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Massively parallel vibration and structural acoustic analysis with SALINAS

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Outline

- Overview of SALINAS
  - History
  - current capabilities
- Vibration analysis capabilities
- Acoustic and structural acoustic capabilities
- Example applications

History

• MP eigensolver LDRD in	1997	
• ASCI funded project		1998
• Beta release		11/1999
• first ASCI milestone		5/2000
• ASCI hostile milestone	12/2001	
• formal release	1.0	11/2002
• Sierra coupling		9/2004
• release	2.1	6/2005
• release	2.2	10/2005
• release	2.3	4/06
• release	2.4	10/06

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Solution Methods

- Eigen
- Complex Eigen
- linear and nonlinear transient dynamics
- linear and nonlinear statics
- direct frequency response
- Random vibration analysis
- modal based solutions for transient dynamics, SRS, frequency response.
- coupled structures (from presto or adagio)
- TSR

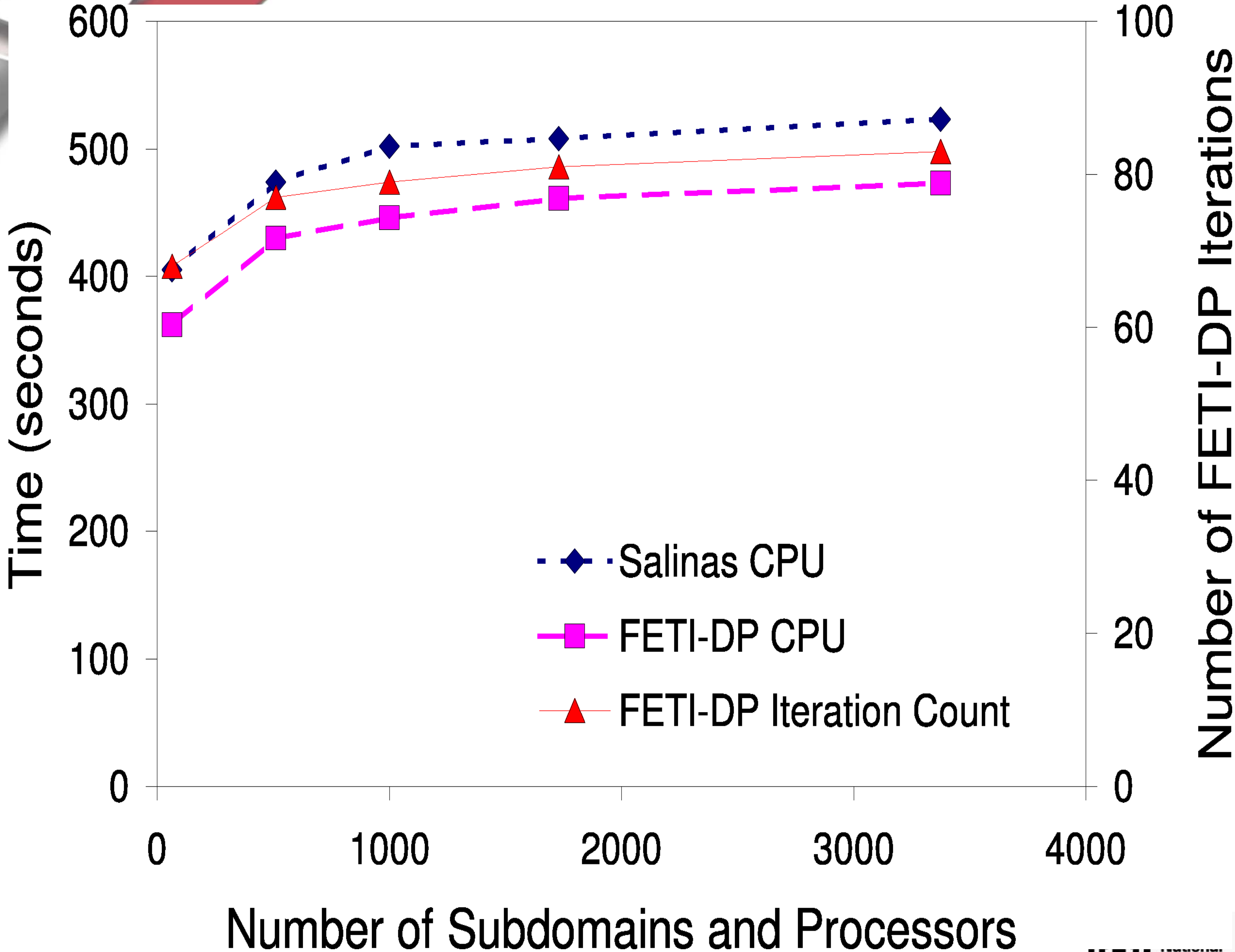
Element Library

- Solid Elements
  - Hex8, Hex20, Tet4, Tet10, Wedge6, Wedge15
  - Hex8 variations
- Shell Elements
  - Tria3, Quad4, (Tria6, Quad8 – not really quadratic)
- Bar/Beam Elements
  - Beam2, Truss, Spring, Dashpot
- Point Elements
  - conmass
- Specialty Elements
  - Iwan, Hys, Shys, Joint2G, Gap

Scalability

- **Solution of an *N* times bigger problem, on *N* times the processors takes about the same amount of time.**

- No change of time step required.
- No change of iteration count.
- No change of start/stop time for the solution.

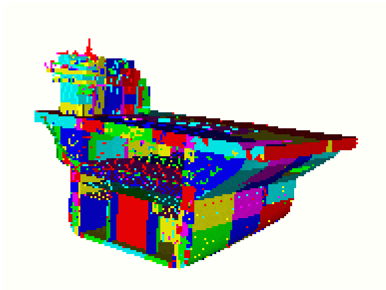


Time (seconds)
Number of FETI-DP Iterations
Number of Subdomains and Processors
Salinas CPU
FETI-DP CPU
FETI-DP Iteration Count
0
100
200
300
400
500
600
0
20
40
60
80
100
0
1000
2000
3000
4000

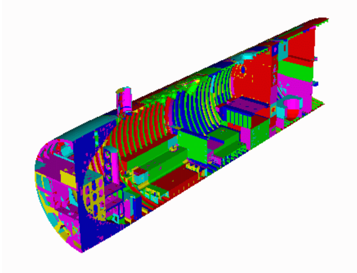
Example Calculations

Description	*DOF*	*NP*	*# solves*	*Time*	*Mach*
Design AF&F	0.5M	256	*40*	*12 min*	*intel*
Screen eigen	1.5M	512	*40*	*12 min*	*intel*
Large RV eigen	1.0M	512	*120*	*8.5 hrs*	*intel*
Milepost Model 5	11M	1980	*200*	*22 hrs*	*intel*
Milepost Model 4	3.5M	2027	*600*	*24 hrs*	*intel*
Brick/Beam	>100M	3375	*1*	*8 min*	*ibm*
MEMS	110M	3375	*1*	*7 min*	*ibm*

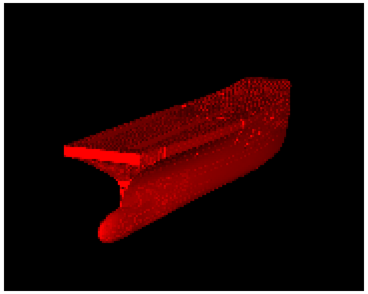
Structural Applications



Sections of the Carrier



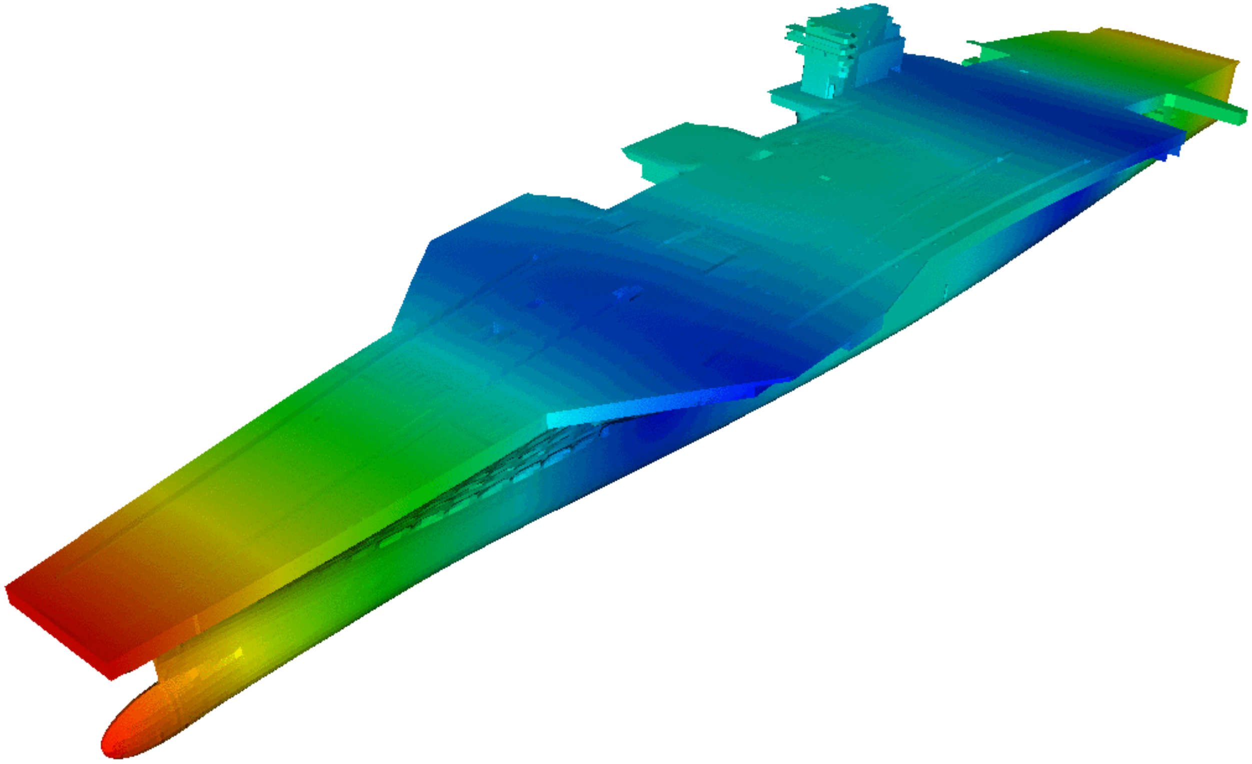
Seawolf



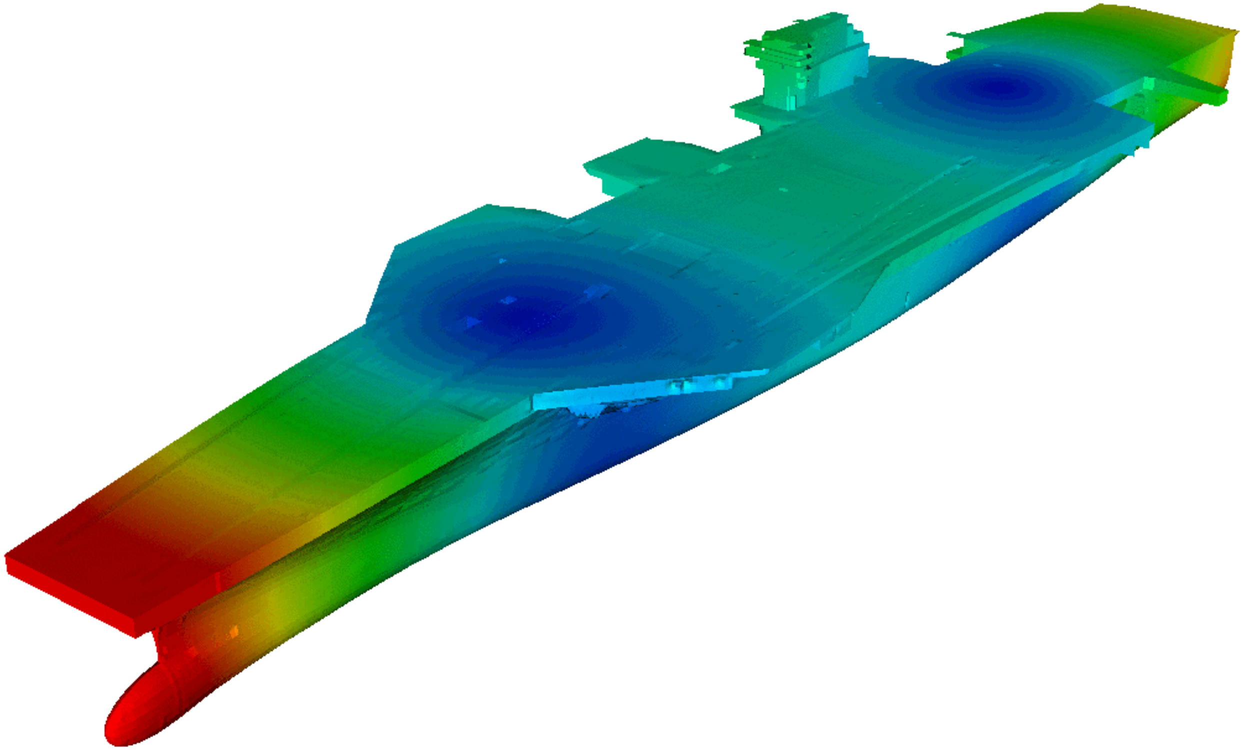
CVN76 - carrier

310,000 elements
170,000 nodes
4,700 material blocks

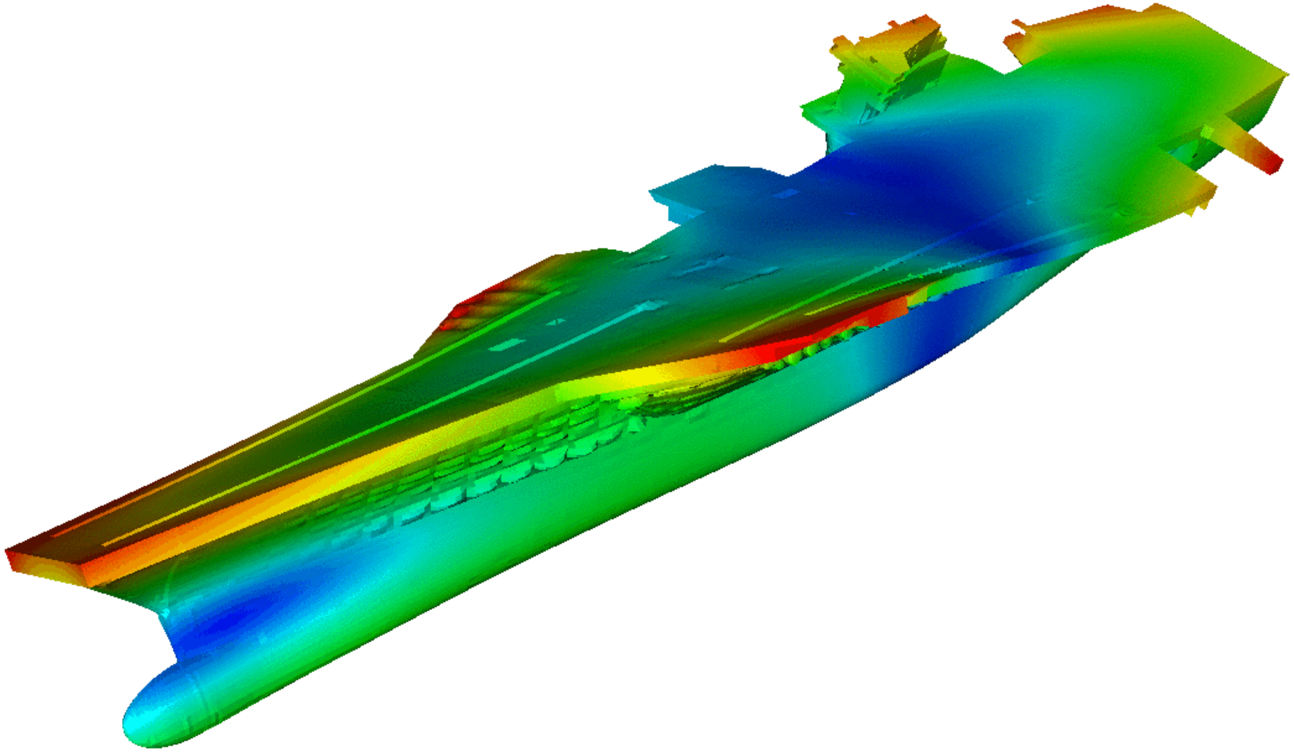
Modes of Aircraft Carrier



Modes of Aircraft Carrier



Modes of Aircraft Carrier



Acoustic Applications

- Coupled seismic/acoustics for deeply buried structures
- Ultrasonics
- Fluid-filled tankers
- Pyro-shock
- MEMS microphones
- Divers in shallow water
- Acoustics of re-entry

Salinas Acoustic Capabilities

- Massively parallel
- Hex, wedge, tet acoustic elements
- Acoustic coupling with both 3D and shell (2D) structural elements
- Linear and nonlinear acoustics
- Allows for mismatched acoustic/solid meshes
- Solvers: FETI-DP, CLIP/CLOP, and FETI-H (for Helmholtz)
- Solution procedures:
  - Frequency response (frequency-domain)
  - Transient (time-domain)
  - Eigenvalue (modal) analysis

Finite Element Methods for Nonlinear Acoustics

Motivation: Extend simulation capability from classical linear acoustics to nonlinear acoustics, for cases involving large-amplitude waves.

- The linear (first-order) acoustic wave equation

$$\frac{1}{c^2}\phi_{tt} - \Delta\phi = 0$$

- The nonlinear (second-order) wave equation

$$\frac{1}{c^2}\phi_{tt} - \Delta\phi + \frac{1}{c^2}\frac{\partial}{\partial t}\left[(\nabla\phi)^2 + \frac{B/A}{2c^2}\left(\frac{\partial\phi}{\partial t}\right)^2 + b\nabla^2\phi\right] = 0$$

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Why Nonlinear Acoustics?

Linear acoustics is inadequate for many applications

- **Resonating cavities**
- **Large-amplitude sources**
- **Far-field of explosions**

Assumptions of Linear Acoustic Theory

- **Small amplitude waves**
- **Linear Constitutive Fluid**
- **No fluid convection**

→

Consequences

- **Resonance leads to infinite amplitude waves**
- **"Sine wave remains a sine wave"**
- **No wave distortion**
- **Wavespeed independent of stress state in fluid**

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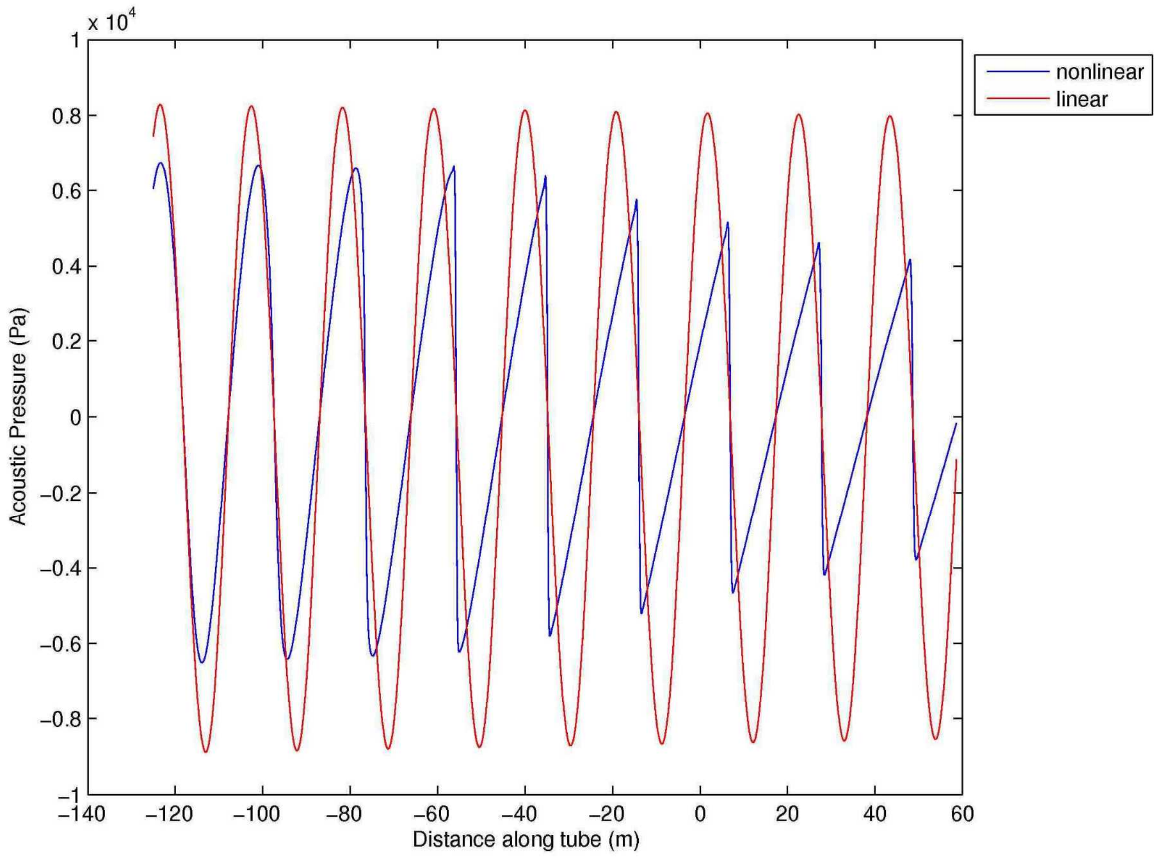
A Comparison of Linear and Nonlinear Acoustic Results

Shock-tube simulation

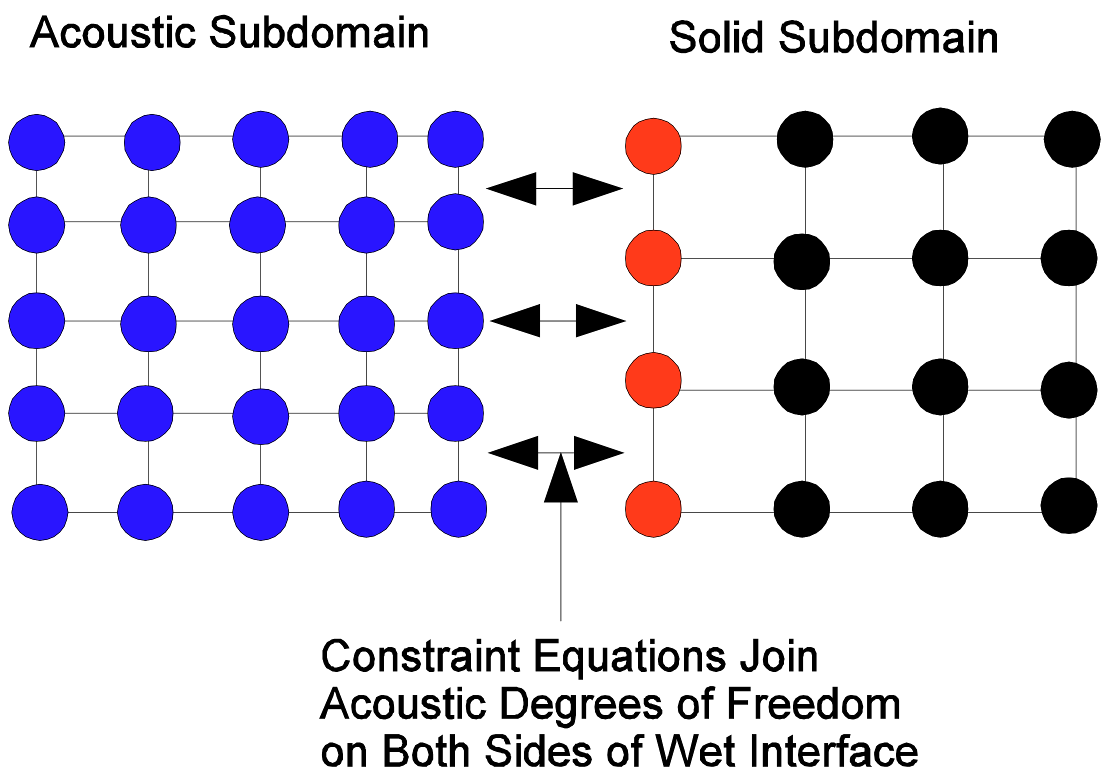


Mismatched Acoustic/Solid Meshes

<u>Our approach:</u>

- Add “ghost” acoustic degrees of freedom to solid nodes on wet interface
- Use conforming coupling operators to couple solid nodes on wet interface to appended acoustic dof
- Couple acoustic dof on both sides of wet interface with constraint equations
    - For conforming meshes, this method reduces to a conforming structural acoustics
    - Same constraint equations for acoustic-acoustic coupling and structural-acoustic coupling

Mismatched Acoustic/Solid Meshes



- 1 degree of freedom per node
- 4 degrees of freedom per node **(solid dof + ghost acoustic dof)**
- 3 degrees of freedom per node

Structural Acoustic Equations of Motion

- **Time domain formulation**

$$\begin{bmatrix} M_s & 0 \\ 0 & -M_a \end{bmatrix} \begin{bmatrix} \ddot{\Delta u} \\ \ddot{\Delta \phi} \end{bmatrix} + \begin{bmatrix} C_s & L^T \\ L & -C_a \end{bmatrix} \begin{bmatrix} \dot{\Delta u} \\ \dot{\Delta \phi} \end{bmatrix} + \begin{bmatrix} K_s & 0 \\ 0 & -K_a \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta \phi \end{bmatrix} = \begin{bmatrix} \mathrm{Re}\, s_s \\ \mathrm{Re}\, s_a \end{bmatrix}$$

- **Eigenanalysis formulation**

$$\lambda^2 \begin{bmatrix} M_s & 0 \\ 0 & -M_a \end{bmatrix} \begin{bmatrix} u \\ \phi \end{bmatrix} + \lambda \begin{bmatrix} C_s & L^T \\ L & -C_a \end{bmatrix} \begin{bmatrix} u \\ \dot{\phi} \end{bmatrix} + \begin{bmatrix} K_s & 0 \\ 0 & -K_a \end{bmatrix} \begin{bmatrix} u \\ \phi \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

- **Frequency-domain formulation**

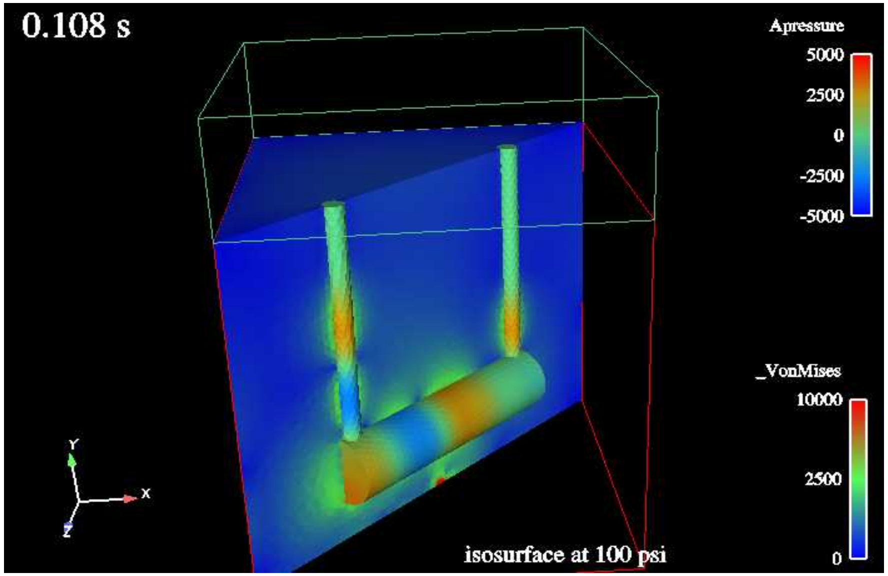
$$-\omega^2 \begin{bmatrix} M_s & 0 \\ 0 & -M_a \end{bmatrix} \begin{bmatrix} u \\ \phi \end{bmatrix} + i\omega \begin{bmatrix} C_s & L^T \\ L & -C_a \end{bmatrix} \begin{bmatrix} u \\ \phi \end{bmatrix} + \begin{bmatrix} K_s & 0 \\ 0 & -K_a \end{bmatrix} \begin{bmatrix} u \\ \phi \end{bmatrix} = \begin{bmatrix} f_s \\ f_a \end{bmatrix}$$

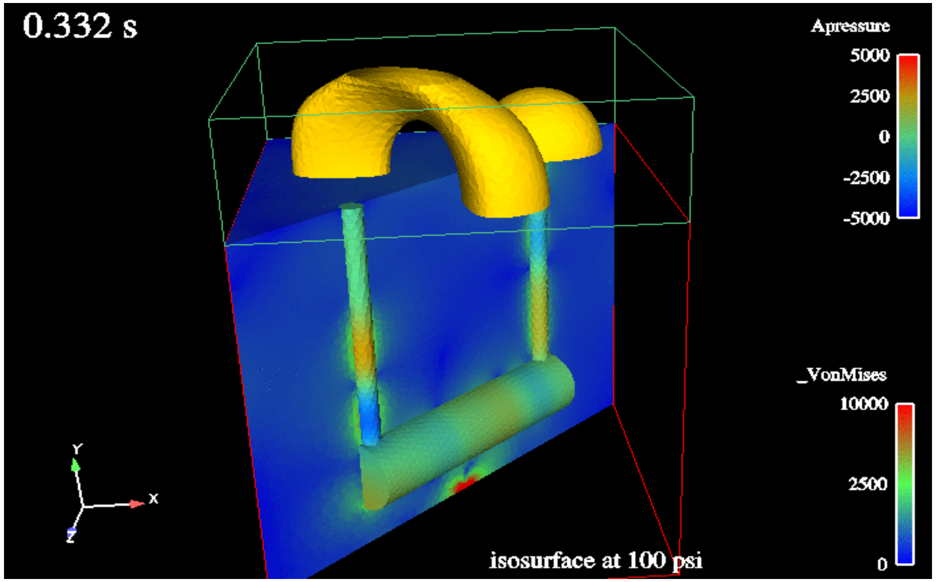
Example Simulations

- Surveillance of deeply buried tunnels
- Acoustic backscatter from diver in shallow water
- Radiation from ultrasonic transducer
- Coupling of CTH with acoustics

Survelence of Deeply Buried Tunnel

Goal: Model acoustic and seismic radiation from deeply buried structures with air portals, for intelligence-gathering purposes.





Time histories of acoustic pressure and structural Von Mises stresses in coupled air tunnel/seismic half-space

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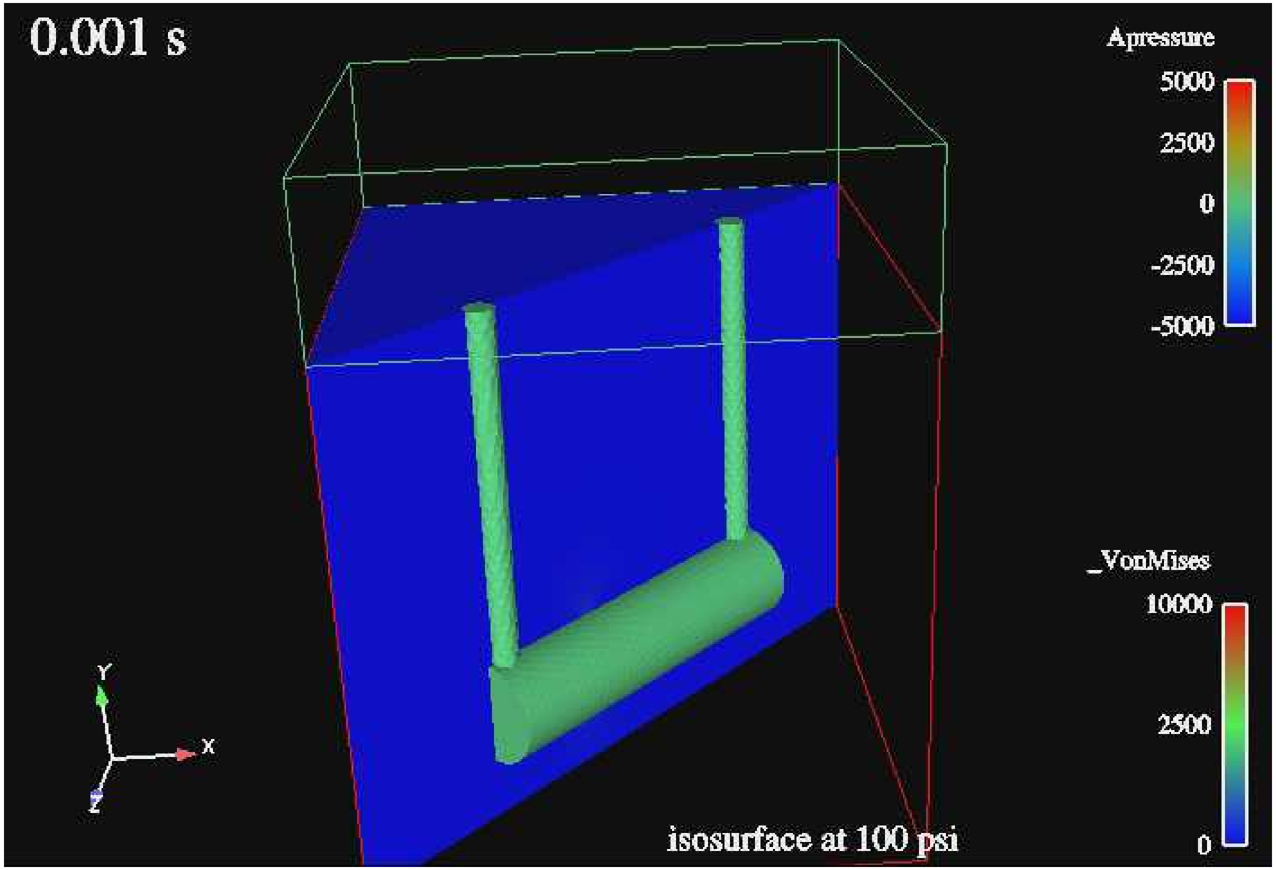

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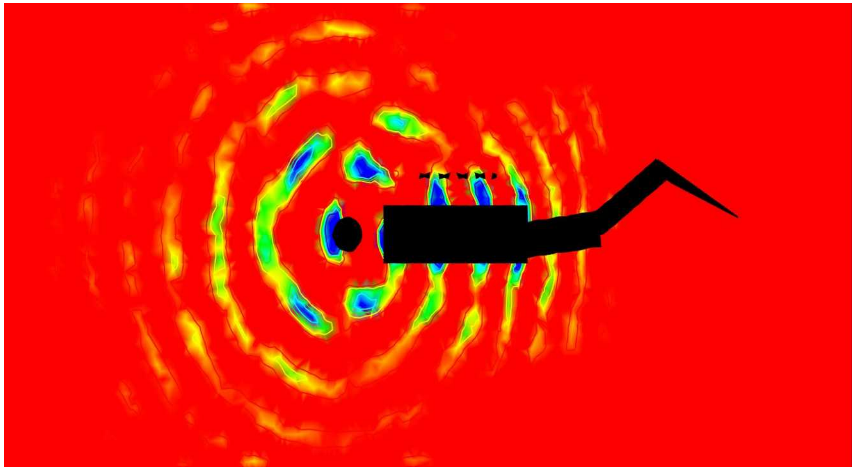
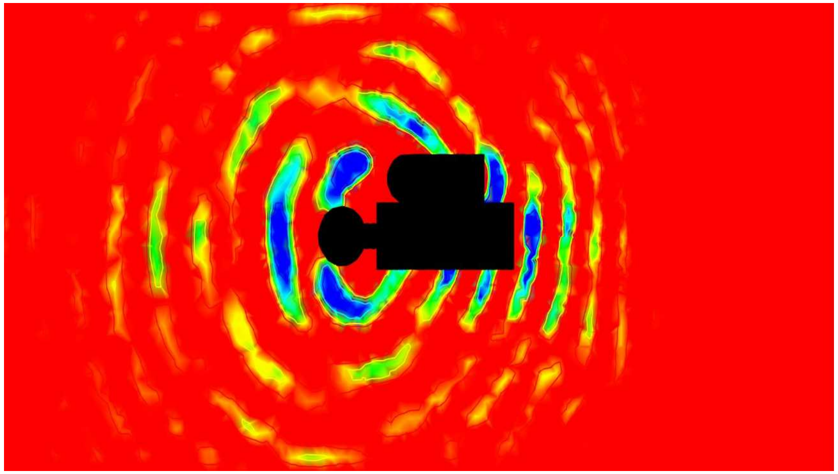
Backscatter from Diver in Shallow Water

Goal: Model the backscatter from divers, mines, and other intruders in shallow coastal waters, for the purpose of designing detection equipment for protecting US coasts, ports for nuclear subs, bridges, and other critical infrastructure.



Acoustic backscatter from diver body



Acoustic backscatter from torso

Backscatter from Diver in Shallow Water

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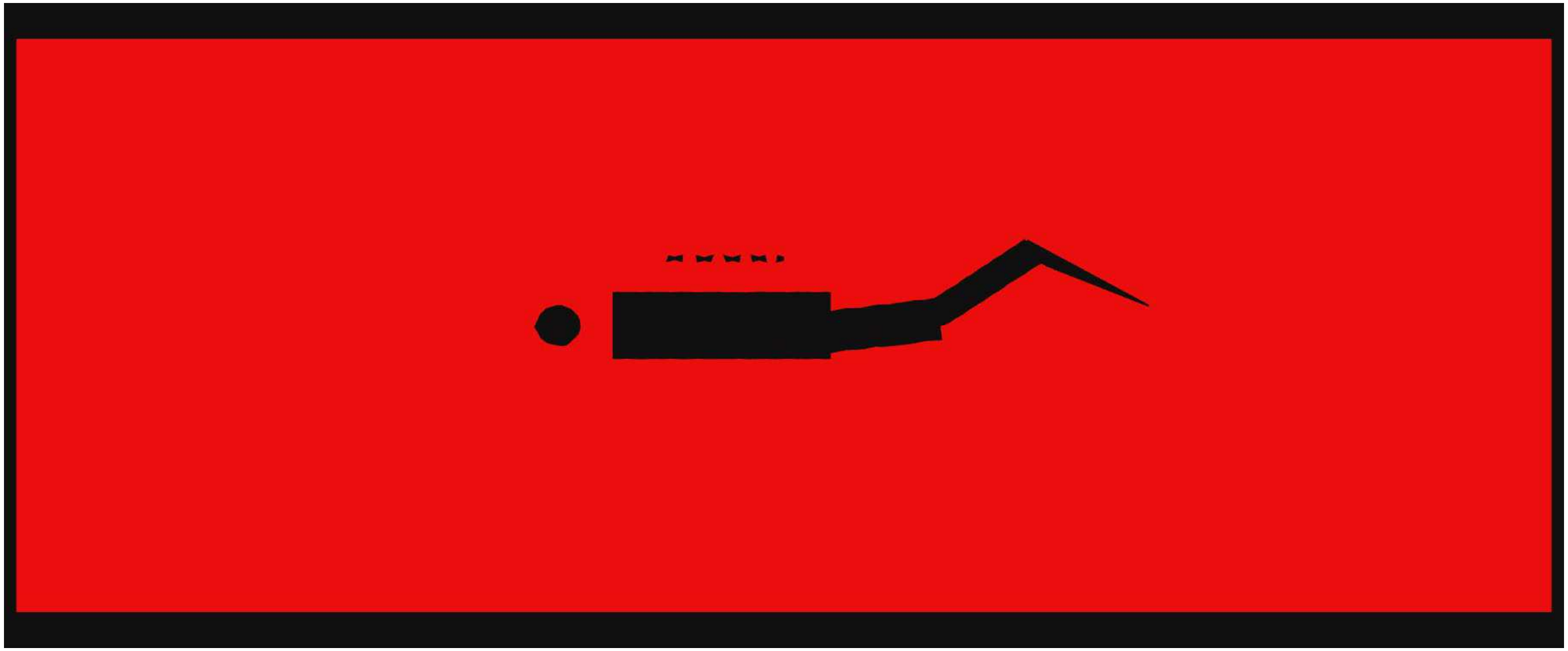

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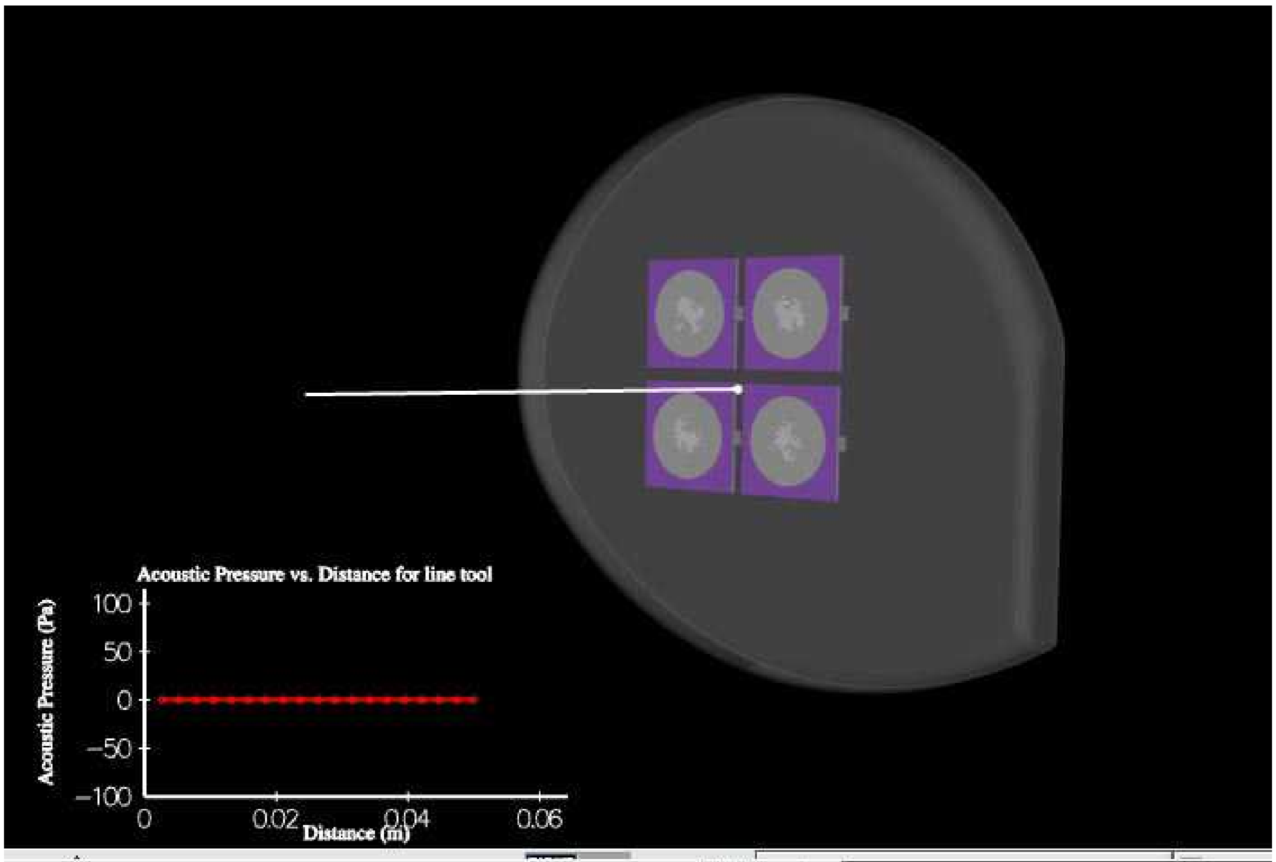
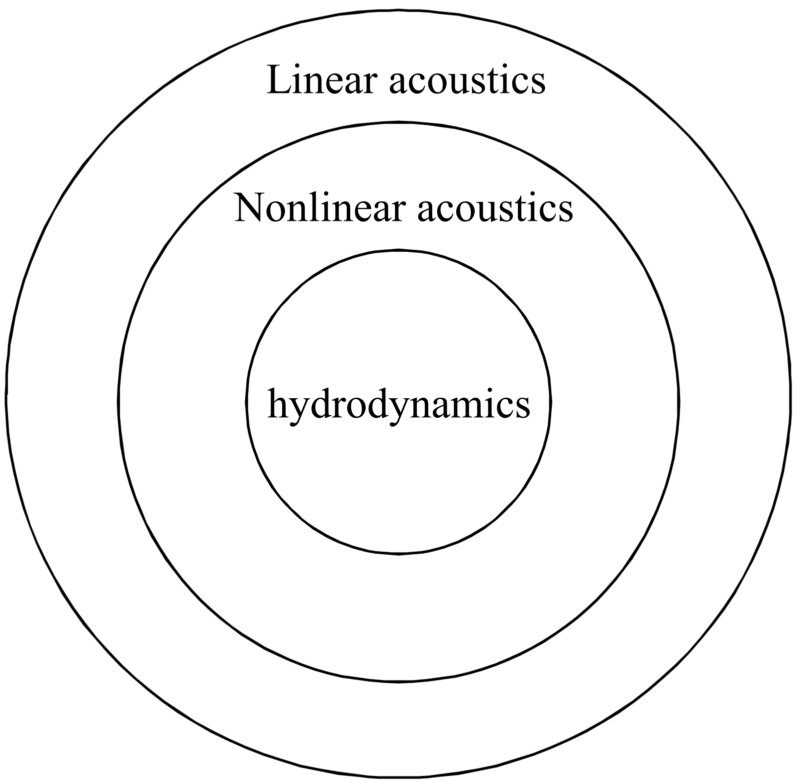
Radiation from Ultrasonic Transducer

Goal: Model acoustic radiation from miniature structures

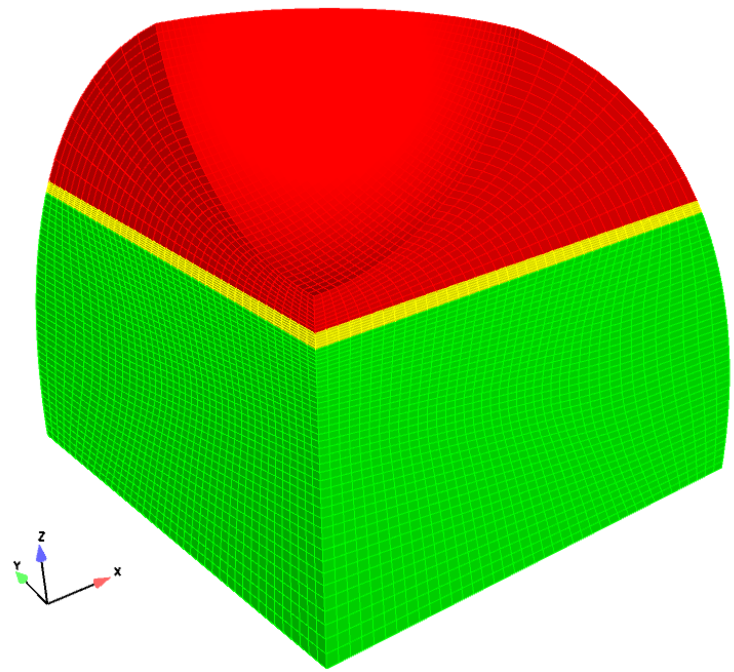


CTH-Acoustic Coupling

Goal: Model the transition from hydrodynamic energy to acoustic energy to structural vibration through air



Schematic of explosion-acoustic coupling scenario



Structural acoustic mesh used to compute the explosive-induced vibration of a structure due to nonlinear acoustic excitation of air.

Conclusions

- Massively parallel capability designed for large-scale vibration, complex acoustic and structural acoustic analysis
- Wide range of analysis procedures: transient (time-domain), eigenanalysis, and frequency domain
- Applied to wide range of applications
  - Deeply buried tunnels
  - Intruder detection in shallow coastal waters
  - IED detection in tanker trucks