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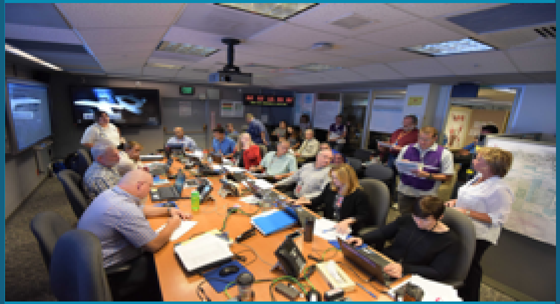
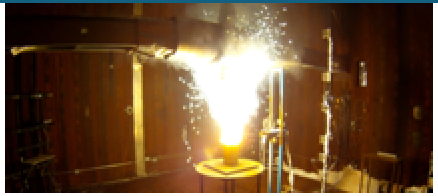
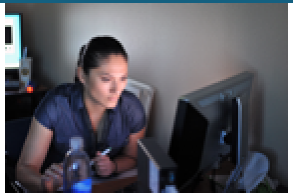
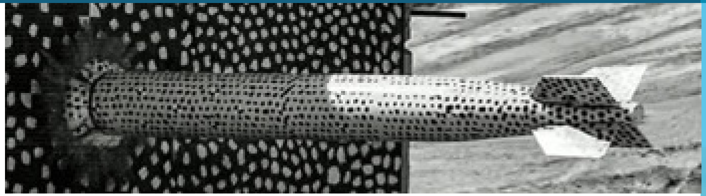


Motion Magnification







IMAC XL Short Course: Optical Techniques for Experimental Modal Analysis

Dan Rohe, Bryan Witt, and Phil Reu

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Outline

What is Motion Magnification?

Overview of Motion Magnification

- Magnifying 1D signals
- Analogies to the FFT Shift Theorem
- Construction of Complex Filters
- Filtering and Reconstruction
- Magnifying 2D Signals

Applications of Motion Magnification

Review

What is Motion Magnification?

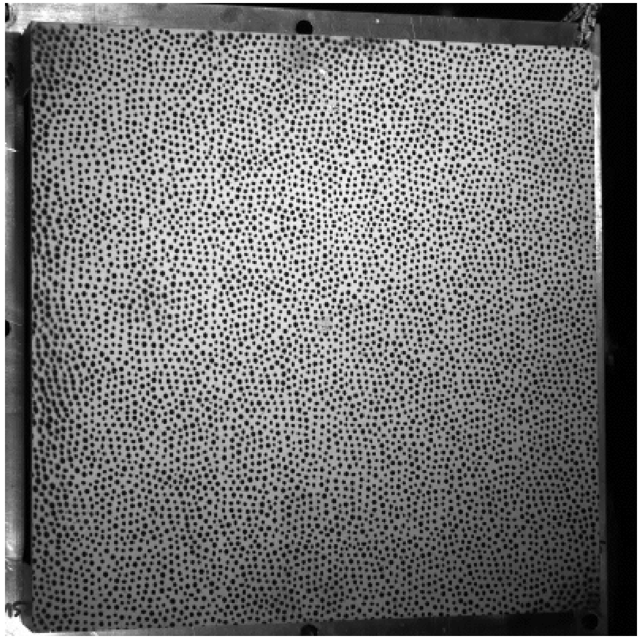
Deformations are generally pretty small in structural dynamics

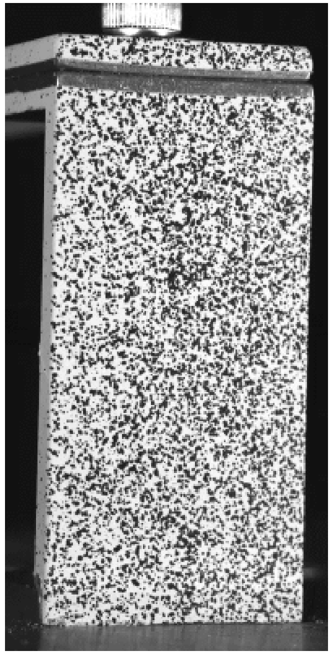
Many structural dynamics tests result in images with incredibly small motions

- Typically 0.01 to 0.1 pixels for a modal test

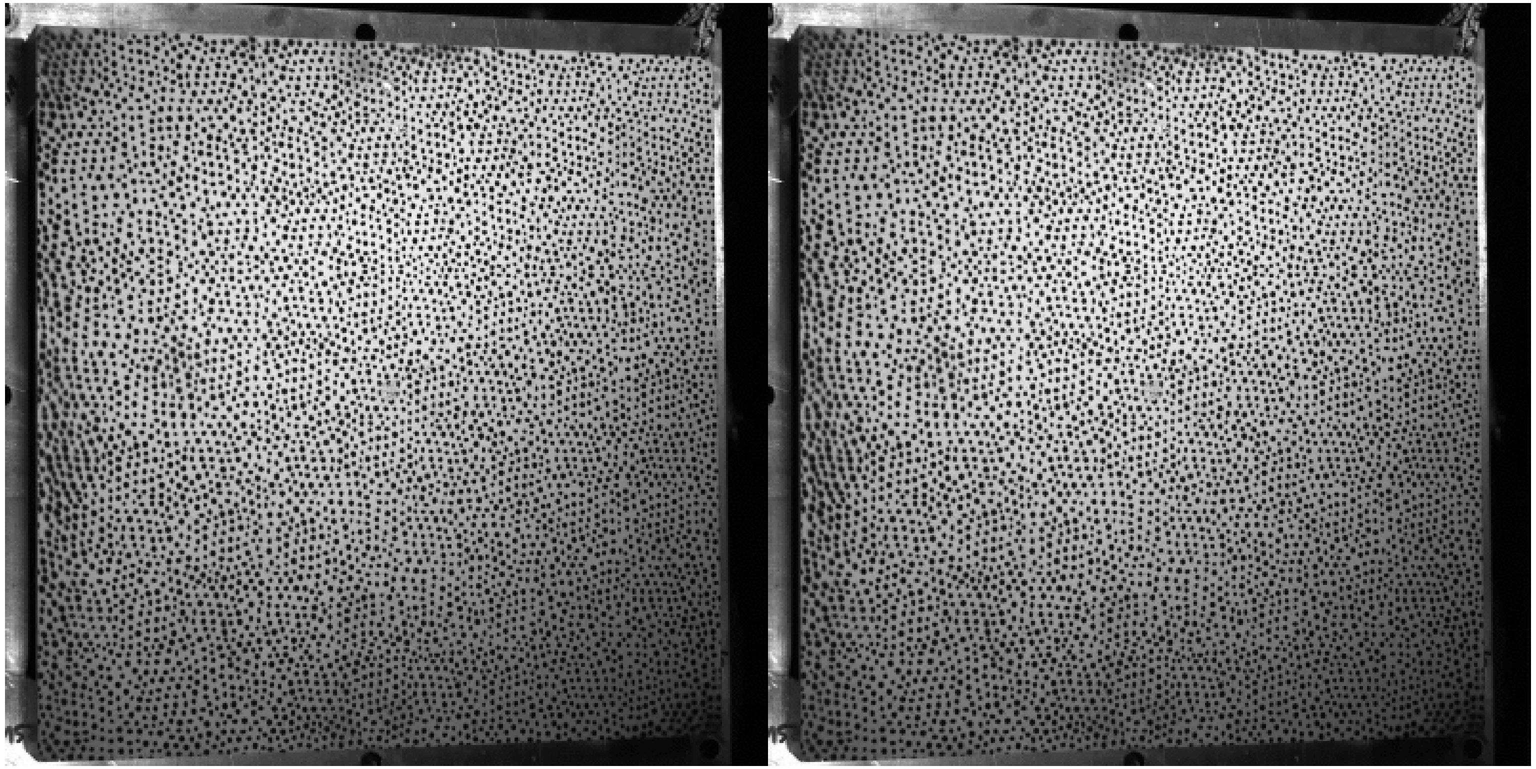
From the test engineer's perspective the all images in a test look identical

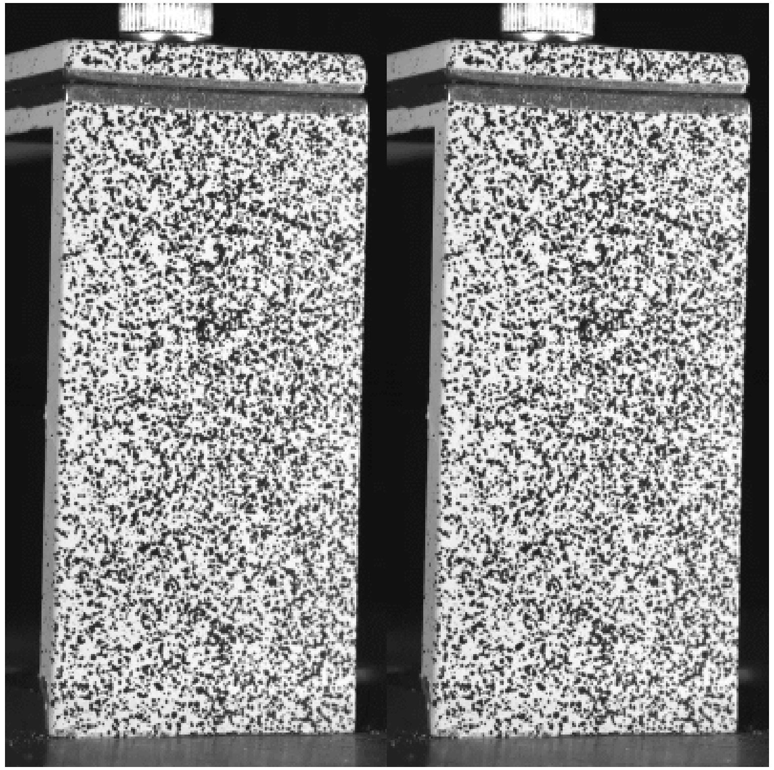
Generally need specialized software to extract motions from test images





Motion Magnification allows us to magnify small, imperceptible motions in images to make them visible to the naked eye





Why do Motion Magnification?

Gain an intuition that isn't possible with stick models

- Can see the entire surface, not just positions you have measurement points

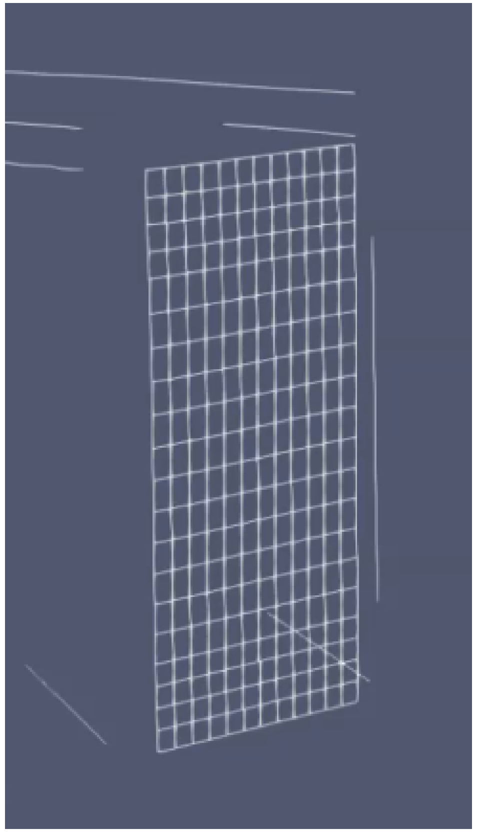
Lower noise floor than other optical techniques

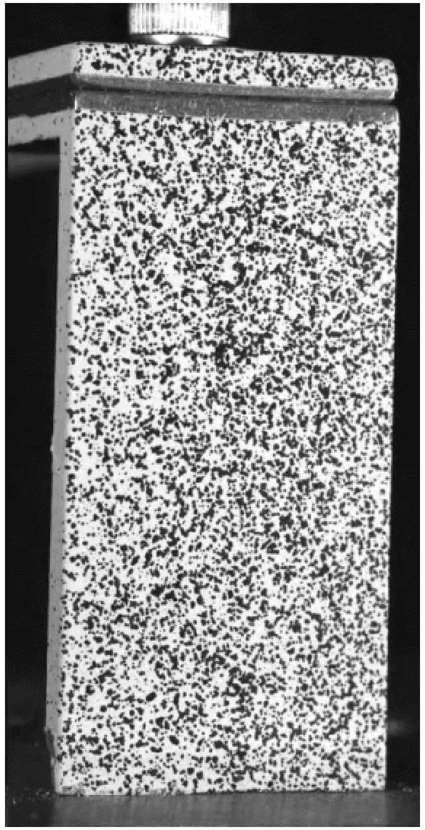
- Literature has shown that using Motion Magnification as a pre-processor to DIC can lower the noise floor

Communicate test results with non-technical people

- Almost anyone looking at it understands what's going on
- Motivate studies, get money

Plus it's just really cool





Overview of Motion Magnification

How is Motion Magnification Performed?

Phase-based Motion Magnification utilizes local complex filters to extract phase information from an image that can be magnified and used to reconstruct magnified motions on an image.

- The reference and deformed images are filtered by a bank of complex filters
- Phase quantities are computed at each pixel in each image for each filter
- Phase changes are computed by subtracting phases from deformed images from those from the reference image
- These phase changes can be scaled by some amplification factor, and the image can then be reconstructed.

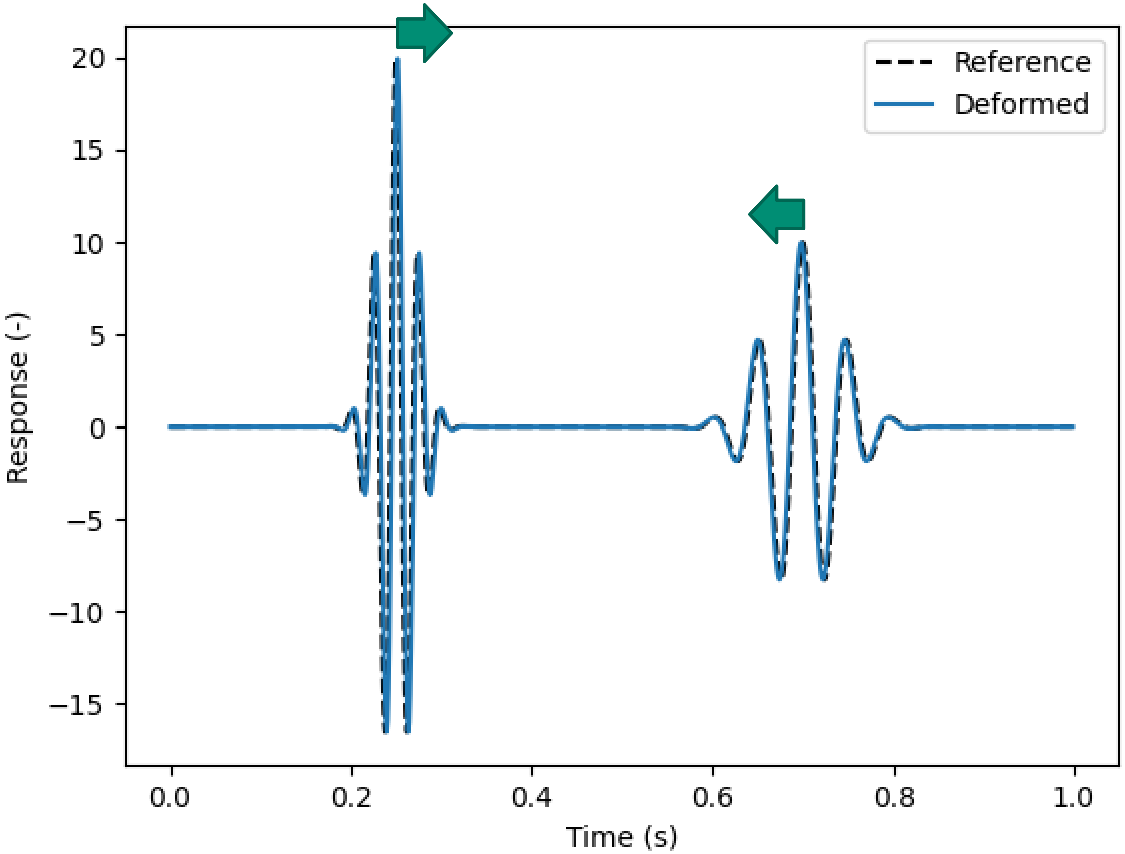
See paper #12641 – Motion Magnification Tutorial for Structural Dynamics in the conference proceedings for complete code to perform these operations

Wadhwa, N.; Rubinstein, M.; Durand, F. & Freeman, W. T. Phase-based Video Motion Processing ACM Trans. Graph., ACM, 2013 , 32 , 80:1-80:10

Starting Small – One-dimensional magnification

Say we have a signal consisting of two moving pulses that we would like to magnify.

- Pulses move left and right in time, similar to how a feature might move throughout an image
- Make sure you understand that we aren't magnifying or scaling the signal itself, we are magnifying motions in the signal

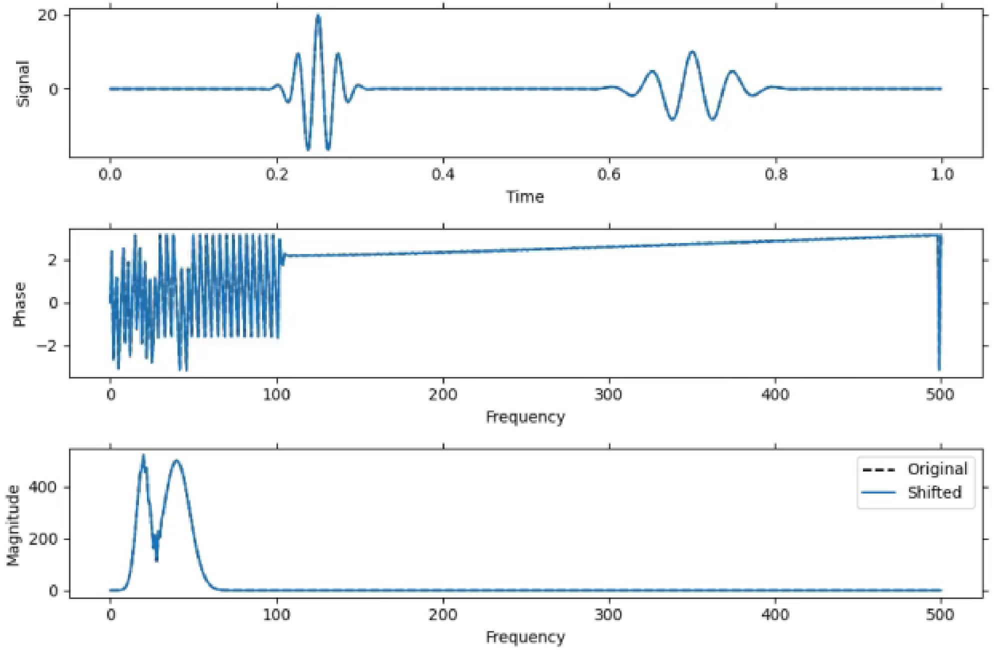


Understanding moving signals via phase modification

The Fourier Shift Theorem is often used in signal processing to translate a signal in time.

The Fourier Shift Theorem says that if we multiply the Frequency-Domain representation of a signal by a linear phase term, the Signal-Domain representation of the signal is shifted by the slope of that linear phase term.

$$\underbrace{\mathcal{F}\big(x(t-\Delta)\big)}_{\text{FFT of Shifted Signal}} = \underbrace{e^{-j\omega\Delta}}_{\text{Linear Phase Term}}\underbrace{\mathcal{F}\big(x(t)\big)}_{\text{FFT of Un-shifted Signal}}$$

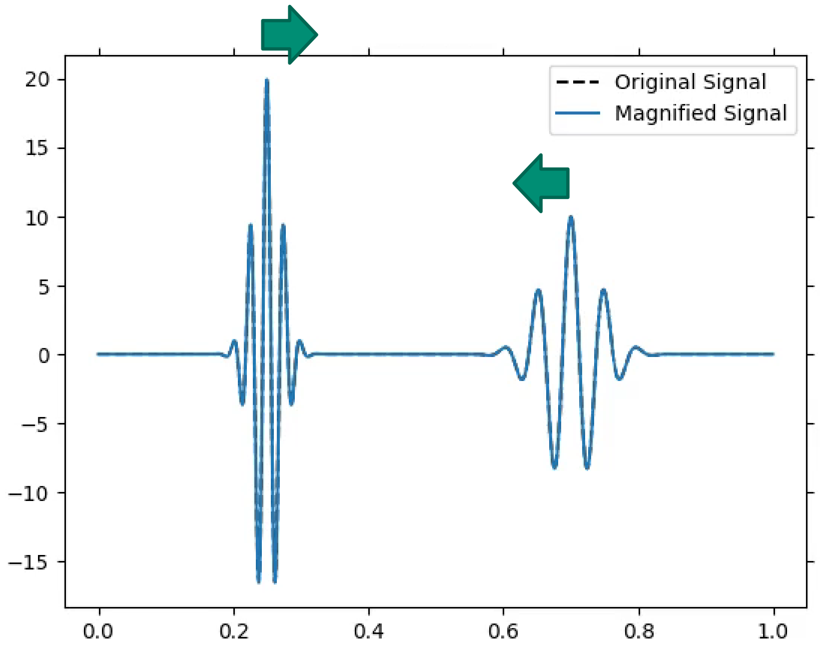


However, we cannot use this to magnify motions!

Given the previous slide, one might expect that if we compute the change in phase of the FFT between some deformed and reference signal, we could magnify that phase change to magnify the difference between the deformed and reference signal.

The issue is that the basis functions used in the FFT (sine waves) span the entire length of the signal.

By adjusting the phase of the sine wave, we can either move the entire sine wave left or right. We cannot mov ıother portion to the right.



Better basis functions for magnification

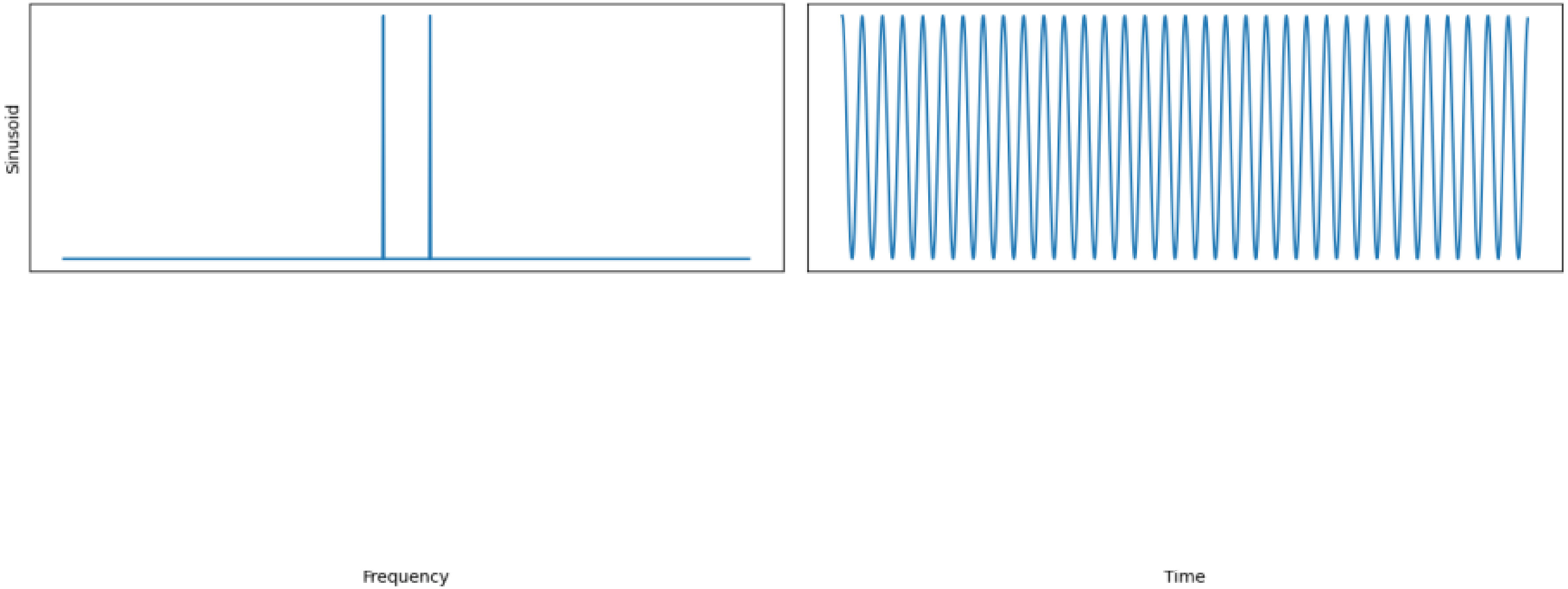
The FFT can very precisely identify frequency, but it cannot identify were in time that frequency occurs

- Ability to localize frequency, but not time

However, if we window the sinusoid, this now lets us localize in time

Frequency representation becomes broader due to time/frequency uncertainty principal

- Note we still need some localization in frequency, so we cannot collapse our window down to a Dirac delta
- Displacement of a signal per phase change depends on the frequency of the signal



Construction of Complex Filters

Creating a set of filters for motion processing

Note that for the FFT to construct a signal from sine waves, we needed all frequency bins to be covered.

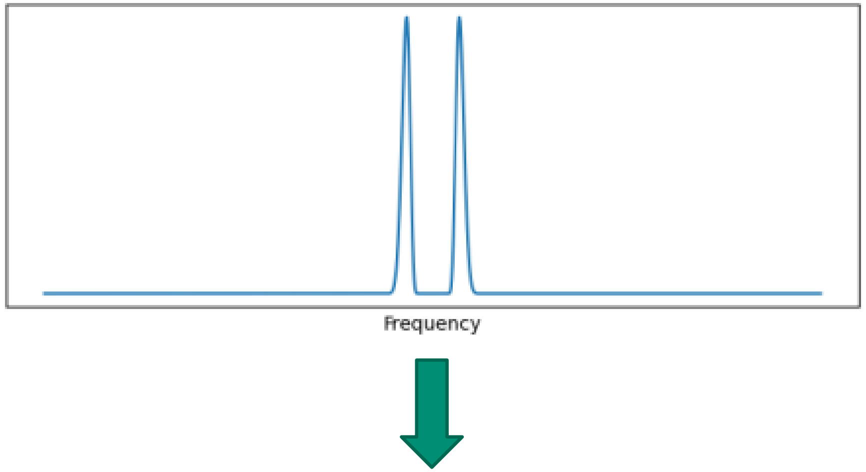
Similar arguments must be made for these filters:

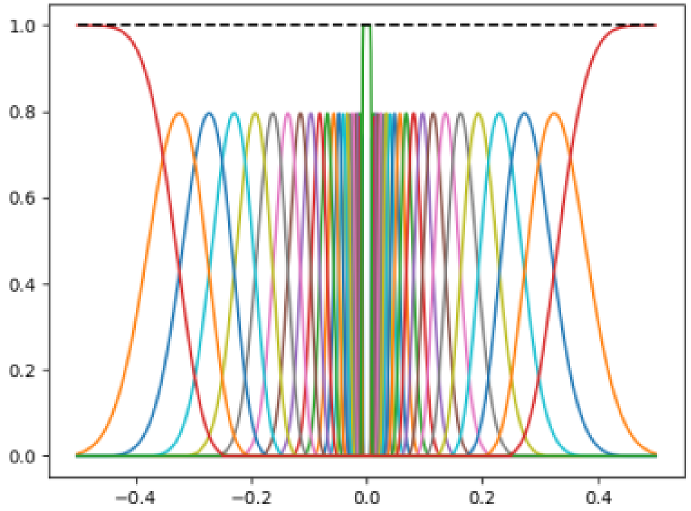
- Filters now span multiple frequency bins
- Rather than having one filter per frequency bin, the summation of all filters must sum-square to a constant value
- Filters will overlap

Wadhwa paper uses constructs cosine-shaped octave filters in the frequency domain

- See paper #12641 – Motion Magnification Tutorial for Structural Dynamics in the conference proceedings for complete code to construct these filters

Note these filters form band-pass filters. We also need to include a low-pass and high-pass filter to sum-square across the entire frequency domain



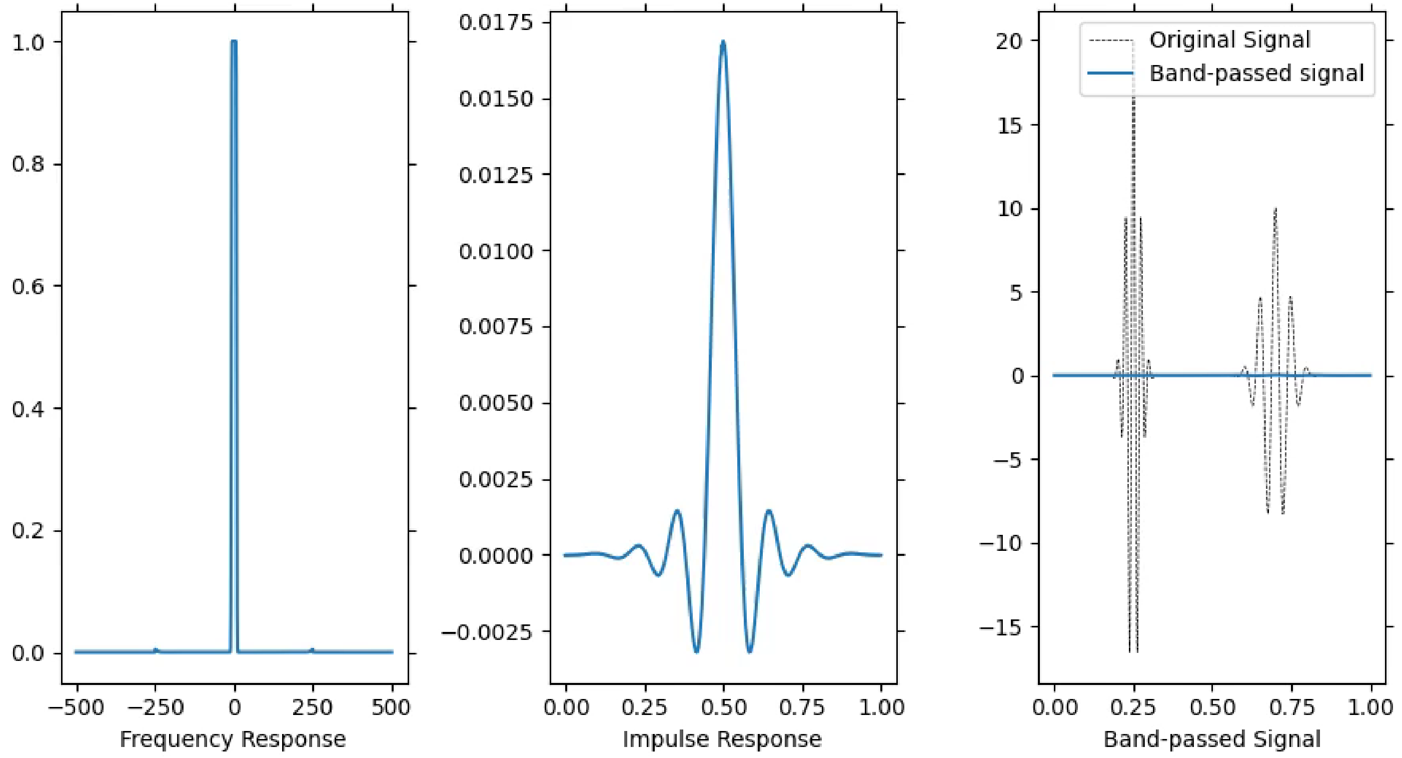


Wadhwa, N.; Rubinstein, M.; Durand, F. & Freeman, W. T. Phase-based Video Motion Processing
ACM Trans. Graph., ACM, 2013 , 32 , 80:1-80:10

What do these filters look like?

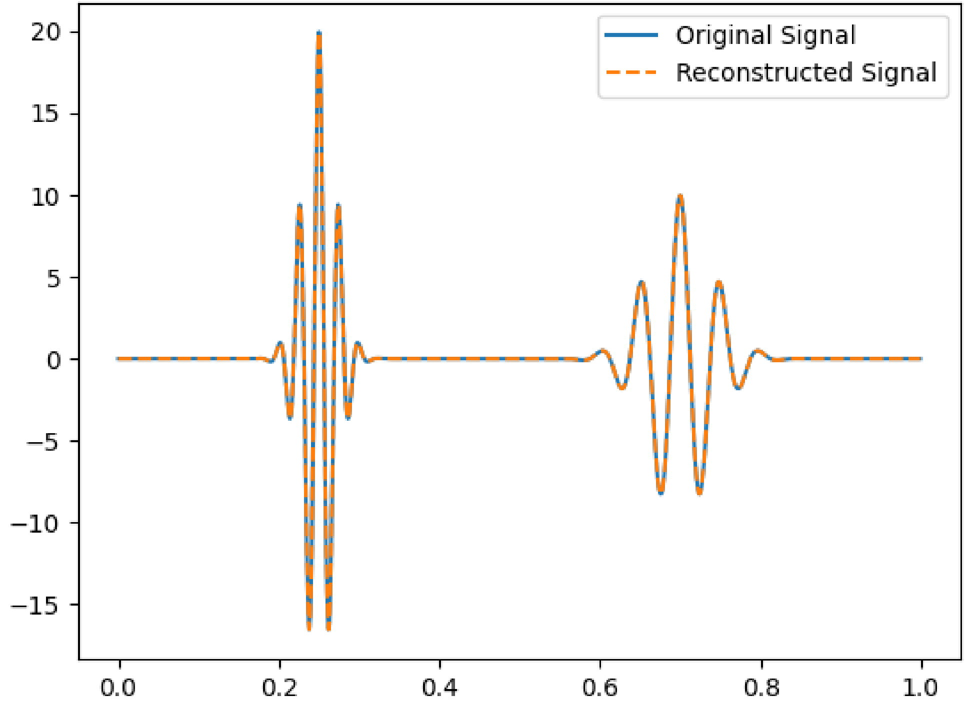
Note:

- Where the frequency of the filter matches the signal, the signal can pass through
- Where the frequency of the filter does not match the signal, the signal is attenuated
- As the frequency representations of the filters get bigger (higher frequencies) the time representations get smaller



Reconstructing the signal from the various filters

Filters sum-square to 1, meaning if we filter the signal twice (e.g. multiply by the frequency representation squared) and sum contributions from each filter, we will exactly reconstruct our original signal.



Where's the phase?

Up to this point, we have:

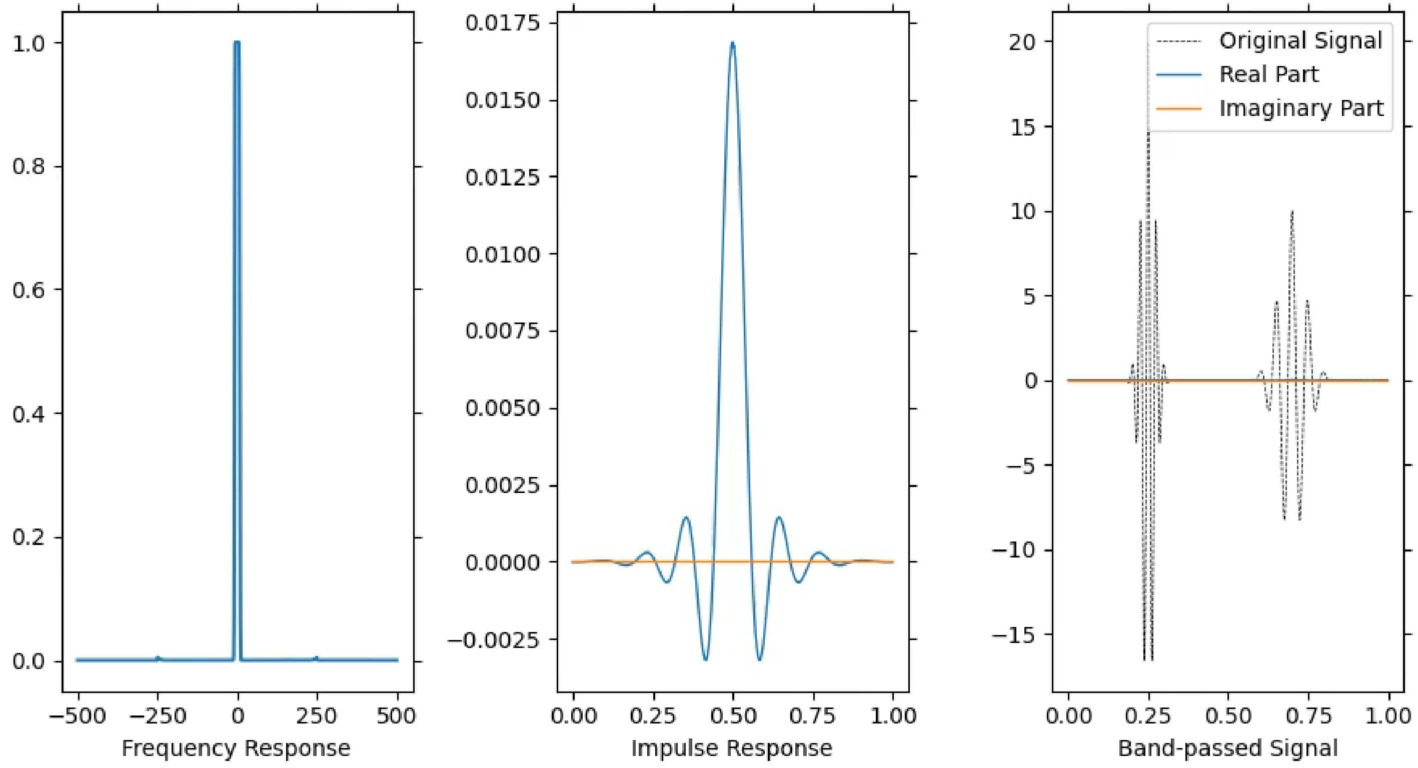
- Generated real-valued signals
- Filtered them with real-valued filters symmetric about the zero frequency
- Obtained real-valued filtered signals

We have been discussing phases and complex filter banks, so how do we obtain those?

Creating and Filtering with Complex Filters

By setting the negative frequency components of a 2-sided FFT to zero and taking the IFFT, we get a complex signal where the real part is 90 degrees out of phase with the imaginary part.

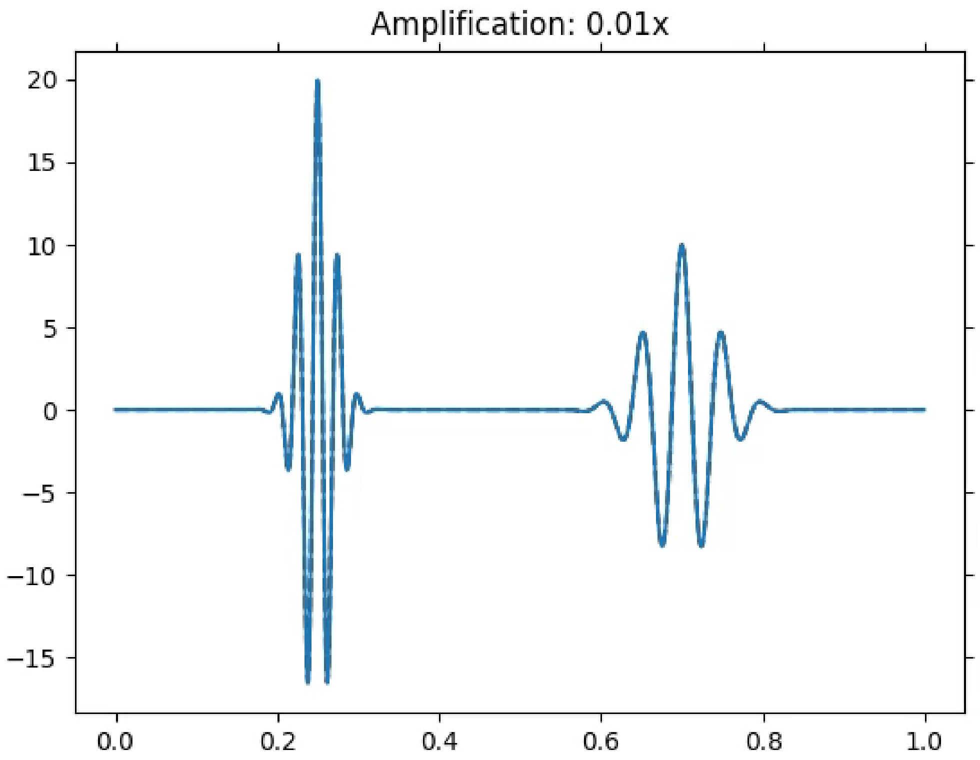
Note that we have halved the amplitude of the bandpass filter response by removing half the frequency domain representation, will need to multiply by 2 to compensate during reconstruction



Performing Motion Magnification

With the filter banks constructed, we can now perform motion magnification:

1. Filter reference and deformed signals with complex filter banks
2. Subtract deformed phases from reference phases (wrap from $-\pi$ to π)
3. Scale phases by an amplification factor
4. Multiply filtered reference signal by a complex number with unit amplitude and amplified phase
5. Filter signal with filters a second time (sum-squared of filter contributions equals to 1, equivalent to filtering twice).
6. Sum low-pass filtered signal with 2x each band-passed filtered signal to reconstruct the magnified images (high-pass is ignored)



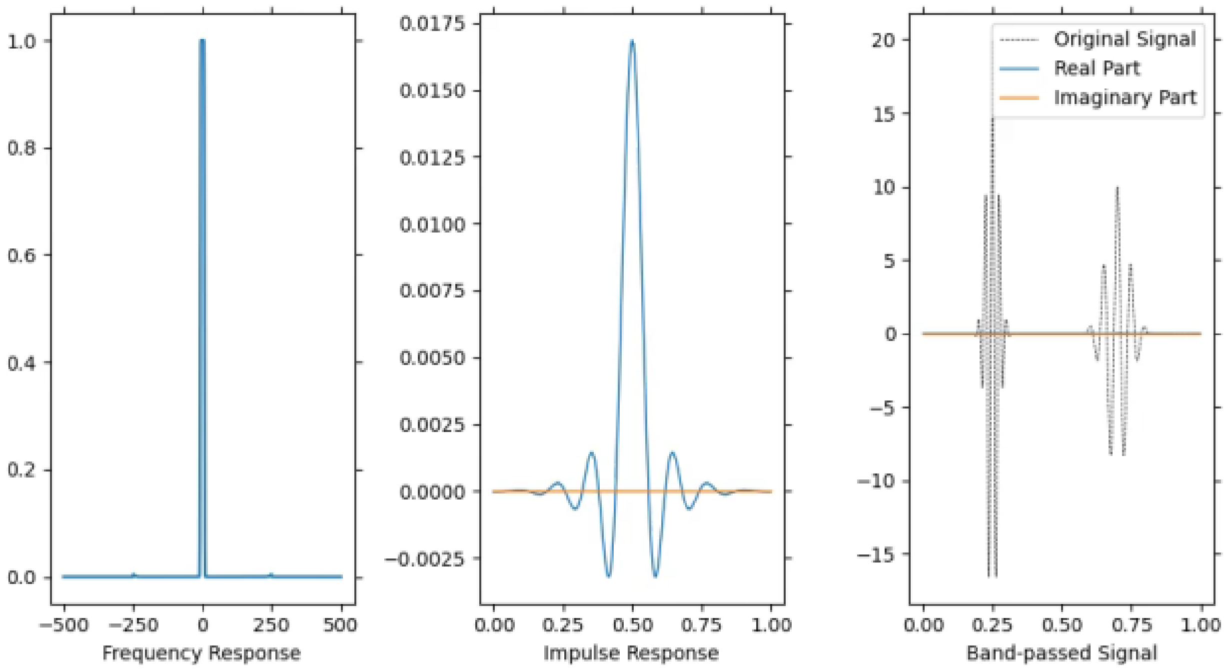
Some notes on motion magnification breakdown

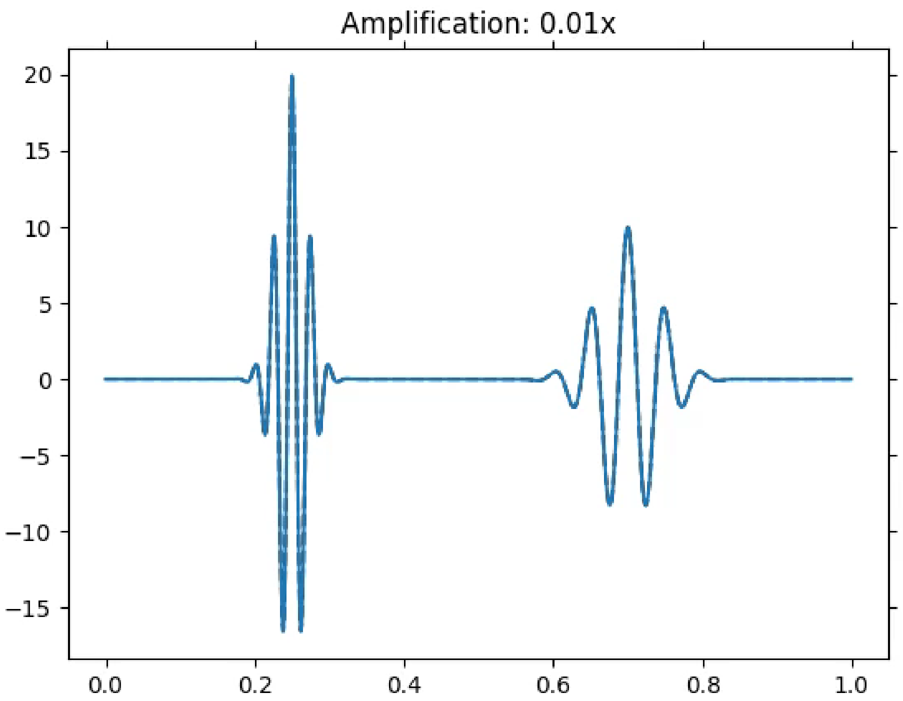
Higher frequency signal tends to break down first

- Already lost significant amplitude of the left pulse by 10x magnification
- Right pulse still looks very good at 10x magnification

Ability to magnify motion depends on the width of the impulse response of the filter

- Sharper filters in the frequency domain will have broader impulse responses, more magnification
- Be aware, broader filters have limited ability to localize motions, and are more computationally intensive
- In the limit that the filters become one frequency bin large, we have reconstructed the FFT





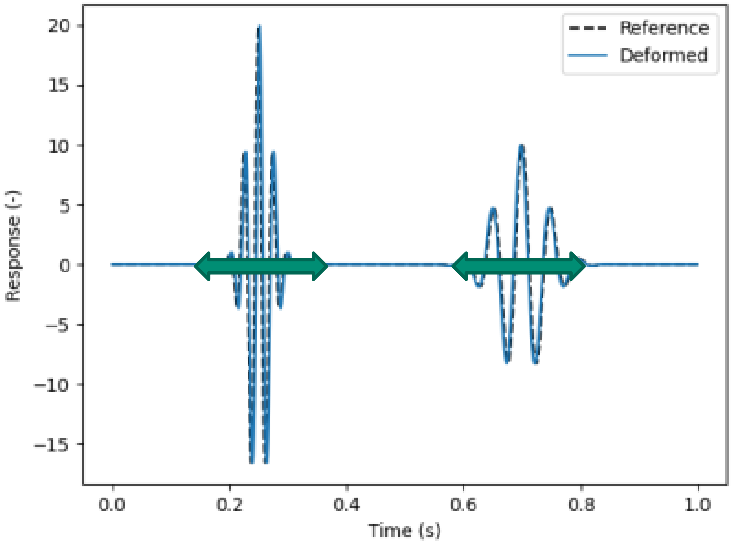
Extending to 2D Magnification

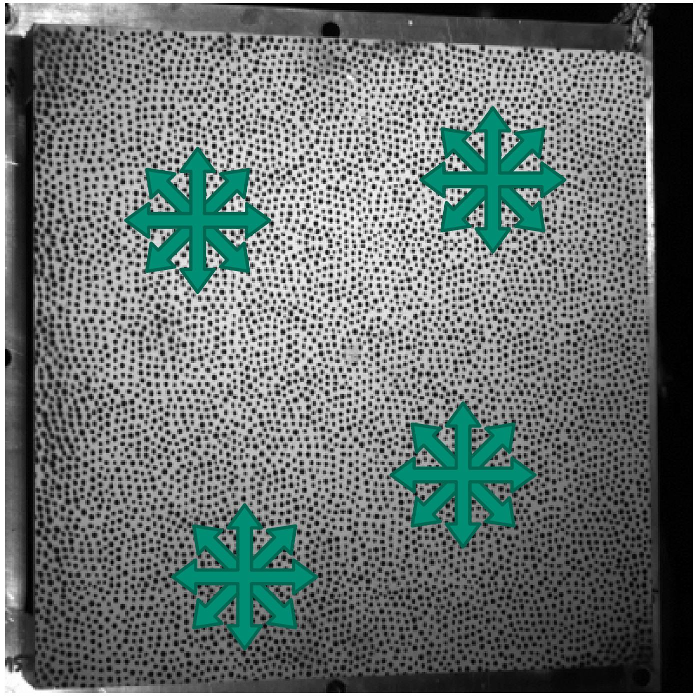
Magnifying Motions in an Image

For a 1D case, the distance a feature moves completely defines its motion

For a 2D case, a feature's motion must be defined not only by a distance but also by a direction.

We will need to set up our filters such that they isolate not only the frequency of the motion, but also the direction of the motion

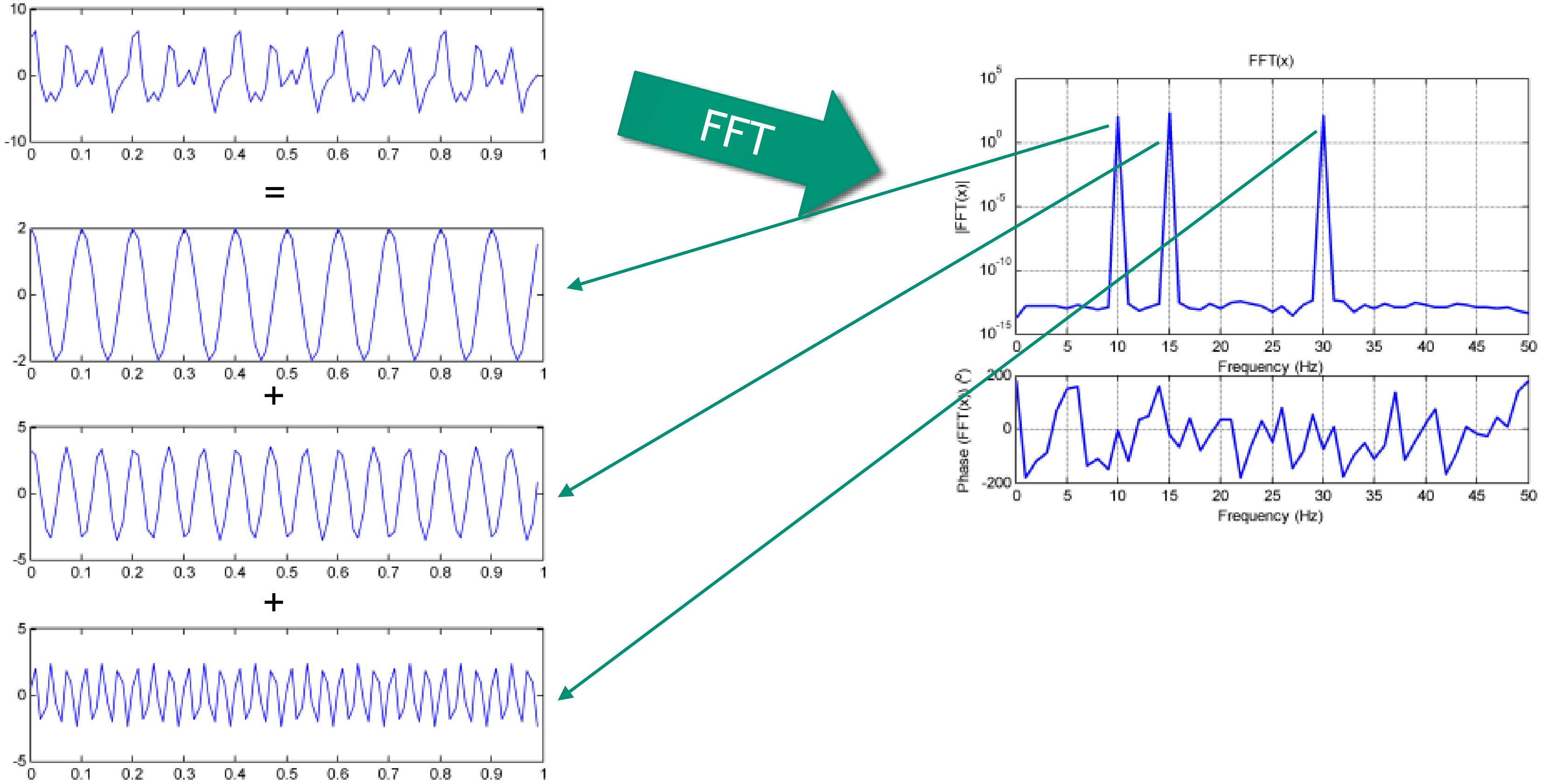




Aside: Review of FFT in 2D

Most modal engineers are intimately familiar with the 1D FFT, but not so much with the 2D FFT

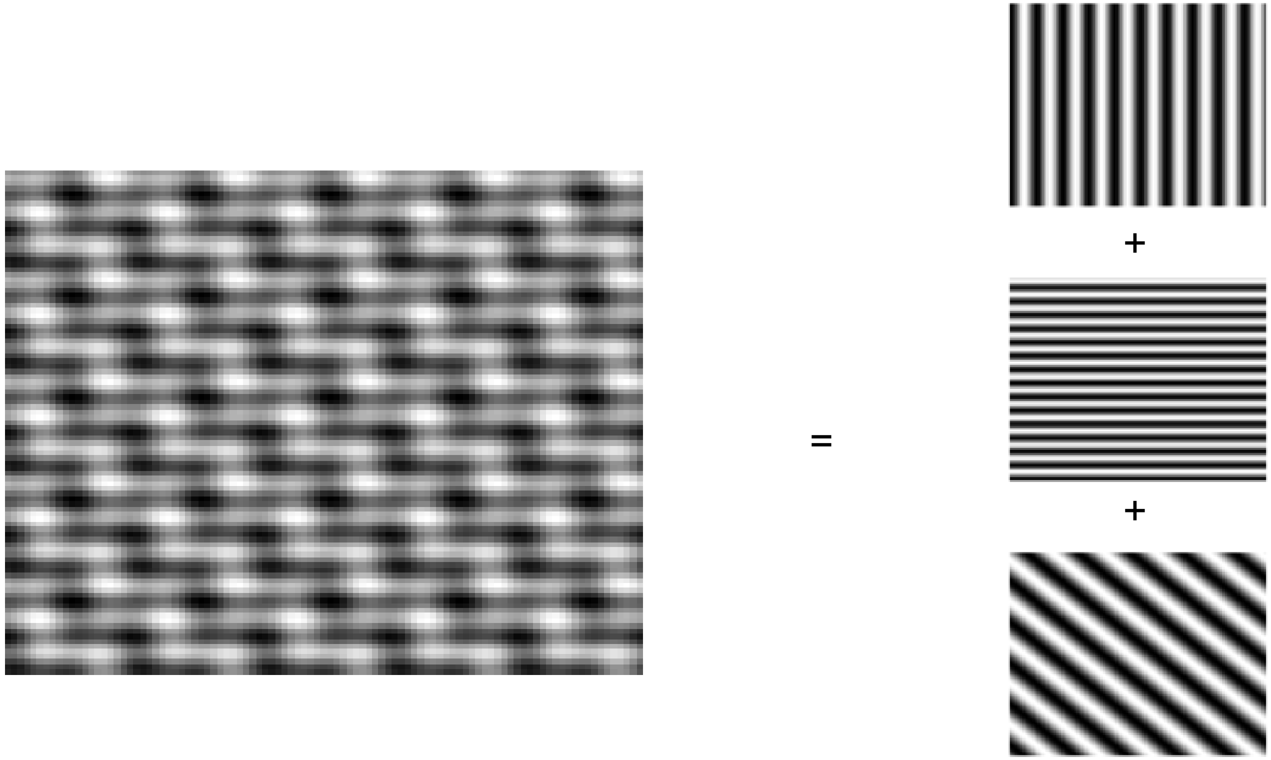
Signals can be decomposed into a sum of sine waves



Aside: Review of FFT in 2D

This can be generalized to 2 dimensions

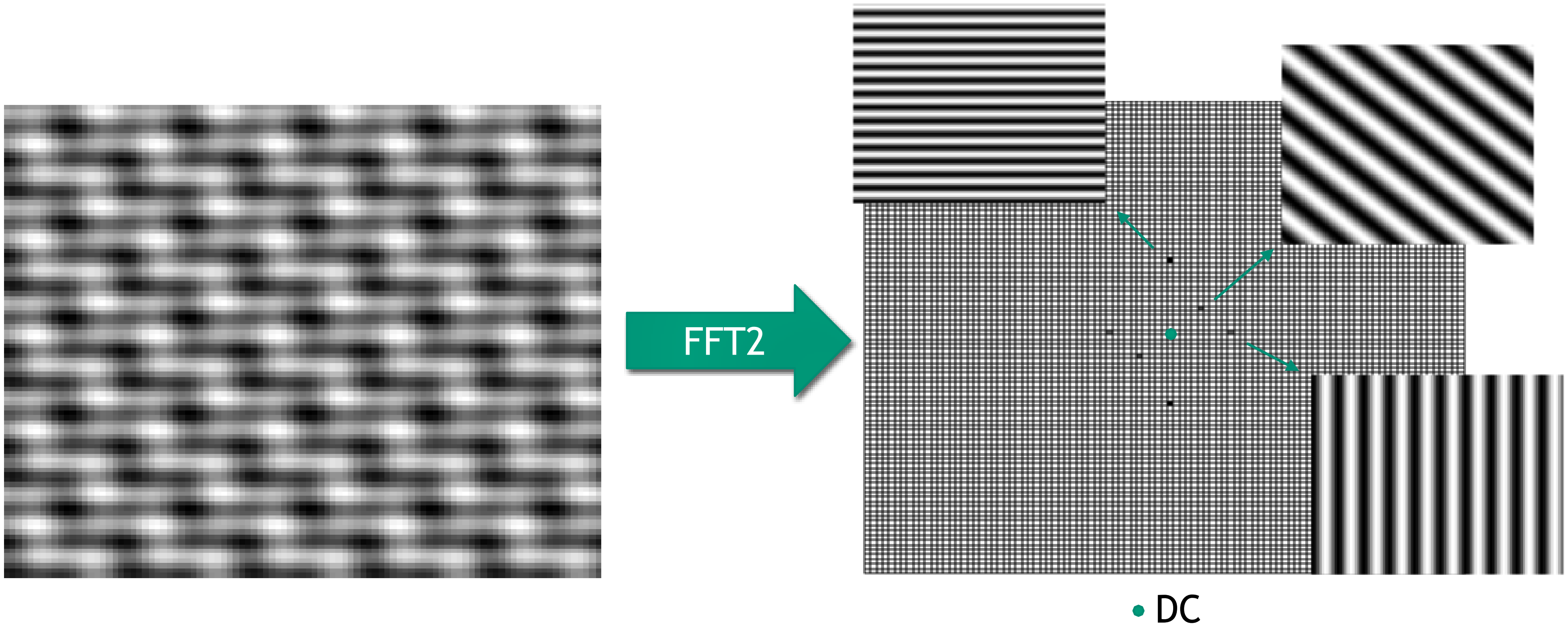
- Image is simply a 2D signal where the intensity, brightness, color, etc. is the dependent variable.
- A 2D image can still be decomposed into a sum of sine waves, but not instead of the waves only having a frequency, they also have a direction.



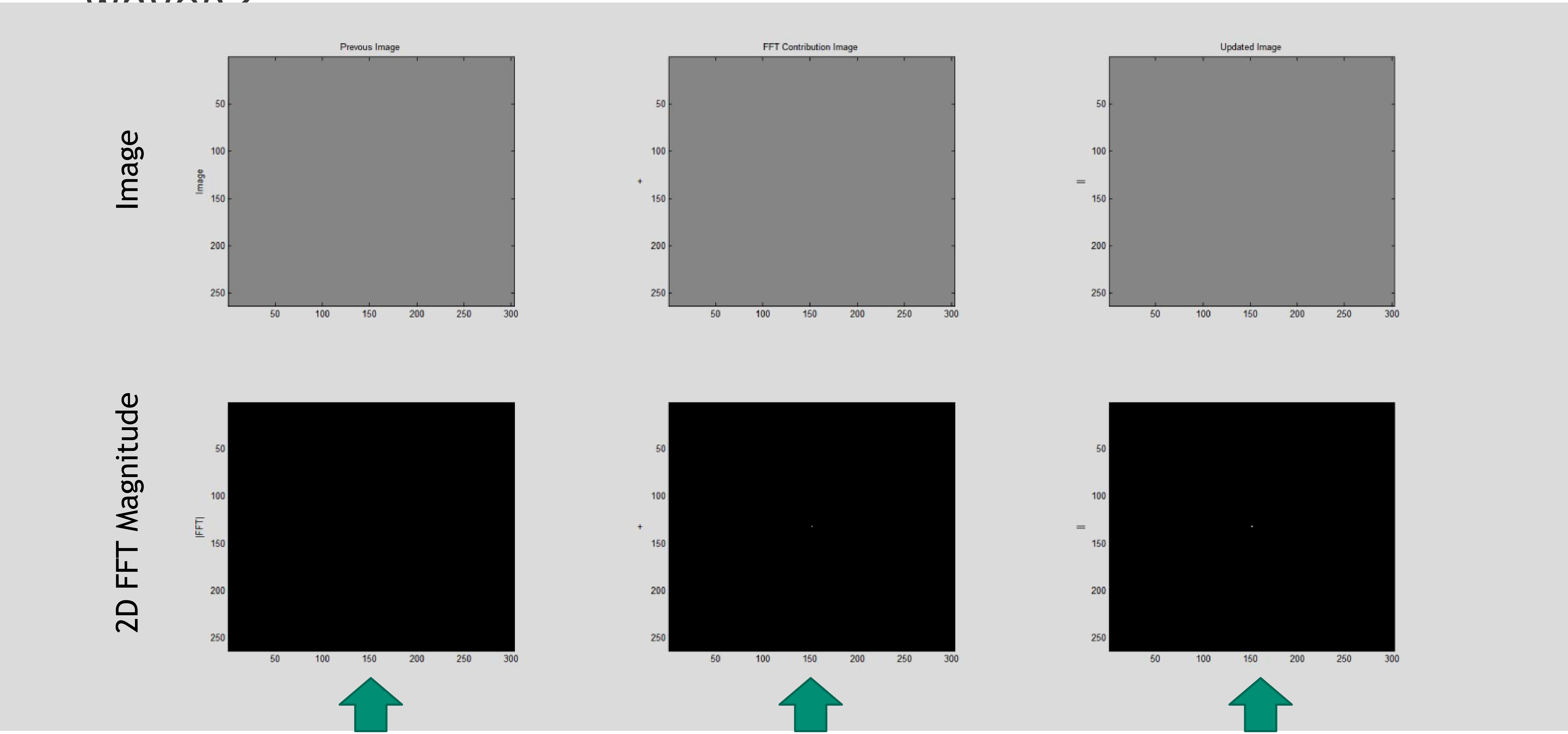
Aside: Review of FFT in 2D

The 2D FFT reveals amplitude and phase of the sine wave corresponding to each frequency and direction

Radius from DC or zero frequency represents the frequency, angle represents direction



Can we really create a complex image from sums of sine waves?



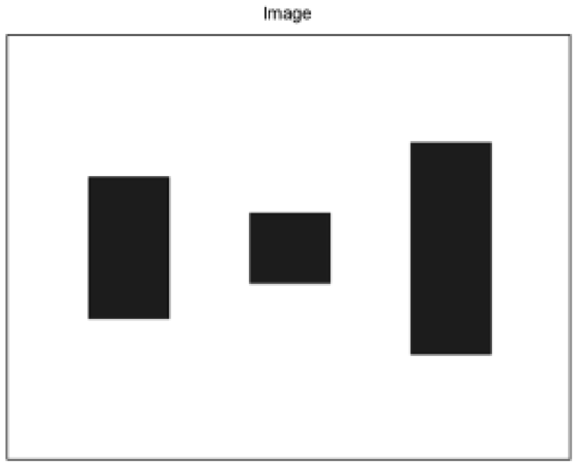
At each step: **Previous Image** is added to a **sinusoidal contribution** to produce and **updated image**

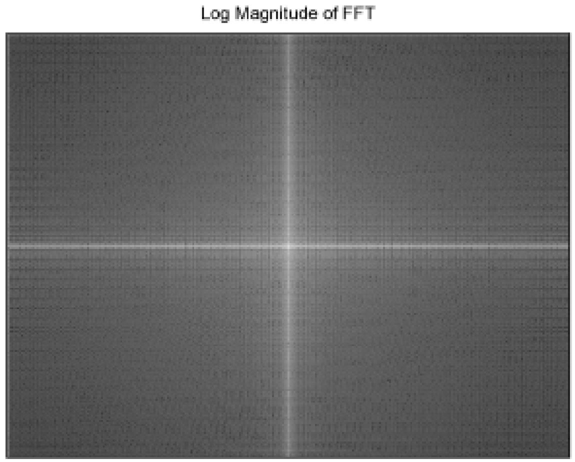
Example 2D FFTs of Images

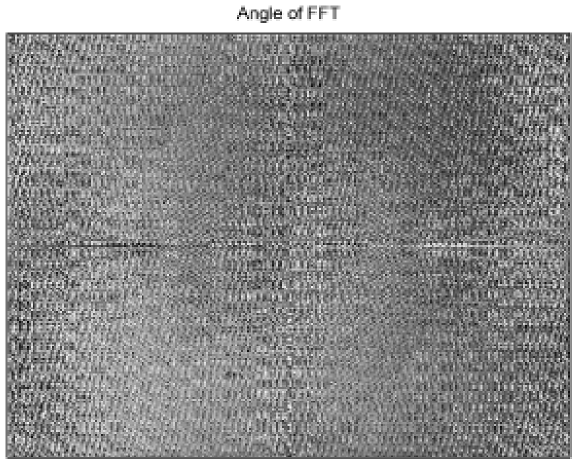
Image of three boxes

Frequency content shows strong amplitudes along the axes of the image

Very little off-axis content, which is due to the boxes being aligned with the image



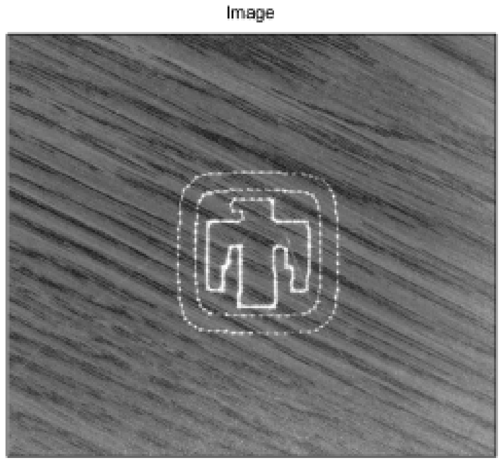


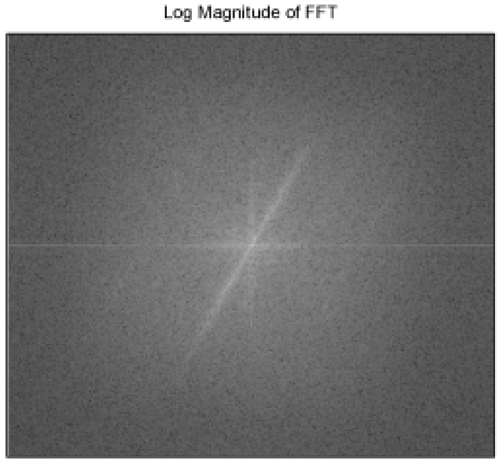


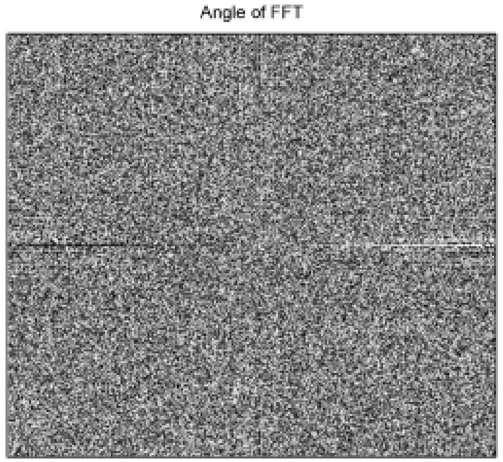
Example 2D FFTs of Images

Sandia Thunderbird drawn with a laser vibrometer on a patterned table

Strong frequency content in the direction of the wood grain pattern



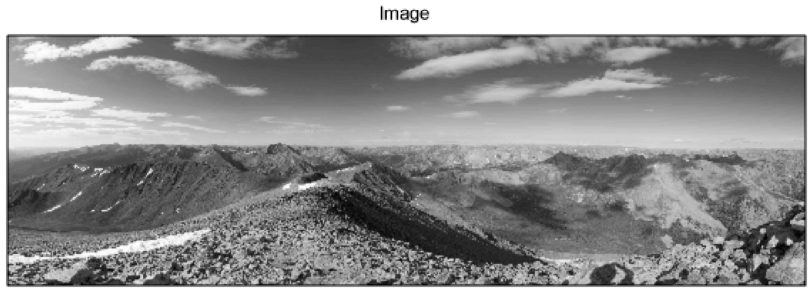


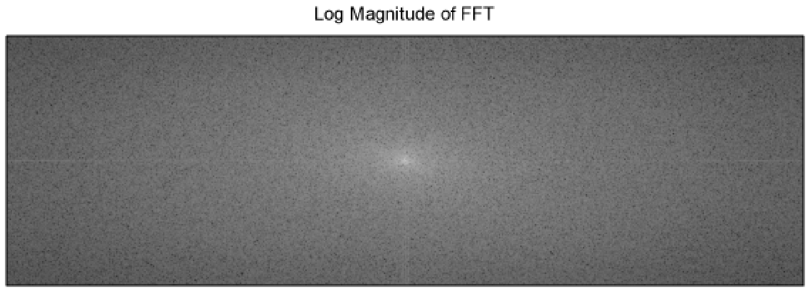


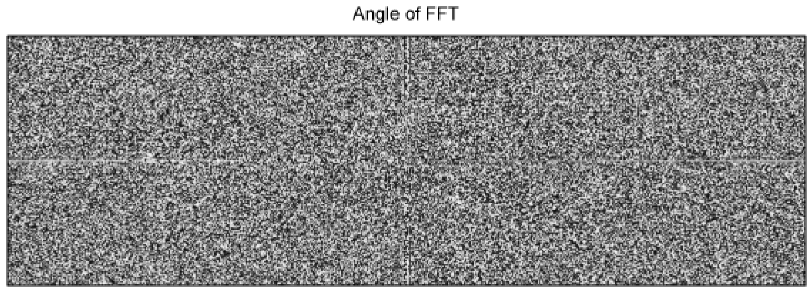
Example 2D FFTs of Images

Panorama view from the highest peak in Colorado

Image doesn’t have a lot of structure; FFT amplitudes also don’t show much structure.



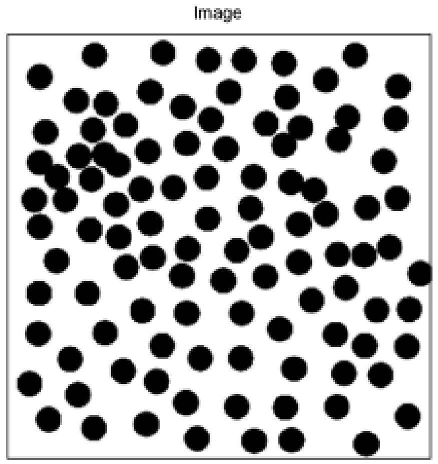


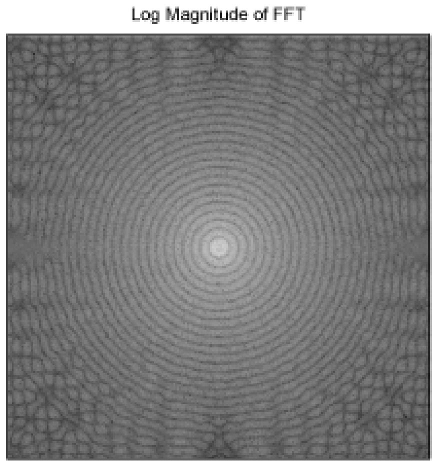


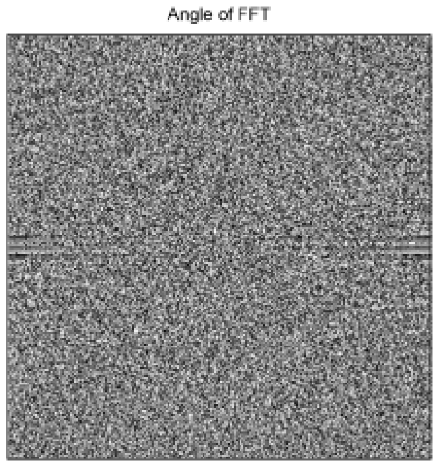
Example 2D FFTs of Images

Black speckles on a white background

FFT has strong radial symmetry, likely due to the circular speckles having no preferred direction in the image



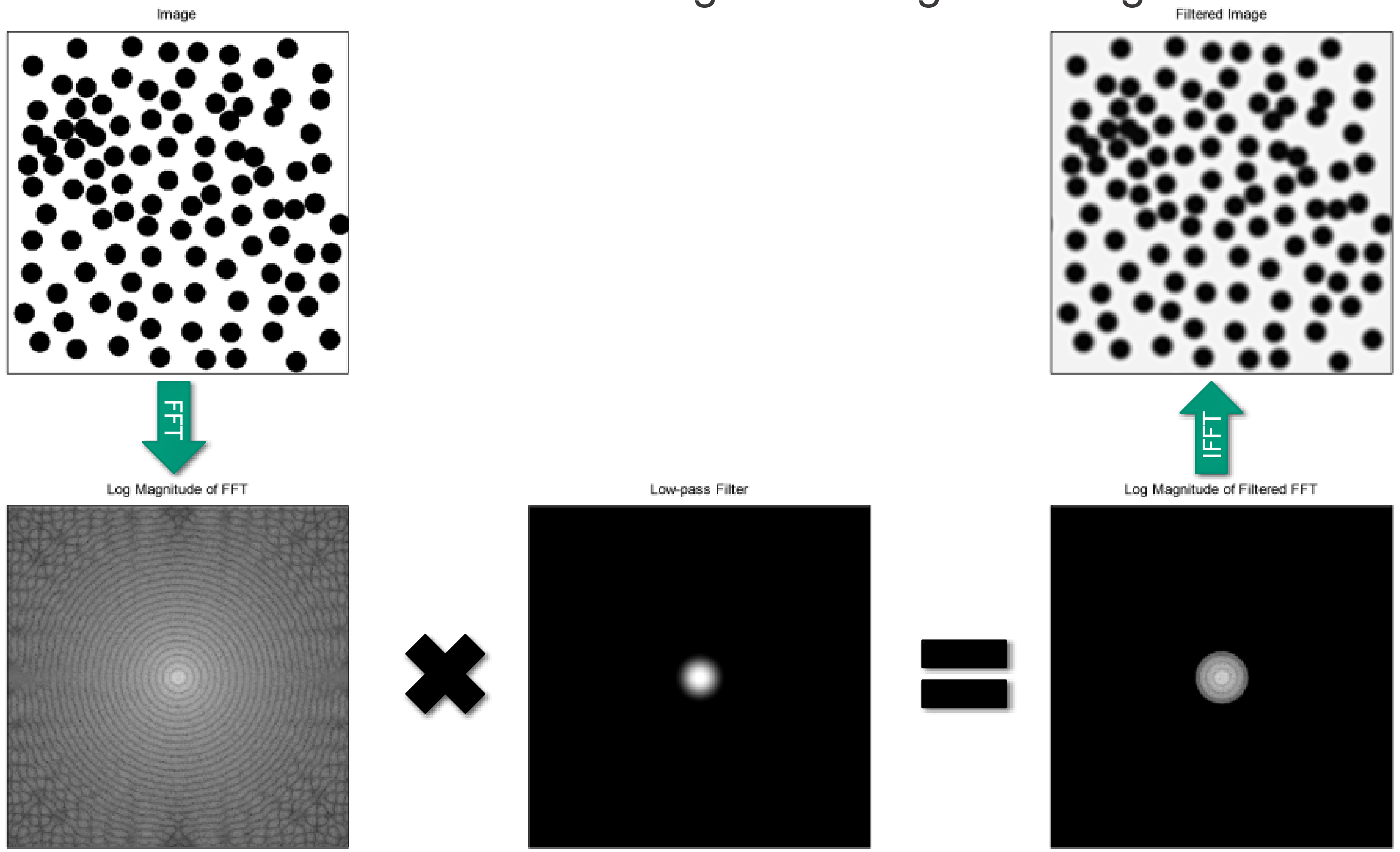




Low Pass Filters

Low pass filters can be created by keeping the portion of the FFT that is near the origin (DC) of the FFT

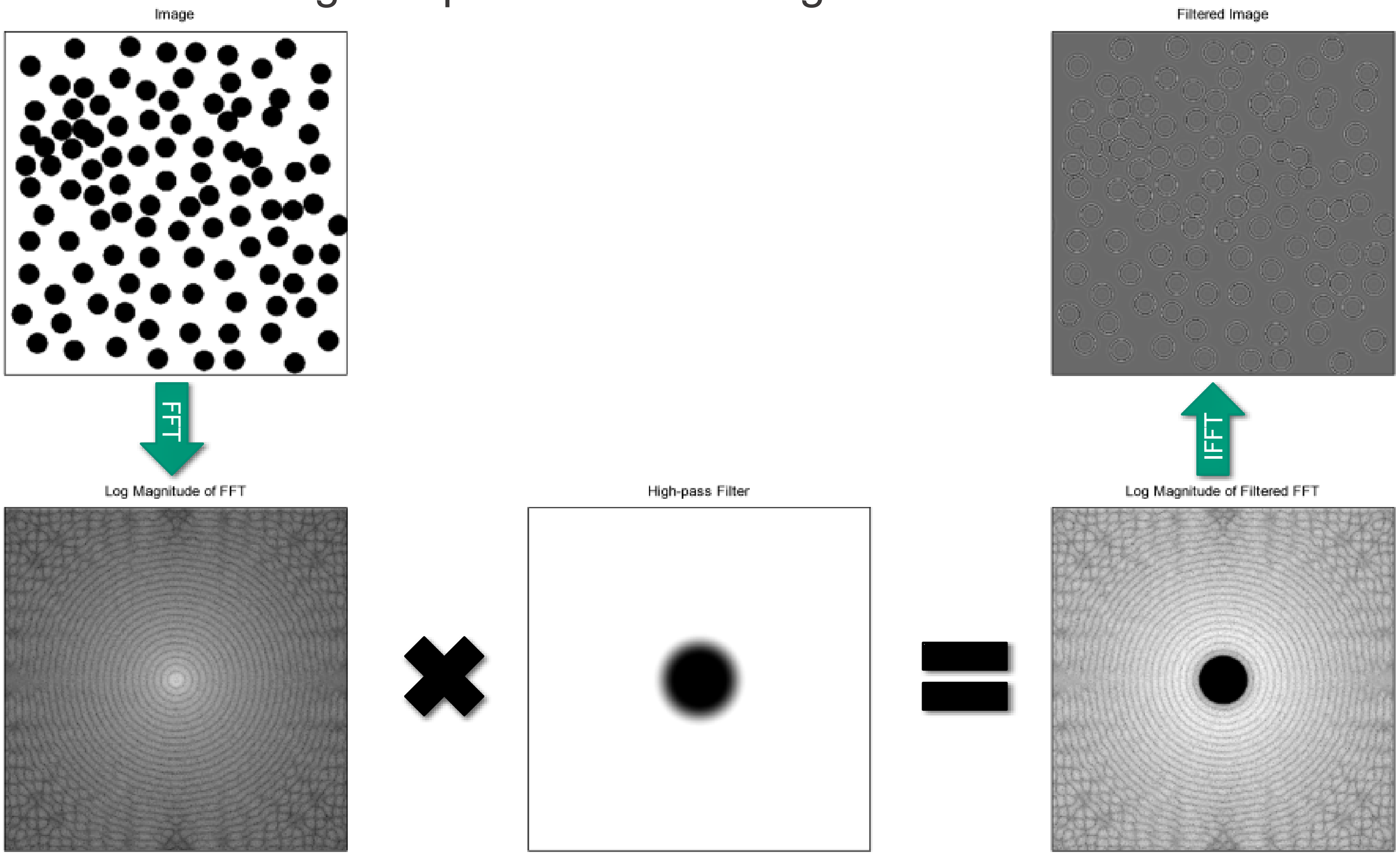
These can be useful for noise reduction and image softening or bluring



High Pass Filters

High pass filters can be created by keeping the portion of the FFT that is far from the origin of the FFT

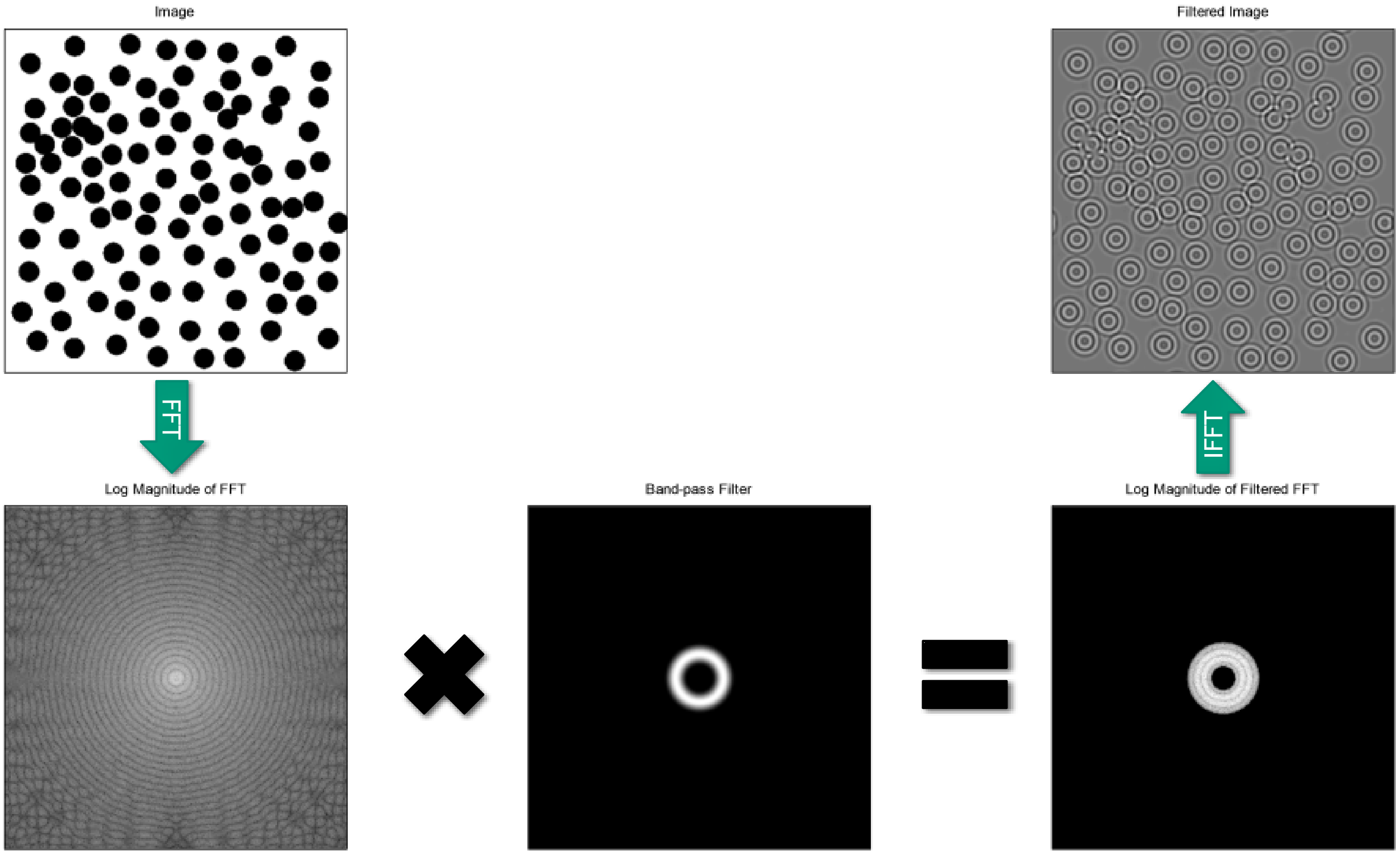
These can be useful for finding sharp features and edge detection



Band Pass Filters

Band pass filters can be created by keeping the portion of the FFT that is a specific distance from the origin of the FFT

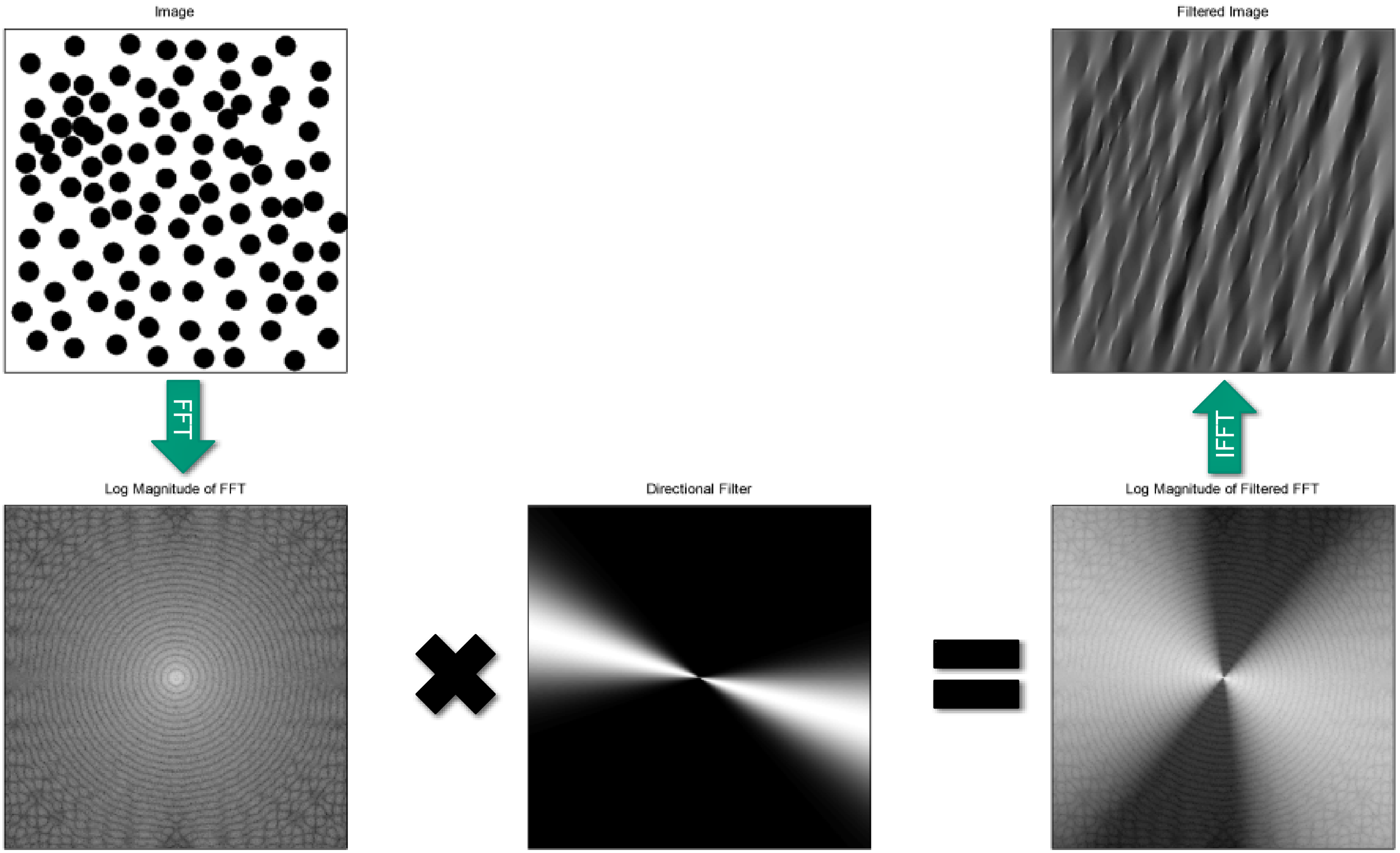
These can be useful for isolating specific spatial frequencies



Directional Filters

Directional filters can be created by keeping portions of the FFT along a specific angle

These will select edges oriented perpendicular to that angle.



Construction of Complex Filters for 2D Images

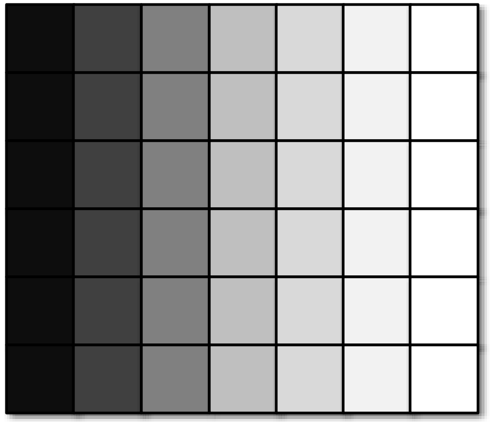
2D Filter Requirements – Frequency and Direction

For 2D filters, we need to isolate the motions into various frequency components and directions

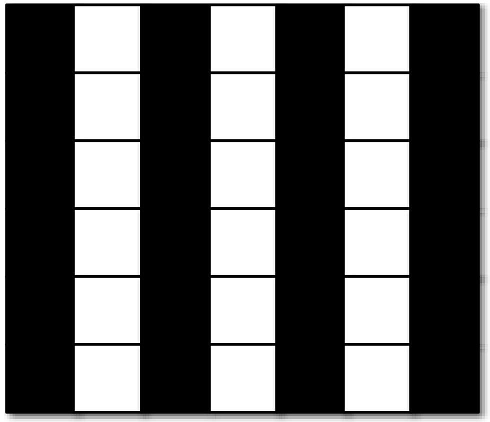
Frequency isolation is required due to motion varying with phase at different frequencies

- Low frequency requires small phase change to move a given distance
- High frequency requires large phase change to move a given distance

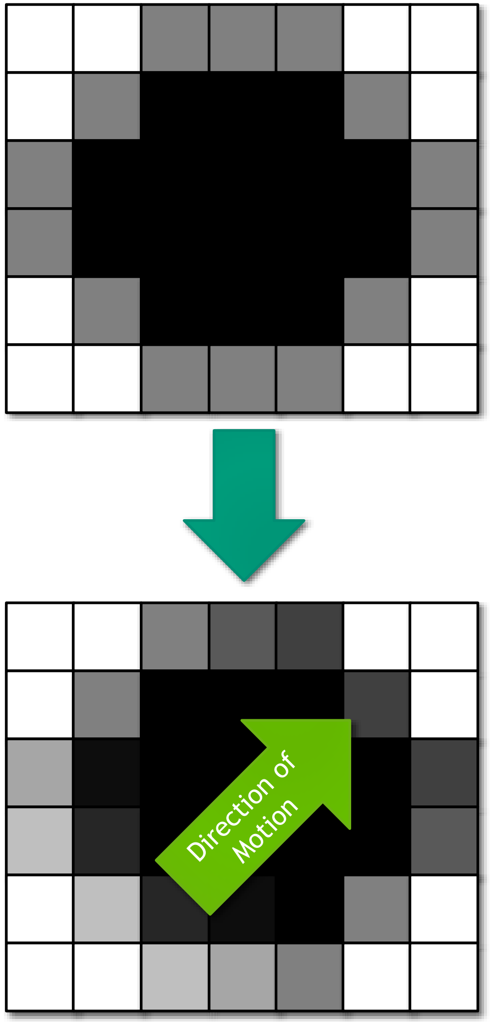
Direction isolation is required due to features moving in specific directions on the image.



Low spatial frequency
Slow change in the image



High spatial frequency
Fast/sharp change in the image



Must also isolate the direction of motion

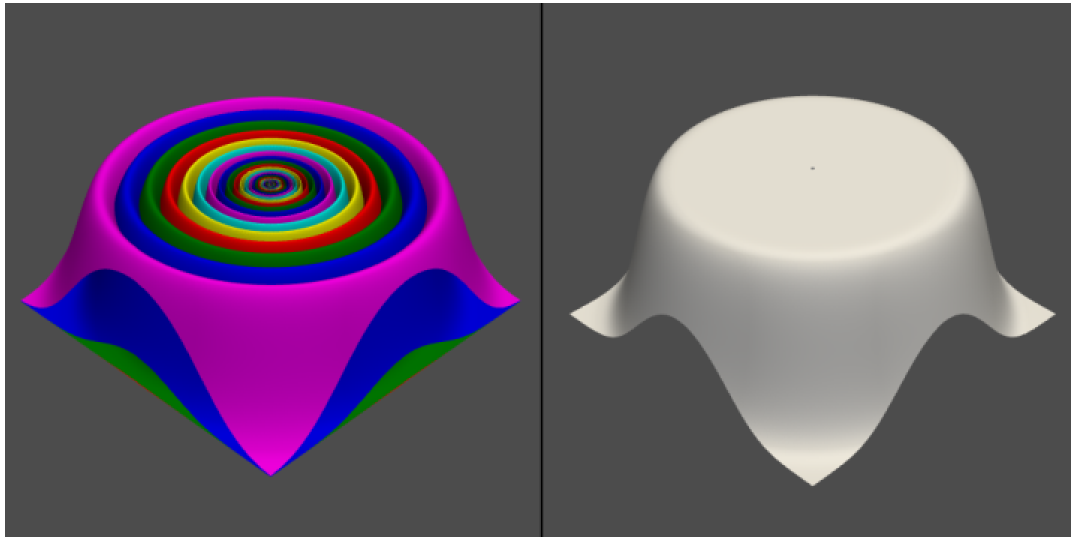
Isolating Spatial Frequency: Generating 2D Band-pass Filters

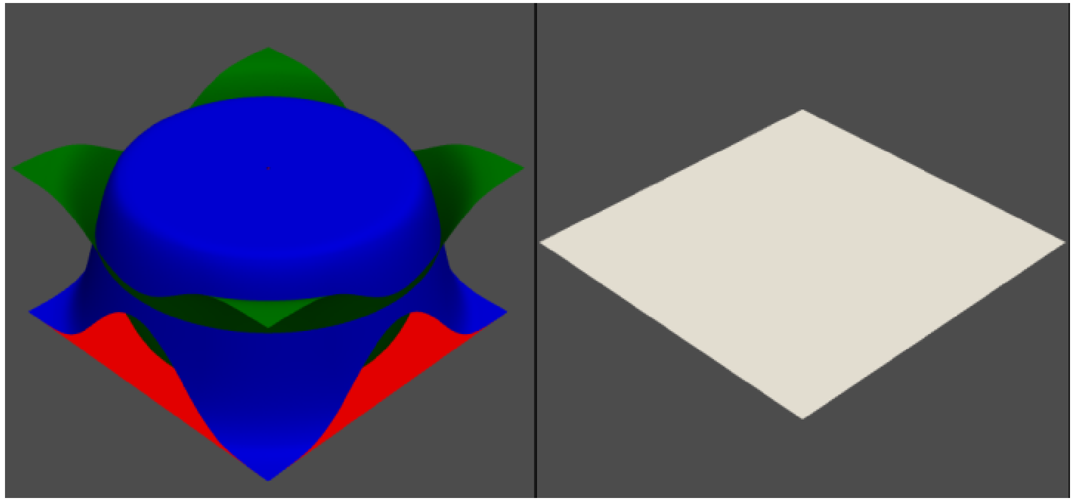
Band-pass filters are constructed identically to the 1D case, except that the radius from the center 0 frequency is used for all directions

Results in concentric rings around the zero frequency

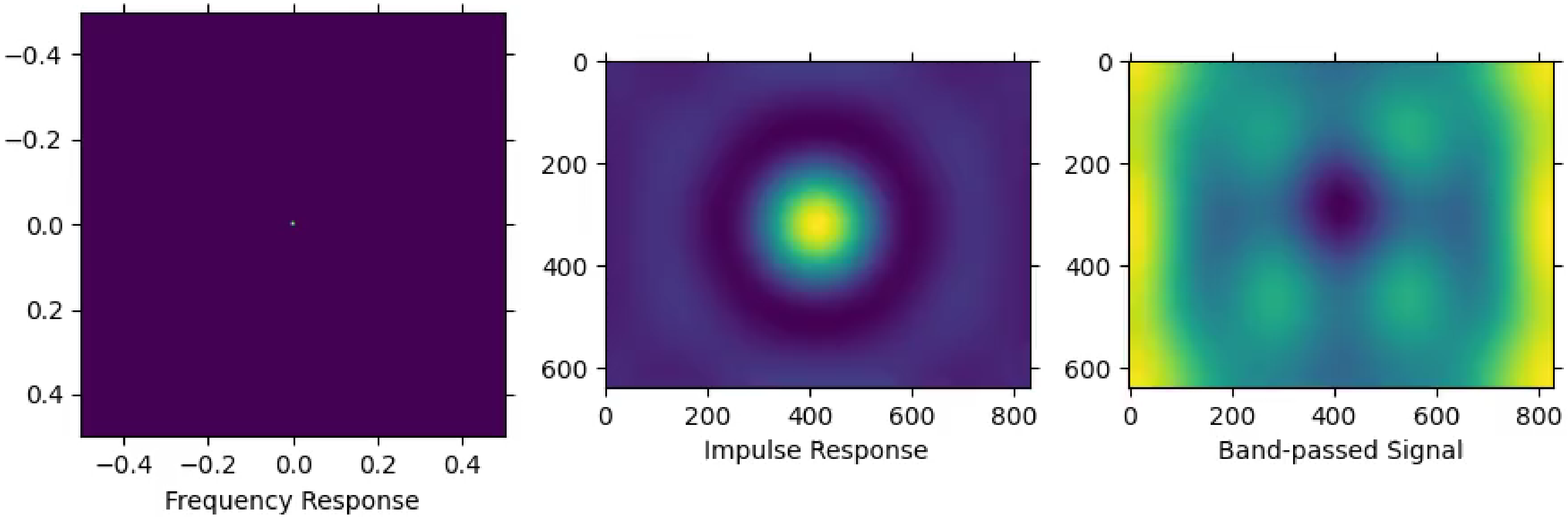
Again, filters must sum-square to 1 across all frequency bins

Low-pass and high-pass filters can be constructed by subtracting the sum-squared of all band-pass filters from 1.





Visualizing the Spatial Frequency Filters



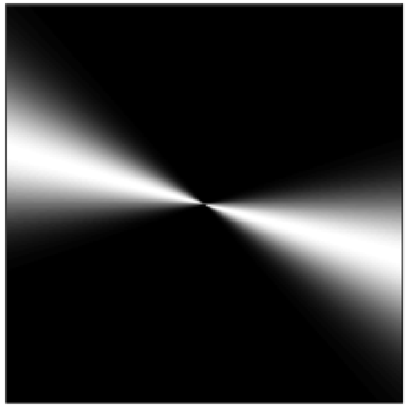
Isolating Spatial Orientations: Generating Direction Filters

Filters that isolate specific directions are now constructed

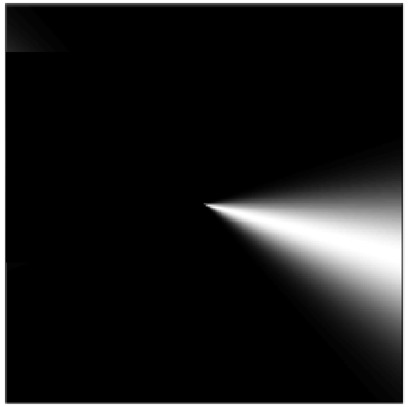
Recall we could create complex filters in the 1D case by removing negative frequency components

Can create complex filters here by zeroing out one side of the zero frequency

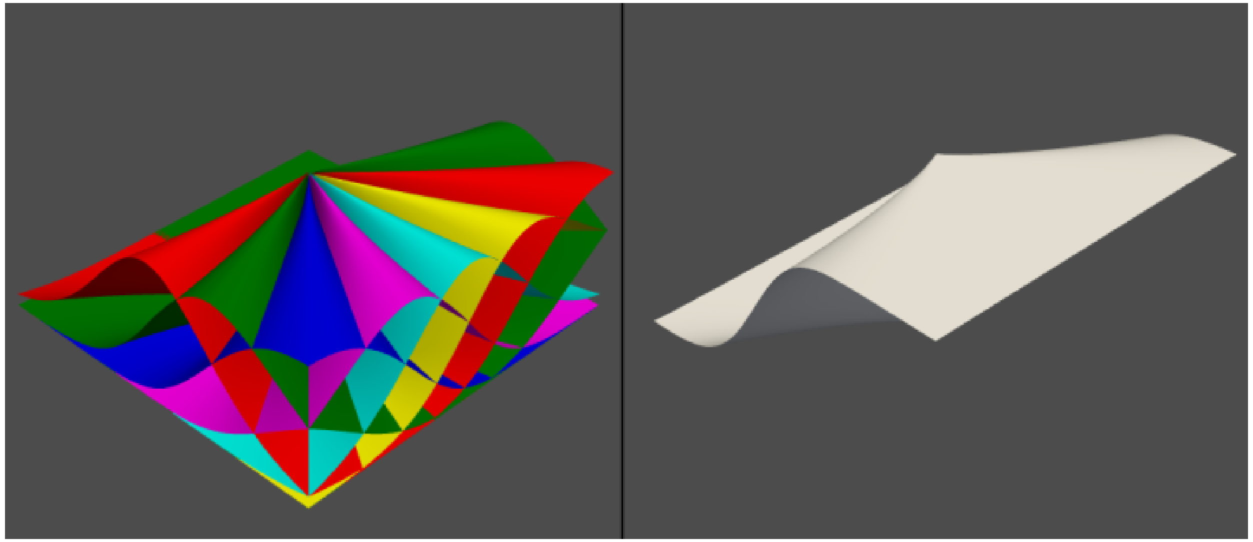
These must also sum-square to 1 across the frequency band (where not zeroed)



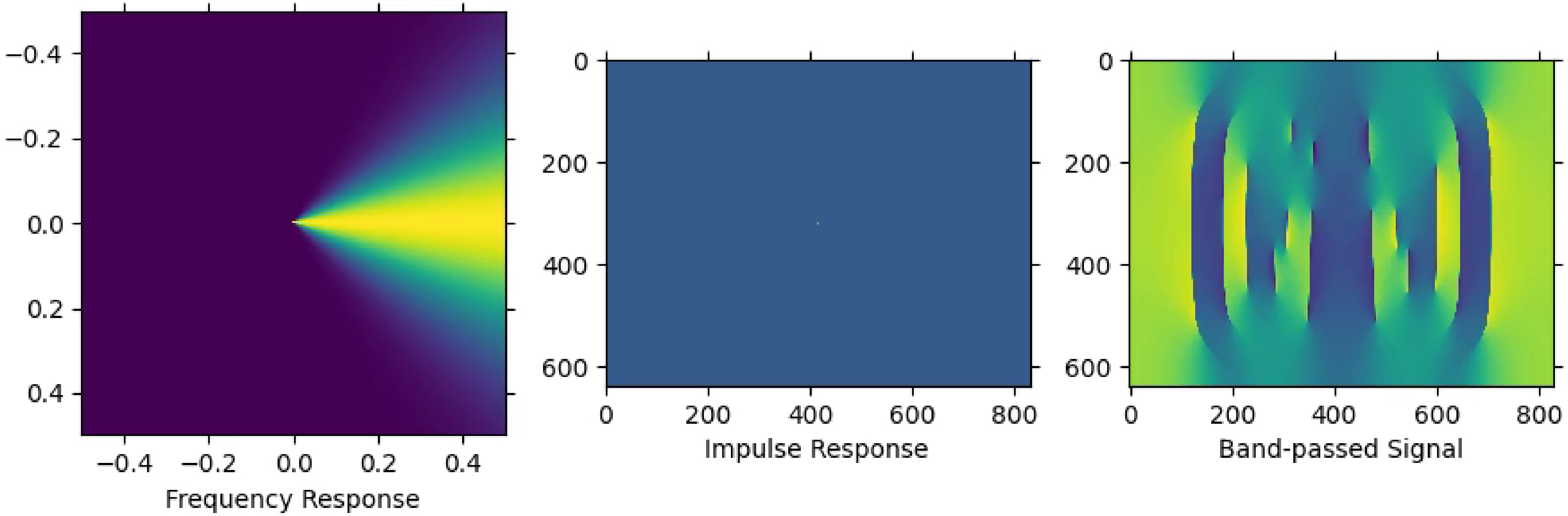
Real Filter, Symmetric about 0



Complex Filter, Only on one side of zero

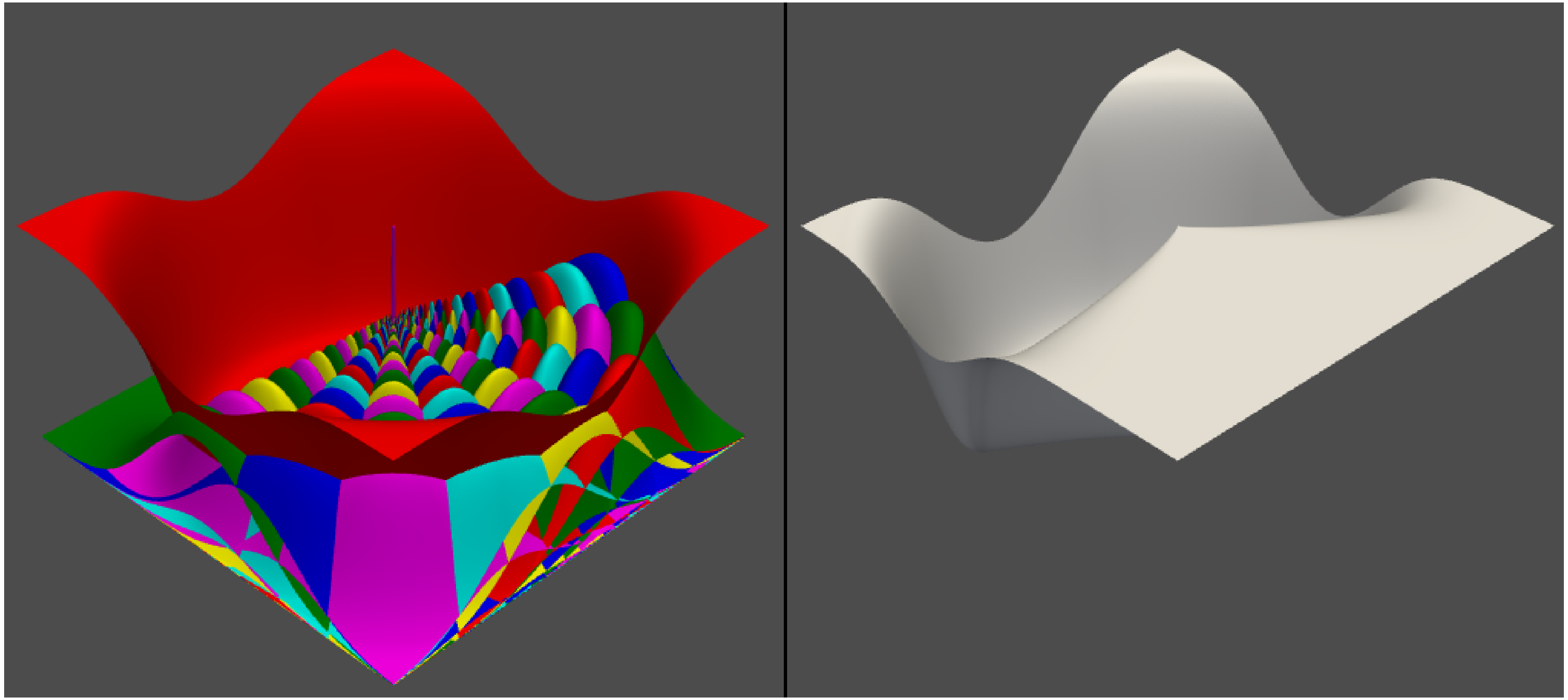


Visualizing the Orientation Filters



Combining Orientation and Frequency Filters

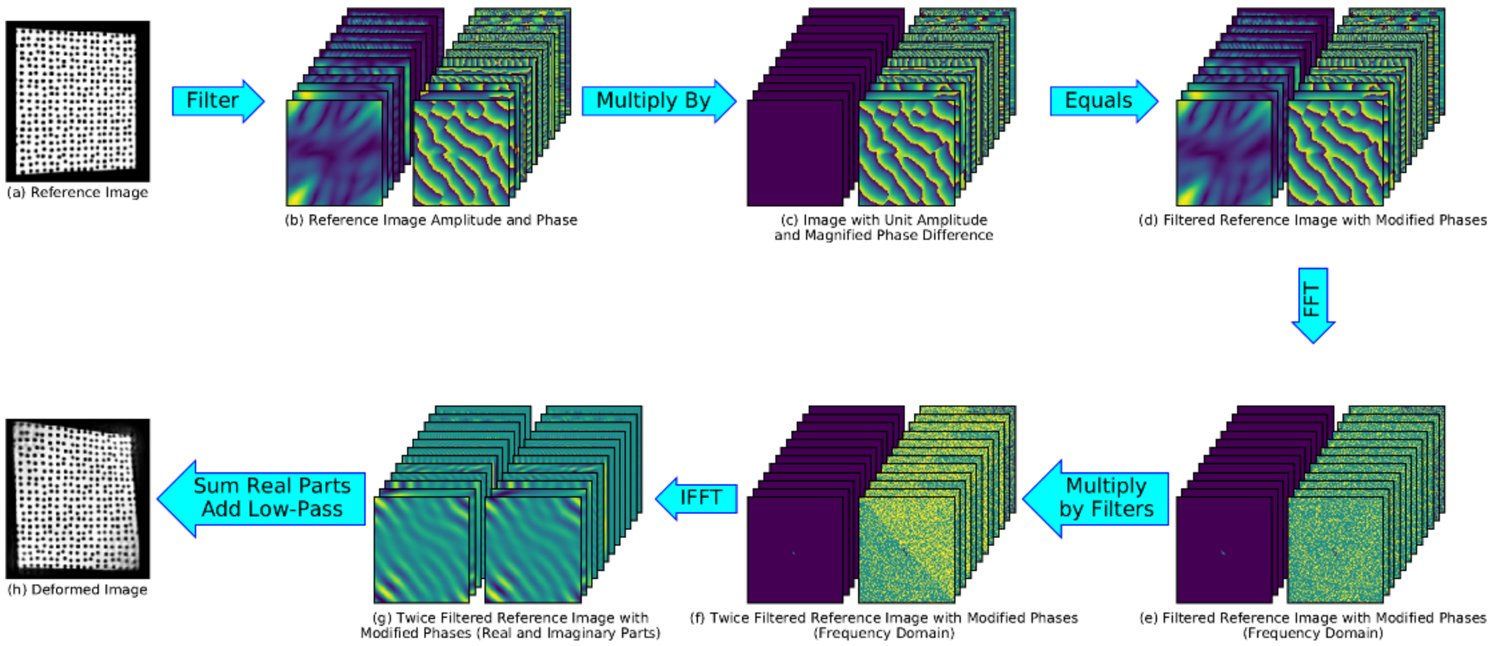
The final set of filters can be created by multiplying band-pass filters by the orientation filters for all combinations.



Performing Motion Magnification on Images

With the filter banks constructed, we can now perform motion magnification:

1. Filter reference and deformed signals with complex filter banks
2. Subtract deformed phases from reference phases (wrap from $-\pi$ to π)
3. Scale phases by an amplification factor
4. Multiply filtered reference signal by a complex number with unit amplitude and amplified phase
5. Filter signal with filters a second time (sum-squared of filter contributions equals to 1, equivalent to filtering twice).
6. Sum low-pass filtered signal with 2x each band-passed filtered signal to reconstruct the magnified images (high-pass is ignored)



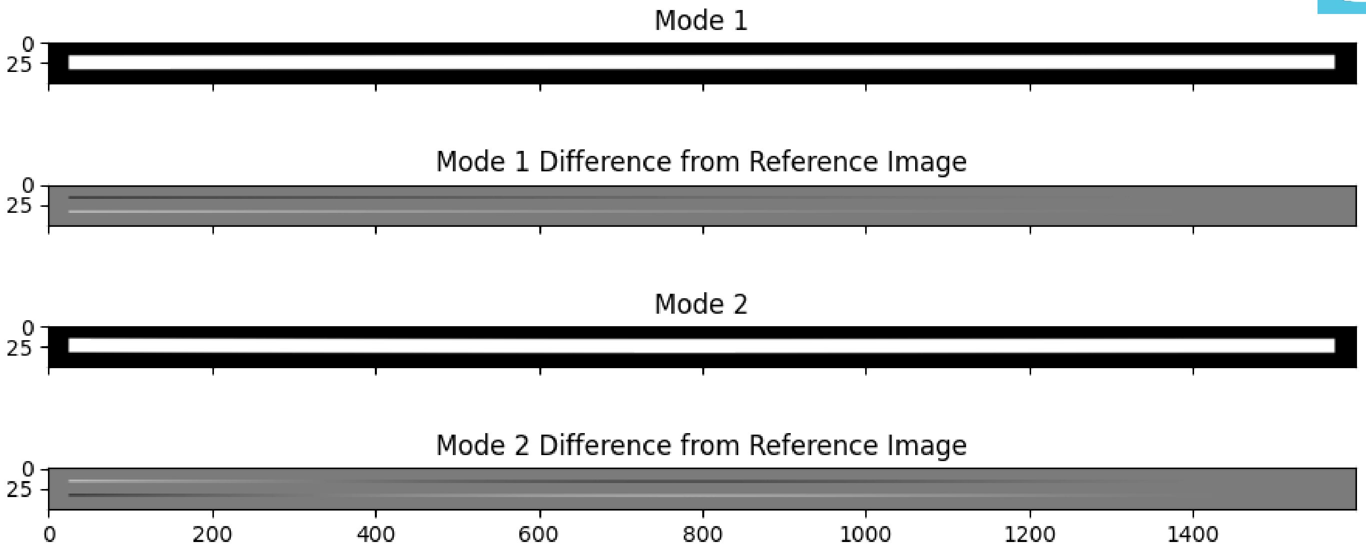
Motion Magnification Examples

Beam Example

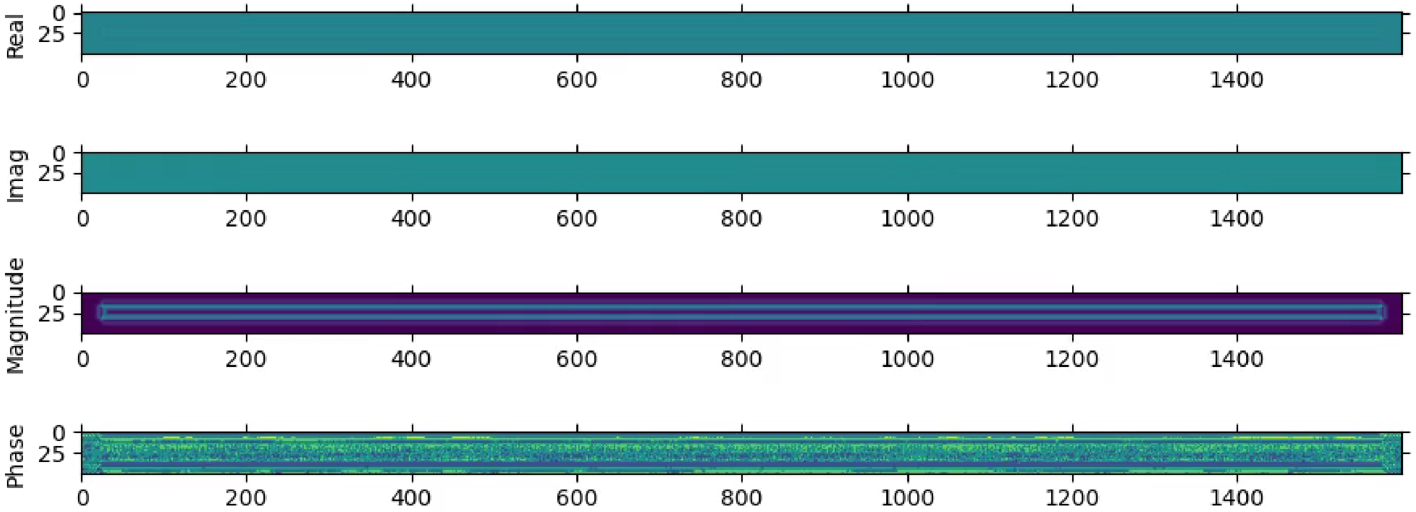
Rendered 2 mode shapes of a beam using Blender at 0.5 px peak displacement.

Motions are invisible to the naked eye.

Beam images are filtered to extract phase and subtracted from the reference images.



Beam Images



Filtered Beam Images

Magnified Beam Images

Phase quantities amplified and used to reconstruct magnified images

Note that for images with small dimensions, it can help to pad the image with zeros to make it larger, which increases the allowable filter size and therefore the allowable magnification

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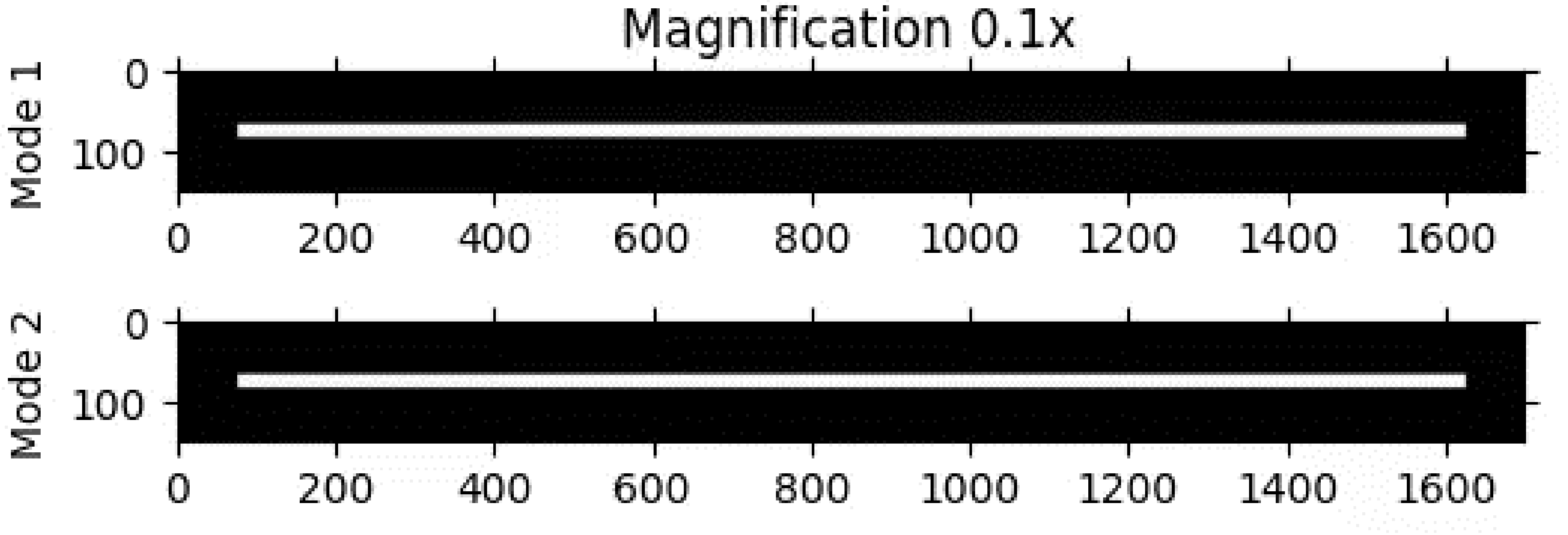


Plate Example

Rendered 2 mode shapes of a plate using Blender at 0.5 px displacements

Pixels invisible to the naked eye.

Beam images are filtered to extract phase and subtracted from the reference images.

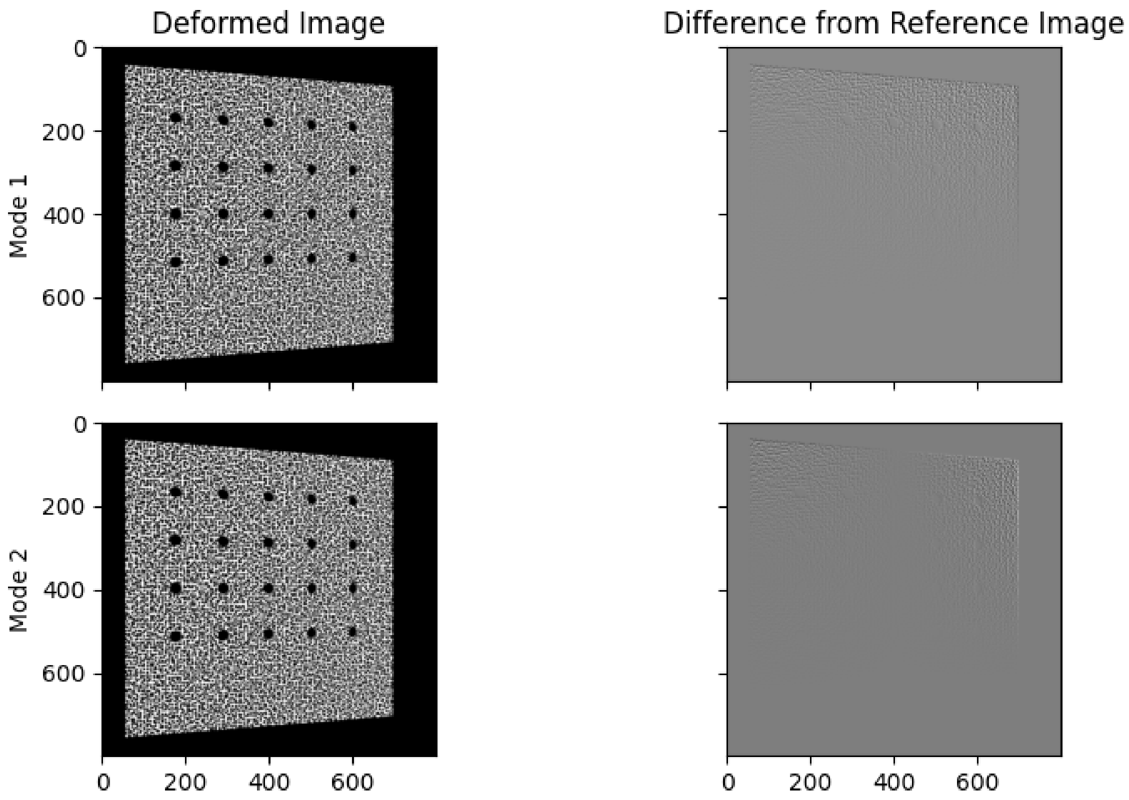
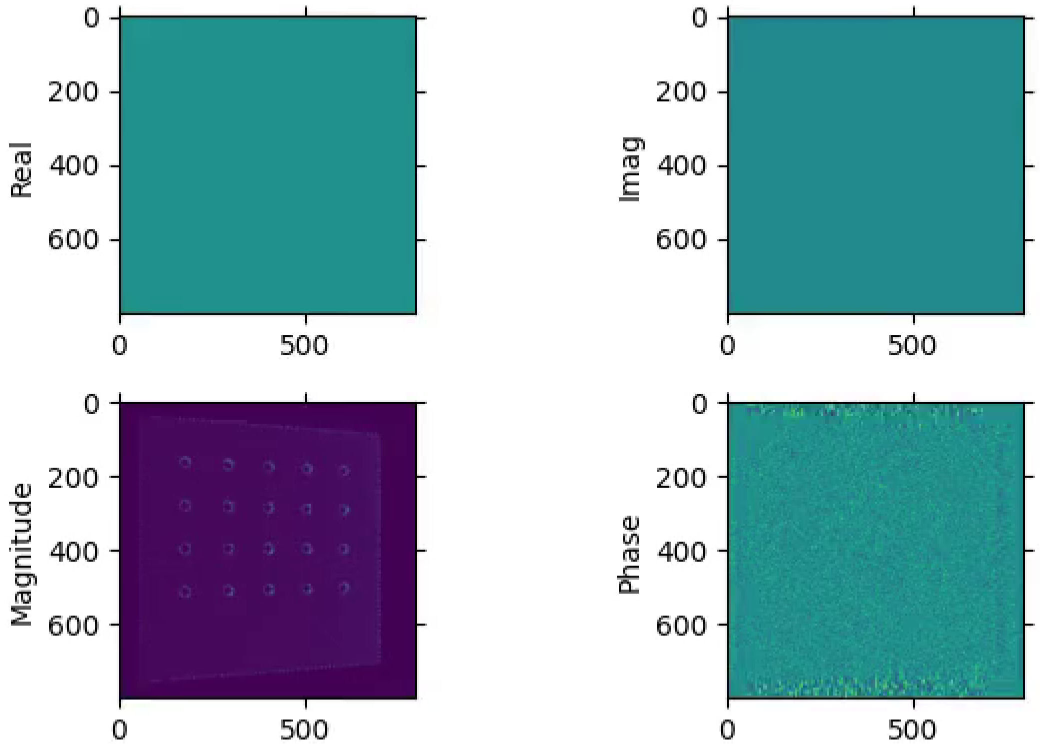


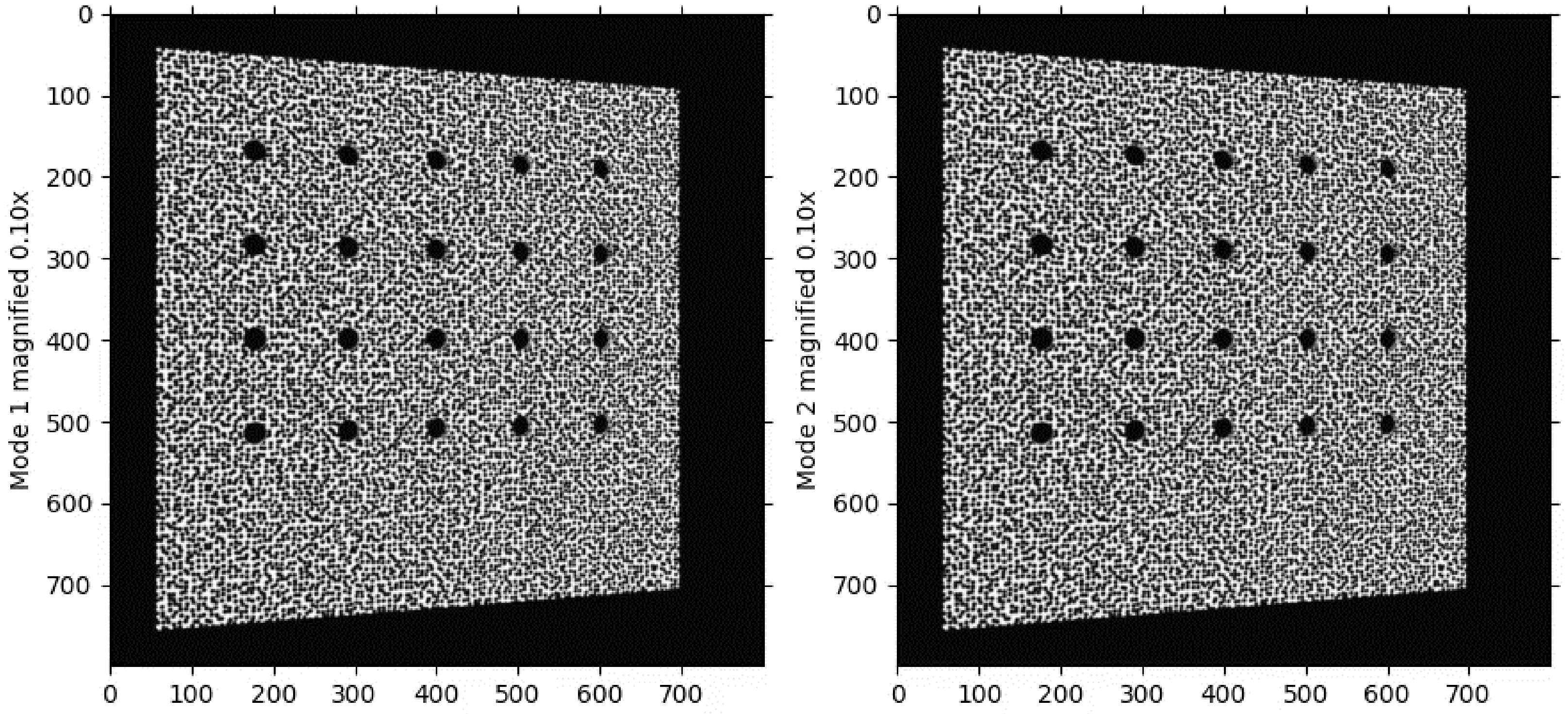
Plate Images



Filtered Plate Images

Magnified Plate Images

Phase quantities amplified and used to reconstruct magnified images



Applications for Phase-Based Motion Magnification

Gaining an Intuitive Understanding of Component Response

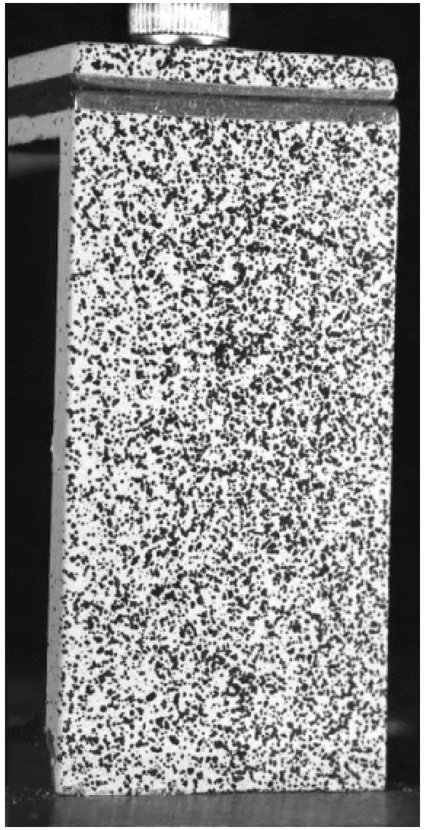
Phase-based motion processing gives an unprecedented intuitive look at the displacements occurring in a test.

Able to see motions on the real test article as they occur

No reduction in fidelity due to conversion to stick models or element models

No assumptions of part motions as occurs in finite element expansion techniques

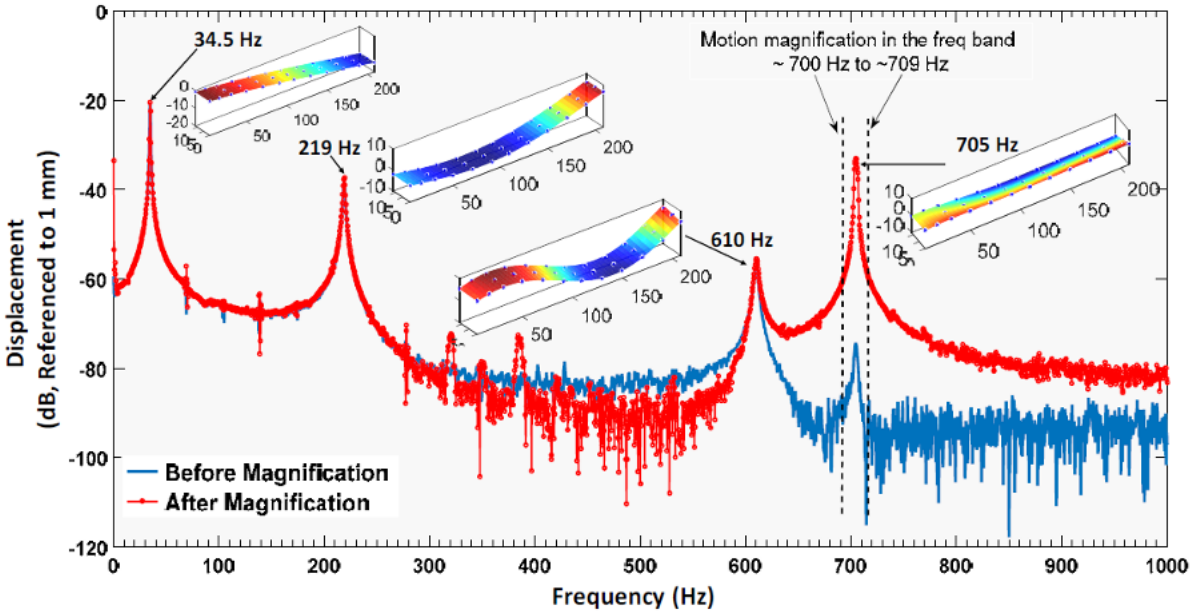
Can treat phases similarly to displacement sensors and filter specific motions



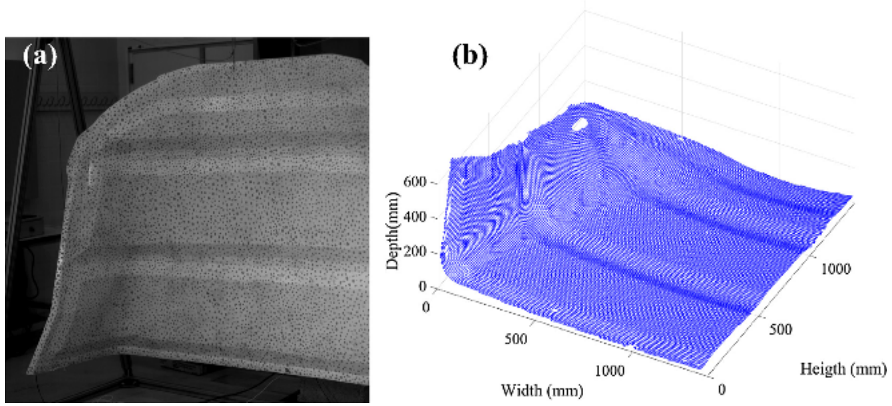
Preprocessor for Digital Image Correlation or other Photogrammetric Techniques

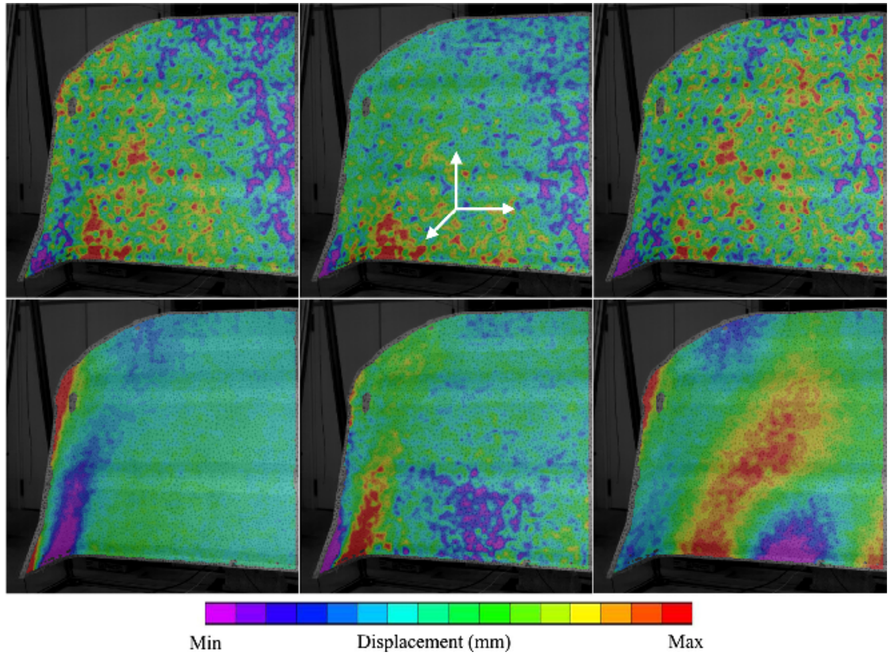
Motion Magnification has been used as a preprocessor for other optical testing strategies

- Motions magnified in images
- Magnified images passed into DIC or Photogrammetry tools.



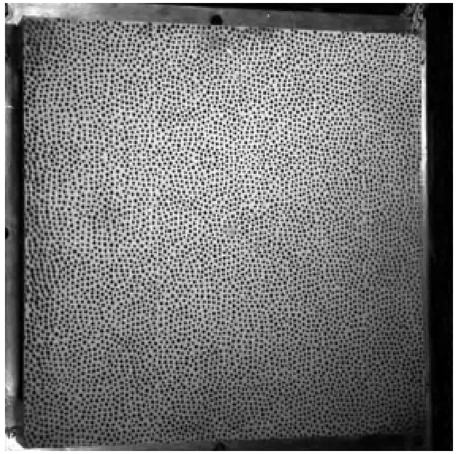
Using High Speed Stereo-Photogrammetry and Phase-Based Motion Magnification Techniques to Extract Operating Modal Data. Poozesh, et al., 2017





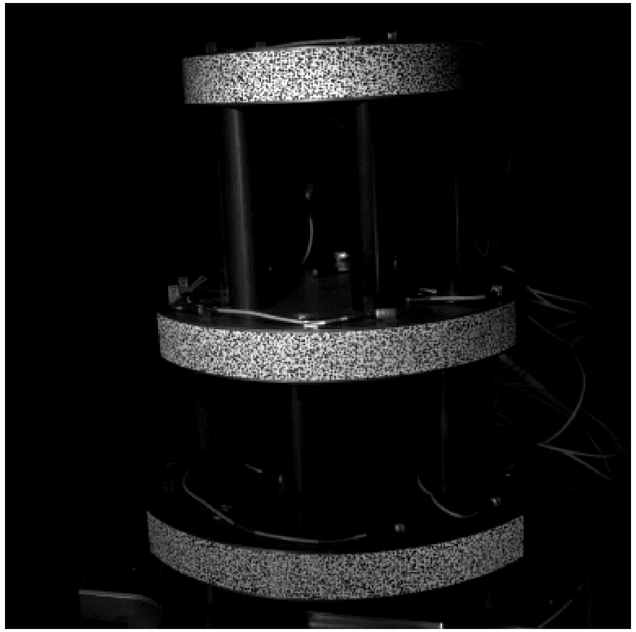
Molina-Viedma, A.; et al. 3D mode shapes characterisation using phase-based motion magnification in large structures using stereoscopic DIC *Mechanical Systems and Signal Processing*, **2018**, *108*, 140 - 155

Modal Analysis and Image-based Expansion



Phases can be treated as displacement sensors, and modes can be fit to them

- Can extract Natural Frequency and Damping from a handful of sensors
- Mode shapes in the Phase domain can be used to reconstruct mode shapes on image



Phase shapes can be used to expand environment data so environments can be visualized on-image

- Instrument field test article and send on environment → x_a
- Instrument lab test article identically and perform modal test → Φ_a
- Repeat modal test with camera viewing test article from desired angle, fit modes to phases → Φ_θ
- Expand sensor data x_a to phase-space x_θ using phase shapes $x_\theta = \Phi_\theta \Phi_a x_a$
- Reconstruct images from phase quantities using motion magnification techniques

Review

Motion Magnification Major Points

Motion Magnification can magnify subtle, imperceptible motions in a set of images so they are visible to the viewer.

Motion magnification is useful for:

- Gaining physical intuition into the motion of your part
- Preprocessing image data for quantitative analysis
- Presenting structural dynamic information to non-technical people

Motion magnification utilizes a bank of complex filters to isolate specific spatial frequencies and directions in the image

- Filters assembled from half-cosine pulses raised to an exponent
- Filters localized in both frequency and image domains
- Extent of filter in image domain denotes the distance a feature can be magnified before breakdown, but also represents the area under which motions cannot be localized
- Sharper filters in the frequency domain provide more magnification capability at larger computational requirements (more filters to span the entire frequency domain)

Phase quantities from motion magnification can be treated as displacement sensors

- Temporally Band-pass filtered to isolate specific motions
- Modes fit to phases can be used to construct on-image mode shapes
- Arbitrary displacements from environments can be visualized on image using modal superposition concepts