test data as well. It is hard to interpret.





Questions?

- Thank you to: Steven Showalter and David Ingersoll for providing the batteries.
- Joe Garney and Kyle Thompson for helping conduct the experiments.