MILPER

Hydro-acoustic Simulations using OpenFOAM

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ITU AYOC 2014 - Milper Pervane Teknolojileri

Company Profile

- MILPER is established in 2011 as a Research and Development company in Istanbul.
- MILPER is located in Teknopark Istanbul which is the largest technology research area project of Turkey.
- MILPER's main focus is design, development and production of propeller and associated propulsion systems for sea vehicles.
- Along with propeller and shaft systems, MILPER also works on design and acoustic analysis of exhaust silencers, which is another branch that needs advanced engineering and analysis backgrounds.
- MILPER also develops a propeller design software, which combines multiple propeller design jobs like series propeller design and wake adapted propeller design in one software package.

Company Profile

- MILPER’s mission is to be a leader propeller and shaft design company in Turkey, and to be a R&D center in Ship Building, Defense, Aerospace, Energy and Maritime sectors.

- MILPER’s vision is to be a pioneering company in design, analysis, optimization and project management using our advanced engineering and analysis capabilities, including computational fluid dynamics, structural, acoustic and vibrational analysis in Turkey and Europe.

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Hydro-acoustics

- Hydro-acoustics: Propagating sound in water
- Ffowcs Williams-Hawkings equation: Analysis of sound generated by a body moving in a fluid

$$
\begin{aligned}
D^2\, p'(x,y) = {} & + \frac{\partial}{\partial t}\left[\rho_0\, \nu_N + \rho\,(u_N - \nu_N)\delta(f)\right] \\
& - \frac{\partial}{\partial x_i}\left[\Delta P_{ij} n_j + \rho u_i (u_N - \nu_N)\,\delta(f)\right] \\
& + \frac{\partial^2}{\partial x_i \partial x_j}\left[Tij\; H(f)\right]
\end{aligned}
$$

  - Three source terms appear because when both the bounding surfaces and the turbulence are compact relative to the radiated length scales, the turbulence is acoustically equivalent to a volume distribution of moving quadrupoles and the surfaces to dipole and monopole distributions.

Hydro-acoustics

- D is the D'Alembert operator:

$$D^2 = \frac{1}{c_0^2}\frac{\partial^2}{\partial t^2} - \nabla^2$$

- T_{ij} is the Lighthill stress tensor:

$$T_{ij} = \rho u_i u_j + P_{ij} - c_0^2\,(\rho - \rho_0)\,\delta_{ij}$$

- P_{ij} is compressible stress tensor:

$$P_{ij} = p\delta_{ij} + \mu\left(-\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} + \frac{2}{3}\frac{\partial u_k}{\partial x_k}\right)\delta_{ij}$$

$$\Delta P_{ij} = P_{ij} - \rho_0\,\delta_{ij}$$

FWH Equation

- Monopole term:

$$+\frac{\partial}{\partial t}\left[\rho_0 \, \mathrm{v}_N + \rho \, (u_N - \mathrm{v}_N)\delta(f)\right]$$

  - *Thickness*
  - *Body geometry and kinematics*
  - *Volume displacement effects when surfaces are moving*

  - u_N is velocity component normal to the surface
  - v_N is the surface velocity component normal to the surface.

FWH Equation

- Dipole term:

$$-\frac{\partial}{\partial x_i}\left[\Delta P_{ij} n_j + \rho u_i (u_N - v_N)\,\delta(f)\right]$$

  - *Loading*
  - *Load distribution upon the blades*
  - *Surface distributions*

  - u_i is the fluid velocity component in x_i direction
  - n_j is the unit normal vector pointing toward the exterior region

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FWH Equation

- Quadrupole term:

$$\frac{\partial^2}{\partial x_i \partial x_j}\,[\,Tij\;H(f)]$$

  - *Non-linear influences in the flow field*
  - *Becomes dominant at high speed flow (hypersonic & supersonic regimes) in aero-acoustics*
  - *Underwater physics might be different*
    - *Cavity occurs even for propellers with low rotational speed*
    - *Cavity bubbles yield shock waves*
    - *Therefore sound is generated*

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Reduced Quadrupole Term

- For incompressible cases:
  - Cancel out the monopole and dipole terms
  - Reduce the Lighthill stress term to:

$$T_{ij} = \rho\, u_i u_j$$

  - Therefore the quadruple term:

$$\frac{\partial^2}{\partial x_i \partial x_j} = \rho\, u_i u_j$$

  - As a result FWH equation we have becomes:

$$\frac{1}{c_0^2}\frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = \frac{\partial^2}{\partial x_i\, \partial x_j}(\rho\, u_i u_j)$$

Acoustic Boundary Conditions

- According to Wagner (2007): ”Because the radiation boundary condition is based on the asymptotic expansion of the solution, it works best if the nonreflecting boundary is far away from the source of the sound”
- Appropriate choice for our problem since it avoids an increase in the total energy of the system by using non-reflective condition.

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OpenFOAM

- Open source CFD tool
  - C++ library based on FVM
  - No licence costs
  - No GUI
  - Runs on Unix systems
  - Easy to develop new solvers, turbulence models etc.

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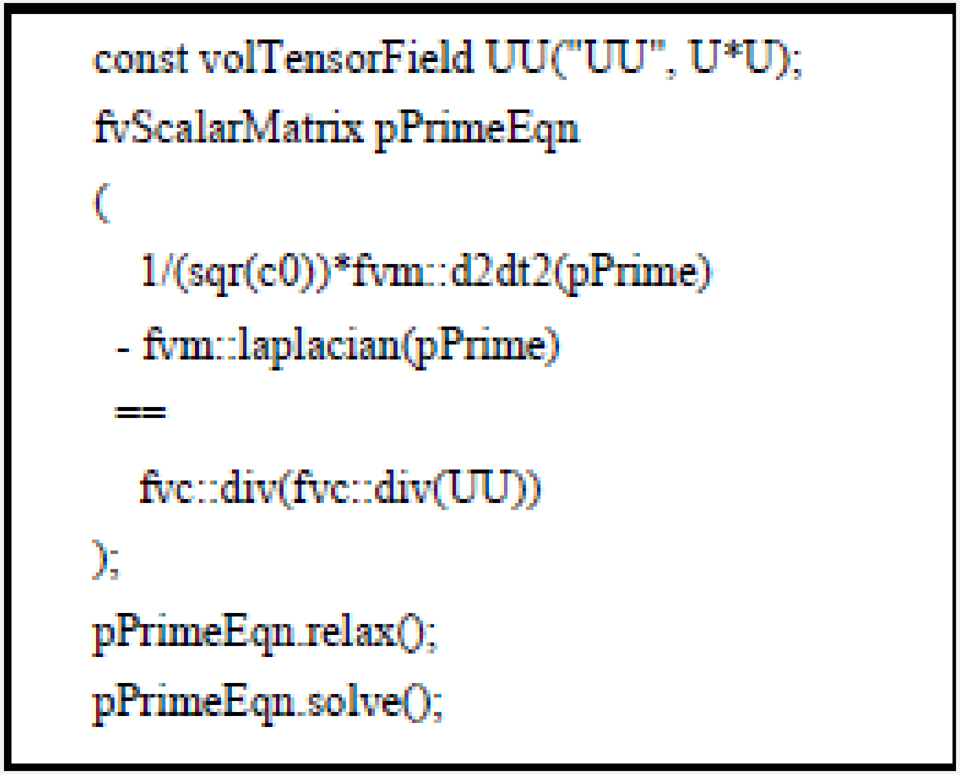
Equation Mimicing in OpenFOAM

- Reduced FWH provided is represented by the following code:



```
const volTensorField UU("UU", U*U);
fvScalarMatrix pPrimeEqn
(
   1/(sqr(c0))*fvm::d2dt2(pPrime)
 - fvm::laplacian(pPrime)
 ==
   fvc::div(fvc::div(UU))
);
pPrimeEqn.relax();
pPrimeEqn.solve();
```

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Acoustic Perturbation Equations

- A different approach derived by Ewert and Schröder:

$$\frac{\partial \rho'}{\partial t} + \nabla \cdot (\rho' \bar{u} + \bar{\rho} u') = 0$$

$$\frac{\partial u'}{\partial t} + \nabla \bar{u} \cdot u' + \nabla \left(\frac{p'}{\bar{\rho}}\right) = q_m$$

$$\frac{\partial p'}{\partial t} + \frac{1}{c^2} \nabla \cdot (\rho' \bar{u} + \bar{\rho} u') = q_e$$

where

$$q_m = -(\omega \times \overline{u} + \overline{\omega} \times u') + T' \nabla s - s' \nabla \overline{T}$$

$$q_e = \frac{\gamma \overline{p}}{c_p} \frac{\partial s'}{\partial t}$$

Acoustic Perturbation Equations

- u is velocity, ω is vorticity, ρ is density, T is temperature, p is pressure, s is entropy and γ is ratio of specific heats:

$$\gamma = \frac{c_P}{c_V}$$

- The coupling between the LES and acoustics is based on the source terms.
- Appropriate LES resolution is still too high in terms of computational complexity
- Timestep needed for acoustics might be larger than CFD hence one can call acoustic solver after a certain number of CFD loops.

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Workflow

- Current solution procedure implemented:
  - Run potentialFoam or icoFoam
  - Call acoustic solver based on reduced FWH and read CFD pressure
  - Compute acoustic pressure fluctutations

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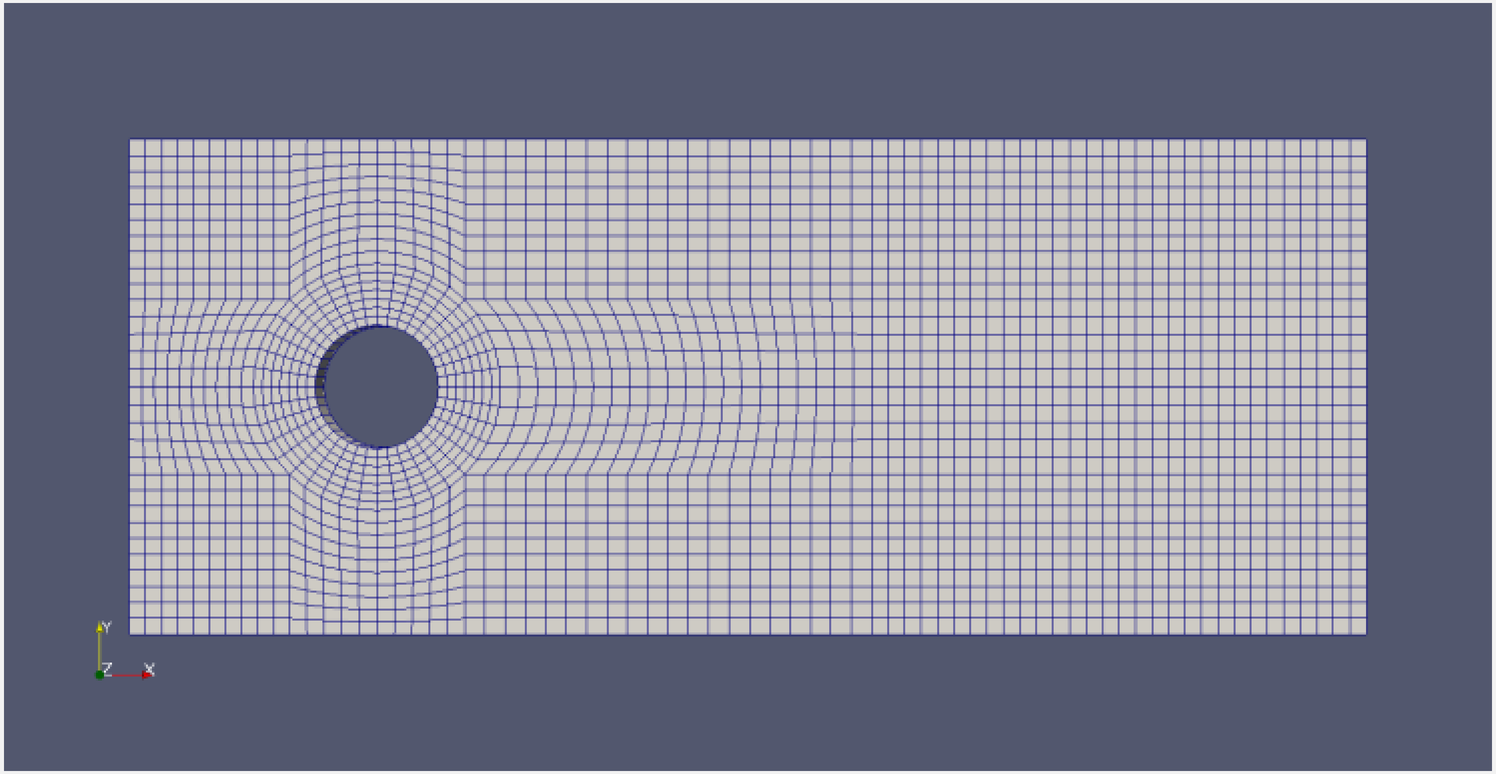
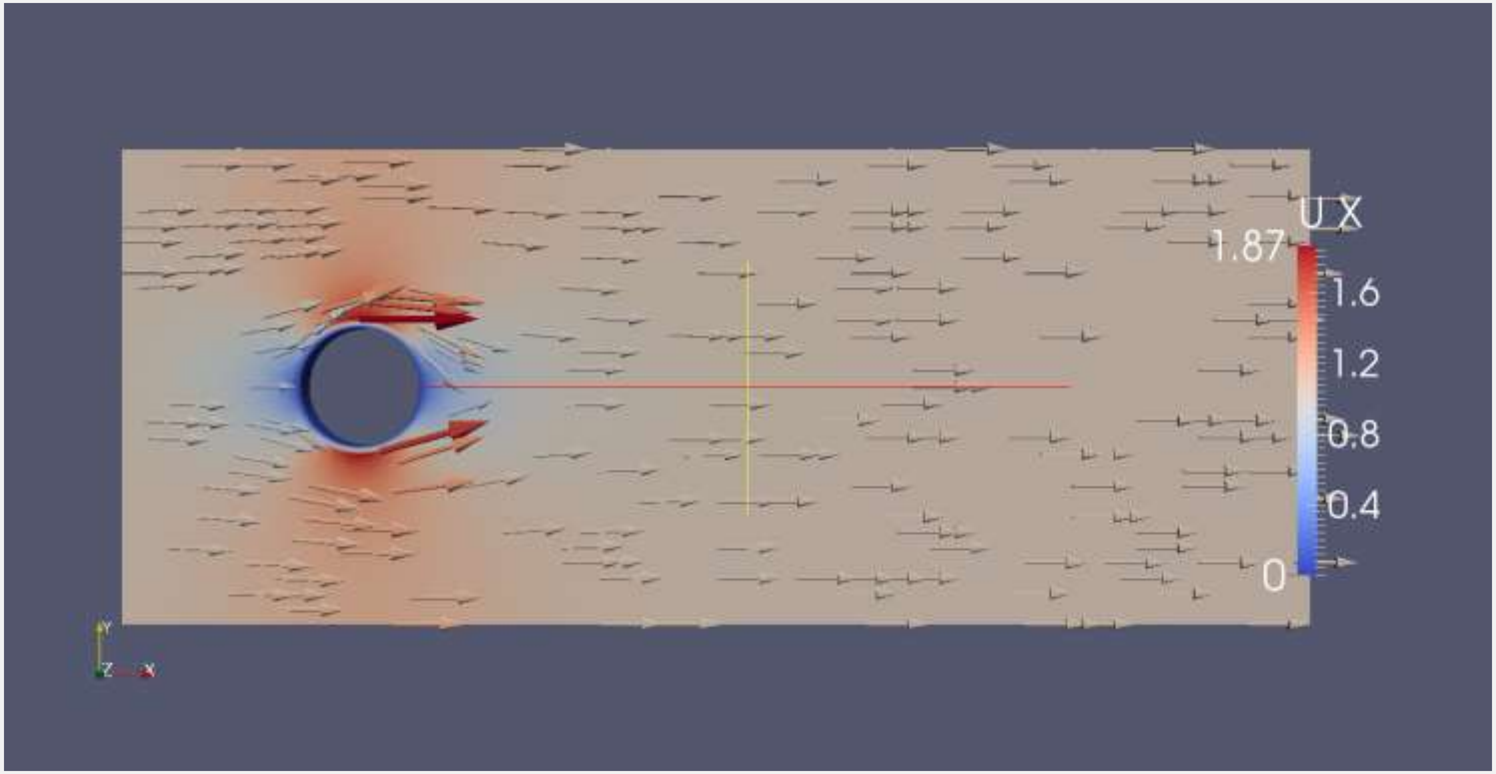
Results

- Various simulations run on a simple cylindrical grid:



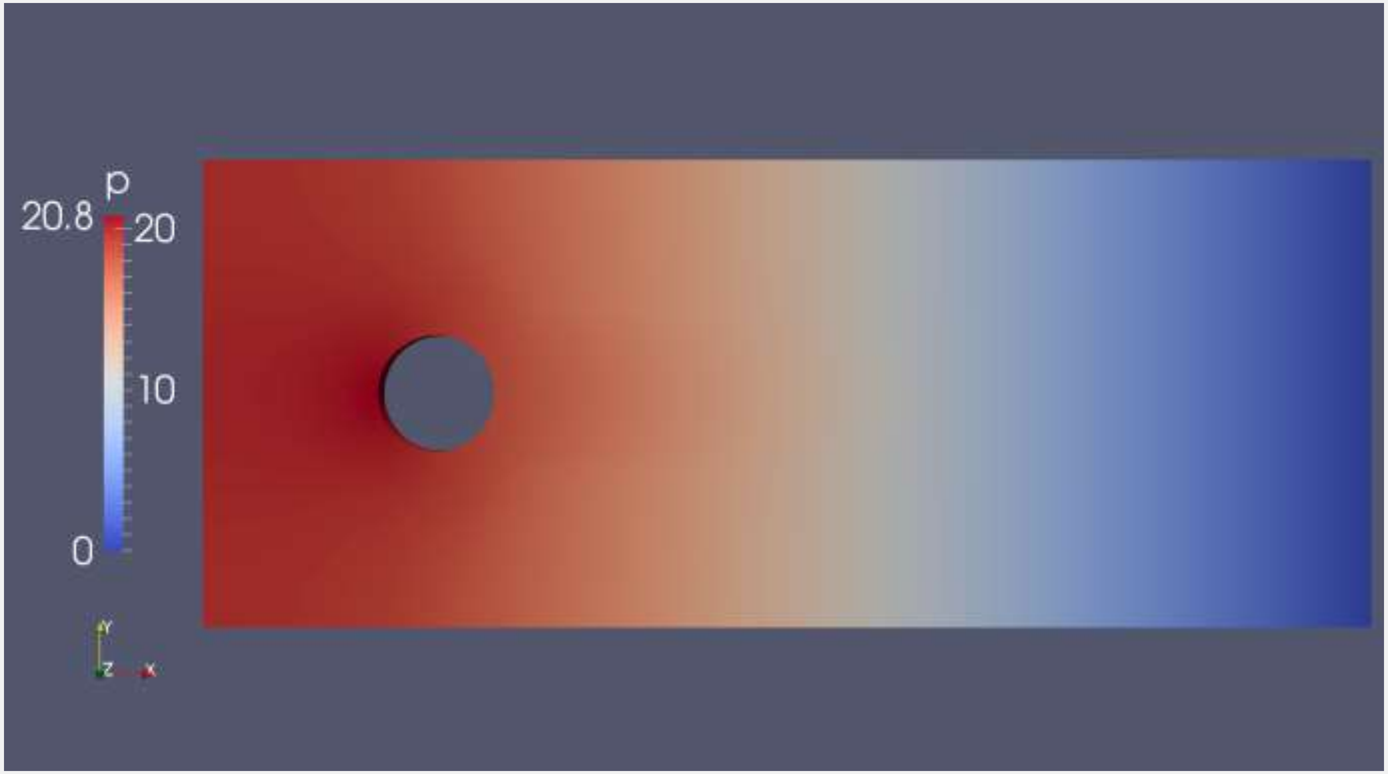
Results

- Using potentialFoam:



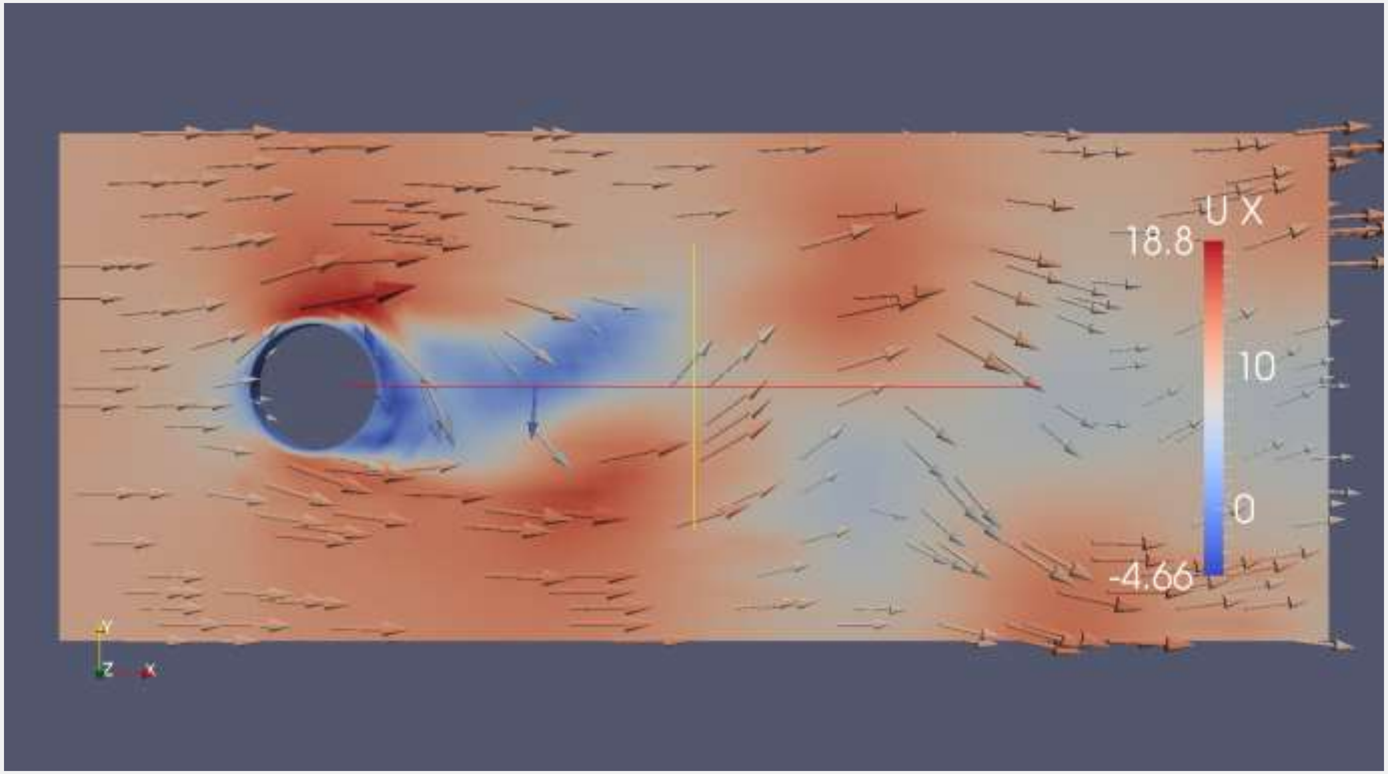
Results

- Using acousticsFoam after potentialFoam:



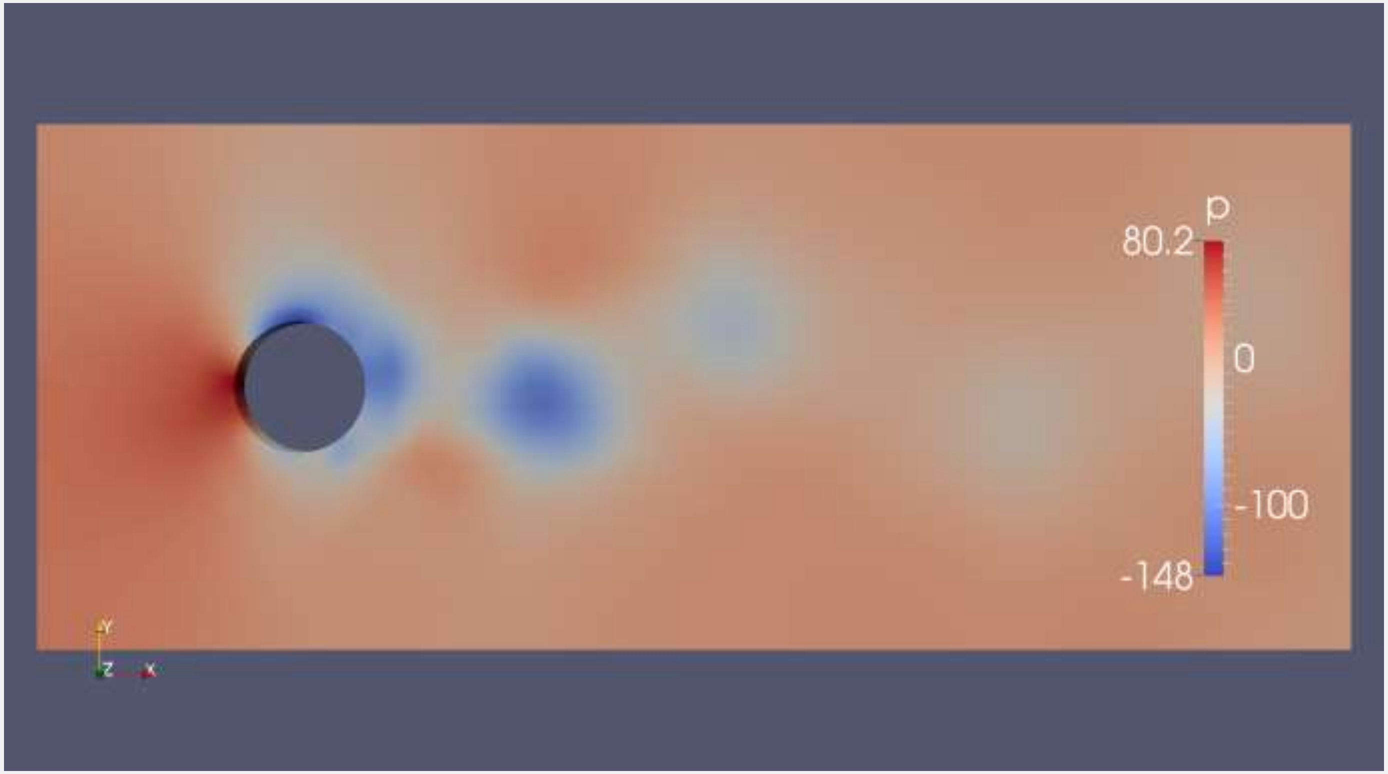
Results

- Using icoFoam:



Results

- Using acousticsFoam after icoFoam:



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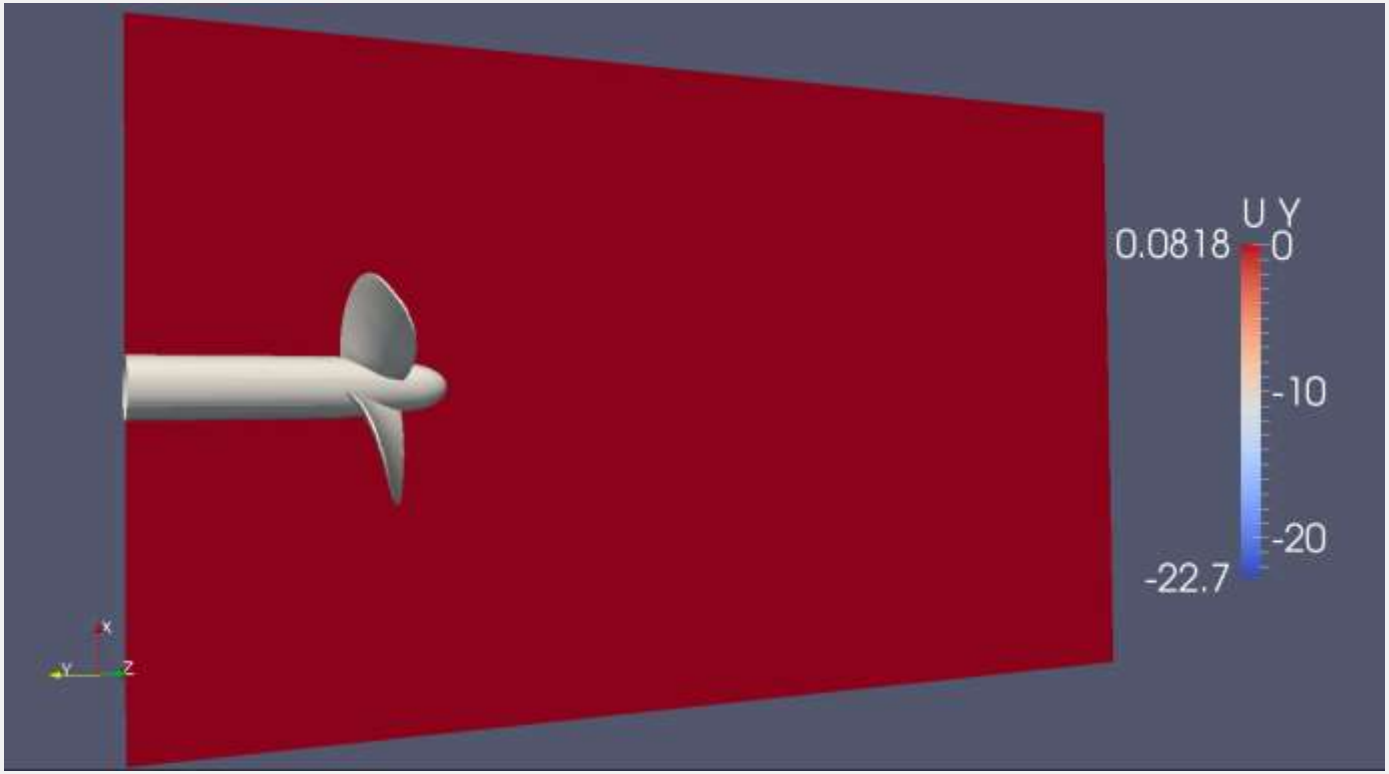
Results

- Using interPhaseChangeDyMFoam:



Results

- Unphysical pressure distribution due to the restricted assumptions of potential solver
- However a new solver implemented, compiled and tested without any errors which is under constant development.
- Current implementation task is to validate icoFoam and acoustics solver coupling

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Future Work

- To validate the icoFoam and acoustic pressure fluctutation distribution for cylinder cases
- Implementation of FWH equation as proposed in the original paper by Williams and Hawkings (1968)
- Implementation of APE proposed by Ewert and Schröder (2003)
- Coupling transient multiphase CFD and Acoustics using LES
- Application to propellers
- Apply FFT to obtain sound spectrum

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Thank you.

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