Development of an OpenFOAM Solver for Hydroacoustic Simulations: An Application for Acoustic Fish Deterrence

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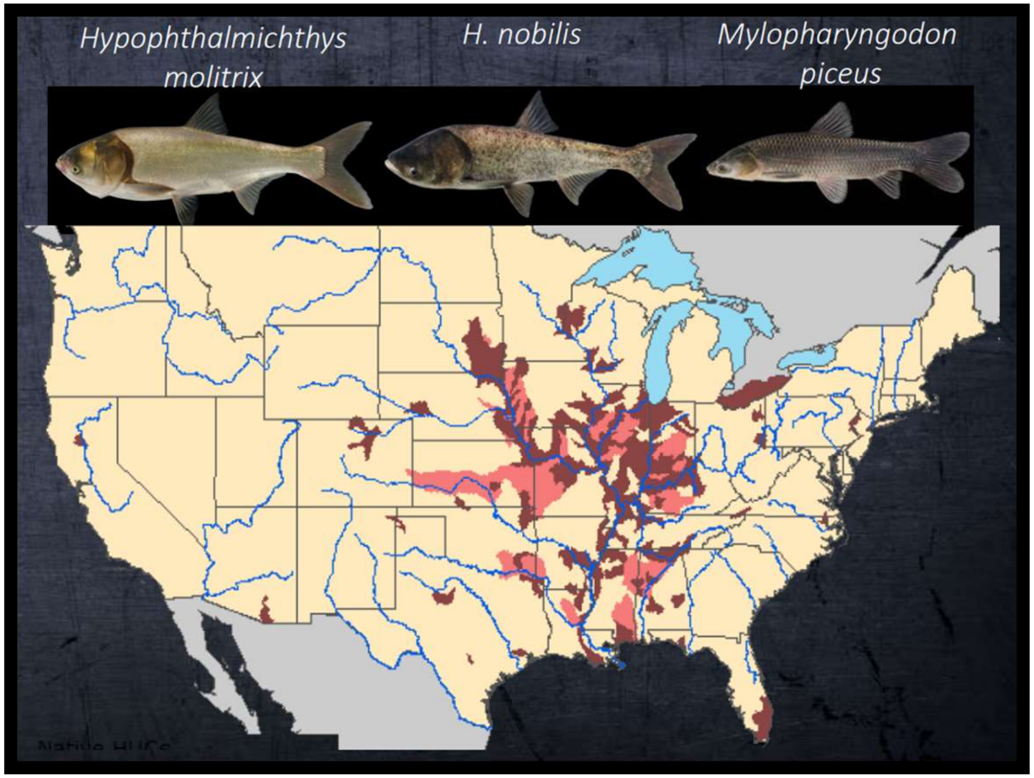
Problem Statement

Prevent expansion of invasive fish species to protect native ecosystem

The invasive species have distinct aural frequency ranges, differing from the native species

This allows for targeted acoustic interventions by focusing on these specific aural ranges, minimizing impact on native aquatic life

underwater Acoustics Deterrence System (uADS)



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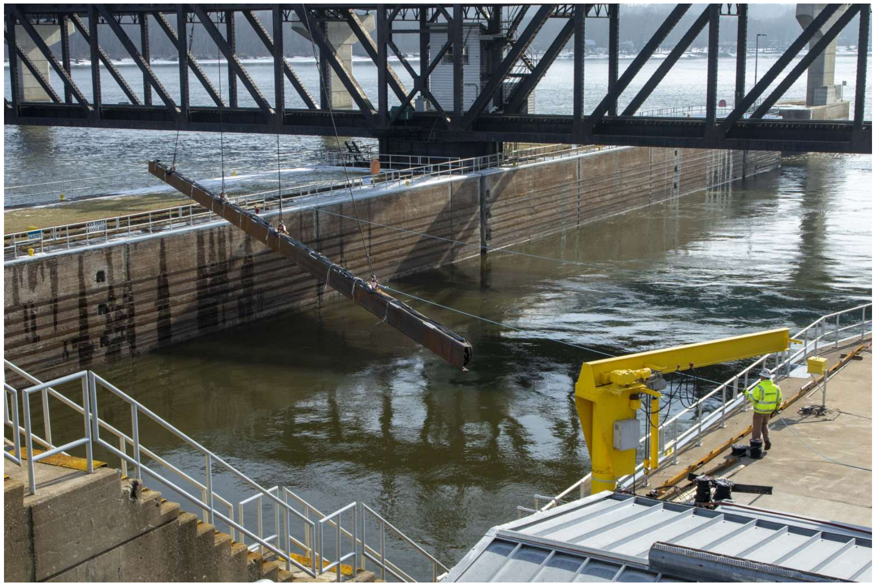
Problem Statement

Develop a general-purpose solver using OpenFOAM framework for acoustics analysis of a shallow water channel (lock)



(image credit - US Army Corps of Engineers)

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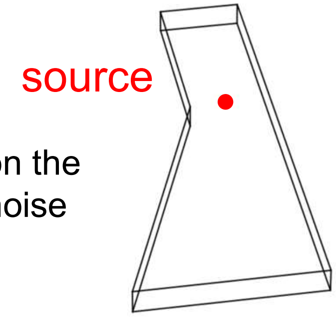


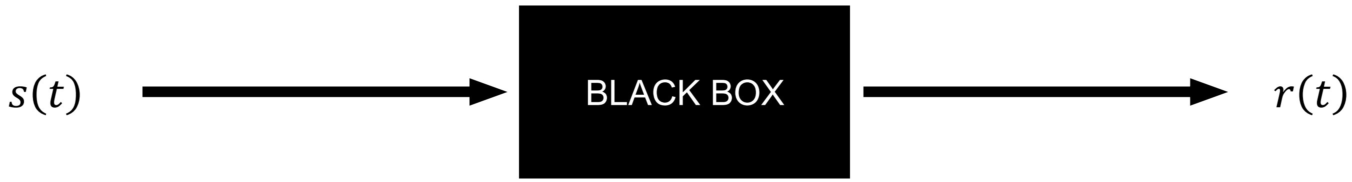
This work focuses on the case without flow noise

Approaches for Studying Acoustics

- Direct Simulation
  - solving the acoustic equation directly
  - conceptually simplest approach
  - very computationally expensive
- Superposition principle
  - Basic
    - decompose a complex signal into a linear combination of sinusoids
    - cuts down computational expense compared to direct method
    - still requires a separate simulation for each frequency
  - Transfer Function
    - relates signal to response

What is a Transfer Function?

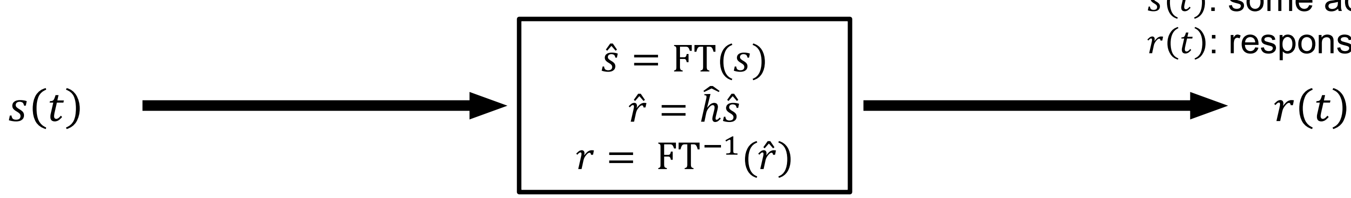
$s(t)$: some acoustic signal
$r(t)$: response to s



What is a Transfer Function?

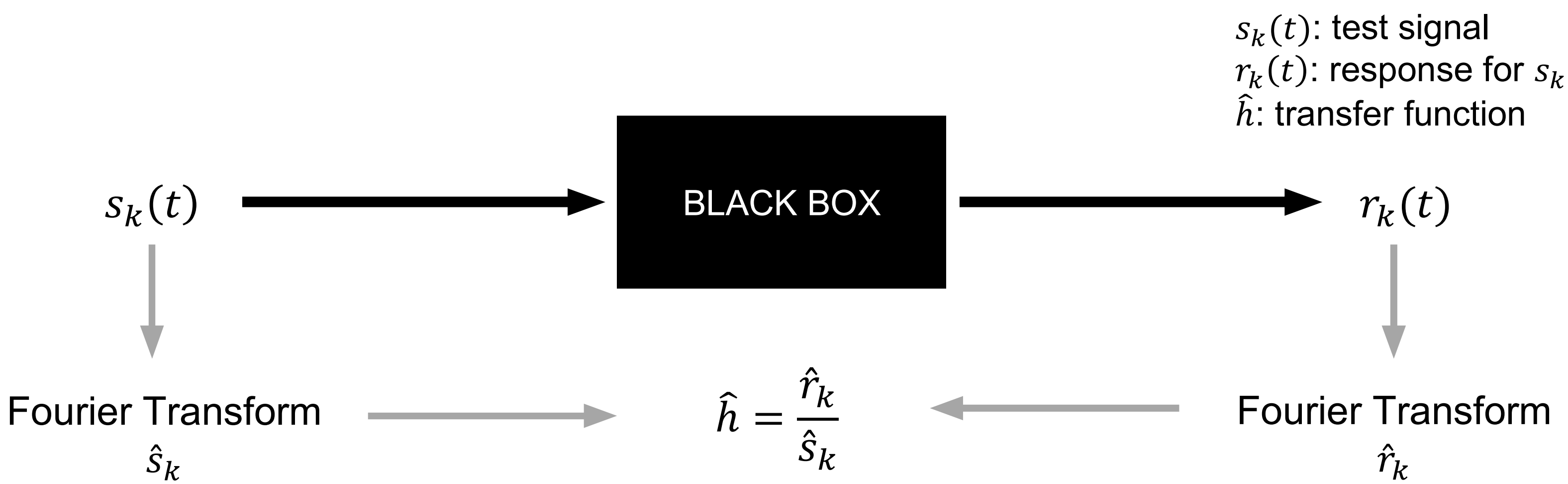
- Through Fourier Analysis, the black box process between a signal and its response can be represented through a function called the ‘transfer function’
- This transfer function ($\hat{h}$) is independent of the signal and response, it is a representation of the black box process itself

$s(t)$: some acoustic signal
$r(t)$: response to s



How to Compute Transfer Function?

A known test signal $\hat{s}_k$ and measured response $\hat{r}_k$ can thus be used to get $\hat{h}$



Transfer Function usage

- Knowing that having the transfer function is equivalent to knowledge of the fully operations of the system, the aim now is to determine $\hat{h}$

- What are the factors that effect the applicability of this method?
  - Is it dependent on the mathematical model (physics)?
  - Is it dependent on the problem (geometry)?
  - Is it dependent on the way $\hat{h}$ was computed?

- How to improve accuracy of the process to compute $\hat{h}$?
  - What is a good test signal?
  - How to determine accuracy of the solver?

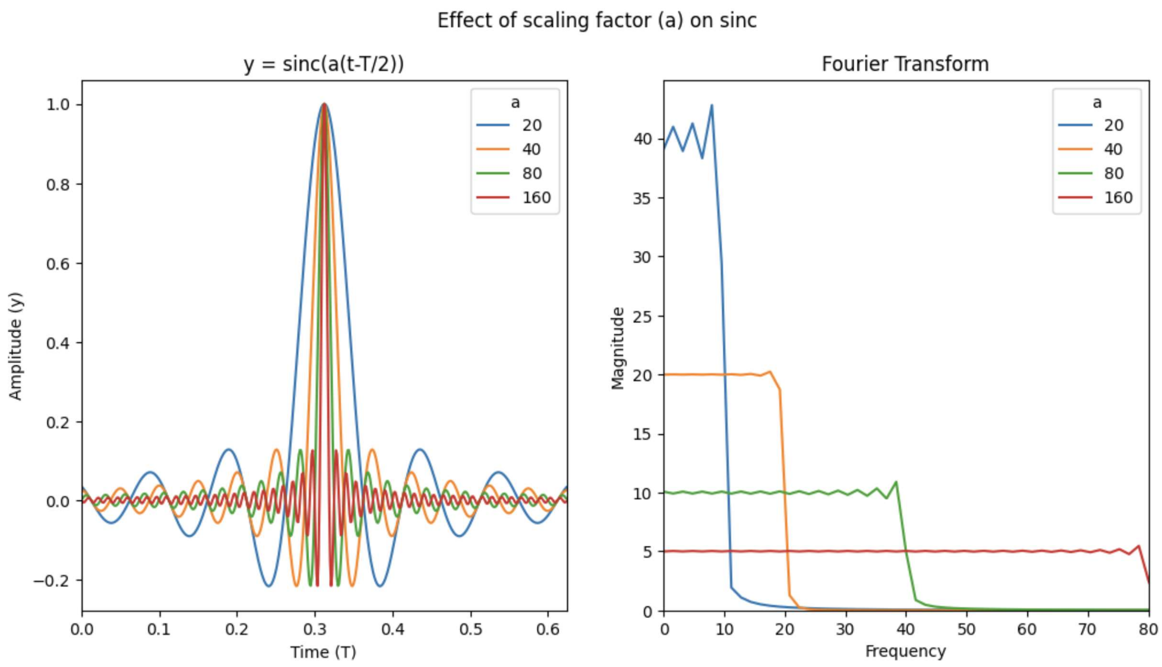
What is a good test signal?

The ideal test signal is the unit impulse (Dirac delta) due to it's uniform frequency response

$\text{sinc}\, at$ approximates the impulse by giving a uniform frequency response till:

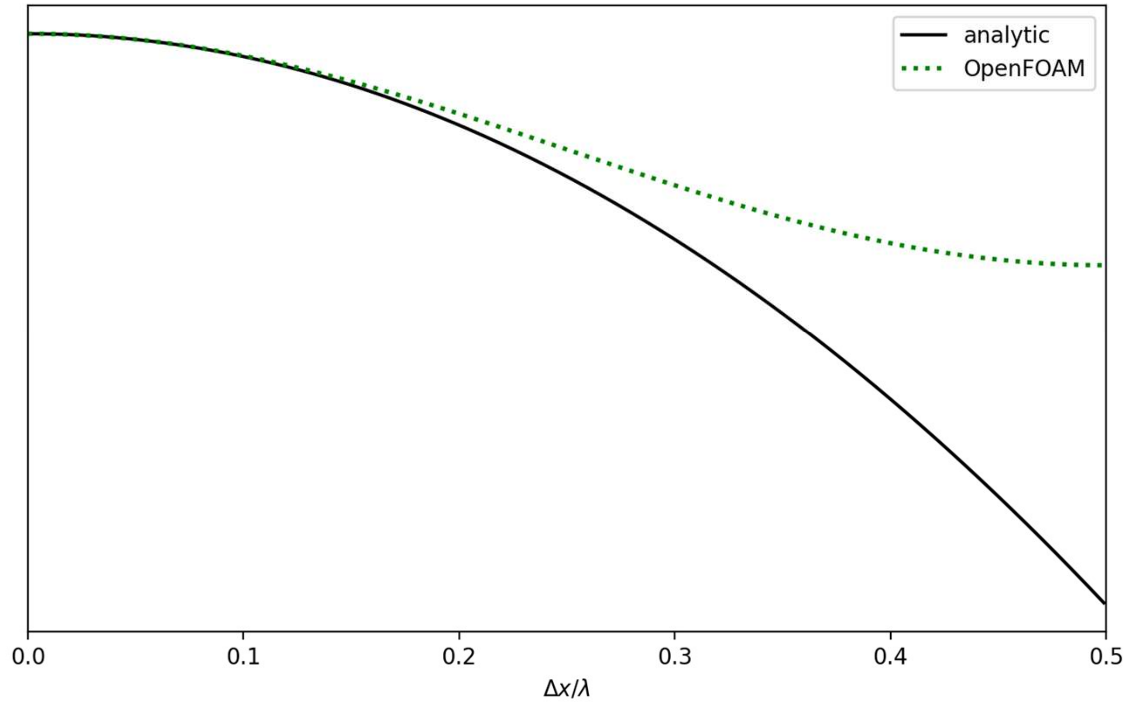
$$F_{max} = a/2$$

$$\text{sinc}\, x = \begin{cases} \dfrac{\sin \pi x}{\pi x} & x \neq 0 \\ 1 & x = 0 \end{cases}$$



How to determine the accuracy of the solver?

- OpenFOAM generally uses Second order accurate finite volume schemes with the (First order accurate) Euler time integration method
- Since this system deals with wave propagation, the best manner to analyze the accuracy is through Fourier techniques
- Each scheme can be used to calculate its effect on a wave of certain frequency, and then be compared to the analytical solution
- Using this the values of Δx and Δt needed can be determined



How to determine the accuracy of the solver?

- Using Fourier analysis, values of Δx and Δt were computed to keep the OpenFOAM error lower than 5% when compared to the analytical result

- Based on 2nd order central Laplacian operator the required mesh size is

$$\Delta x < \frac{\lambda}{8}$$

- Based on 1st order finite difference gradient used at the boundary the required mesh size is

$$\Delta x < \frac{\lambda}{14}$$

- Based on 1st order Euler time integration scheme the required time step is

$$\Delta t < \frac{\Delta x}{20c}$$

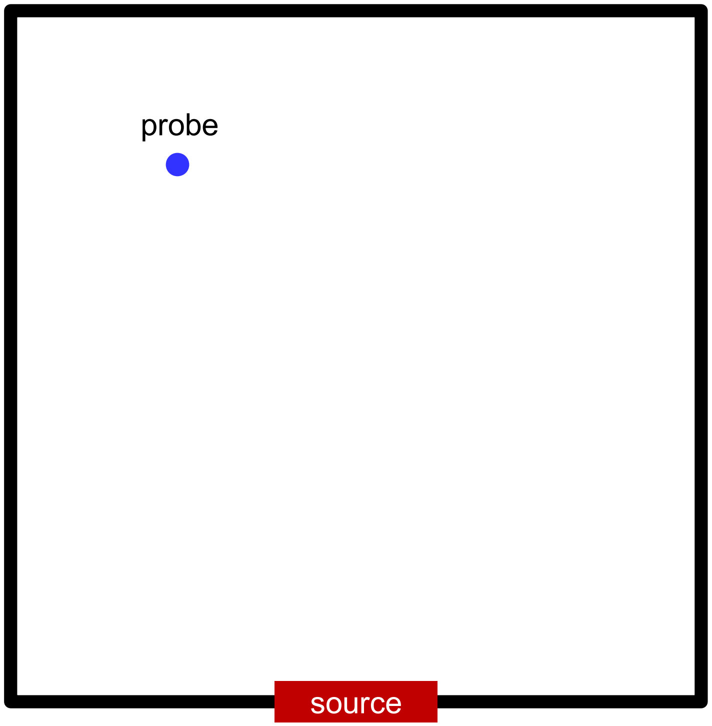
- The requirements for hydroacoustics are substantially more stringent than typical CFD
- Initially some inexpensive 2D testing was done to confirm the hypotheses before transitioning to 3D

Acoustic Test Case in OpenFOAM

Acoustic wave equation:

$$\frac{\partial^2 p'}{\partial t^2} - c^2 \nabla^2 p' = 0$$

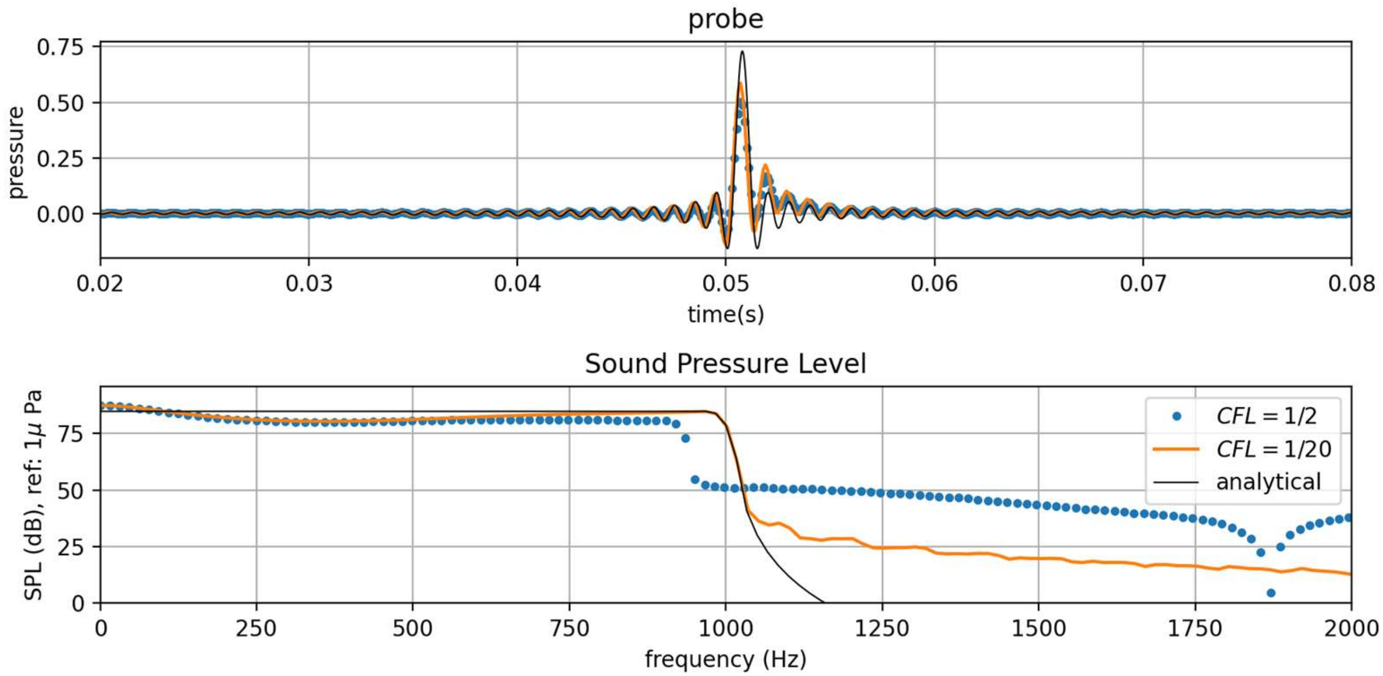
- 2D case
- source: distributed region with a spatially varying pressure that mimics the point source solution
- signal: sinc function (max frequency: 1000Hz)
- probe offset to capture non-orthogonal traveling waves
- domain side = wavelength of max frequency = 1.48m
- speed of sound (c) = 1480m/s (water)
- non-reflective boundary conditions



Acoustic Test Case in OpenFOAM

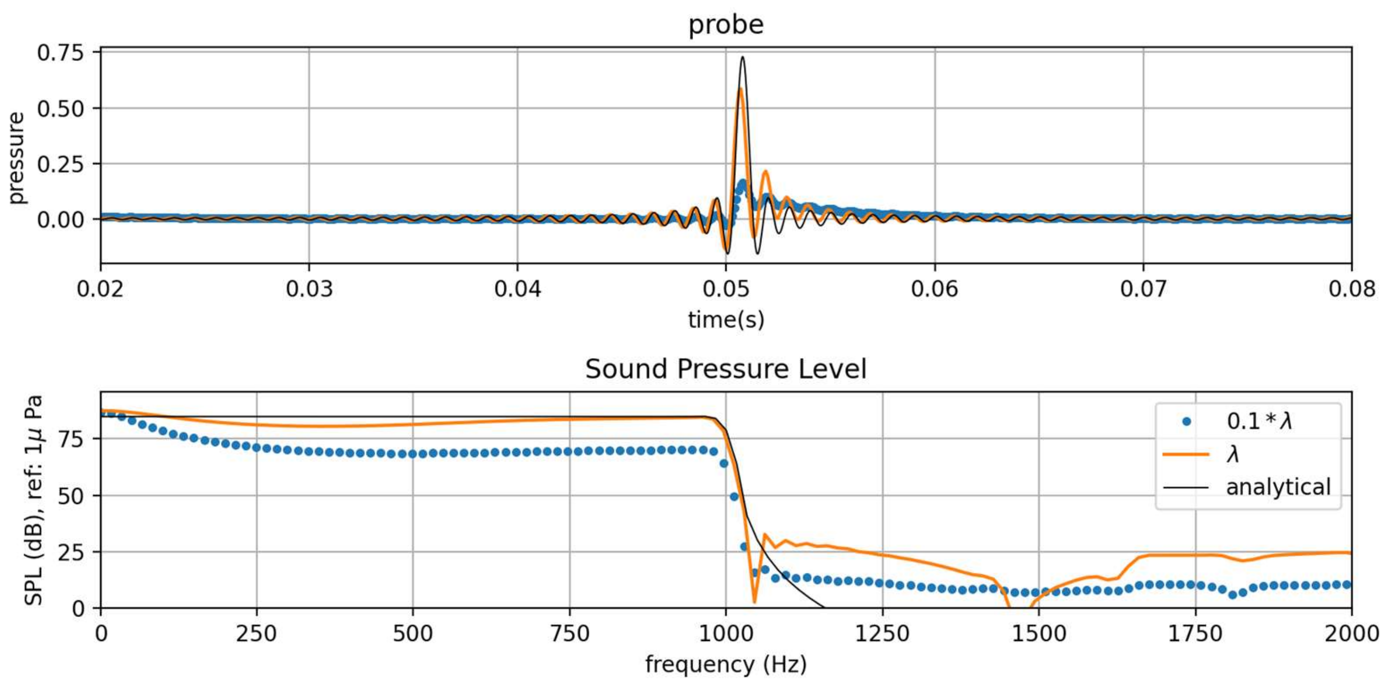
$$\Delta x = \frac{\lambda}{14}$$

$$\mathrm{CFL} = \frac{\mathrm{c}\Delta t}{\Delta x}$$



Appropriate timestep – better frequency response

Acoustic Test Case in OpenFOAM



Appropriate source size – better response

$$\Delta x = \frac{\lambda}{14}$$

$$\text{CFL} = \frac{c\Delta t}{\Delta x} = \frac{1}{20}$$

Acoustic Test Case in OpenFOAM

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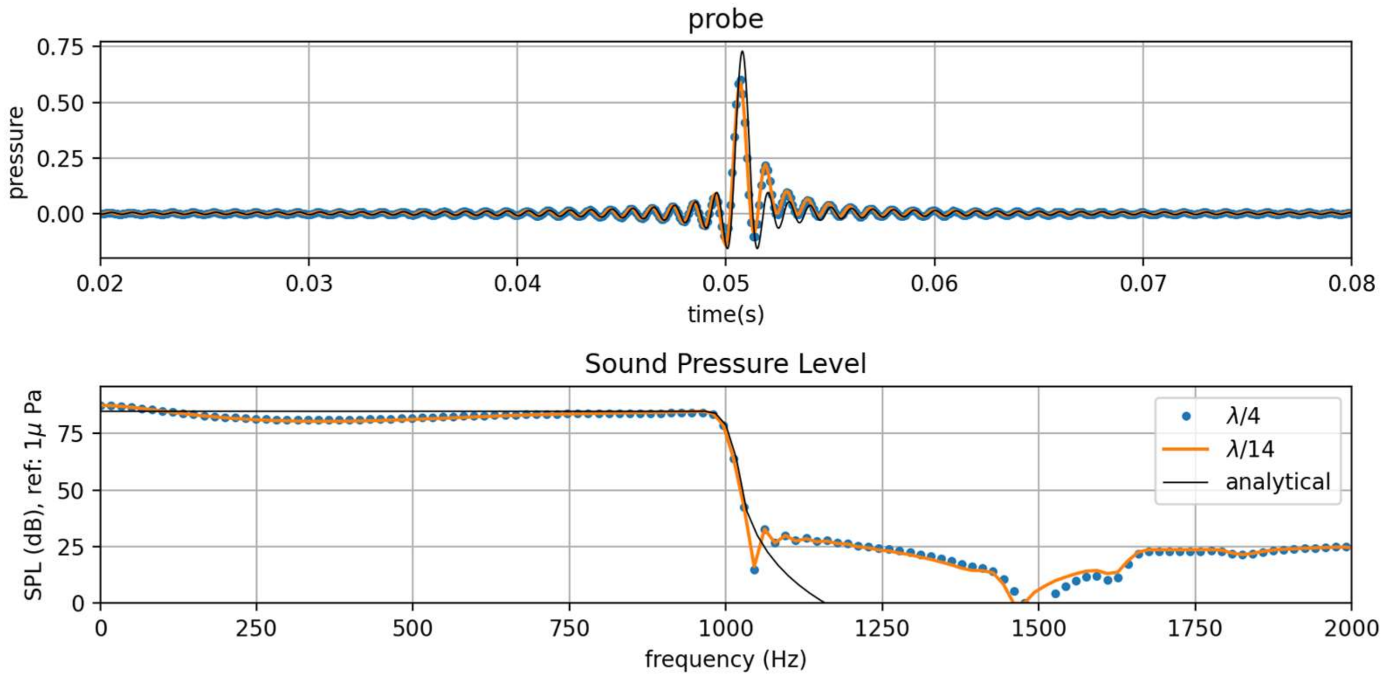
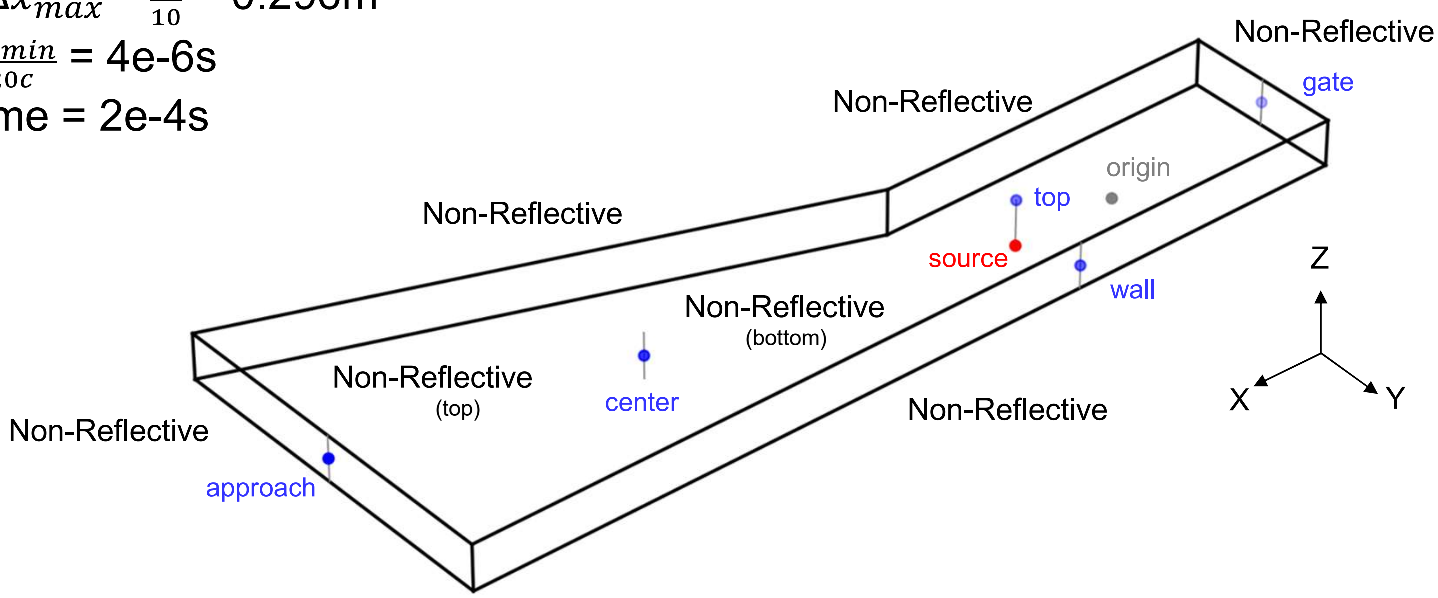


Timestep dominates error
(results largely independent of mesh size)

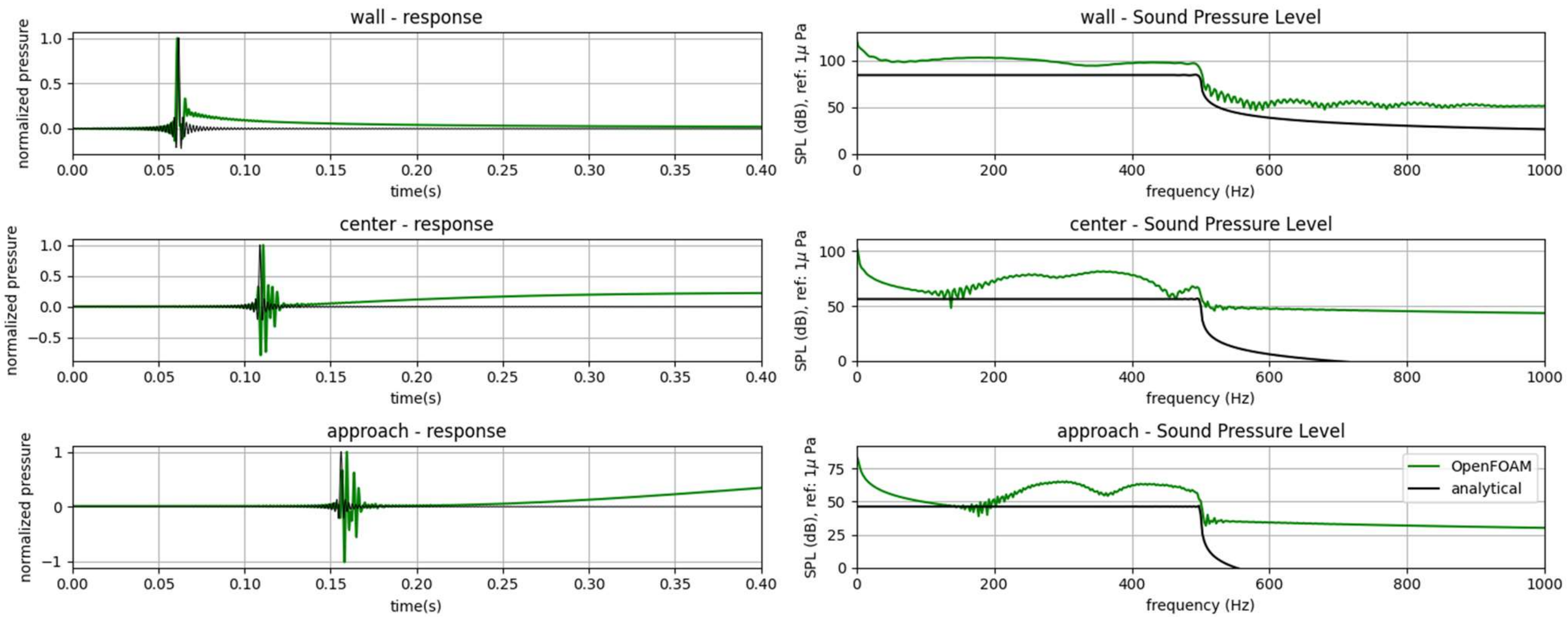
Lock Geometry Acoustics

- speed of sound = 1480 m/s
- source: sinc function (f_{max}= 500Hz)
- mesh size = Δx_{max} = $\frac{\lambda}{10}$ = 0.296m
- time step = $\frac{\Delta x_{min}}{20c}$ = 4e-6s
- probe write time = 2e-4s



Lock Geometry Acoustics

Error increases with distance from source



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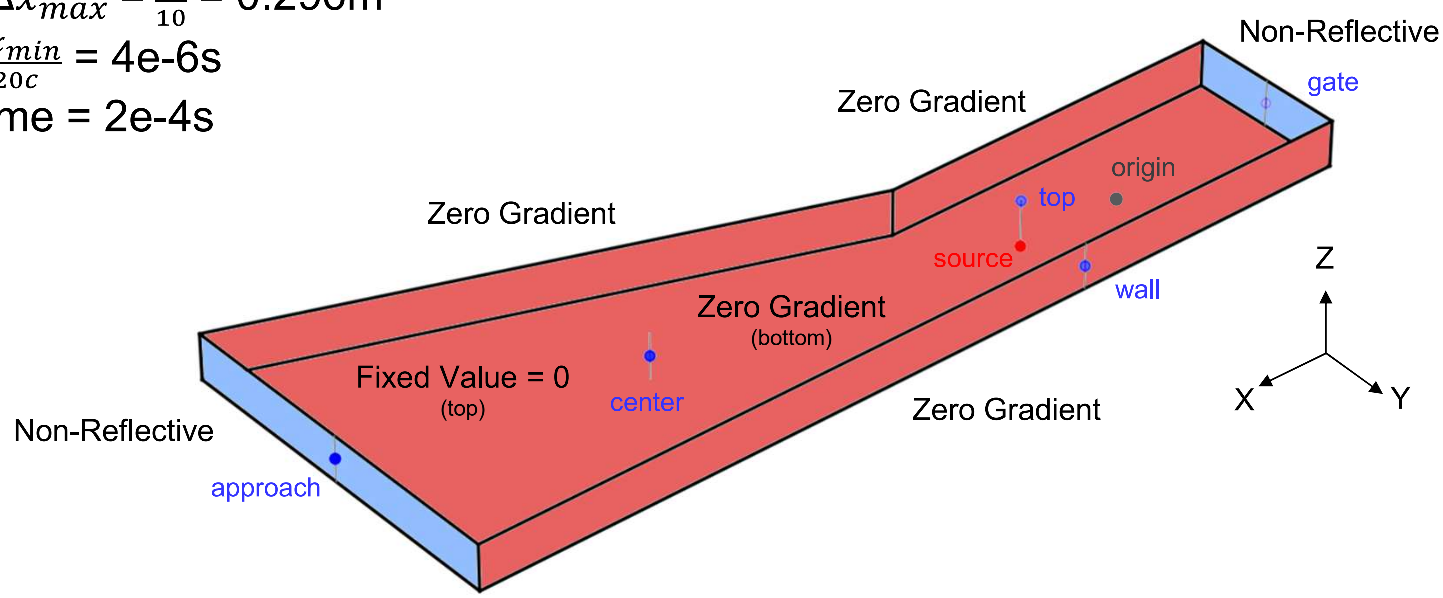

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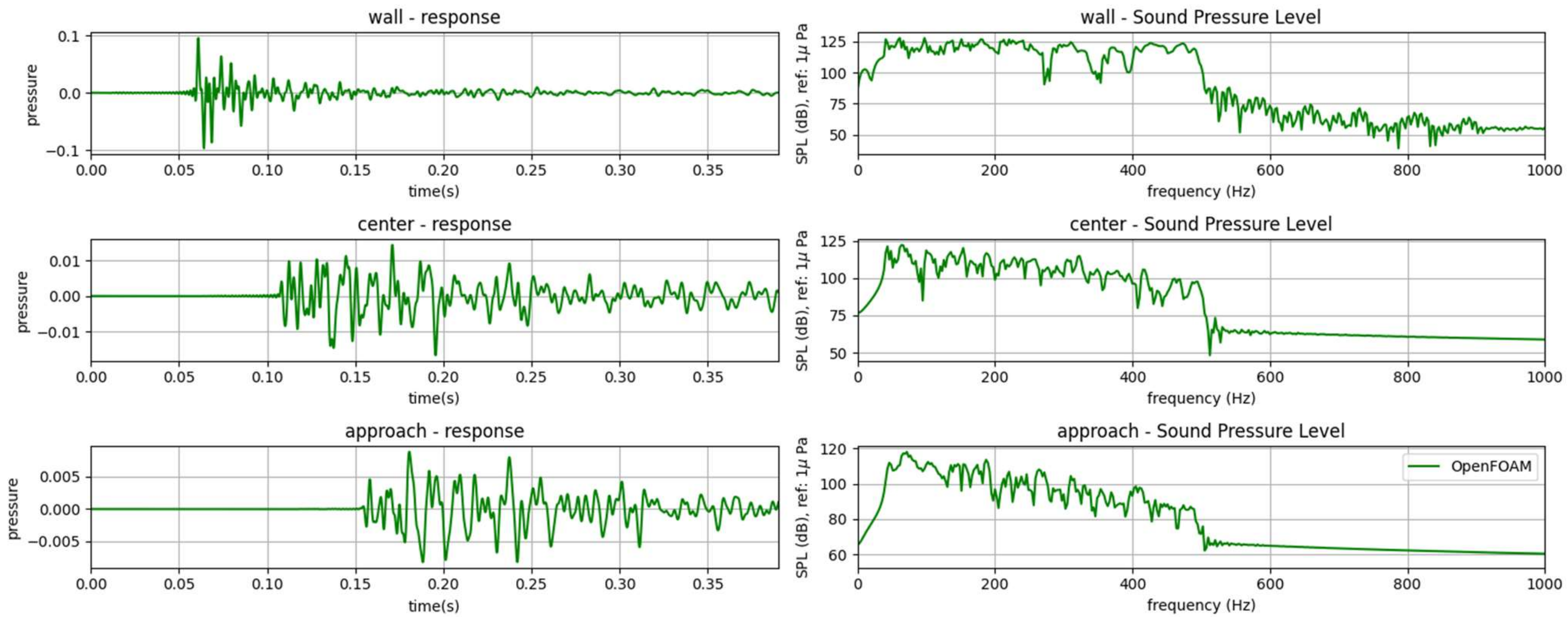

Conclusion

- The simulation requirements for hydroacoustics are substantially more stringent than typical CFD
- Timestep dominates error, results are largely independent of mesh size

- Improved spectral response which equates to more accurate transfer function predictions
- Recognized probable sources of error in the simulation and ways to deal with them

- Future work should focus on developing higher order schemes in OpenFOAM

Acknowledgment

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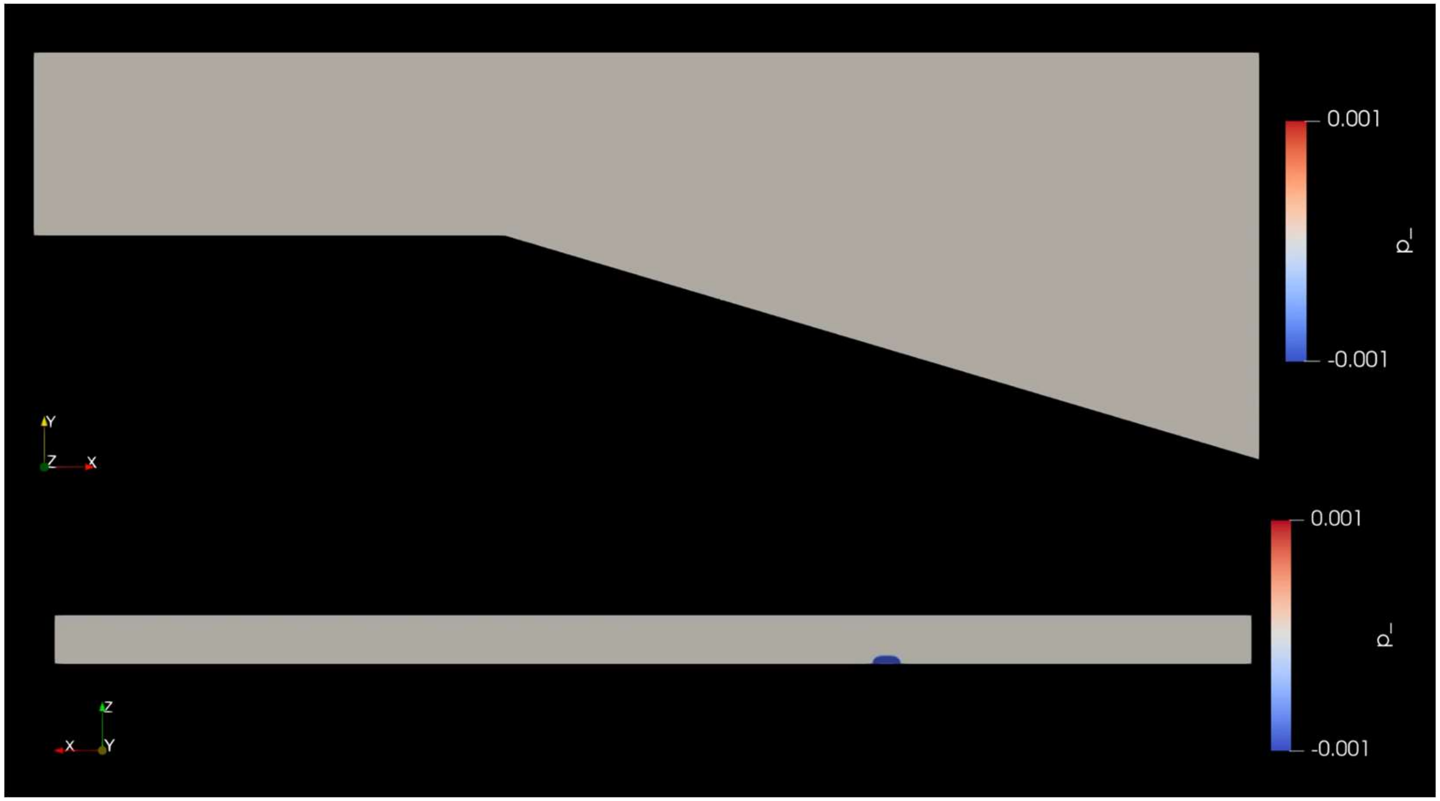
- Advanced Research Computing at Virginia Tech for providing computational resources and technical support

Questions?



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