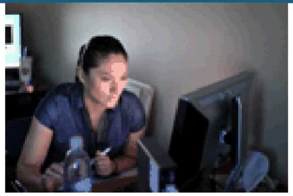
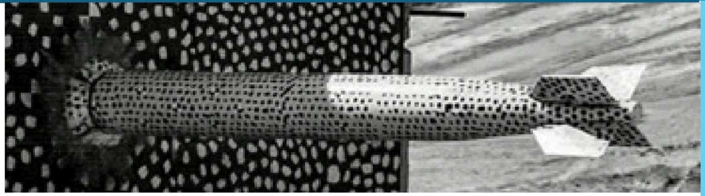
SAND2020-1460C

Experimental Modal Analysis using Phase Quantities from Phase-Based Motion Processing and Motion Magnification





IMAC XXXVIII

Dan Rohe

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Combining Modal Analysis and Phase-Based Processing

Phase-based processing is popular for striking videos of traditionally stiff structures undergoing large displacements.

Often used as a “preprocessor” for digital image correlation, improving signal to noise, implemented using band-pass filtering.

Alternative approach by Yang, et al. [1] utilizes phase quantities directly as displacements and performs dimensionality reduction and blind-source separation to fit deflection shapes.

This approach takes a similar approach to Yang, et al., treating phase quantities as displacement sensors, modes fit directly to these quantities.

Mode “shapes” are phase quantities that can be visualized using typical motion magnification techniques.

[1] Y. Yang, C. Dorn, T. Mancini, Z. Talken, G. Kenyon, C. Farrar, and D. Mascarenas, “Blind identification of full-field vibration modes from video measurements with phase-based video motion magnification,” Mechanical Systems and Signal Processing, vol. 85, pp. 567 – 590, 2017.

Experimentation with Synthetic Images

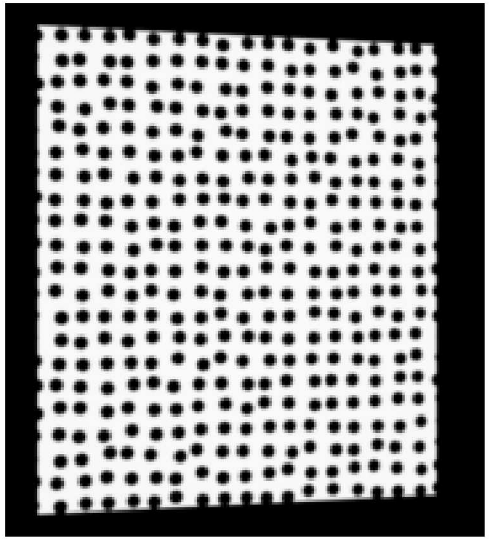
A large amount of data was expected, so the technique was first investigated using small (180x200 pixel) synthetic images.

Plate finite element model (6”x7” plate)

Pseudorandom excitation at corner, applied such that 1 pixel of displacement was expected.

10,000 deformation images rendered using the Blender software

- For more information: An Optical Test Simulator Based on the Open-Source Blender Software #8013, Thursday 12:10 p.m.



Synthetic Reference Image

Extracting Phase Quantities for Modal Analysis

Phase-based processing consists of computing a local phase at each pixel in the image for a series of spatial frequency bands and orientations.

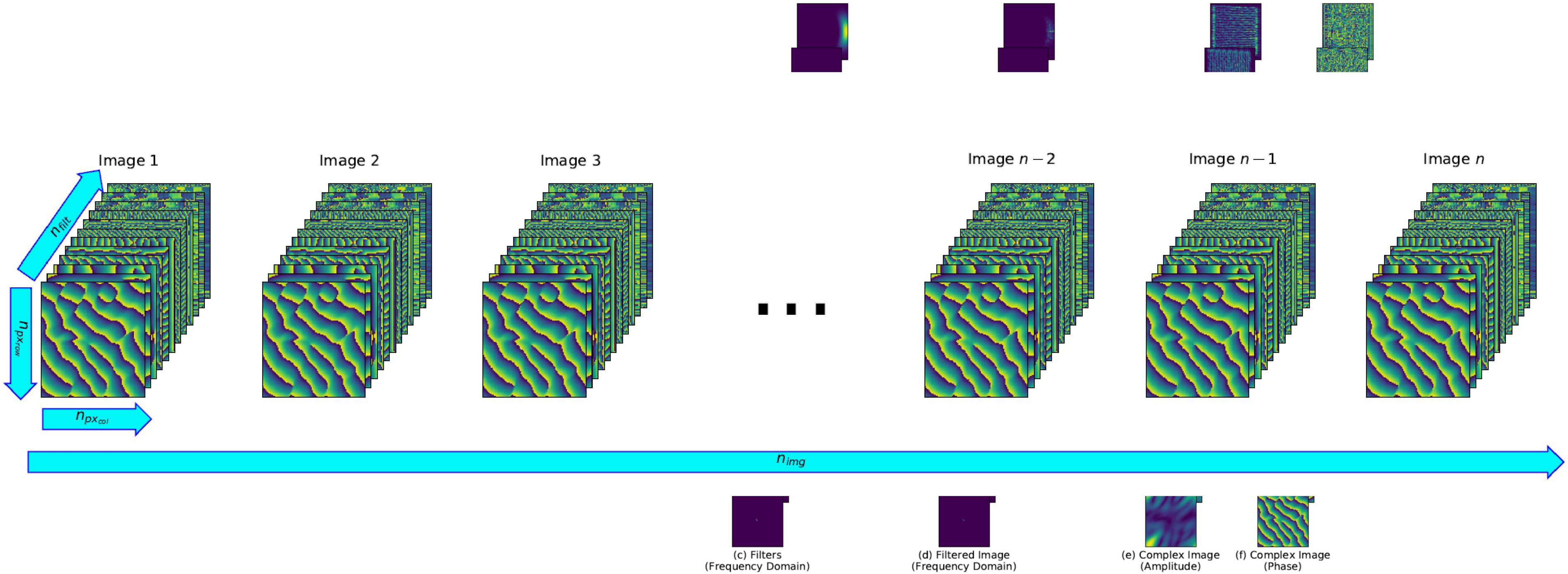
Filters specified with 8 orientation filters and 4 spatial frequency filters per image octave, for 160 complex filters.

Extracting Phase Quantities for Modal Analysis

Filters applied in the spatial frequency domain to produce a complex amplitude and phase for each image for each filter.

Subtracting the deformation image phases from the reference image phases gives a phase difference that can be magnified

Phase time histories are created that will be transformed into spectra.



What have we done?!

We just created 160 filters × 180 pixels × 200 pixels × 10,000 time steps = 57.6 billion pieces of data!

- If each phase quantity were a US quarter dollar, this analysis would weigh as much as the Empire State Building!
- If each phase quantity were a MATLAB floating point number (more realistic), it would take 460 GB to store this data.

Options for reducing data:

- Use single-precision rather than default double-precision (460 GB -> 230 GB)
- Reduce image size – also reduces number of filters, loss of measurement resolution
- Reduce number of images – reduces frequency resolution or number of averages
- Image averaging – if excitation is deterministic and repeating, measurement frames can be averaged together
- Number of filters can be reduced – lower amount of magnification possible
- **Deal with it! – I work at a National Laboratory, and we have supercomputers**

Similar to saving time histories in the early days of modal; large amount of data required only temporarily. Once modes are fit, the 10,000 time steps become a handful of mode shapes.

The paper goes into detail about processing large datasets, implementing optimized data storage and processing approaches reduced processing time from an estimated 58 years to 8 hours

Fitting Modes to Phases

Previously we created 5.76 million "sensors", all with time data.

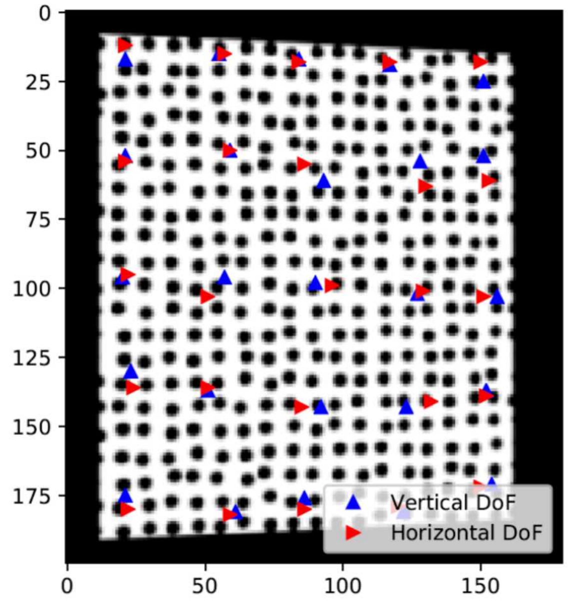
- All sensors will be necessary to create motion magnified mode shape images
- Only a handful of sensors are necessary to distinguish shapes and fit modes

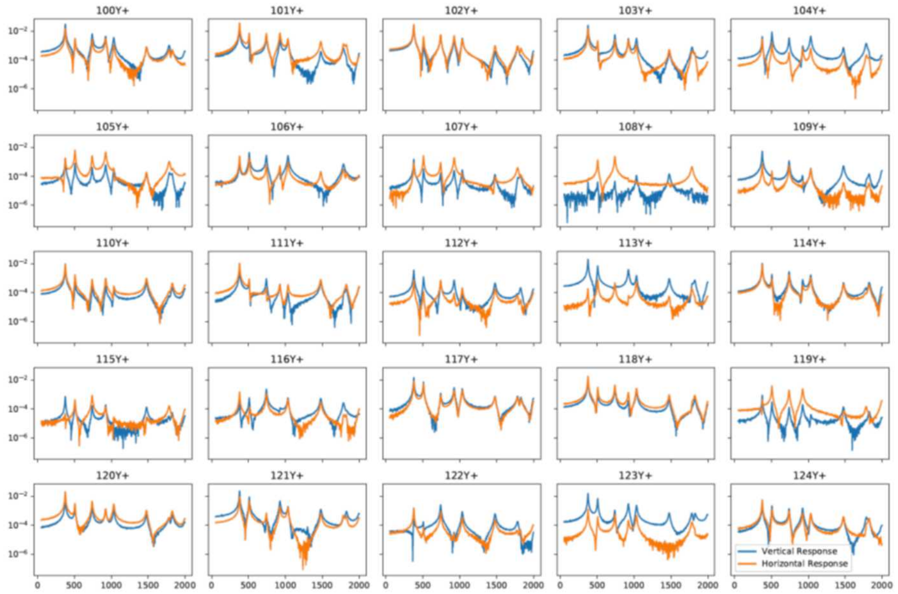
Mode fitting split in two parts:

- Fit frequencies and damping ratios using a small subset of phases
- Fit shapes using all data

For the plate, used a 5x5 grid of pixel locations, with only vertical and horizontal filter orientations (50 degrees of freedom)

- At each pixel location, investigate a 10x10 pixel area
- Select pixel and spatial frequency filter with highest amplitude after filtering (best signal-to-noise)
- FRFs computed between force input and phase response at each location.



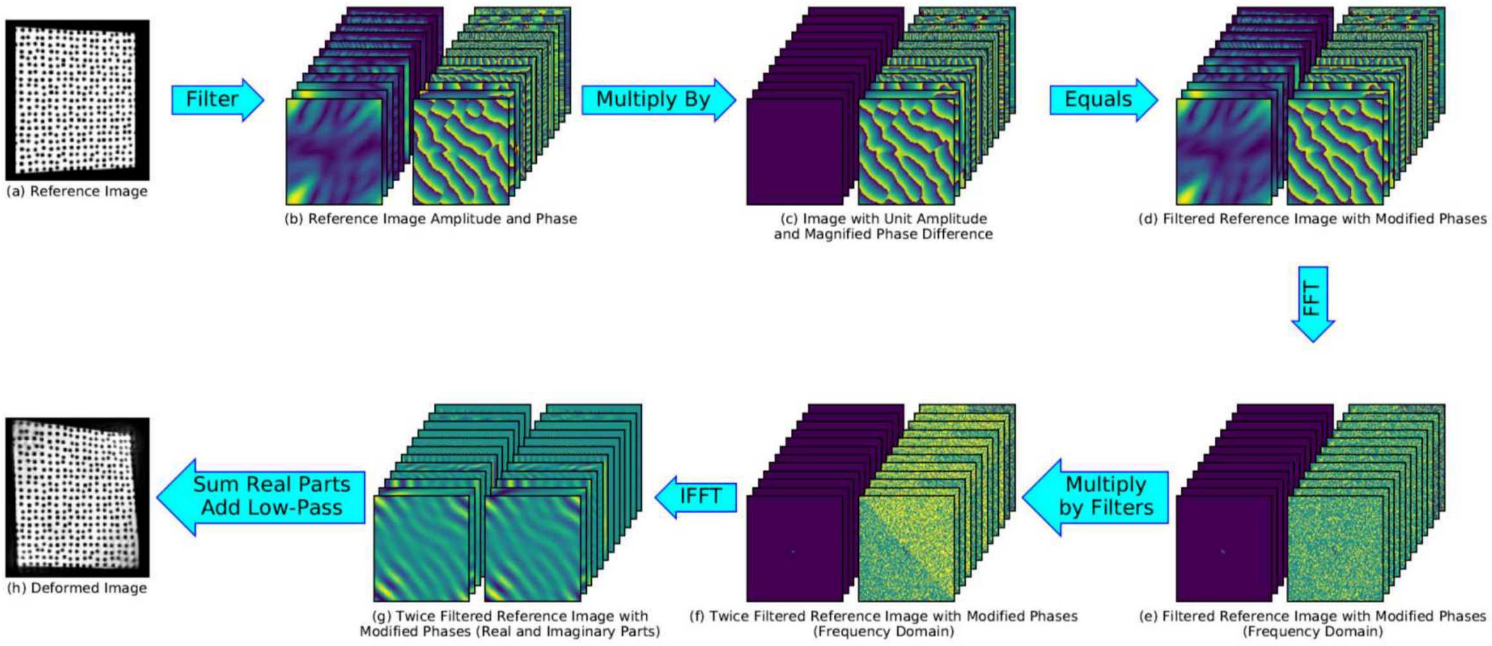


Extracting Full-Image Mode Shapes

FRFs were computed using all pixels and filters, and shapes were fit to the FRFs using the frequencies and damping ratios fit previously.

Full-image phase mode shapes were computed from these FRFs.

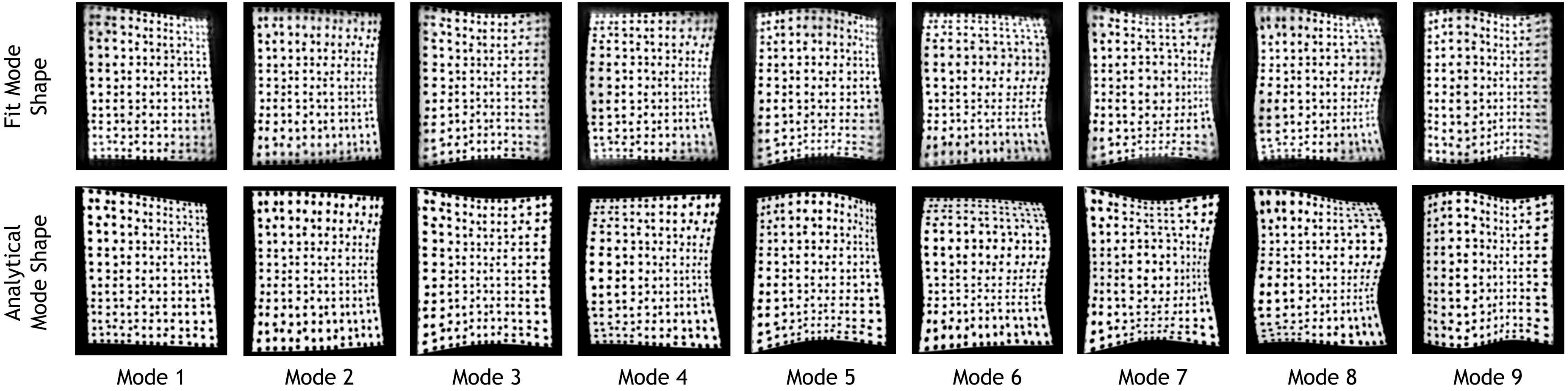
Mode shape images were constructed by "magnifying" the extracted phases using the typical motion magnification process.



Comparison to Truth Data

Synthetic images allow comparison to truth data for frequencies, damping ratios, and mode shapes.

Mode	True Freq (Hz)	Fit Freq (Hz)	% Error	True Damp (%)	Fit Damp (%)	% Error
1	376.30	376.37	0.018	0.50	0.49	-2.00
2	507.45	507.37	-0.014	0.50	0.51	2.51
3	740.19	740.00	-0.026	0.50	0.50	0.00
4	923.31	923.19	-0.013	0.50	0.51	1.49
5	1032.90	1033.02	0.012	0.50	0.50	-0.50
6	1477.30	1477.13	-0.012	0.50	0.52	4.00
7	1784.22	1784.11	-0.007	0.50	0.52	4.07
8	1824.54	1824.54	0.000	0.50	0.50	0.48
9	1996.59	1996.50	-0.005	0.50	0.52	4.49



Experimental Validation

Experimental images from a previous test comparing laser vibrometry and DIC for modal applications were passed into the technique.

Phase information extracted for 226 filters × 800 pixels × 800 pixels × 20,000 time steps = 2.9 trillion pieces of data (13 TB)!

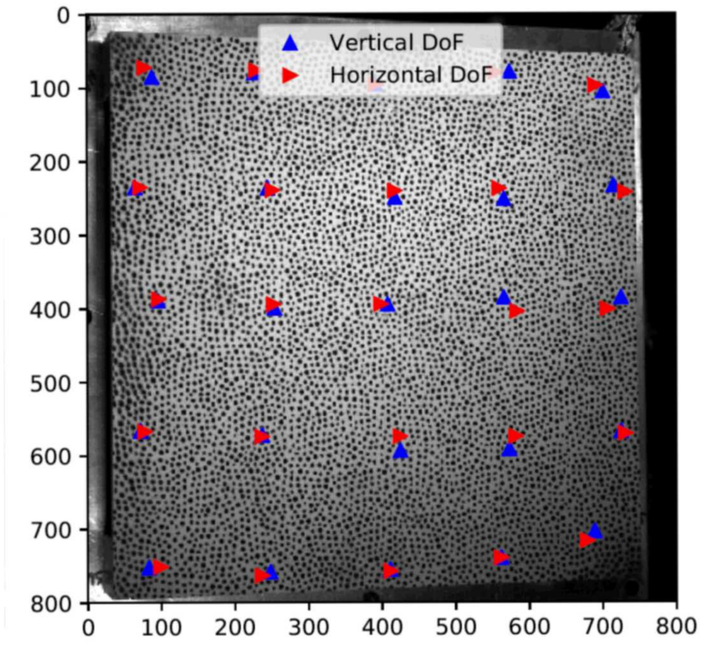
Data processed in parallel on Intel Xeon E7-4870 Westmere compute server.

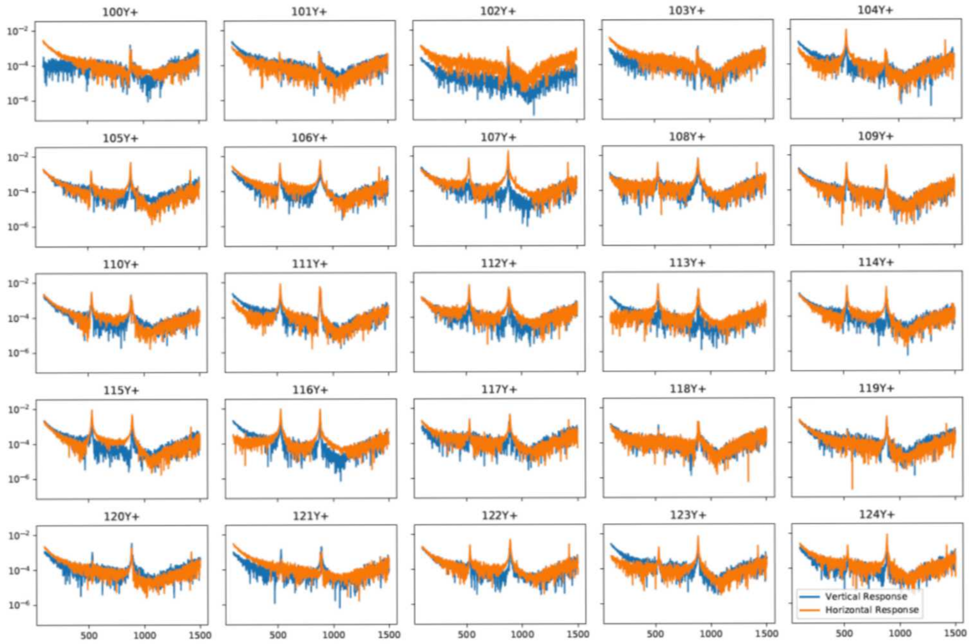
- 226 filters split between 20 processors,
- Each processor has 11-12 filters, 650 GB of phase data.

Same two-step process to fit shapes.

- 5x5 grid of pixels chosen to fit frequencies and damping ratios
- Shapes fit to full image data set.

5 modes fit to the experimental FRFs



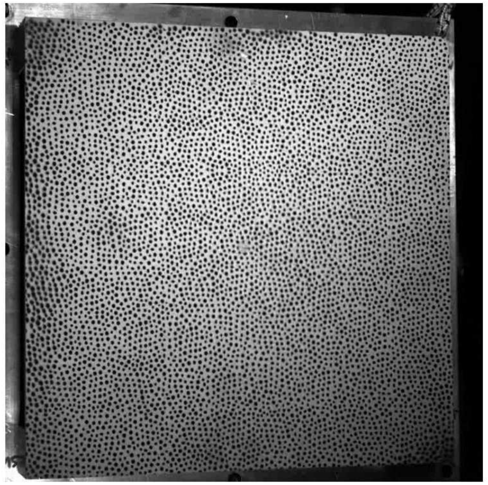
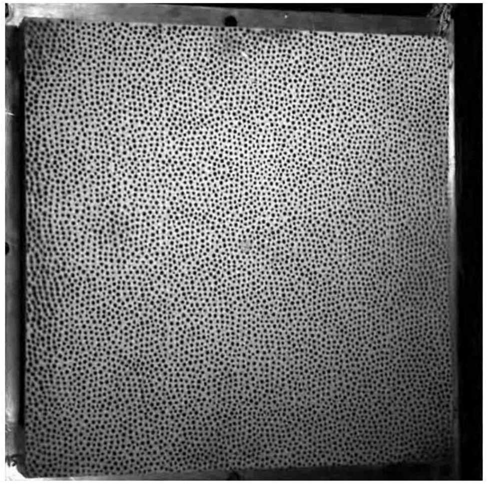
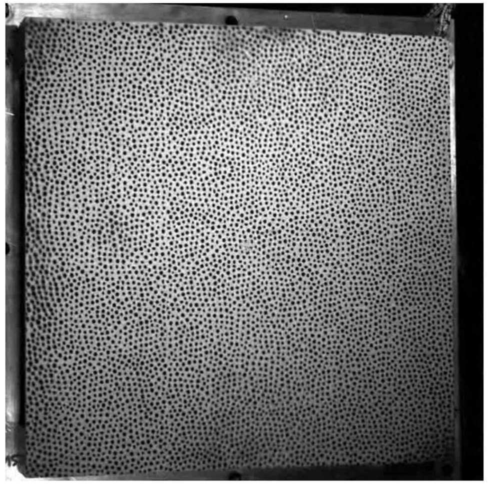
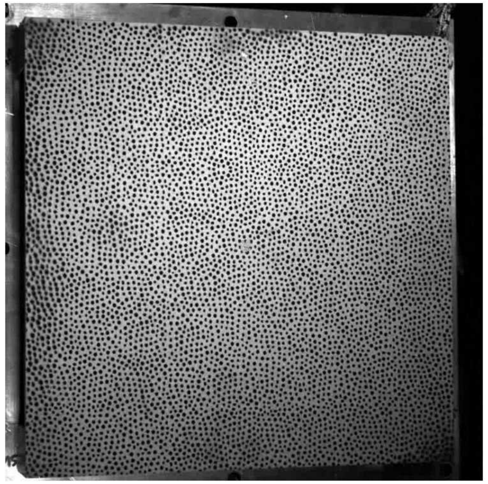
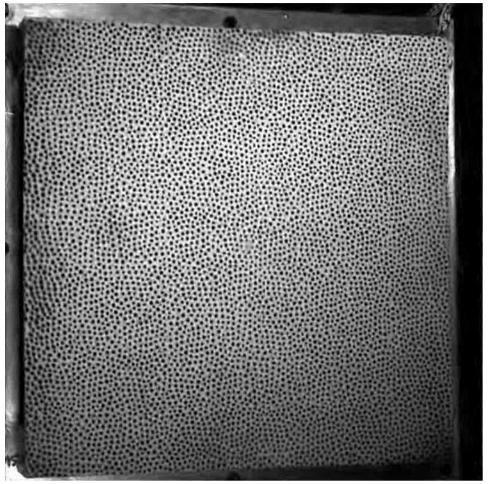


Comparison to other techniques

Phase-based Modal Analysis compared reasonably to DIC and LDV measurements

Able to separate closely spaced modes, which the bandpass approach would not be able to do

Mode	DIC Freq (Hz)	DIC Damp (%)	LDV Freq (Hz)	LDV Damp (%)	Phase Freq (Hz)	Phase Damp (%)
1	529.4	0.0420	529.5	0.0420	529.3	0.0448
2	883.0	0.0220	883.1	0.0240	883.0	0.0229
3	891.7	0.0150	891.7	0.0260	891.6	0.0266
4	948.3	0.0190	948.4	0.0190	948.2	0.0138
5	1420.1	0.0150	1420.4	0.0200	1419.9	0.0271

Visualization of Response in an Environment

Phase mode shapes can be transformed into images of the deformed shape using the motion magnification approach.

Arbitrary displacements can be filtered to generate linear combinations of phase mode shapes, which can be rendered on image.

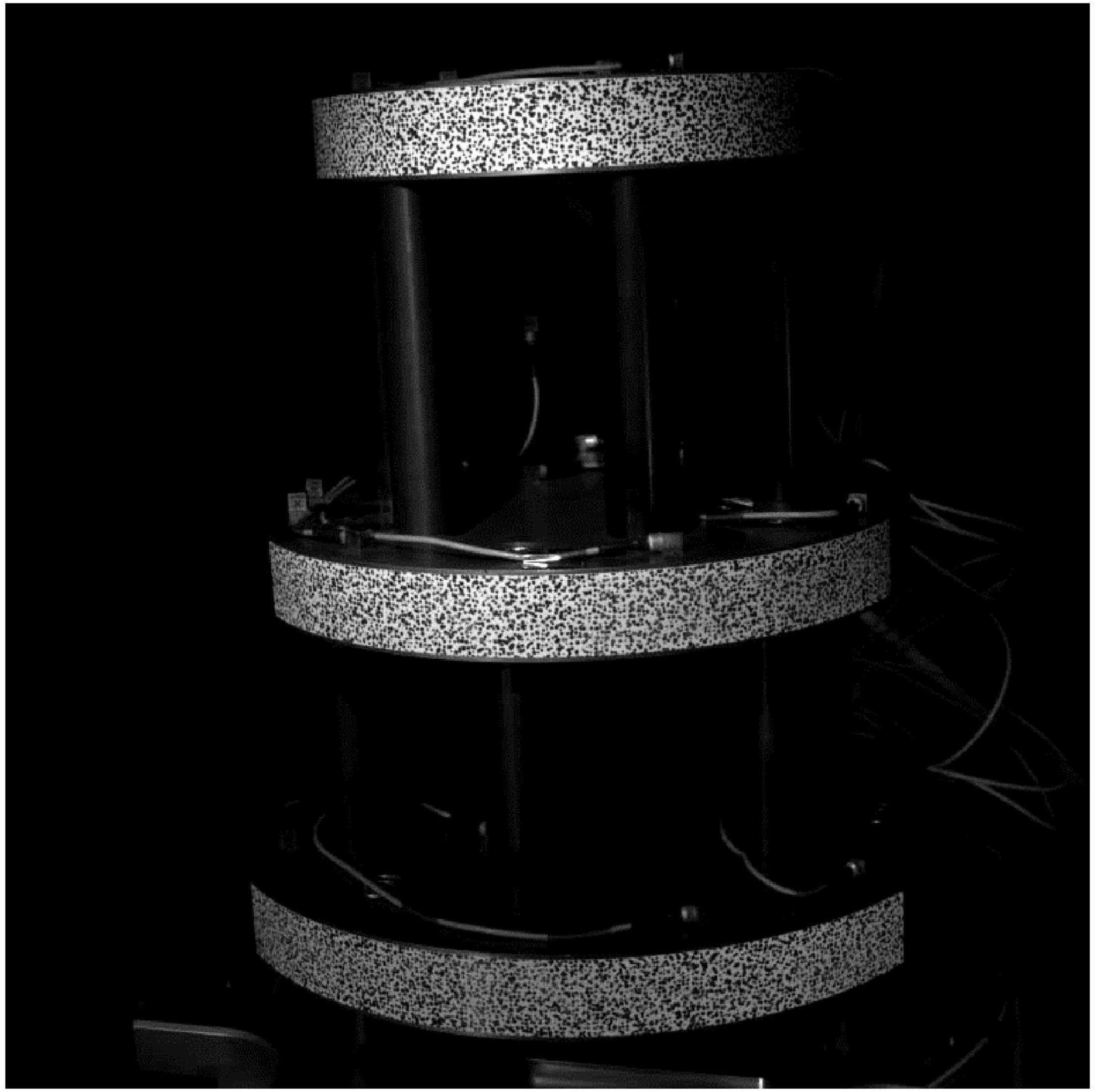
Have applied this technique to the "Wedding Cake" structure:

- Structure placed on rocket, accelerometer measurements of the response made ($\mathbf{x}_a$)
- Modal tests performed on ground test unit, modes fit to accelerometer ($\mathbf{\Phi}_a$) and image phase ($\mathbf{\Phi}_\theta$) degrees of freedom.
- Accelerometer mode shapes used to filter environment response into modal coefficients ($\mathbf{q}$)
- Images of the environment created by multiplying the phase mode shapes by the modal coefficients ($\mathbf{x}_\theta$)

$$\mathbf{x}_\theta = \mathbf{\Phi}_\theta \mathbf{q} = \mathbf{\Phi}_\theta \mathbf{\Phi}_a^+ \mathbf{x}_a$$

Alternatively, could go the other way, predicting displacement response from a single camera image (no stereo pair required)

$$\mathbf{x}_a = \mathbf{\Phi}_a \mathbf{q} = \mathbf{\Phi}_a \mathbf{\Phi}_\theta^+ \mathbf{x}_\theta$$

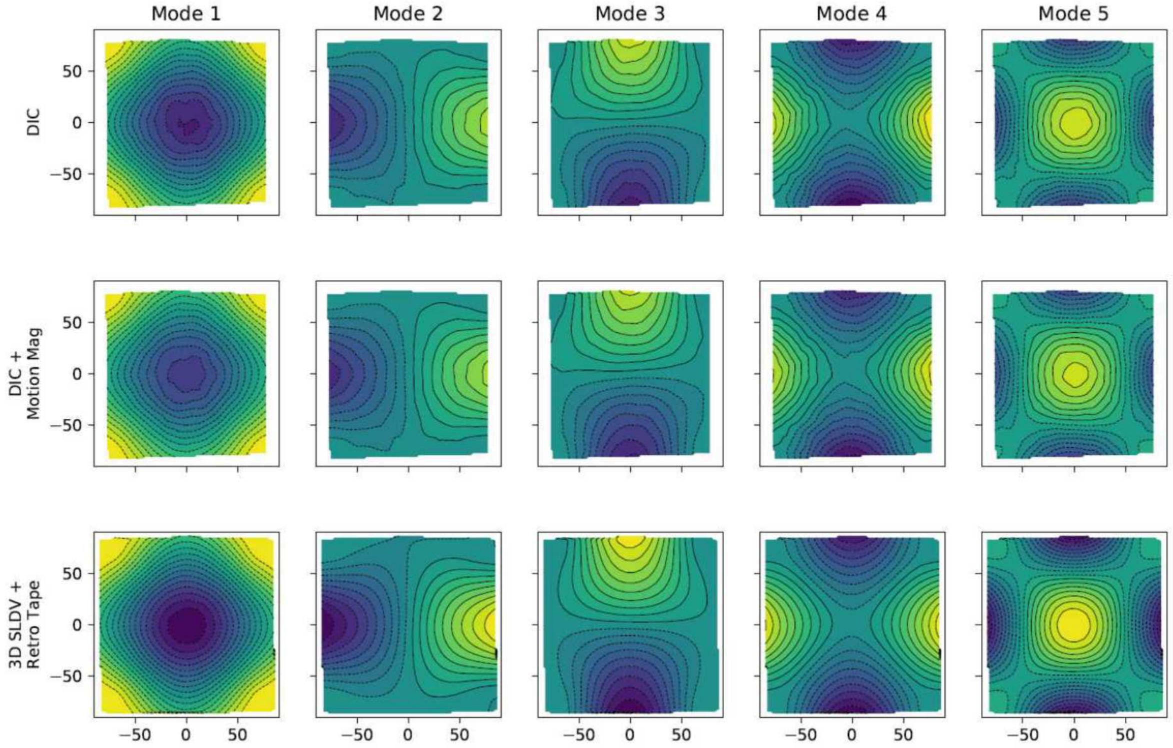


Preprocessor for Optical Techniques

Similar to work done using motion magnification with a band-pass filter, motion magnified mode shapes can be passed through DIC or other optical techniques to extract physical displacements.

Phase mode shapes were fit to both cameras in the experimental validation and then passed through a DIC analysis to compare against traditional DIC and LDV modal testing.

Motion magnification results were not a significant improvement over raw DIC, but we were already pretty well out of the noise floor for the raw DIC approach.



Conclusions

Phase quantities from Phase-based Motion Processing can be used directly in experimental modal analysis.

Extracted mode shapes are phase quantities that must be passed through the motion magnification technique to produce visualizations of the shape on-image.

The huge amount of data and processing is only required if mode shapes are to be visualized on-image. Fitting frequencies and damping ratios only require enough "sensors" to distinguish modes.

Motion-magnified mode shapes can be linearly combined to visualize environments.

Motion-magnified mode shapes can be fed into DIC analysis to extract true displacements.

While computationally intensive, it provides advantages over the typical bandpass filter approach in that it can split closely spaced modes, and it provides scaled outputs; the comparison is similar to mode shapes vs. deflection shapes.