GPU-based SPH Modeling of Sub-Surface Wave Energy Converters

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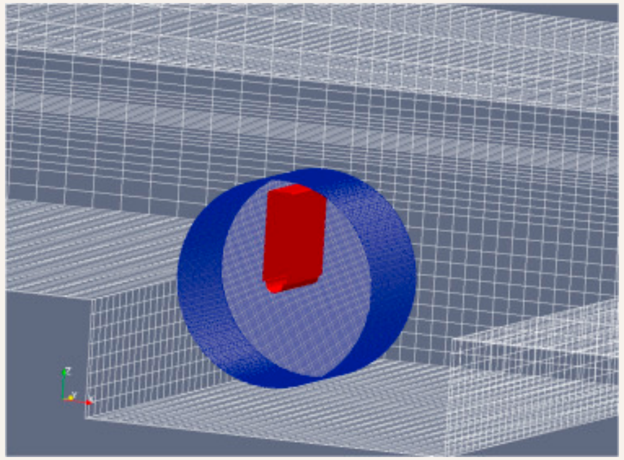
Overview

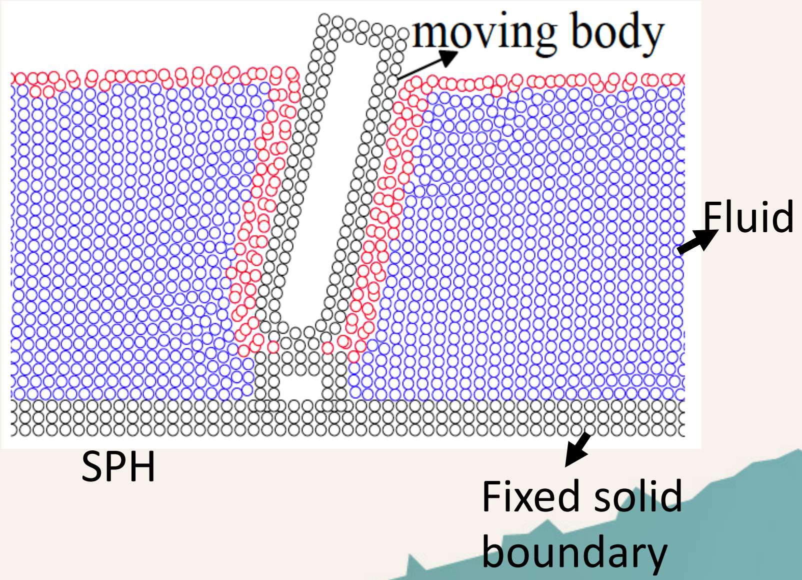
- Modeling Frameworks
  - Inviscid Models
  - CFD
- SPH Formulation (GPUSPH - beta.gpusph.org)
- Ongoing Work
  - Sub-Surface WECs

Conventional Frameworks

- Inviscid/Linear Models
  - Computationally efficient
  - Requires tuning
    - Does not directly resolve viscous fluid flows
- CFD
  - Mesh-based Eulerian Framework
    - Utilizes mesh-morphing or arbitrary mesh interfaces (AMI) for object interfaces
  - SPH Lagrangian Framework



AMI Mesh (Schmitt et al, 2015)



SPH

SPH Formulation

Implicit

Explicit

Eulerian formulation

Conservation of mass

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{u}) = 0$$

Incompressible fluid: $\nabla.\mathbf{u} = 0$

Conservation of momentum

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}.\nabla \mathbf{u} = -\frac{1}{\rho}\nabla(p+\tau) + \mathbf{g} + \nu \nabla^2 \mathbf{u}$$

Pressure

Poisson equation:

$$\nabla^2 p = f(\nu, \mathbf{u})$$

Free surface detection

VOF method:

$$\frac{\partial \Phi}{\partial t} + \nabla.(\mathbf{u}\Phi) = 0$$

Lagrangian formulation

$$\frac{1}{\rho}\frac{d\rho}{dt} = -\nabla.\mathbf{u}$$

$$\frac{d\mathbf{u}}{dt} = -\frac{1}{\rho}\nabla(p+\tau) + \mathbf{g} + \nu \nabla^2 \mathbf{u}$$

Equation of State:

$$p = \frac{c_0^2 \rho_0}{\gamma}\left[(\frac{\rho}{\rho_0})^\gamma - 1\right]$$

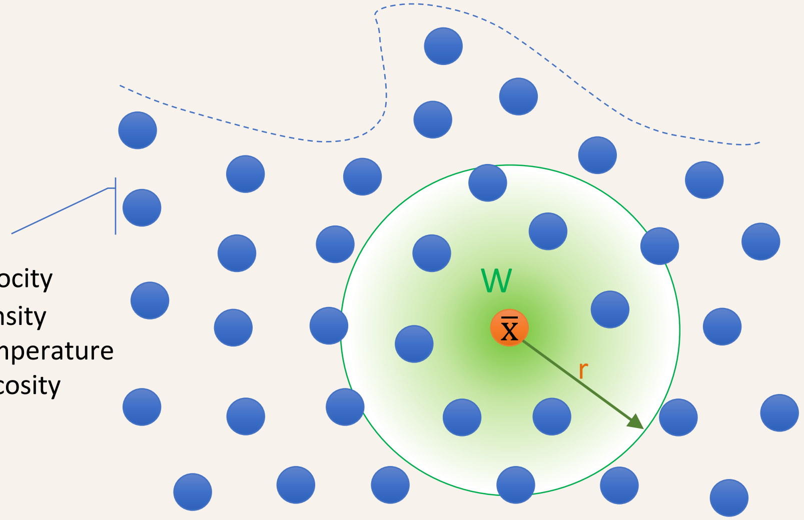
Intrinsic

SPH

SPH Kernel

- Critical to SPH is the kernel approximation of quantities (velocity, pressure, etc…)
- Gradients transfer to the kernel

- Velocity
- Density
- Temperature
- Viscosity
- etc

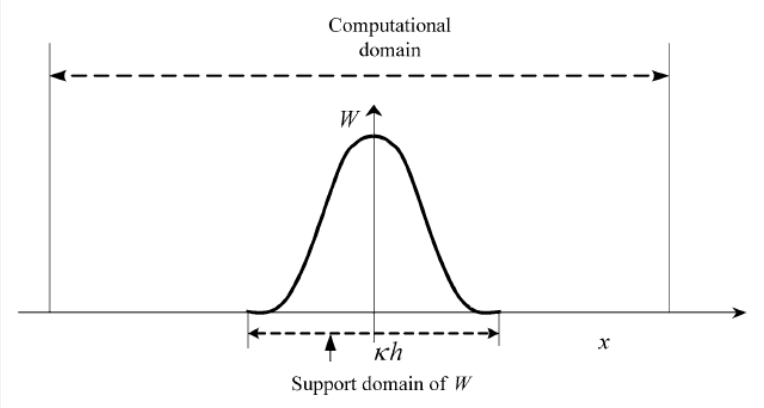


Kernel approximation of derivatives

$$\langle \nabla \cdot f(\boldsymbol{x}) \rangle = \int_{\Omega} [\nabla \cdot f(\boldsymbol{x}')] W(\boldsymbol{x} - \boldsymbol{x}', h) d\boldsymbol{x}' = -\int_{\Omega} f(\boldsymbol{x}') \cdot \nabla W(\boldsymbol{x} - \boldsymbol{x}', h) d\boldsymbol{x}'.$$

$$= -\sum_{j=1}^{N} \frac{m_j}{\rho_j} f(\boldsymbol{x}_j) \cdot \nabla W(\boldsymbol{x} - \boldsymbol{x}_j, h),$$

SPH kernel

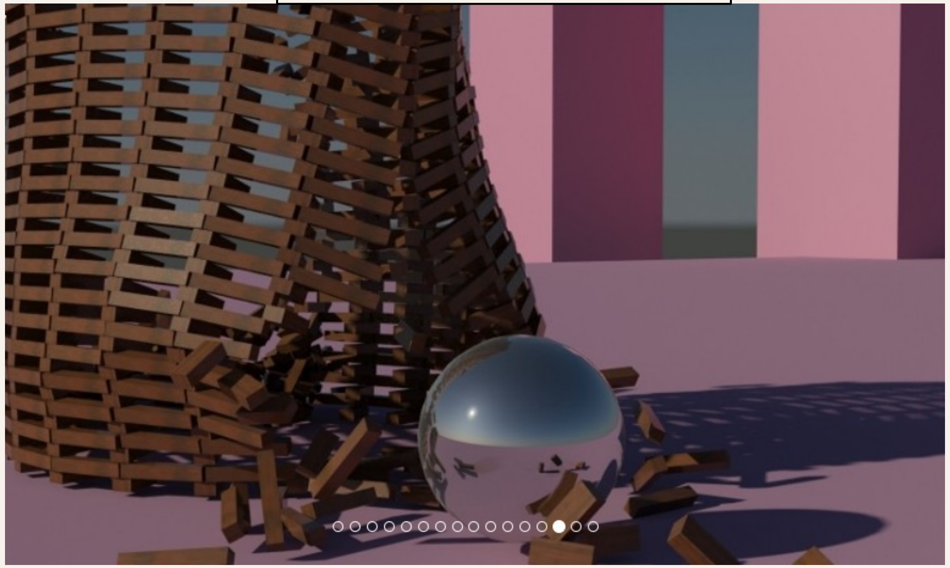


SPH Recap

GPUSPH

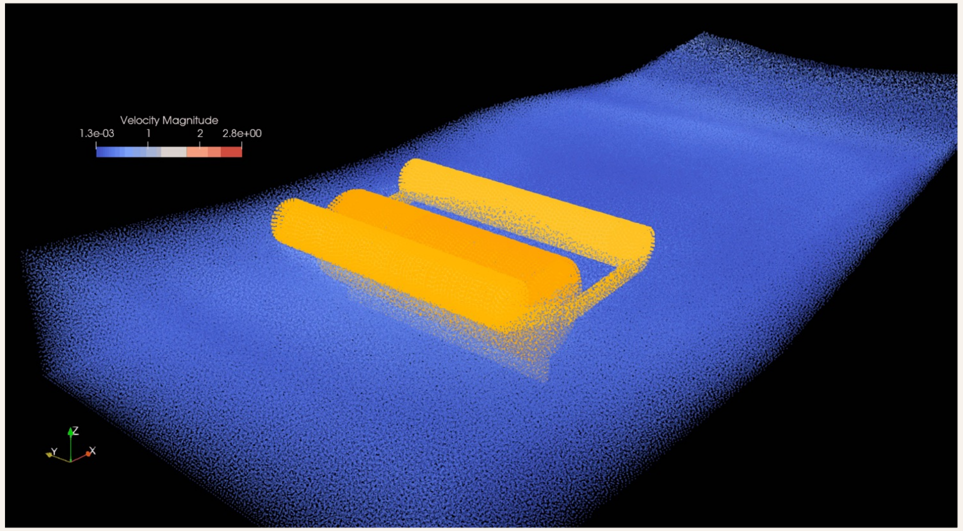
- Smoothed Particle Hydrodynamics (SPH), a Lagrangian mesh-free method. Some advantages include:
  - Mesh-free means no explicit surface tracking
  - Lagrangian explicit formulation
  - Large Eddy Simulation (LES)
  - Can couple with multi-physics engines
    - Project Chrono

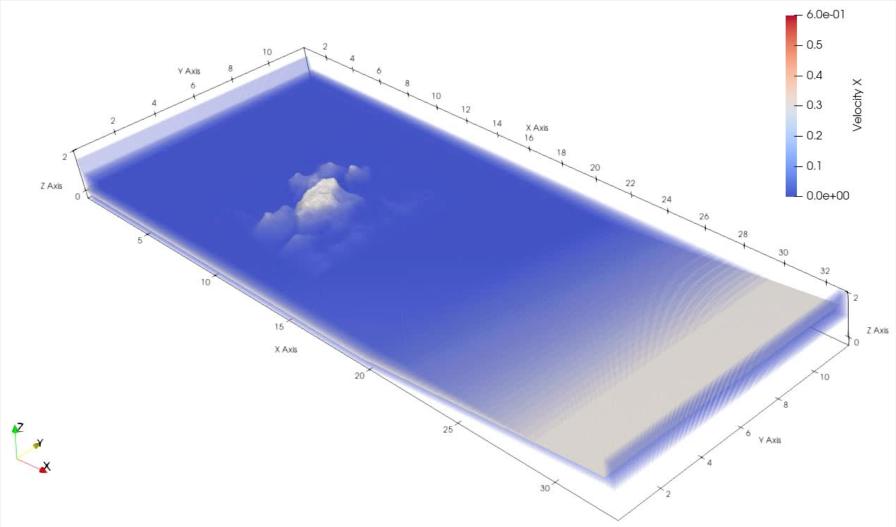
Project Chrono



General GPUSPH Examples

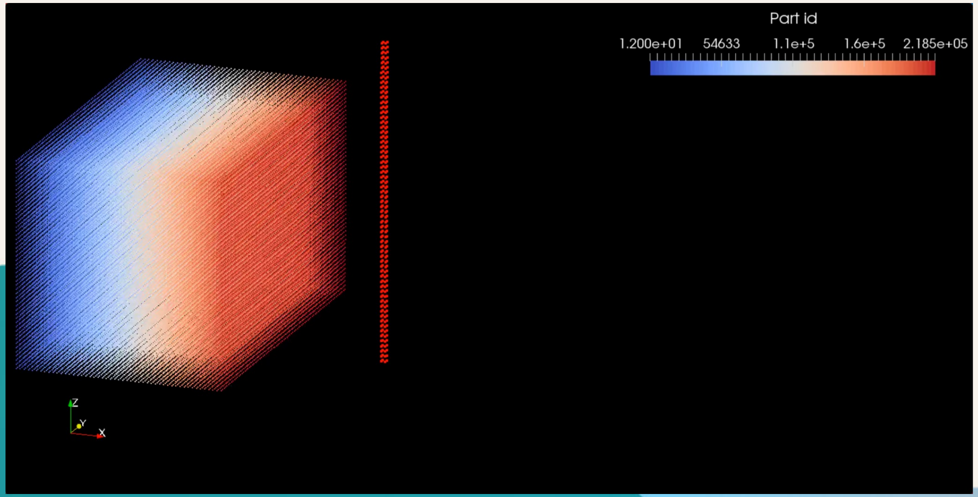
WEC-UUV

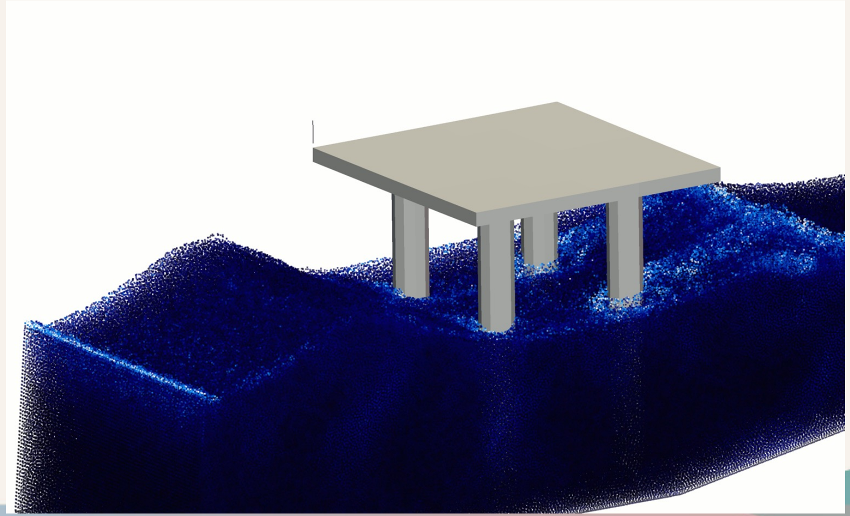




Waves over a rock outcropping

Flexible fluid structure interaction

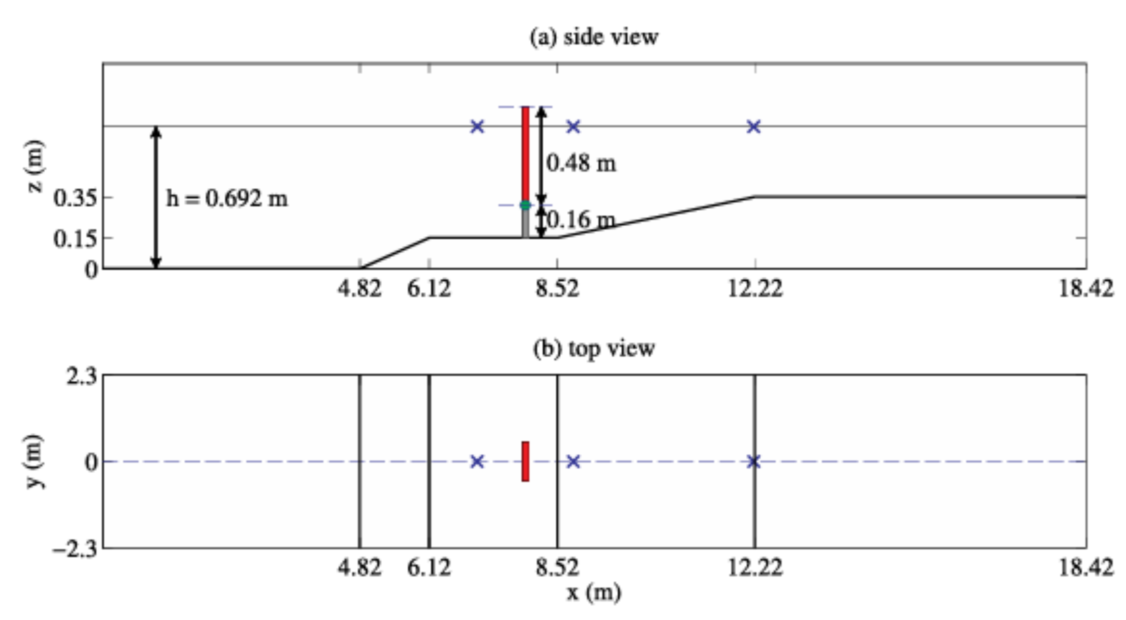


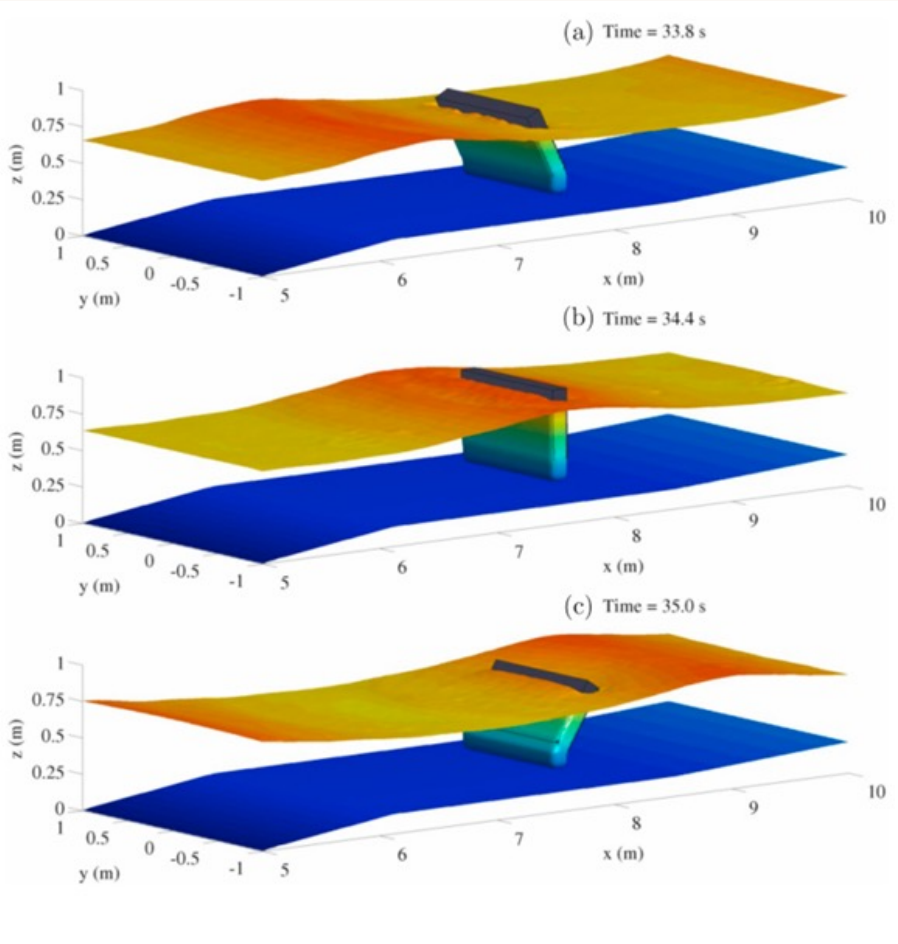


Flexible Offshore Platform

GPUSPH Model Validation

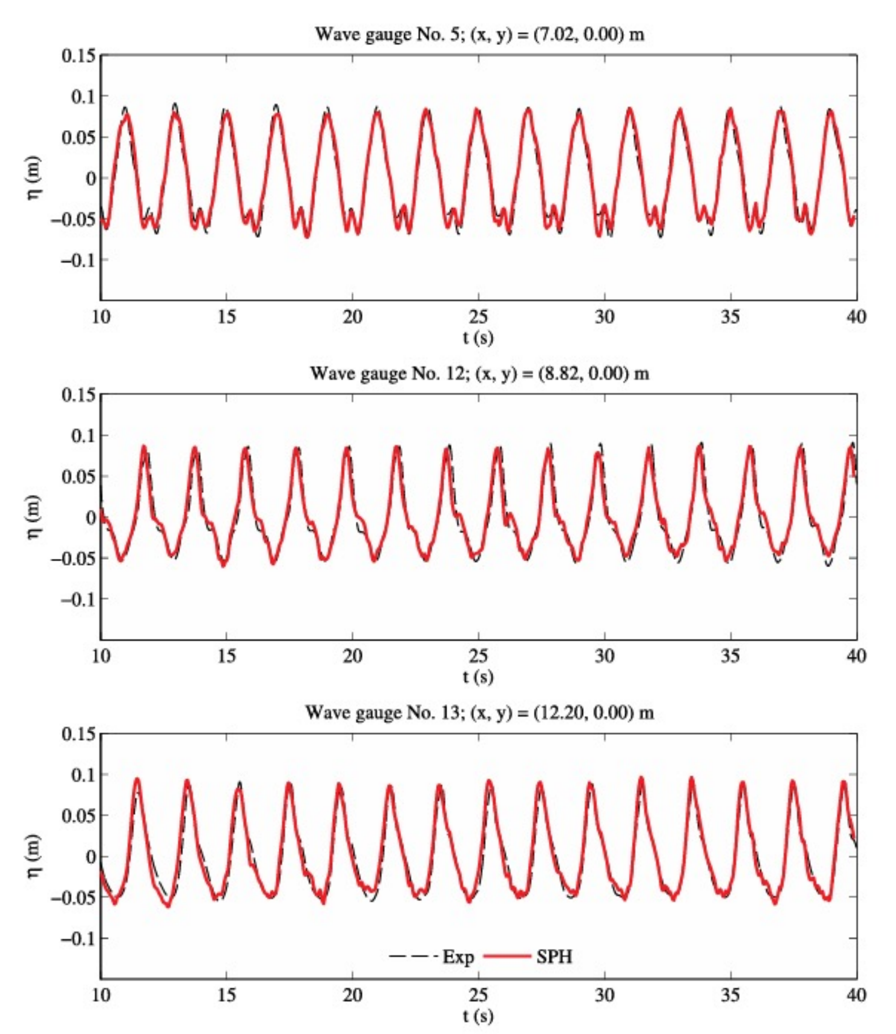
- Several validation studies exist
  - One example is (Wei et al, 2019)

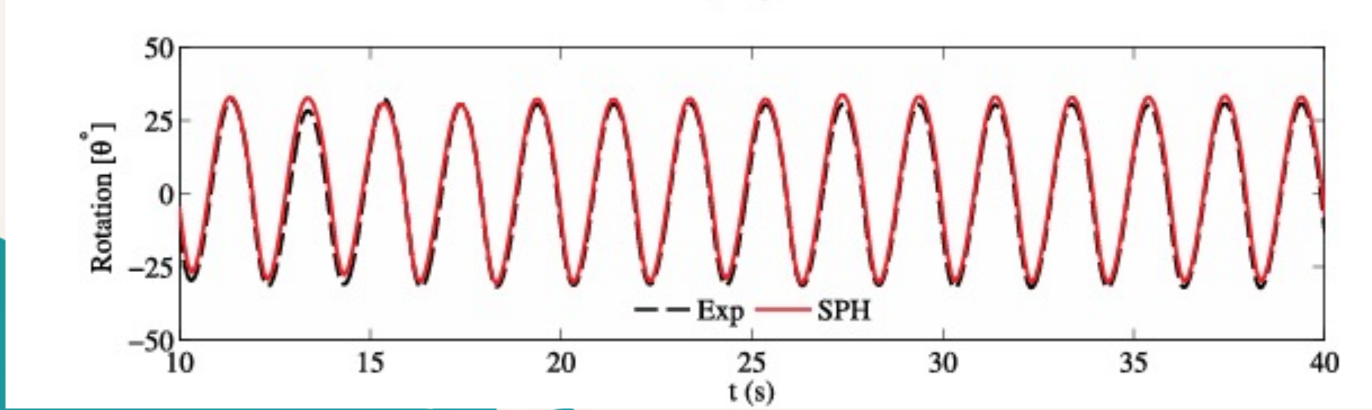




Model Validation Results

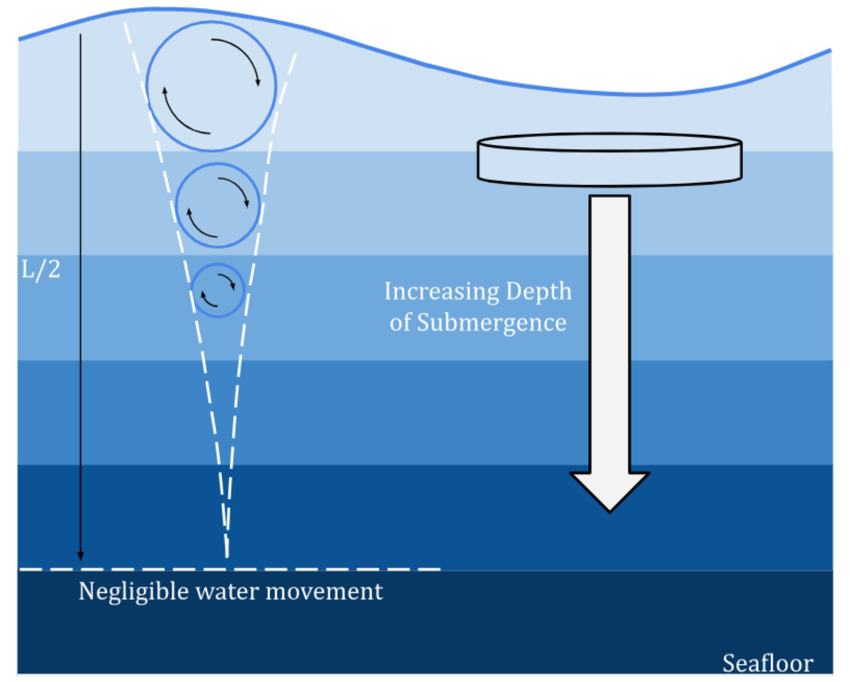
- Wave forcing matched experimental results well
- Additionally, rotation had only slight variation



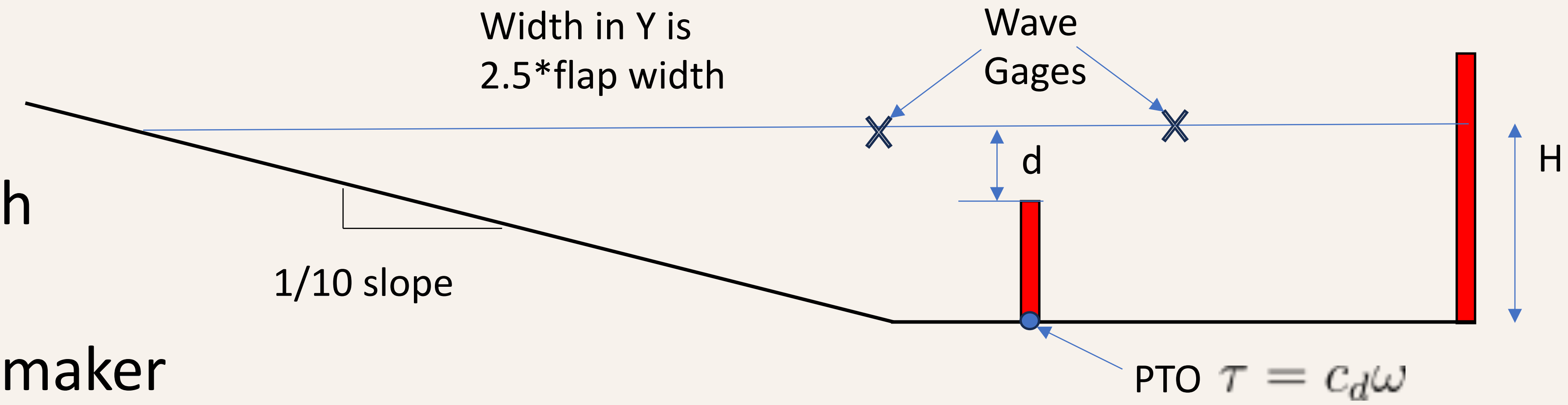


Ongoing Work – Motivation and Goals

- Motivation
  - Reduces surface expression
  - Enhances survivability
    - Reduction of Ship-WEC interactions
    - More consistent wave forcing
  - Reduction in power density
- Goals
  - Understand the dynamics and power generation as a function of submergence depth

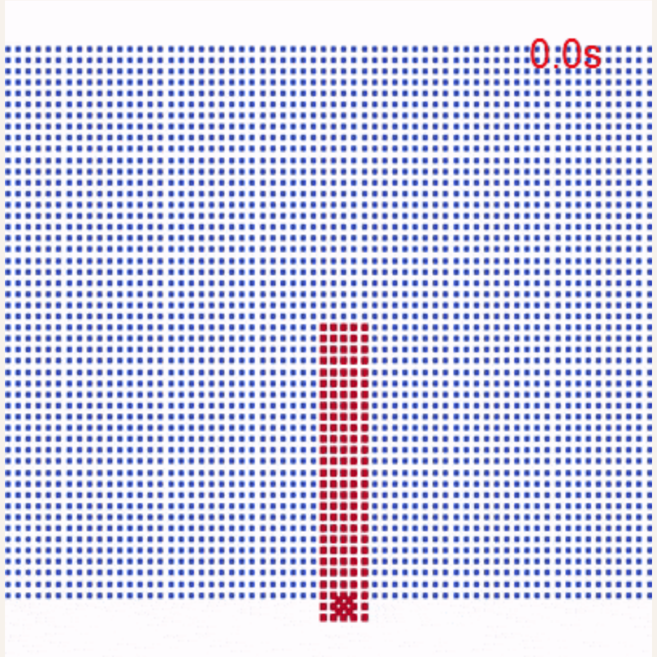


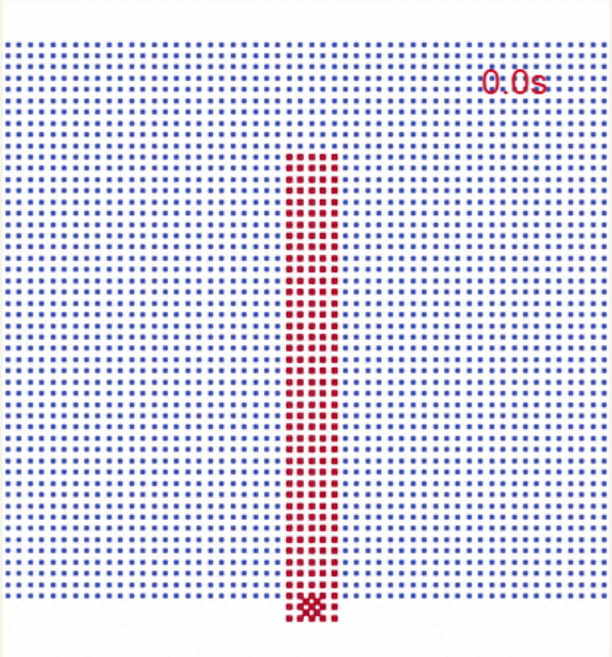
Ongoing Work - Domain



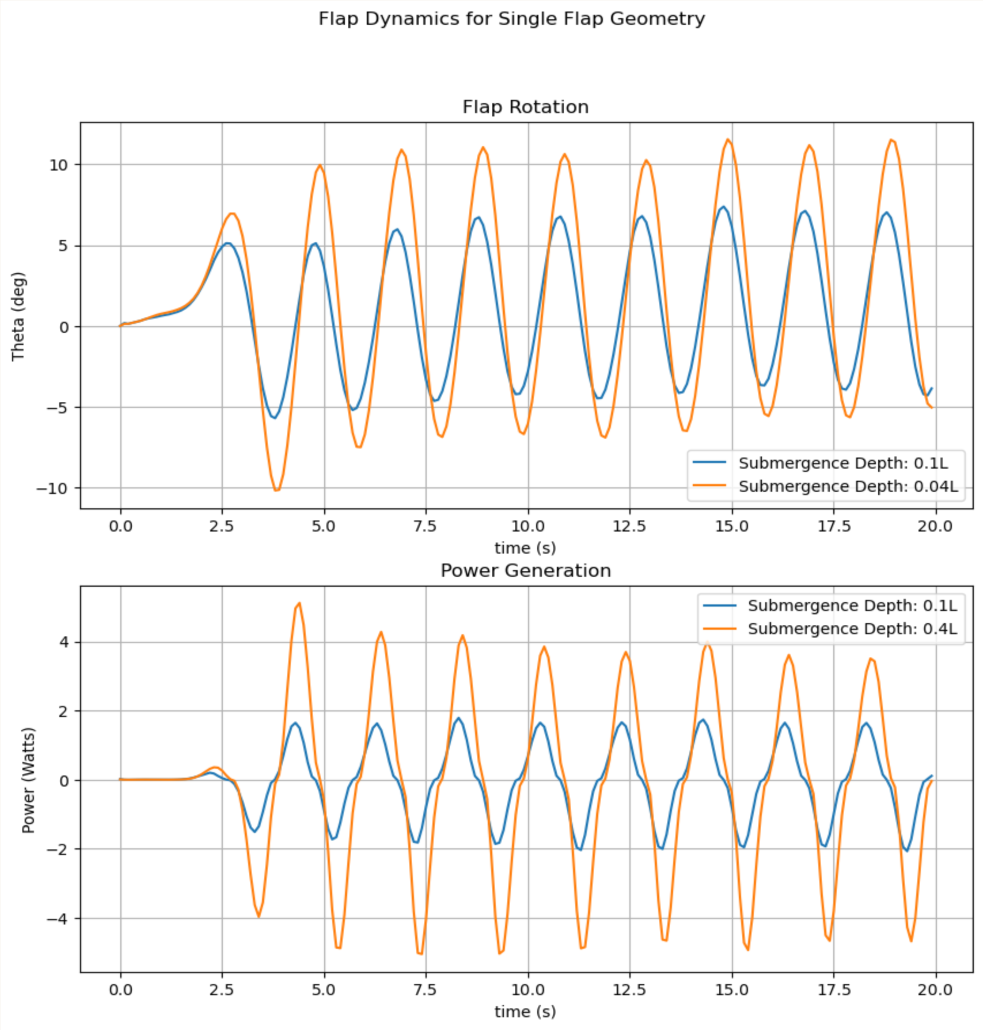
- 3D domain with Periodic BC
- Arbitrary wavemaker and wave profile
- Custom PTO and solid body constraints

Ongoing Work - OSWEC

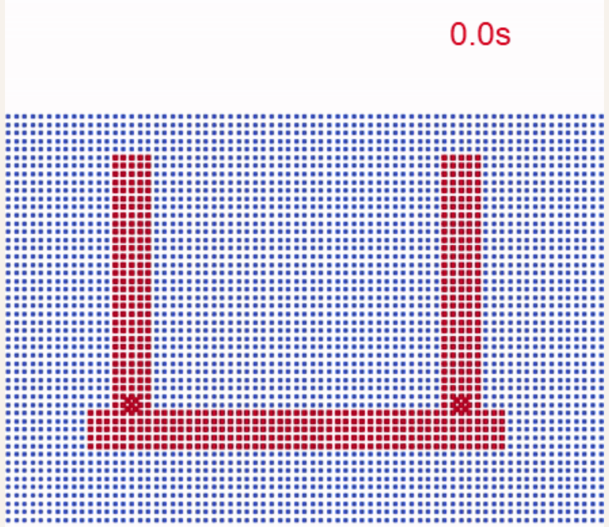


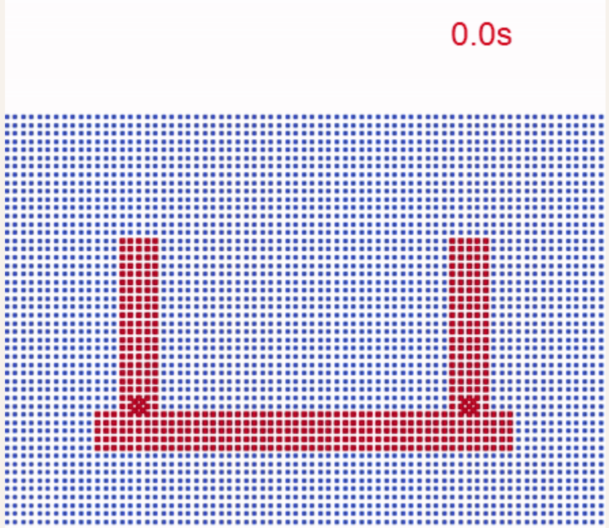


Color scale is velocity magnitude



Ongoing Work – Dual Flap





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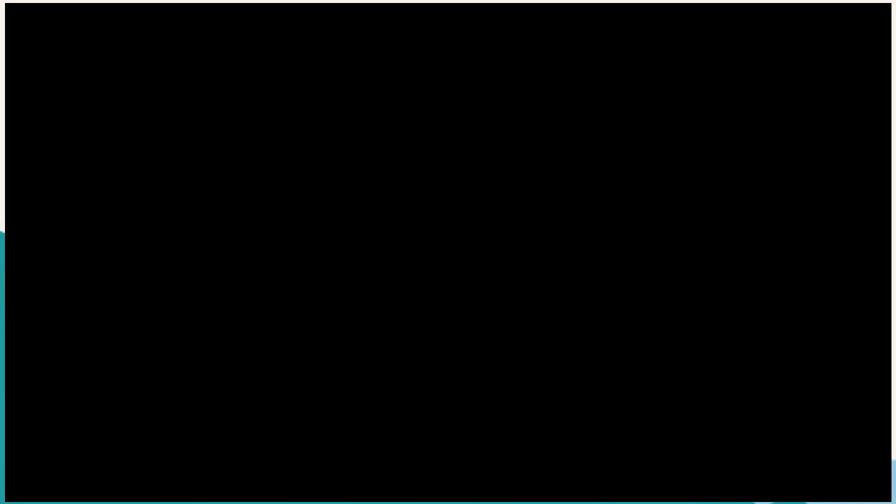
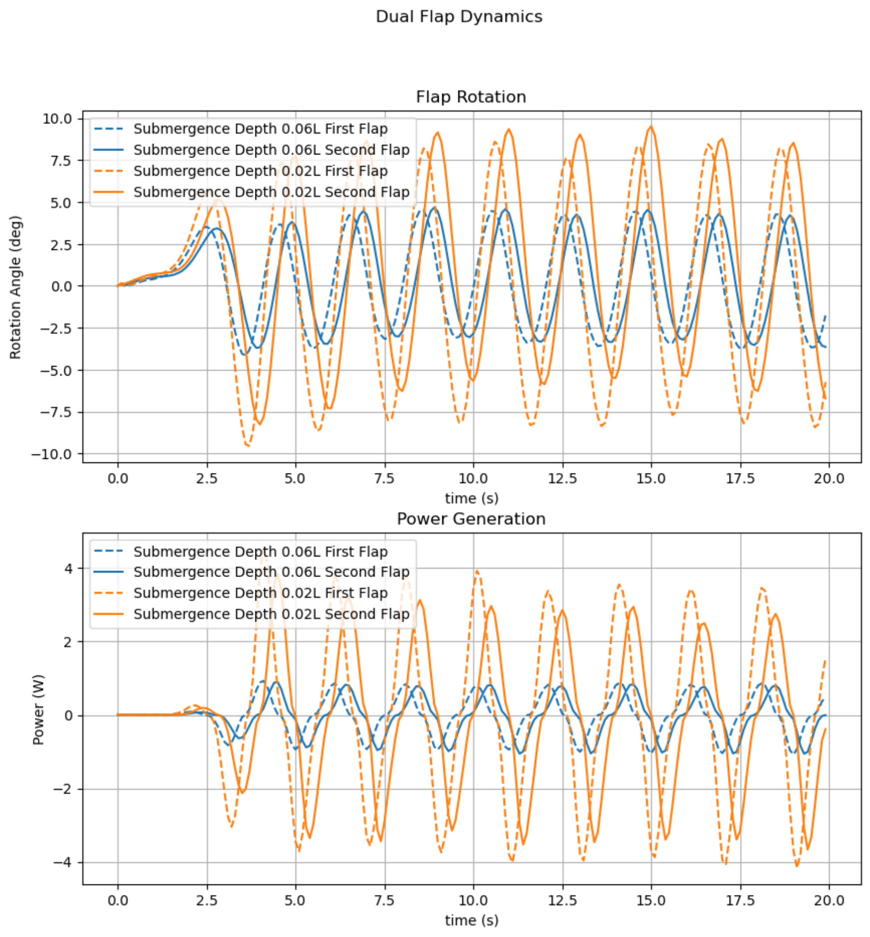
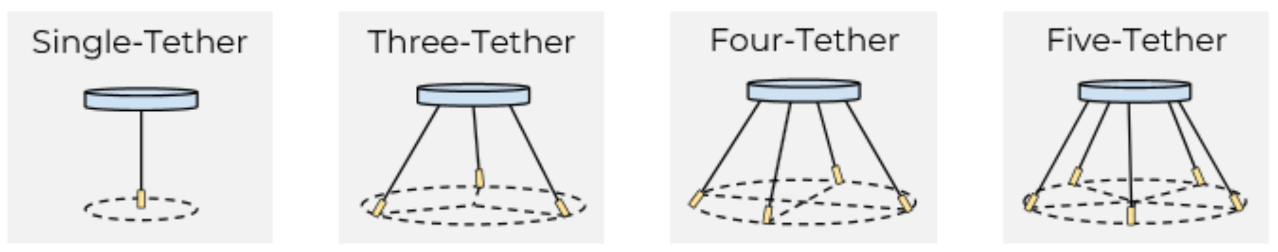
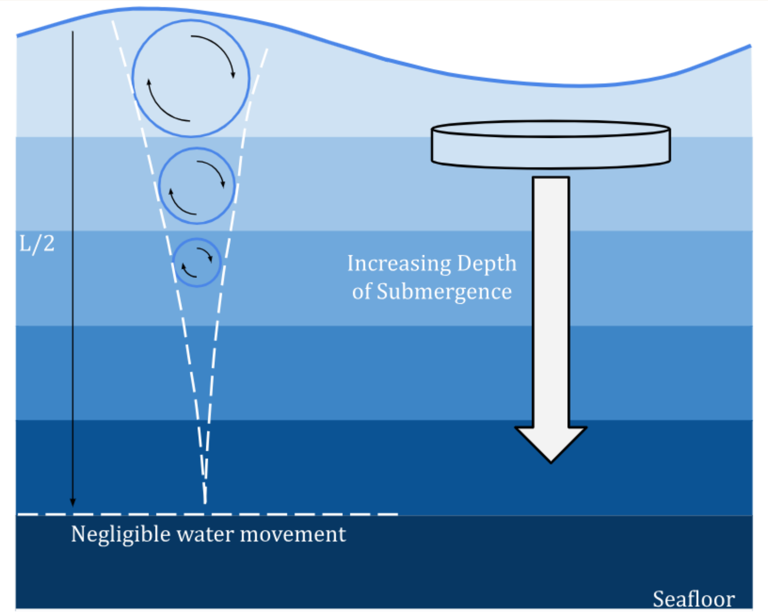
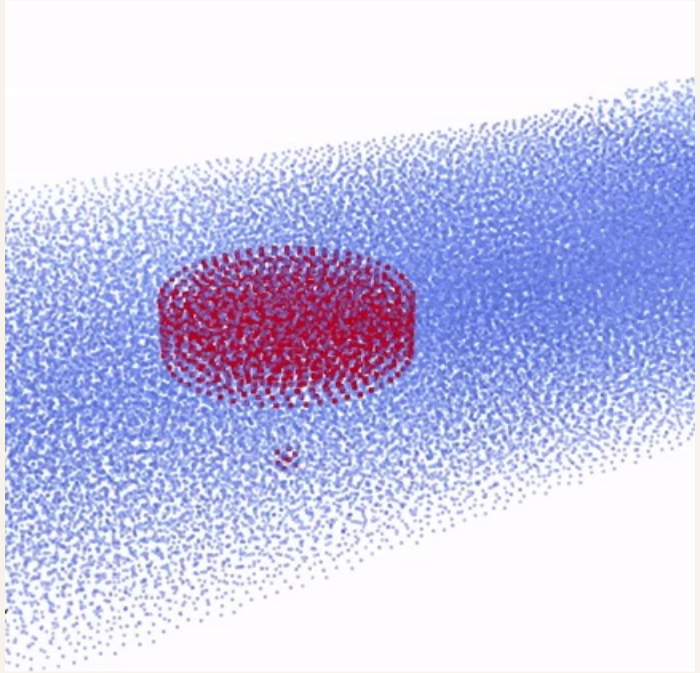




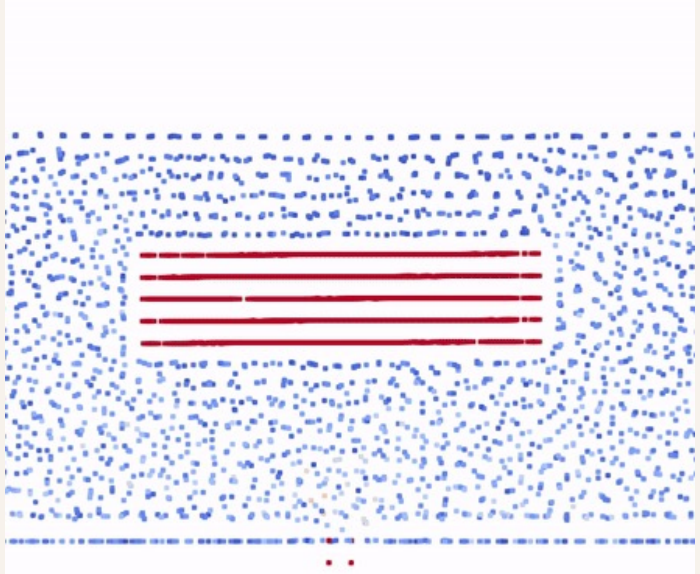
Ongoing Work - Float WEC







Isometric View

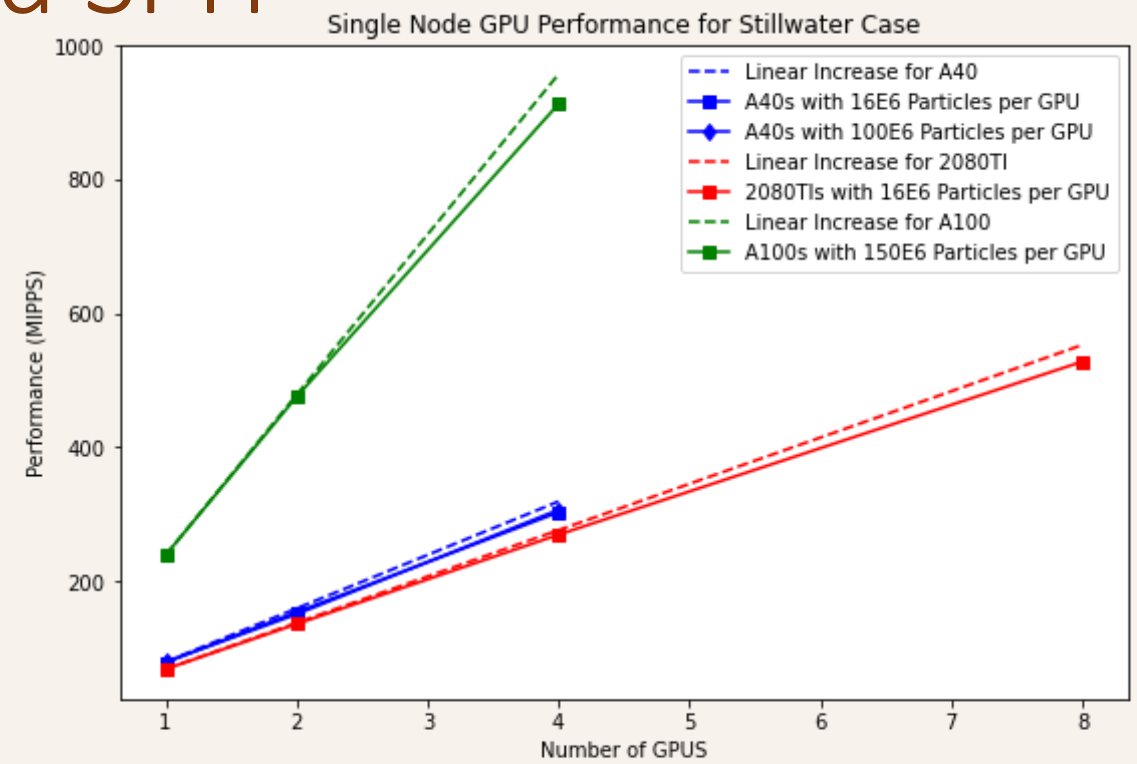


2D Slice

Color scale is velocity magnitude

Conclusion - GPU-based SPH

- Explicit formulation allows for parallel computing on GPU nodes
- GPU capacity is limited by DRAM
- Speed scales with GPU number at ~85% efficiency



NVIDIA GEFORCE <u>RTX 2080 TI</u> GPU
- 11GB GDDR6 Memory
- FP32 performance: 13.4 TFLOPS
- NVIDIA CUDA Cores: 4,352
- ~$500

Conclusion

- Significant work still needs to be done especially in boundary condition improvements
- SPH is powerful CFD tool for complex geometries outside the reach of other frameworks
- Rapid advancement in GPU power will correlate directly to resolvable domain and speed

Questions?

- Thank you!

References

Schmitt, P., & Elsaesser, B. (2015). On the use of OpenFOAM to model oscillating wave surge converters. Ocean Engineering, 108, 98-104.

Wei, Z., Edge, B. L., Dalrymple, R. A., & Hérault, A. (2019). Modeling of wave energy converters by GPUSPH and Project Chrono. Ocean Engineering, 183, 332-349.