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Massively Parallel Acoustic and Structural Acoustic Analysis with SALINAS

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[1]Computational Solid Mechanics and Structural Dynamics

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[3]Structural Dynamics

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Outline

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

SALINAS 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)

Element Library

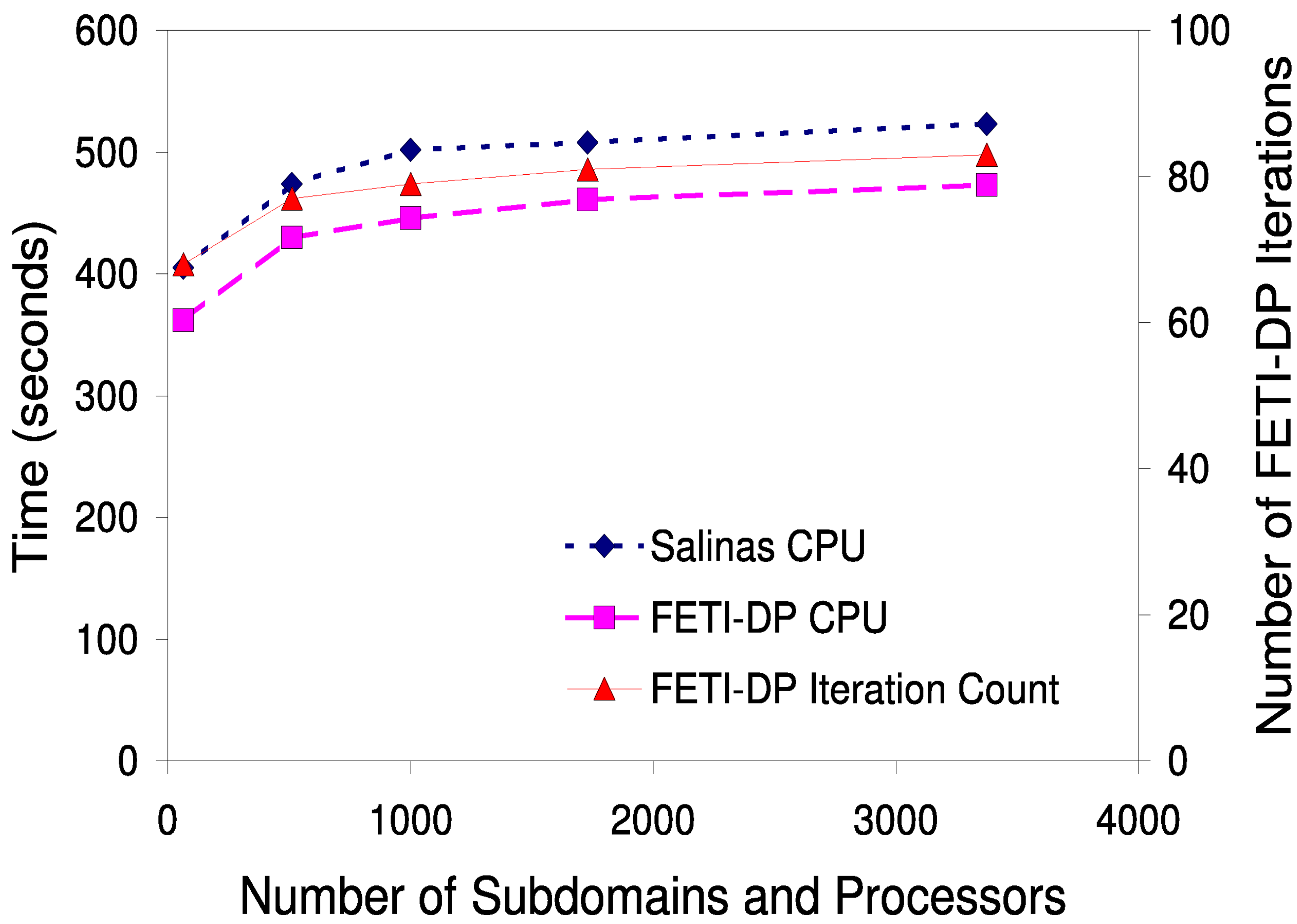
- Solid Elements
  - Hex8, Hex20, Tet4, Tet10, Wedge6, Wedge15
  - Hex8 variations
- Shell Elements
  - Tria3, Quad4, (Tria6, Quad8 – not really quadratic)
- Bar/Beam Elements
  - Beam2, Truss, Spring, Dashpot
- Point Elements
  - conmass
- Specialty Elements
  - Iwan, Hys, Shys, Joint2G, Gap

Definition of 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.

SALINAS Scalability Study



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Acoustic Applications at Sandia

- Coupled seismic/acoustics for deeply buried structures
- Ultrasonics
- Urban acoustic propagation
- Fluid-filled tankers
- 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
  - Coupled acoustic-structural eigenvalue analysis

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Finite Element (FE) vs. Time-Domain Finite Difference (TDFD) Acoustics Approach

TDFD

- Difficulty representing complex geometries
  - Spurious grid reflections
- Difficult to couple with finite-element based structural dynamics codes
- Difficult to model free surfaces/surface topography

FE

- Complex geometries conform naturally to element boundaries
- Easy integration with finite-element based structural dynamics codes
- Free surfaces treated as part of formulation
  - Surface topography represented as boundaries of elements
- New technologies (discontinuous Galerkin, infinite elements) designed specifically for FE

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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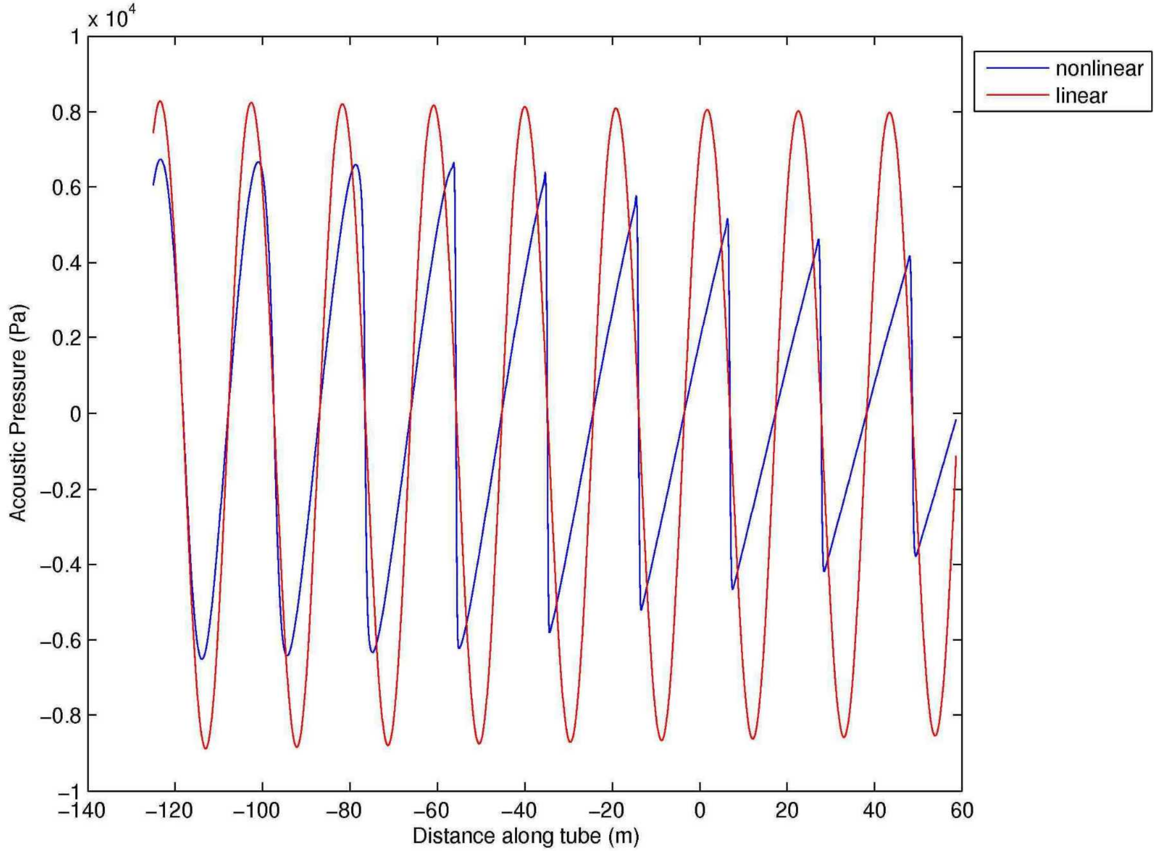
A Comparison of Linear and Nonlinear Acoustic Results

Far-field pressure from a high velocity source

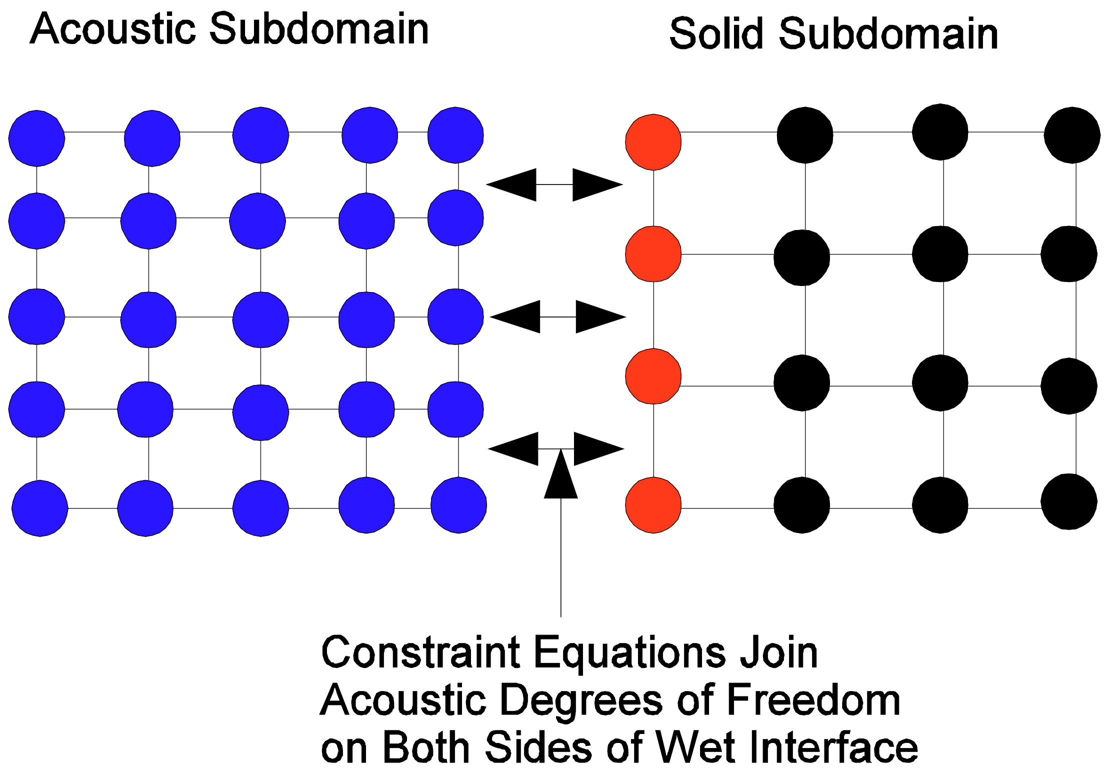


Mismatched Acoustic/Solid Meshes

Our approach:

- 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



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

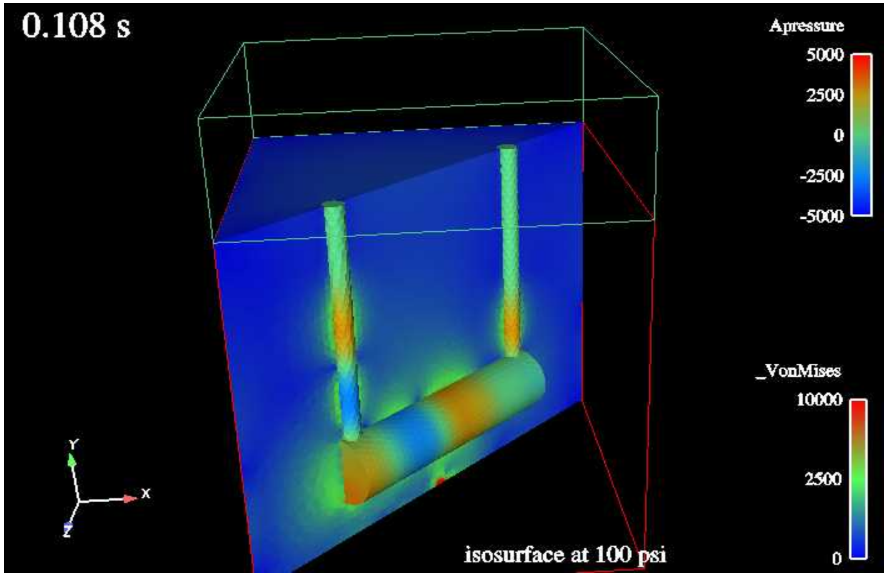
$$-\omega^2 \begin{bmatrix} M_s & 0 \\ 0 & -M_a \end{bmatrix} \begin{bmatrix} u \\ \phi \end{bmatrix} + i\omega \begin{bmatrix} C_s & L^T \\ L & -C_a \end{bmatrix} \begin{bmatrix} u \\ \phi \end{bmatrix} + \begin{bmatrix} K_s & 0 \\ 0 & -K_a \end{bmatrix} \begin{bmatrix} u \\ \phi \end{bmatrix} = \begin{bmatrix}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

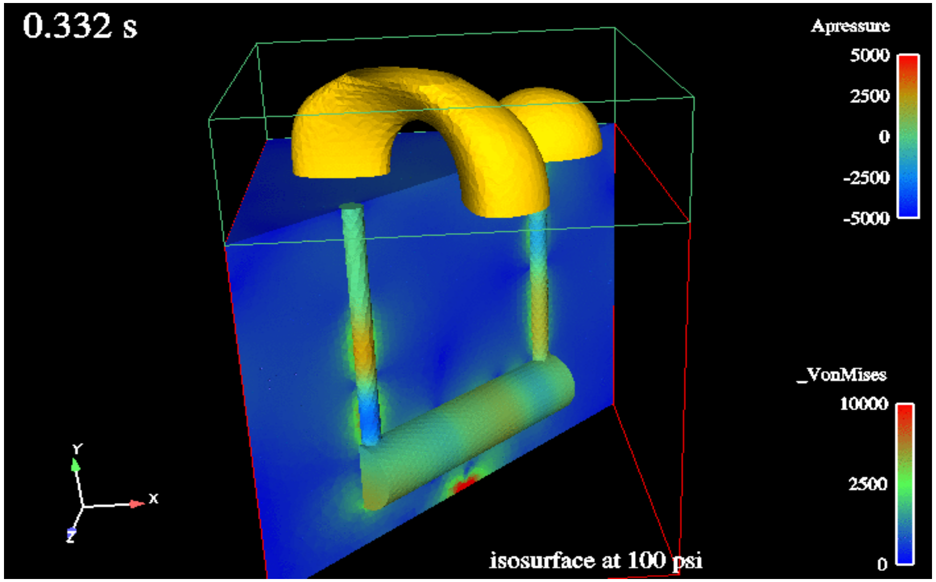
Example Simulations

- Surveillance of deeply buried tunnels
- Acoustic backscatter from diver in shallow water
- 3D urban acoustic propagation
- Inspection of tanker trucks
- Coupling of CTH with acoustics

Surveillance 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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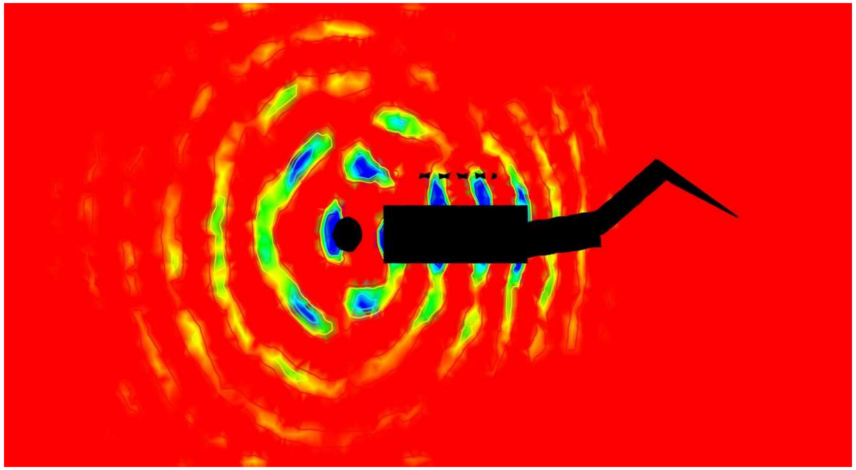
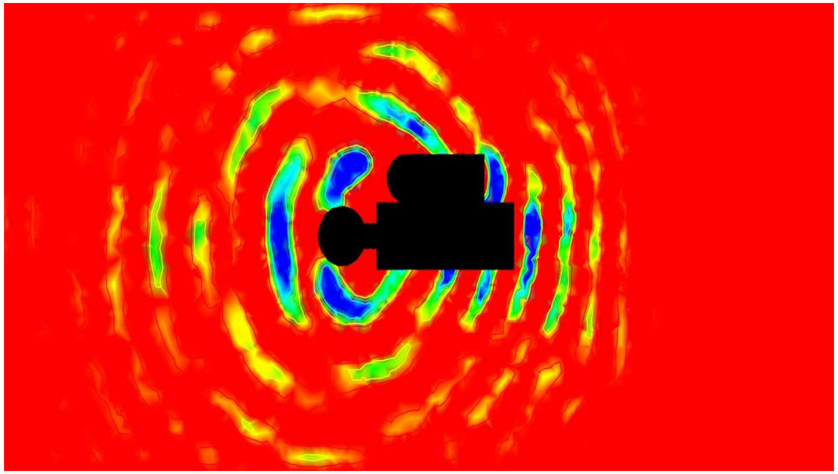
Backscatter from Diver in Shallow Water

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 and other critical infrastructure.



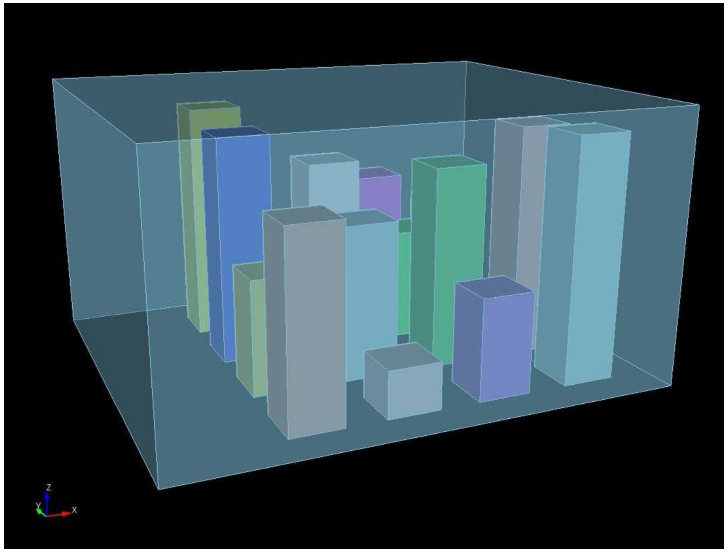
Acoustic backscatter from diver body



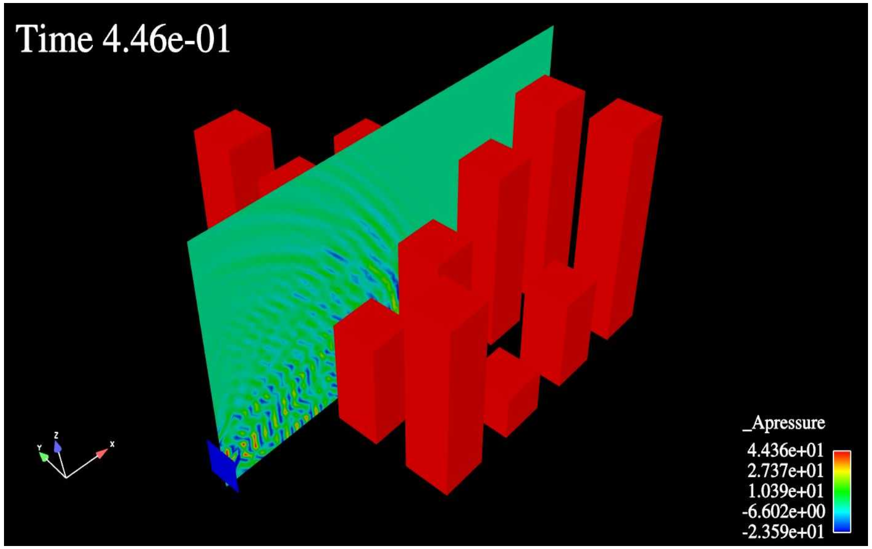
Acoustic backscatter from torso

3D Urban Acoustic Propagation

Goal: Model acoustic propagation in 3D urban environment, using state-of-the-art finite element meshing tools and nonlinear acoustic modeling



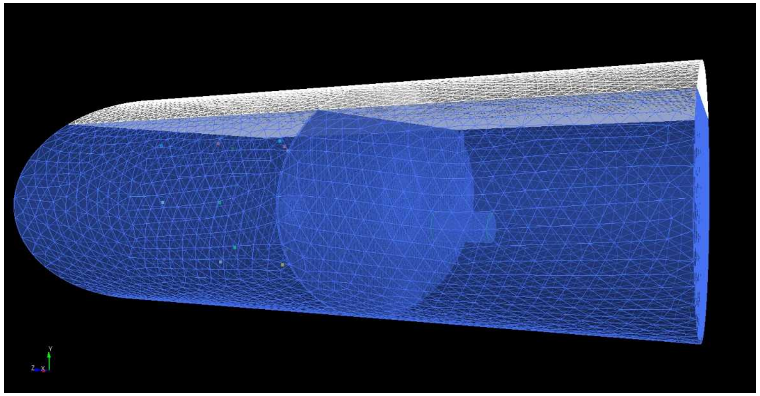
3D finite element mesh of urban environment



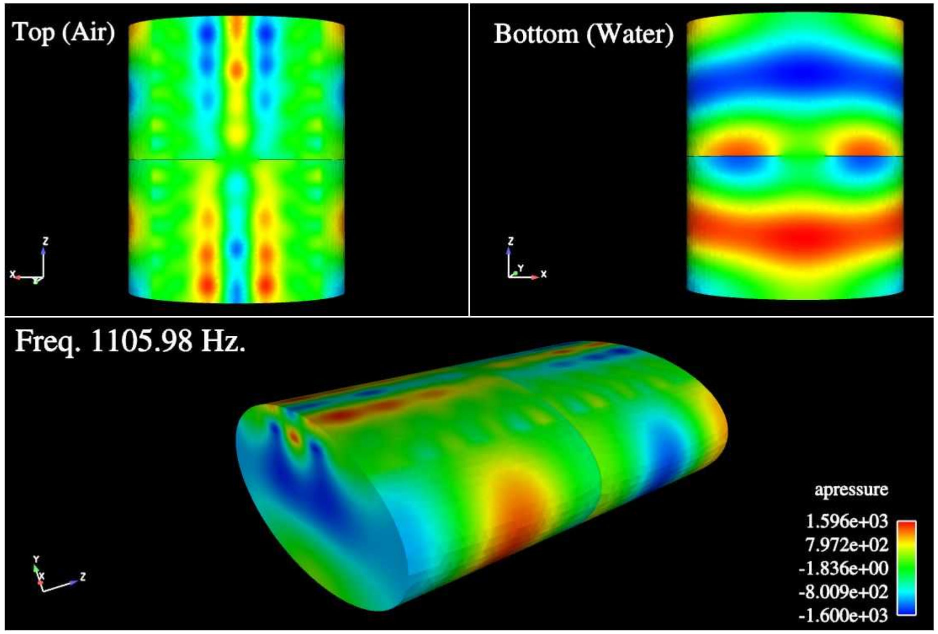
Acoustic wave propagation analysis

Inspection of Tanker Trucks

Goal: Model the backscatter from fluid-filled tanker trucks, to assist inspectors in looking for contraband materials



Acoustic mesh of fluid-filled tanker



Acoustic analysis of water-air interface in partially-filled tanker

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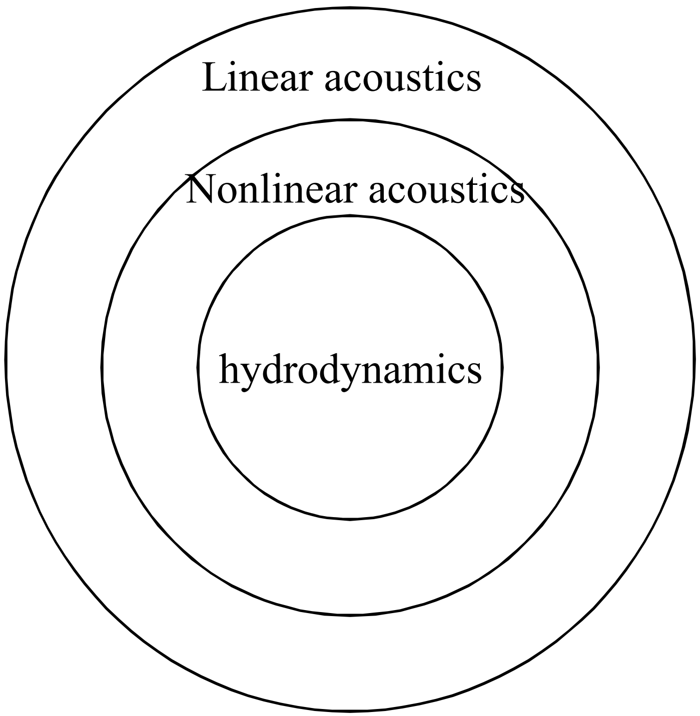
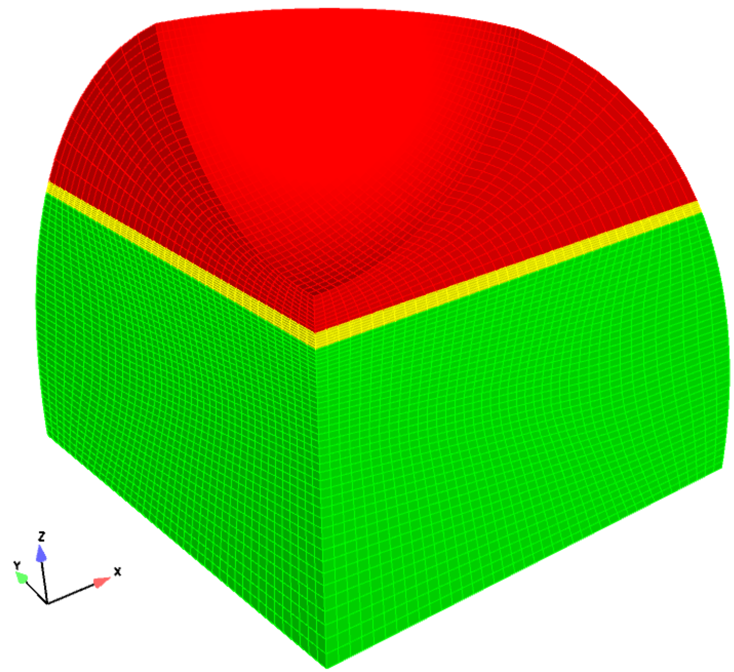
CTH-Acoustic Coupling

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.

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Other Possible Applications

- Acoustic sniper detection
  - Both military and domestic
- Monitoring tunnels at US border crossings
- Large-scale seismic wave propagation
  - Underground nuclear test monitoring

Conclusions

- Massively parallel finite element 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 a variety of applications