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Development of Large-Scale Inverse Methods in Sierra-SD

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Outline

- Inverse problems in computational mechanics
- Discussion of inverse methods in Sierra-SD
- Connections with design of materials and acoustic metamaterials

What is an Inverse Problem?

What is an Inverse Problem?

Inverse problems arise when we have partial information and indirect observations of a system and need to infer (hidden) quantities of interest of the system.

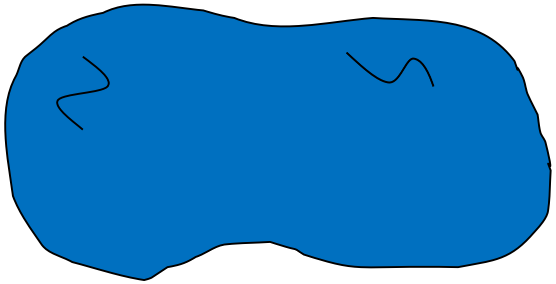
An inverse problem can be viewed as a quest for information that is not directly available from observations or measurements.

The pursuit of a solution to an inverse problem calls for a balance synergy between analysis and experimentation.

Inverse Problems: Observing the Unobservable

Suppose we have a “black box” system in the *as-manufactured* state that has only partially known parameters

Question: can we *non-destructively* interrogate the system to “see what is inside”?



Typical unknown parameters:

- Material properties
- Loads
- Boundary conditions
- Residual stresses
- Size/shape/location of inclusions (e.g. composite materials)

Example applications:

- Seismic imaging
- Medical imaging
- Non-destructive evaluation

Challenges

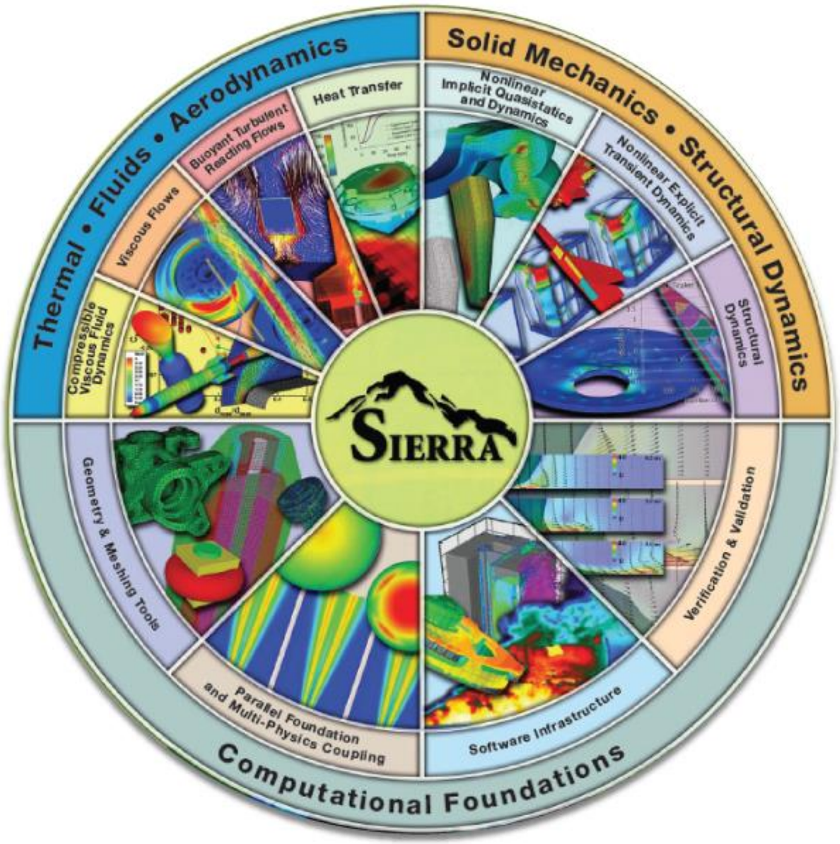
- Inverse problems can be ill-posed.
  - Solution may not exist.
  - Solution may not be unique.
  - Solution may be unstable. That is, it may be sensitive to small changes in the input data.
- Can be very computationally demanding.
- But… regularization can be used to mitigate these issues
- Or we can re-formulate the problem (different objective)

Categories of Inverse Problems

- Imaging
  - Ultrasound medical
  - seismic
- Calibration of material models
  - Structural material properties, circuits, thermal properties, etc.
- Optimal Experimental Design
  - Best placement of sensors, test fixture setups
- Shape reconstruction
  - E.g. inverse scattering
- Design of materials
  - Design material microstructure to achieve desired properties
  - E.g. Cloaking, camouflage, noise suppression, etc

Inverse Problems - Motivation

For long-term monitoring of structural systems, parallel multiphysics forward solvers (Sierra Mechanics) are not enough

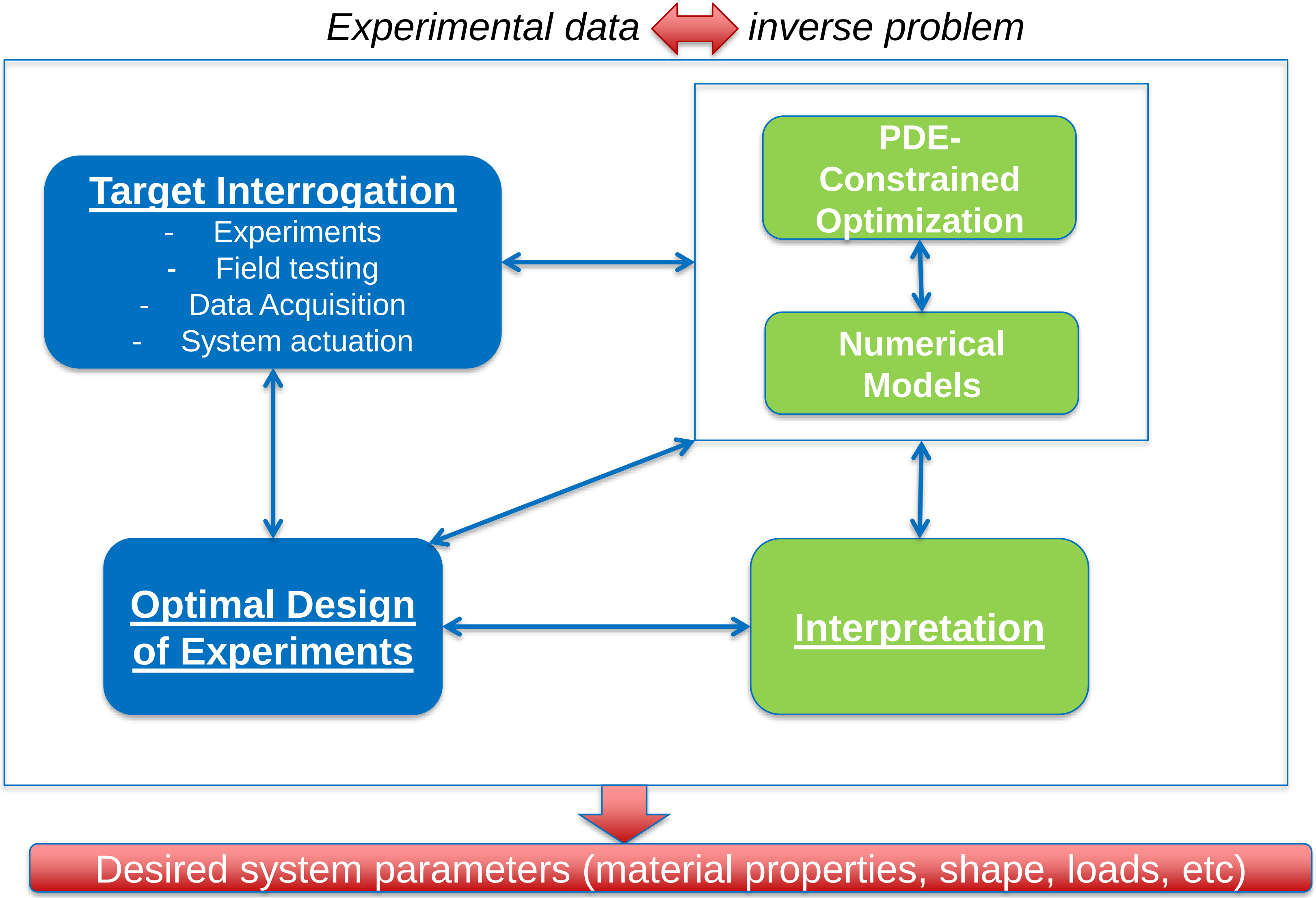


Partially known information:

- material properties?
- boundary conditions?
- loading conditions?
- Internal flaws from aging?
- Preloading effects?

The missing link:
Experimental measurements and solution of inverse problem

Inverse Problems - The Interaction of Experiments and Simulation



PDE-Constrained Optimization Formulation

Abstract optimization formulation

$$\underset{\boldsymbol{u},\boldsymbol{p}}{\text{minimize}} \quad J(\boldsymbol{u},\boldsymbol{p})$$

Objective function

$$\text{subject to} \quad \boldsymbol{g}(\boldsymbol{u},\boldsymbol{p}) = \boldsymbol{0}$$

PDE constraint

$$\mathcal{L}(\boldsymbol{u},\boldsymbol{p},\boldsymbol{w}) := J + \boldsymbol{w}^T\boldsymbol{g}$$

Lagrangian

$$\begin{Bmatrix} \mathcal{L}_u \\ \mathcal{L}_p \\ \mathcal{L}_w \end{Bmatrix} = \begin{Bmatrix} J_u + \boldsymbol{g}_u^T\boldsymbol{w} \\ J_p + \boldsymbol{g}_p^T\boldsymbol{w} \\ \boldsymbol{g} \end{Bmatrix} = \{0\}$$

First order optimality conditions

$$\begin{bmatrix} \mathcal{L}_{uu} & \mathcal{L}_{up} & \boldsymbol{g}_u^T \\ \mathcal{L}_{pu} & \mathcal{L}_{pp} & \boldsymbol{g}_p^T \\ \boldsymbol{g}_u & \boldsymbol{g}_p & 0 \end{bmatrix} \begin{Bmatrix} \delta\boldsymbol{u} \\ \delta\boldsymbol{p} \\ \boldsymbol{w}^\star \end{Bmatrix} = - \begin{Bmatrix} J_u \\ J_p \\ \boldsymbol{g} \end{Bmatrix}$$

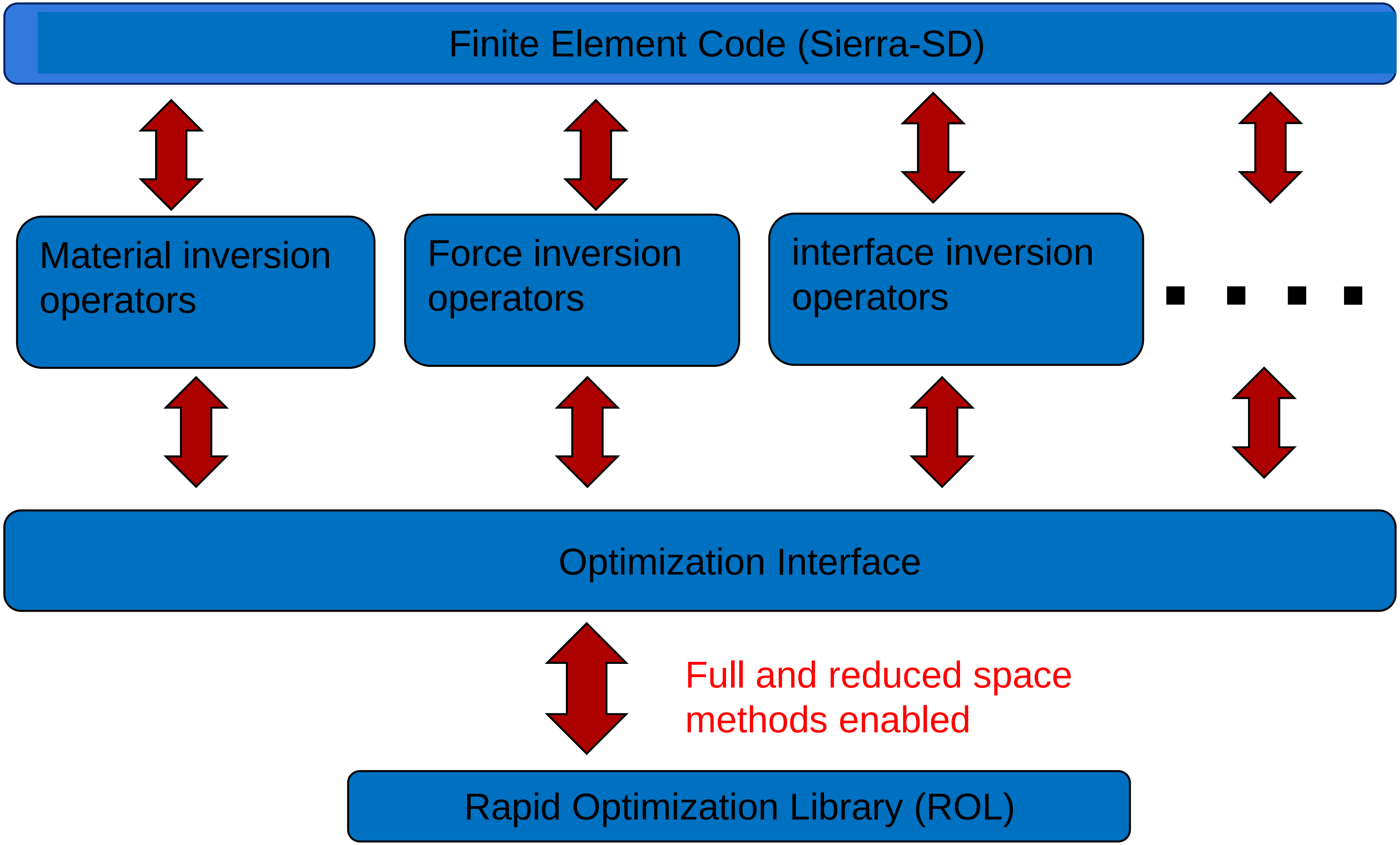
Newton iteration

$$\boldsymbol{W}\Delta\boldsymbol{p} = -\hat{J}',$$

$$\boldsymbol{W} = \boldsymbol{g}_p^T\boldsymbol{g}_u^{-T}(\mathcal{L}_{uu}\boldsymbol{g}_u^{-1}\boldsymbol{g}_p - \mathcal{L}_{up}) - \mathcal{L}_{pu}\boldsymbol{g}_u^{-1}\boldsymbol{g}_p + \mathcal{L}_{pp}$$

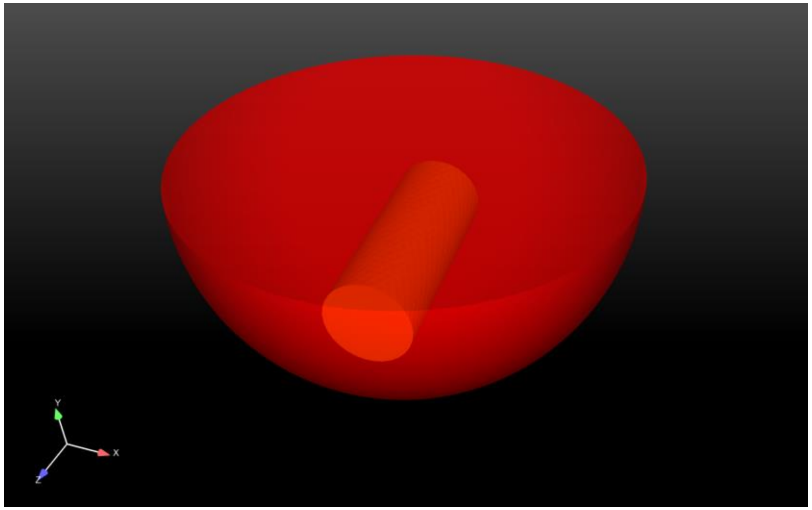
Hessian calculation

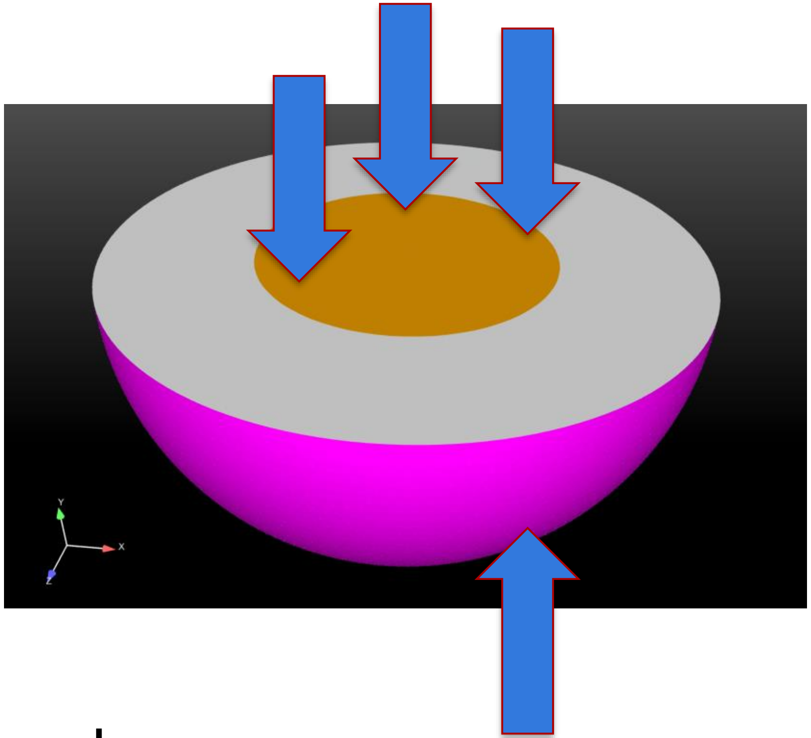
Operator-Based Inverse Problems



Buried Tunnel Model – MECE vs Least Squares Objectives

Buried inclusion model

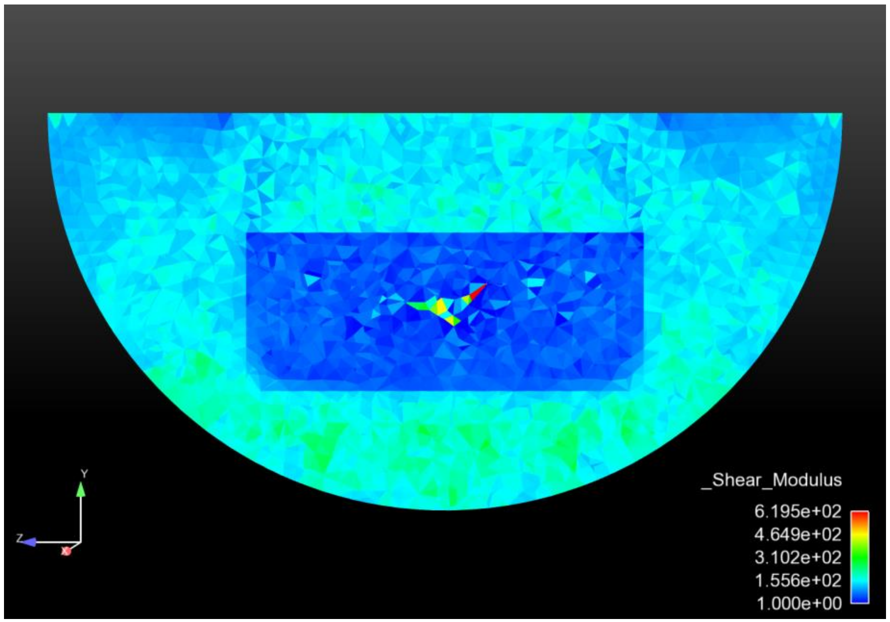




Goal: locate buried inclusion and surrounding material properties

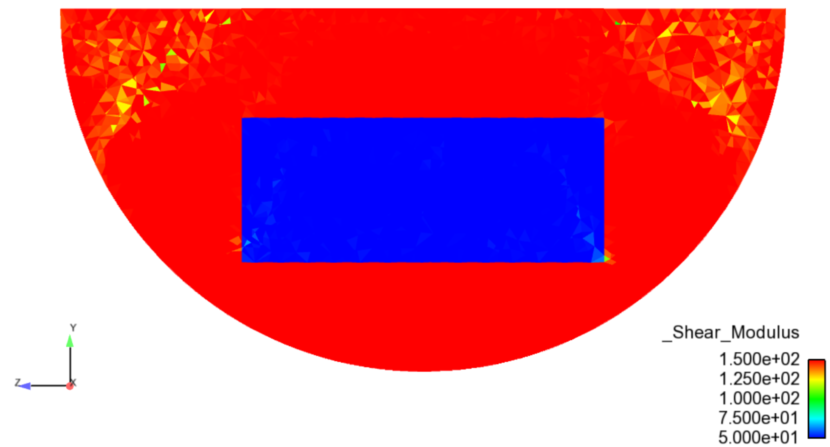
Shear Modulus – MECE vs Least Squares Objectives

Least Squares



1000 iterations

MECE



30 iterations

Exact bulk moduli: 50 (matrix), 150 (inclusion)

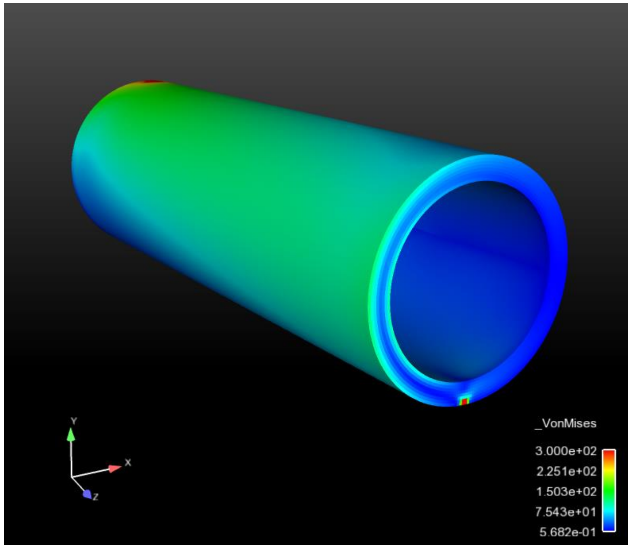
Residual Stress Inversion

Equilibrium constraint: $\nabla \cdot \sigma = 0$

Approach: source inversion for tractions on cut-plane

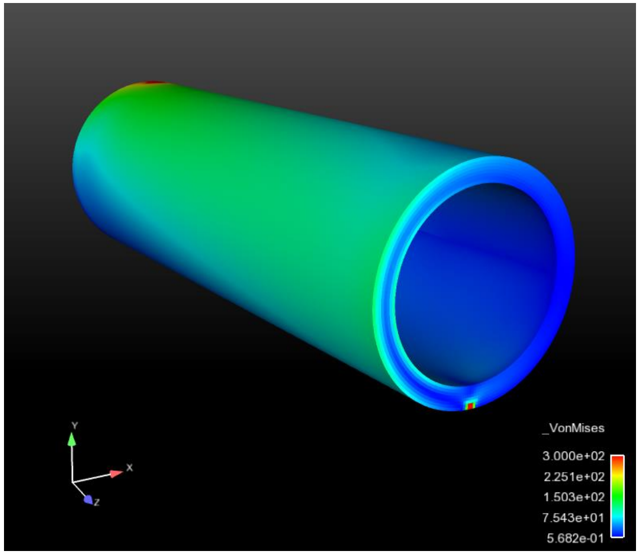
Prestressed Tube Example

Exact stress field (from forward solution)



Stress concentrated around fixed points

Stress field from inverted tractions

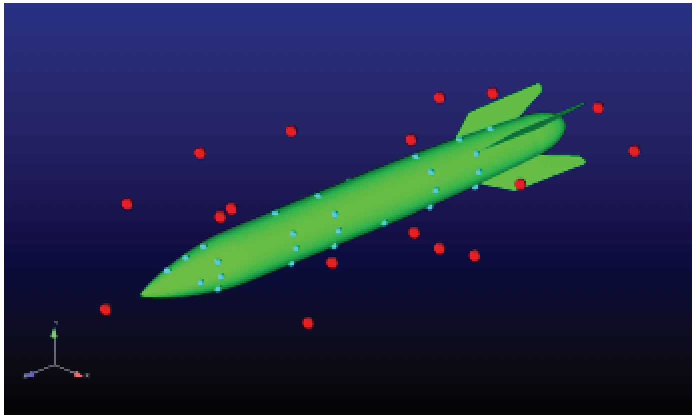


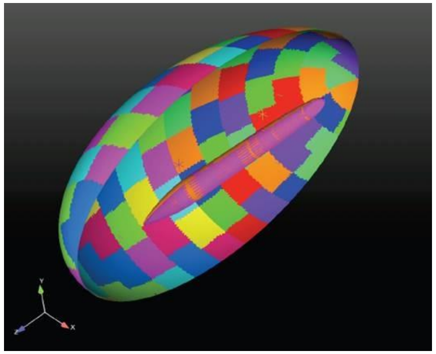
Inverted stresses

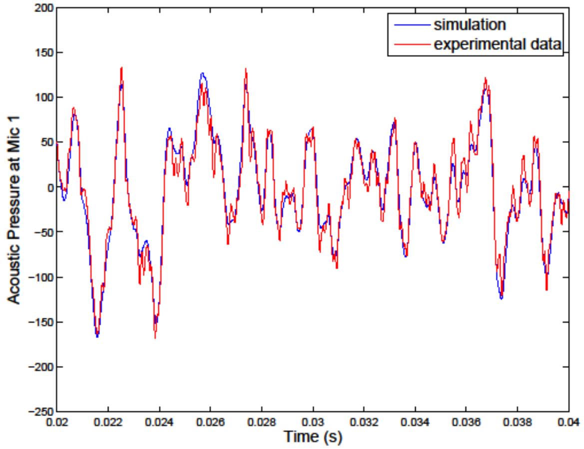
*Joint work with Joe Bishop (1554)

Source Inversion in Sierra-SD

- Goal: reconstruct acoustic field using inverse problem to obtain acoustic patch inputs that produce the given microphone measurements





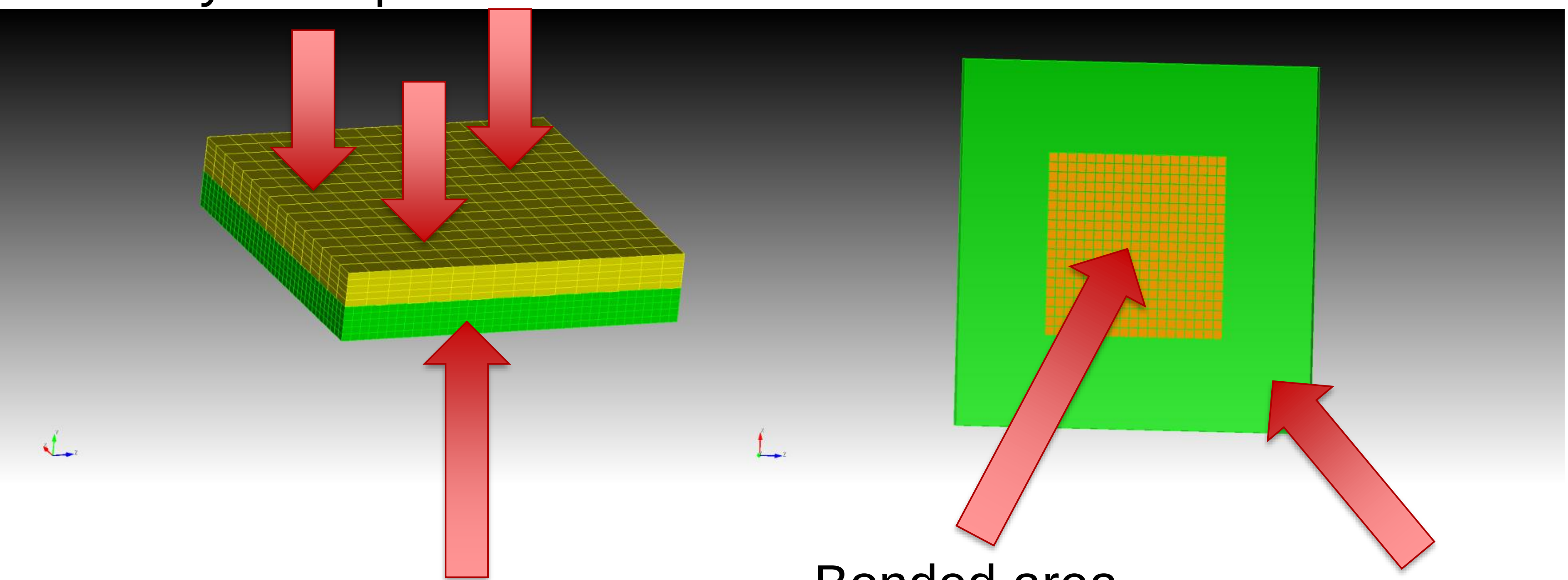


- Additional research on-going
- How to regularize the inverse problem – gradient regularization (penalize jumps across neighboring patches)
- How to place microphones

Delamination Detection

Partially-bonded plates – can we invert for the bonded/debonded regions?

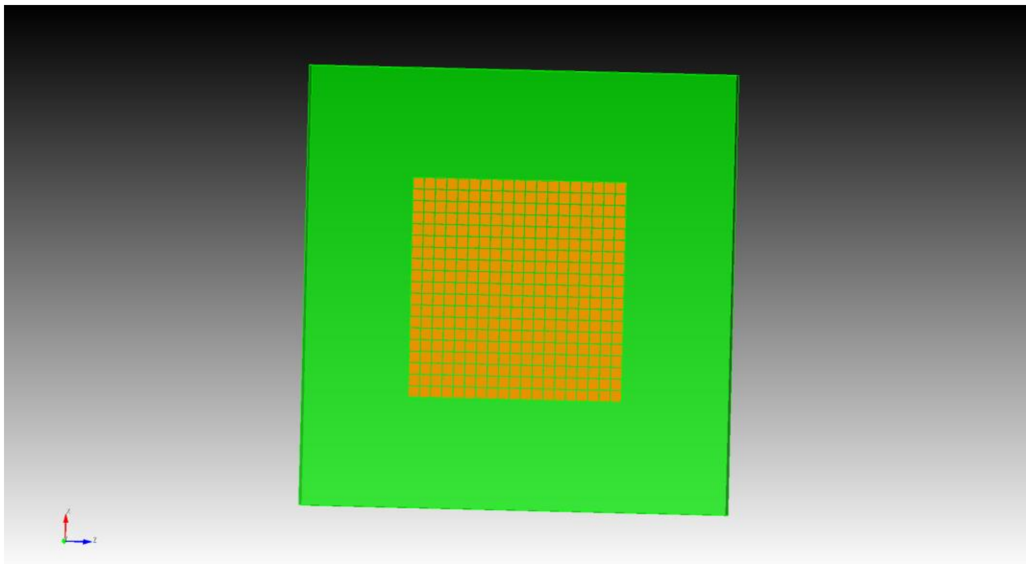
Steady-state pressure load at 2000Hz

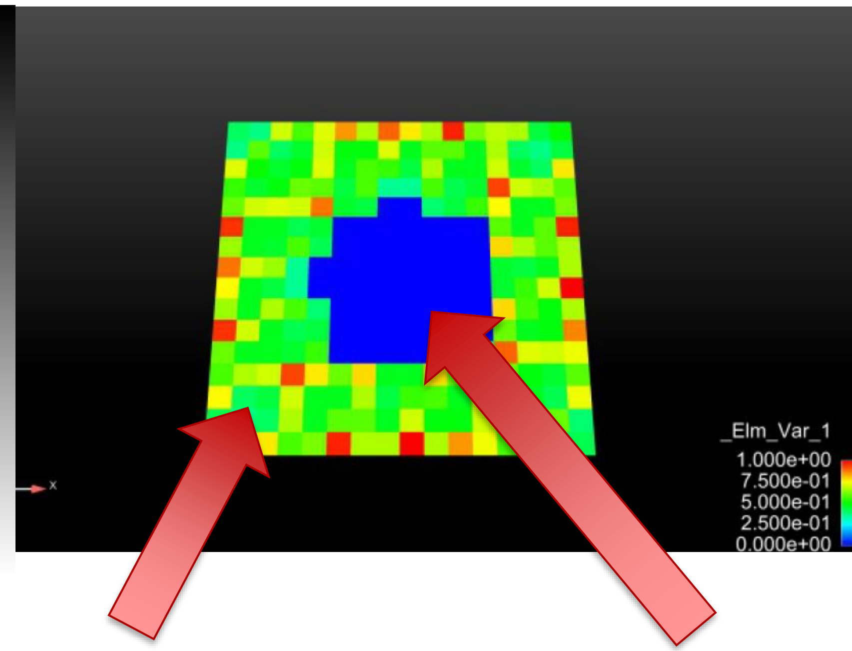


Delamination Example

Partially-bonded plates – can we invert for the bonded/debonded regions?

Exact bonded/de-bonded areas





Initial guess for optimization: Completely de-bonded

Bonded area (penalty=1)

De-bonded Area (penalty=0)

A Revolution in Acoustic Metamaterials

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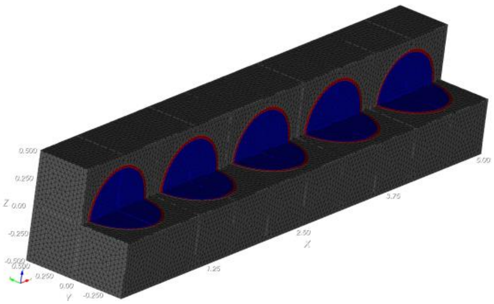
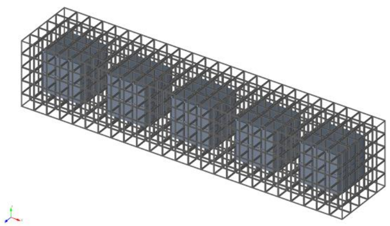
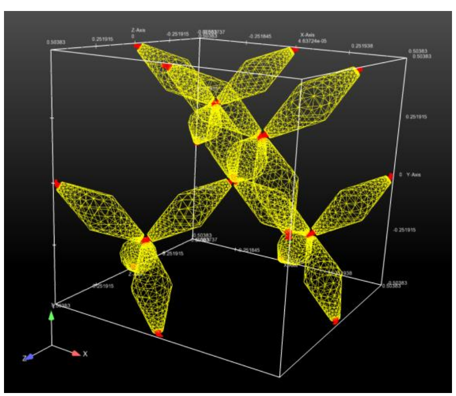
Breakthrough technology could allow us to mitigate harsh vibration environments



Multiphase composite



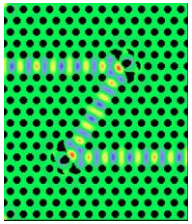
Lattice with embedded masses

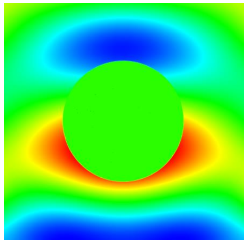


Pentamode lattice

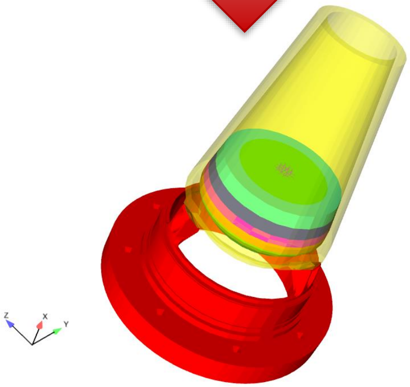
Transformative technology

Re-directed load paths





cloaking



Vibration isolation

Vibration Control with Acoustic Metamaterials

Problem: Harsh vibration environments pose serious threat to sensitive components in structural systems.

Challenge:

- Existing damping materials only provide limited vibration protection and cannot re-direct energy

As a Result:

- Sensitive components are exposed to potentially damaging vibration profiles.
  - Electronics packages, accelerometers, etc

Proposal: Large-scale optimization and multi-material additive manufacturing to design acoustic metamaterials for vibration control.

What is an acoustic metamaterial

- Acoustic metamaterials: Multiphase composite materials designed to produce dynamic material properties not found in individual materials themselves
  - Negative moduli, negative density, negative refractive index, imaginary speed of sound!!! (not possible in traditional composite materials)
- First demonstrated in 2000 by Liu et al, *Science*

Mechanical Filter Design

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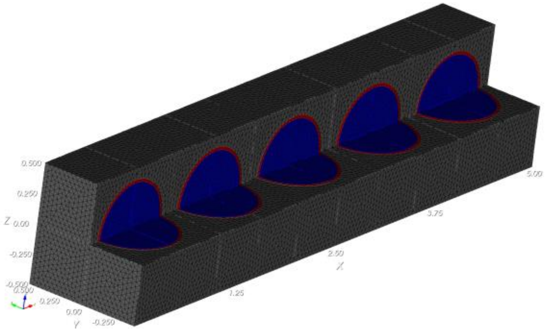
Uniqueness of metamaterials – allow for frequency-selective designs!

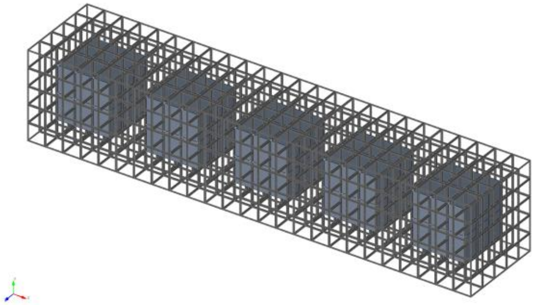
- Broadband – goal is to eliminate vibration in wide (or entire) frequency band - foam pads work well for this
- Band-stop – negative stiffness or negative density
- Band-pass – negative stiffness AND negative density (see paper on sharepoint)
- Notch – only filter at one particular frequency

Candidate Metamaterial Designs

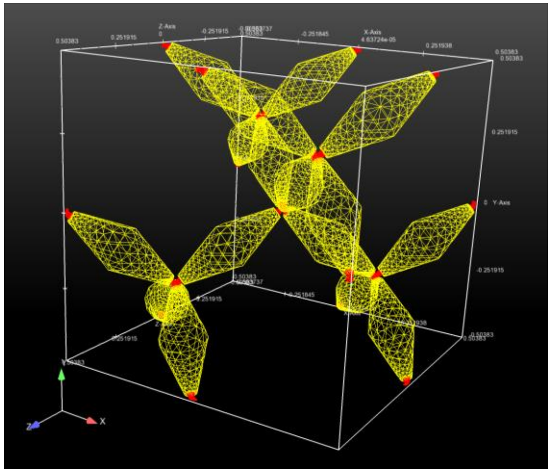
Finite element models have been developed and analysis is on-going for 3 classes of metamaterial designs. In all cases, local resonating elements are embedded in a host material.



Multiphase composite



Lattice with embedded masses



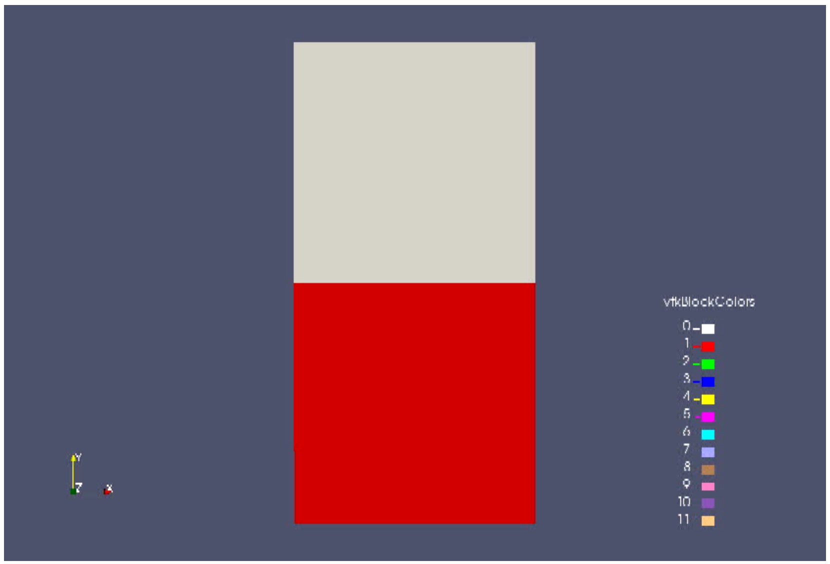
Pentamode lattice

Inverse homogenization – to achieve spatially distributed material properties

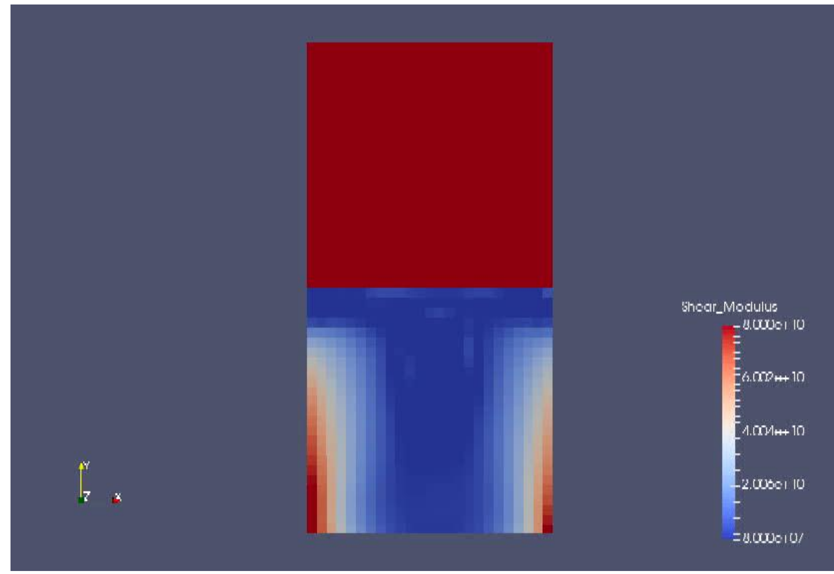
Transient Shock Isolation

Goal: design the bottom material such that the top block does not move

Initial guess



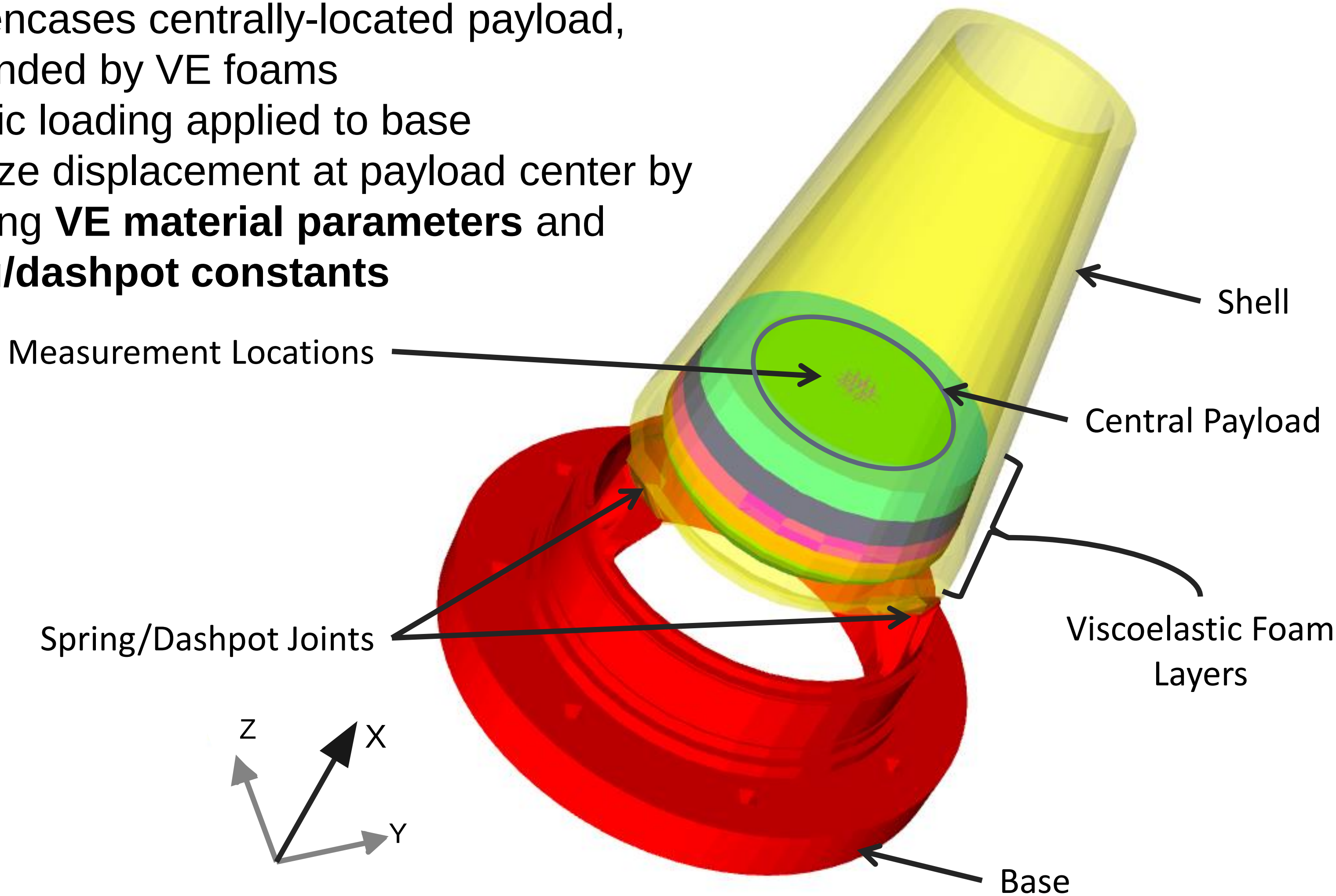
optimized



Top block: steel
Bottom block: single phase fixed, two-phase, multi-phase

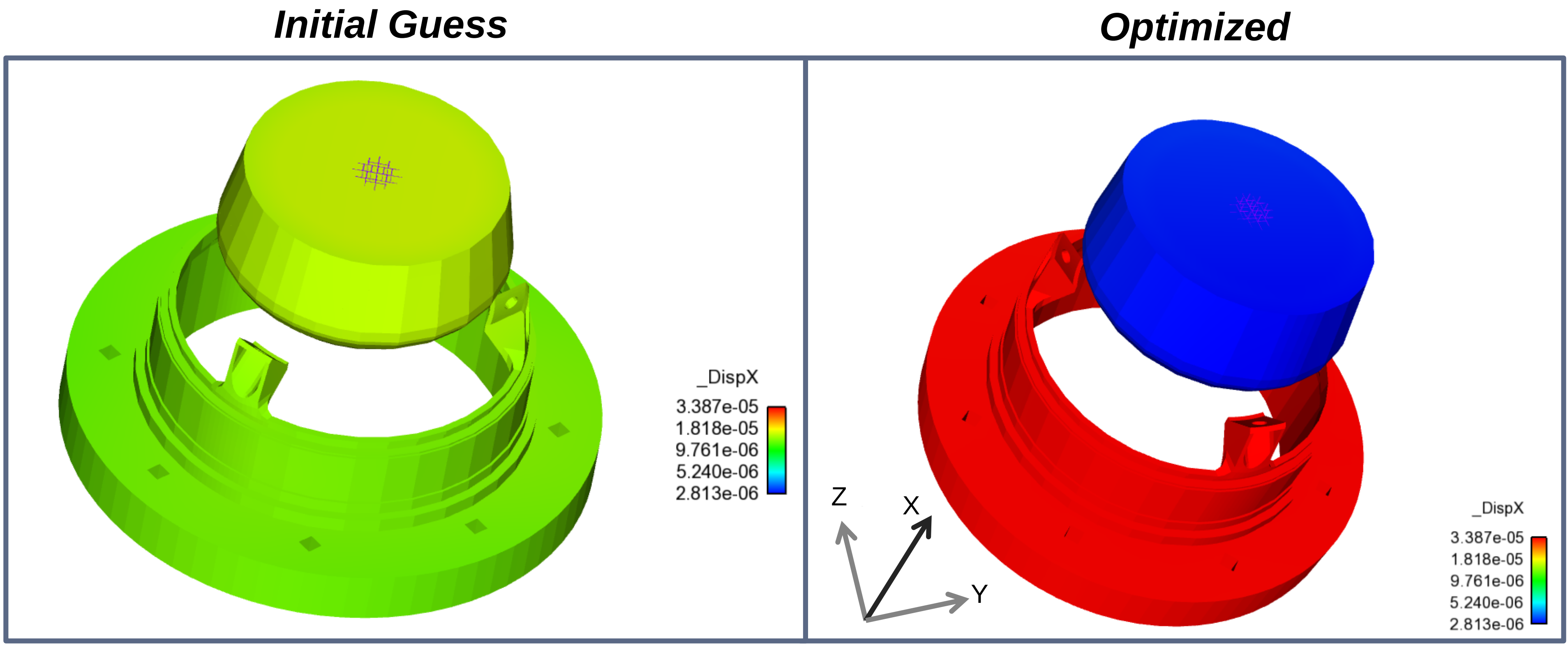
Inverse Problems: *Mechanical Vibration Reduction*

- Shell encases centrally-located payload, surrounded by VE foams
- Periodic loading applied to base
- Minimize displacement at payload center by adjusting **VE material parameters** and **spring/dashpot constants**



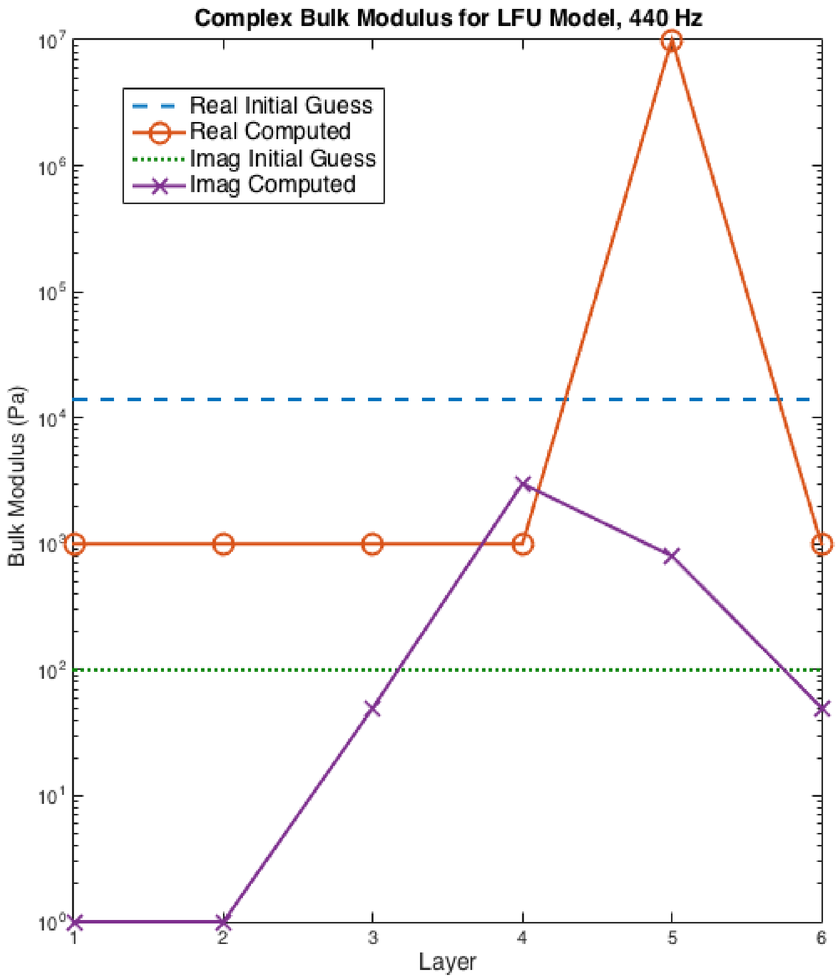
Case Study 1: *Mechanical Vibration Reduction*

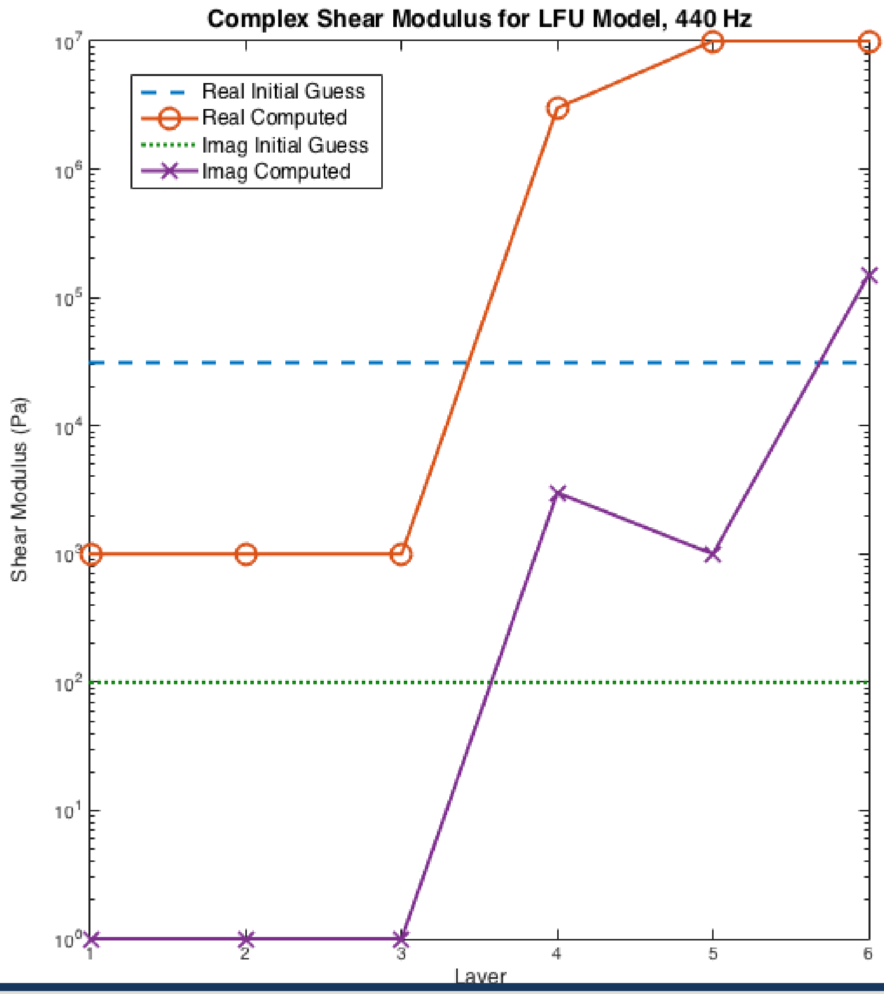
- Displacement at measurement locations minimized (dependent on frequency)



Left: X-displacement in base and payload with initial material guesses, 440 Hz loading;
Right: X-displacement in design

Case Study 1: *Mechanical Vibration Reduction*



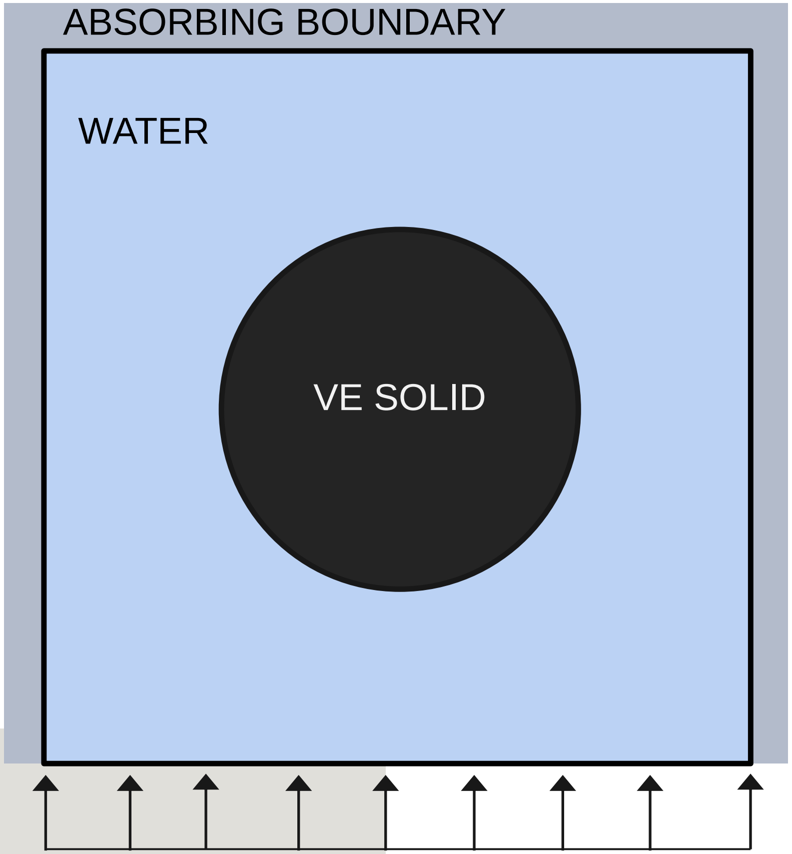


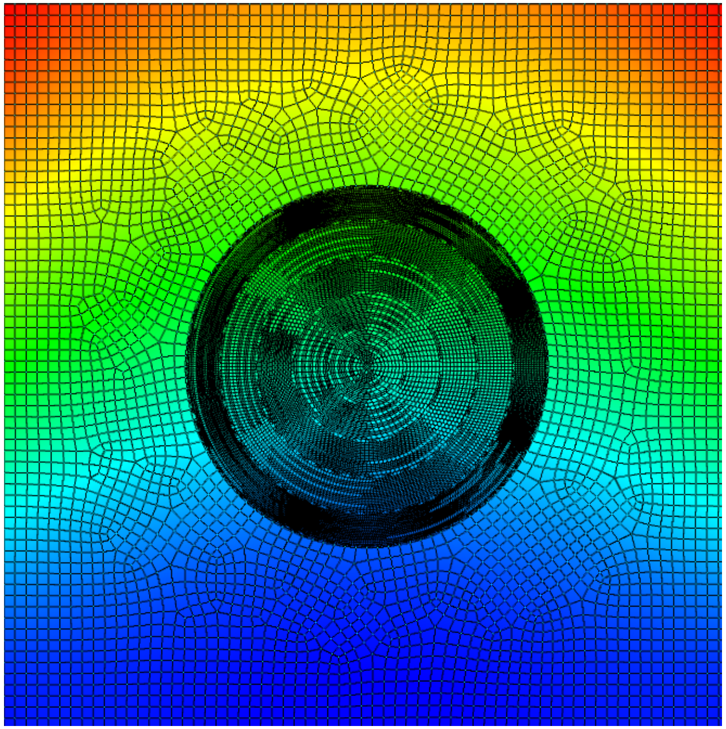
OBSERVATIONS:

- Elastic Properties: Soft materials selected towards top, stiffer materials near base
- Viscous Properties: Damping is added towards base of viscoelastic region

Inverse Problems: *Acoustic Cloaking*

- 2-D fluid region with circular VE solid inclusion
- Inclusion consists of concentric rings w/ distinct material properties
- Periodic acoustic load applied to end
- Match forward problem pressure distribution by adjusting **VE material parameters**

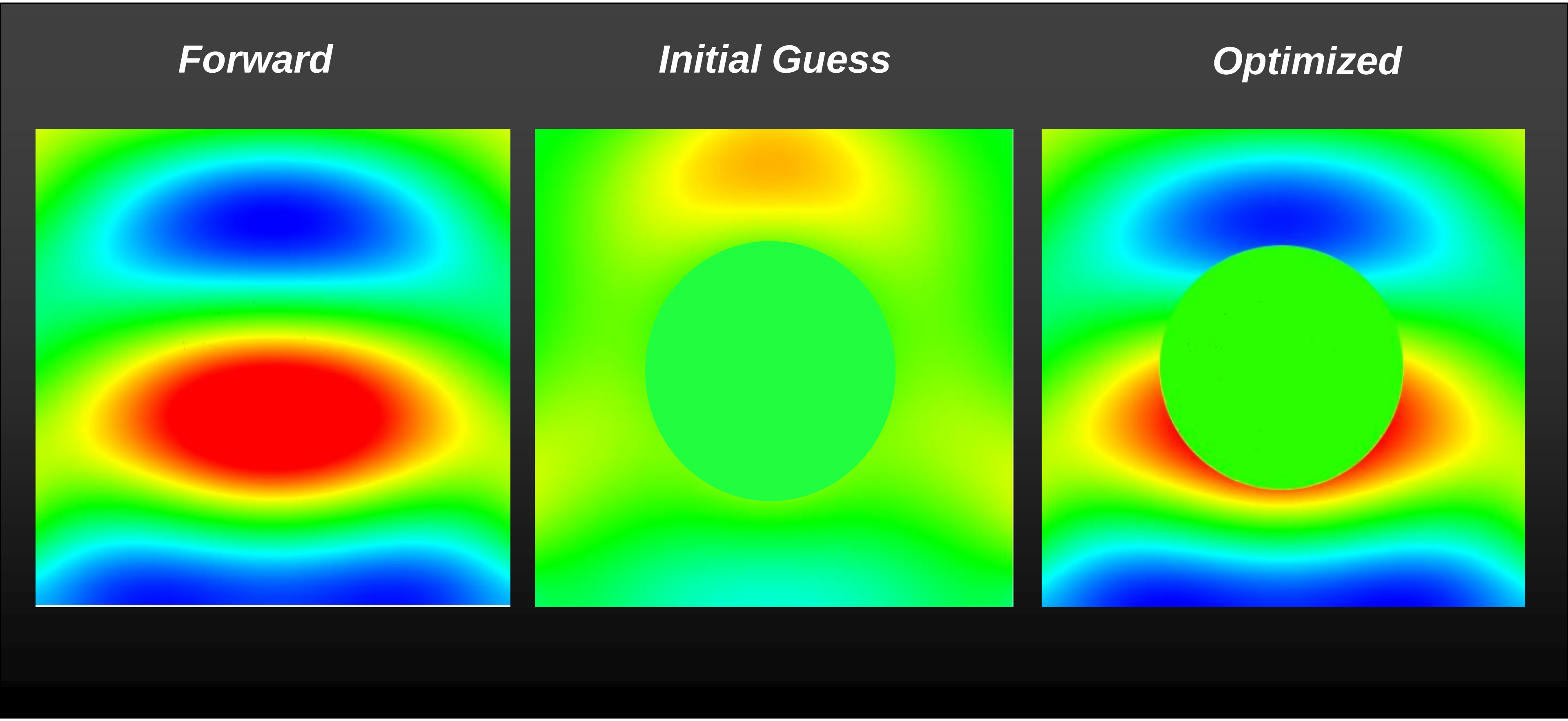




Left: Model Set up
Right: Forward problem pressure distribution (500 Hz loading) in model with 50 layers

Acoustic Cloaking

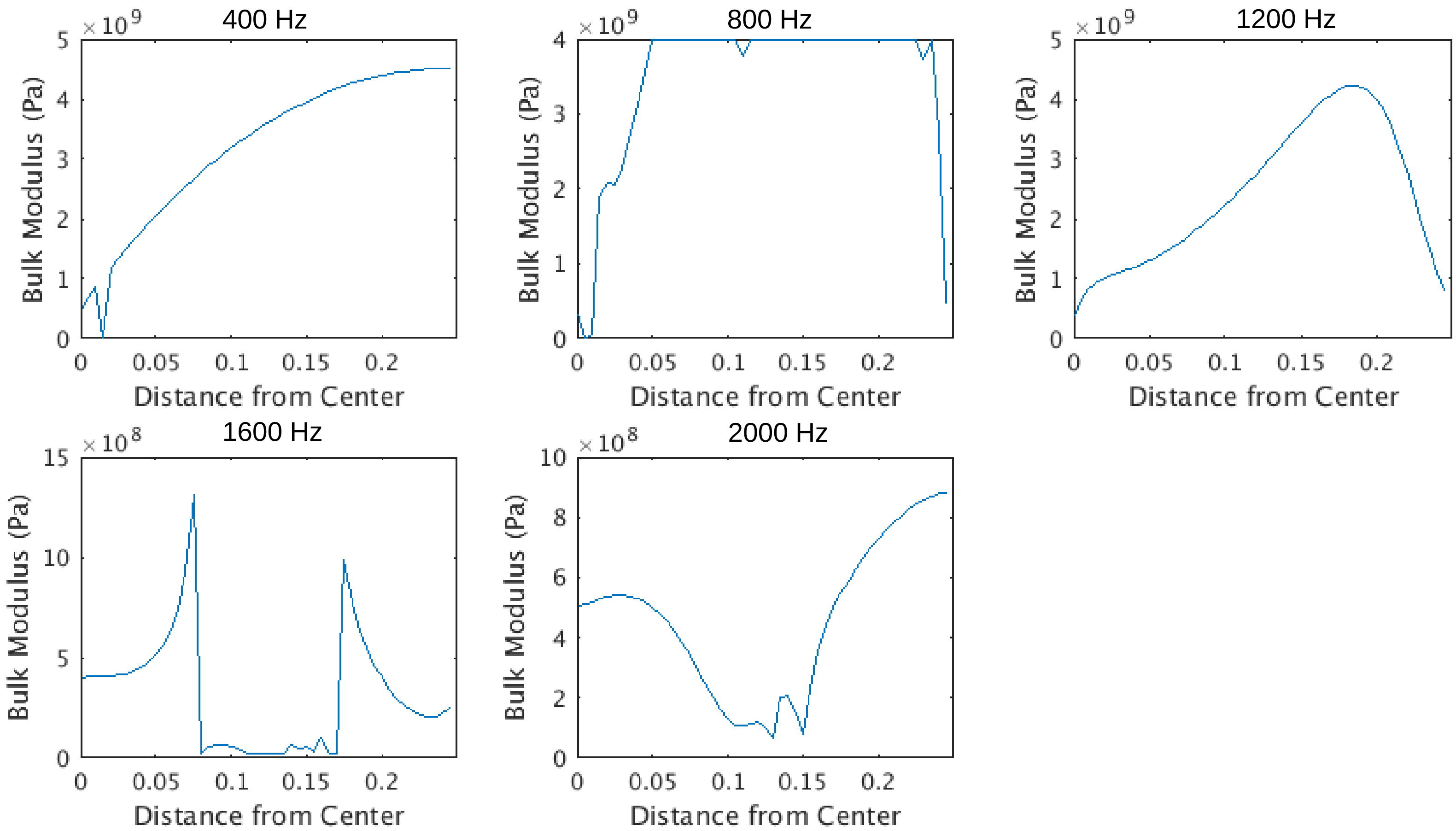
- Optimized VE foams allow recovery of desired pressure distribution



Left: Target acoustic pressure distribution, from forward problem
Center: Acoustic pressure distribution with initial material guess (2000 Hz Loading)
Right: Pressure distribution after convergence to optimized design

Acoustic Cloaking Results: Bulk Modulus

Bulk modulus sensitive to frequency, and varies nontrivially along disk radius



Figures: Real component of bulk modulus along radius, for various frequency