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High Fidelity Simulations of Wave Energy Converters

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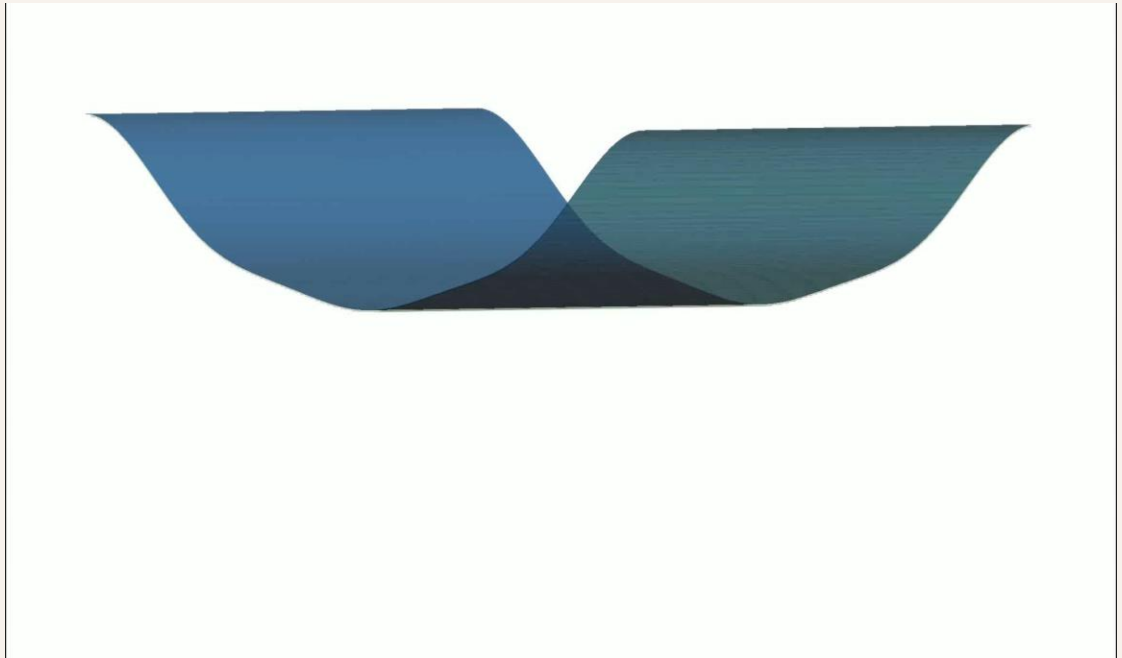
Outline

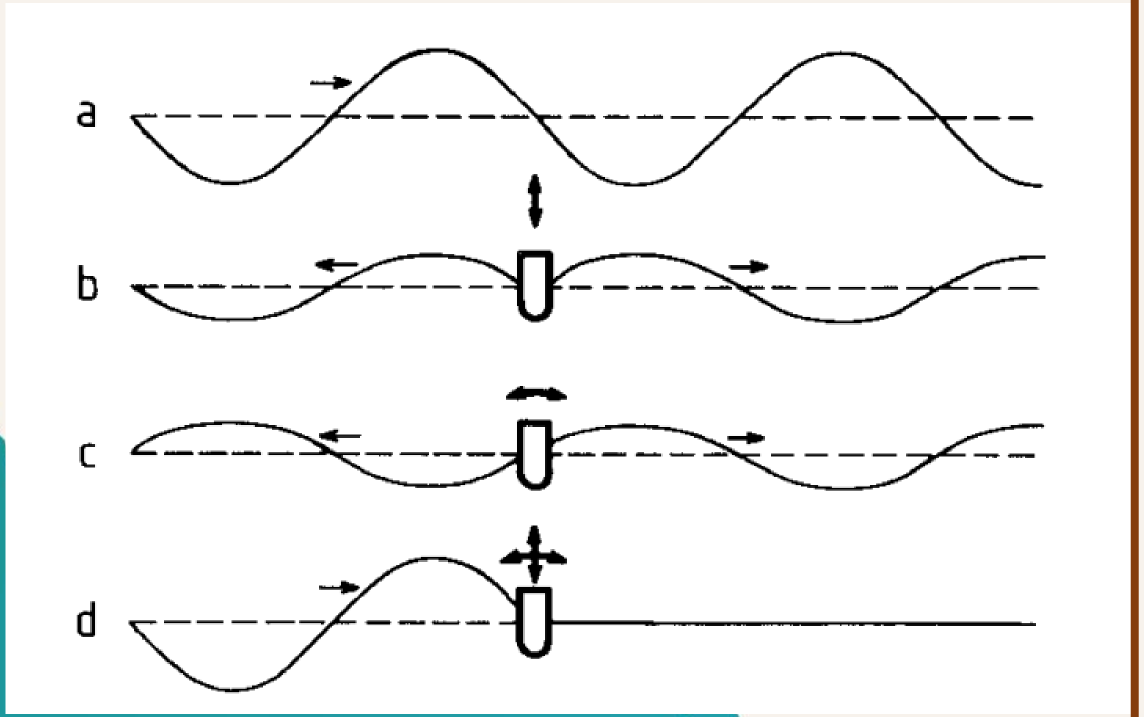

Plunging breaking wave with dilute gas transfer

- WEC introduction
- Computational framework
- Simulation set-up
- Control method analysis and results
- Future plans

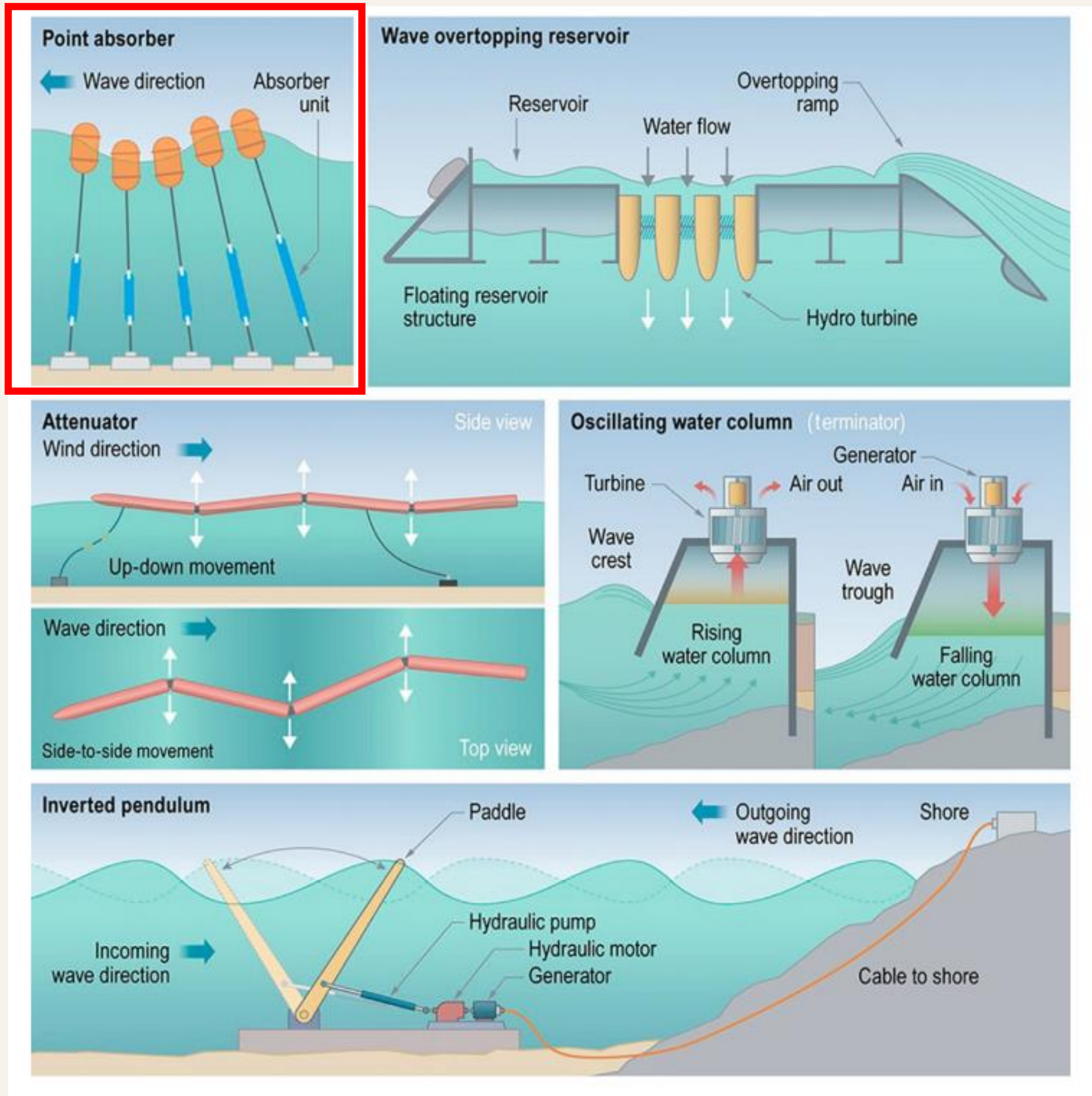
Point Absorber WEC

- Higher hydrodynamic efficiencies in oscillating WECs
- Point absorbers can absorb both vertical and horizontal oscillations
- Control and power take-off essential for efficiency

Wave Absorption and Radiation of a Buoy



Falnes (2004)

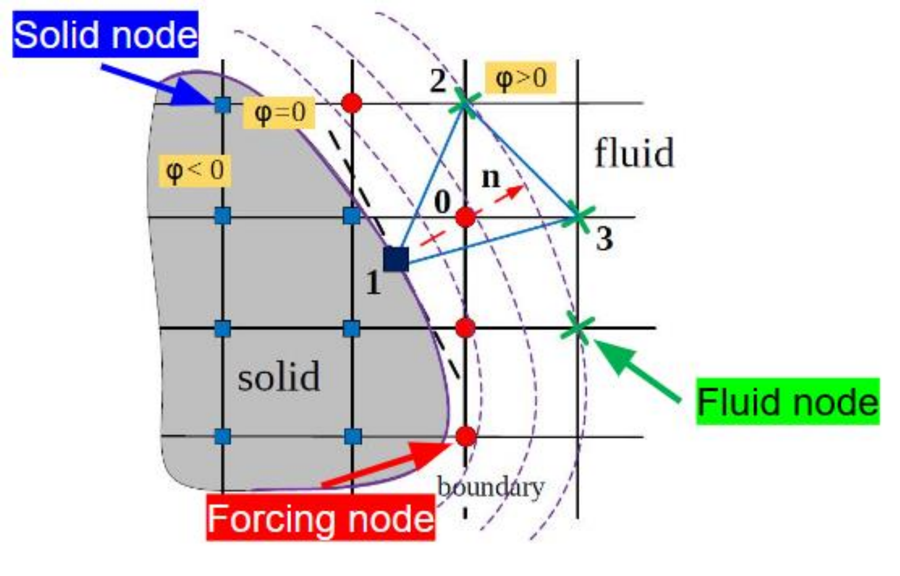


Neill and Hashemi (2018)

Computational Framework

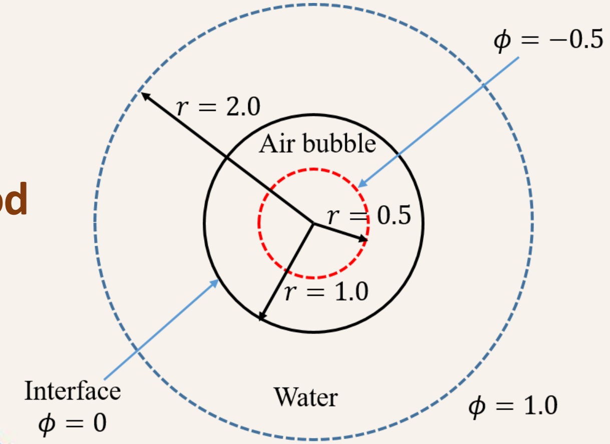
- In-house high-fidelity Computational Fluid Dynamics (CFD) code
- Simulation of the Navier-Stokes equations using the Finite Difference Method (FDM)
- A Cartesian rectangular grid with refinement capabilities
- Additional frameworks used:
  - For air-water interface, we use the coupled Level-Set and Volume-of-Fluid method (CLSVOF)
  - For fluid-structure interaction, we use the discrete Immersed Boundary (IB) method

Immersed Boundary Method

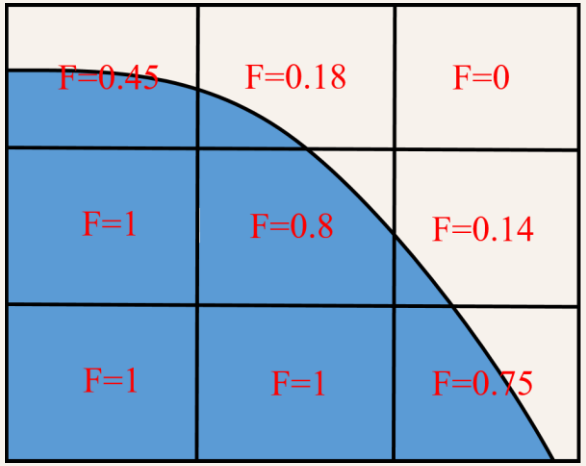


Cui et al. (2018)

Level-Set Method



Volume-of-Fluid Method



Validation of Our Code

- Our lab's fluid-structure interaction codes have been extensively validated against established computational and experimental results
- Previous publications:

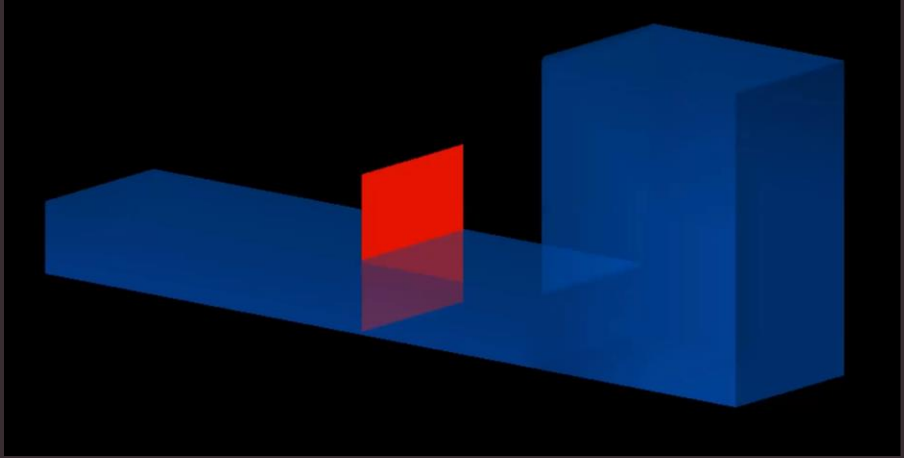
  •He, S., Liu, H. & Shen, L. (2022), "Simulation-based study of turbulent aquatic canopy flows with flexible stems," Journal of Fluid Mechanics, Vol. 947, A33.

  •Zeng, Y., Bhalla, A. & Shen, L. (2022), "A subcycling/non-subcycling time advancement scheme-based DLM immersed boundary method framework for solving single and multiphase fluid-structure interaction problems on dynamically adaptive grids," Computers and Fluids, Vol. 238, 105358.

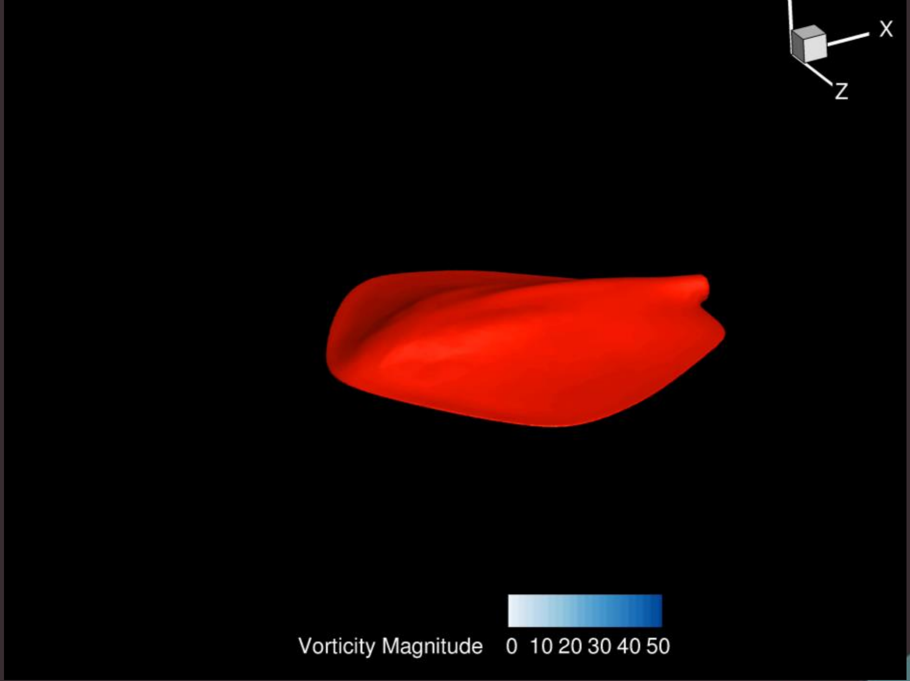
  •He, S., Yang, Z., Sotiropoulos, F. & Shen, L. (2022), "Numerical simulation of interaction between multiphase flows and thin flexible structures," Journal of Computational Physics, Vol. 448, 110691.

  •Calderer, A., Guo, X., Shen, L. & Sotiropoulos, F. (2018), "Fluid-structure interaction simulation of floating structures interacting with complex, large-scale ocean waves and atmospheric turbulence with application to floating offshore wind turbines," Journal of Computational Physics, Vol. 355, pp. 144-175.

  •Cui, Z., Yang, Z., Jiang, H., Huang, W. & Shen, L. (2017), "A sharp interface immersed boundary method for simulating incompressible flows with arbitrarily deforming smooth boundaries," International Journal of Computational Methods, Vol. 14, No. 2, 1750080.



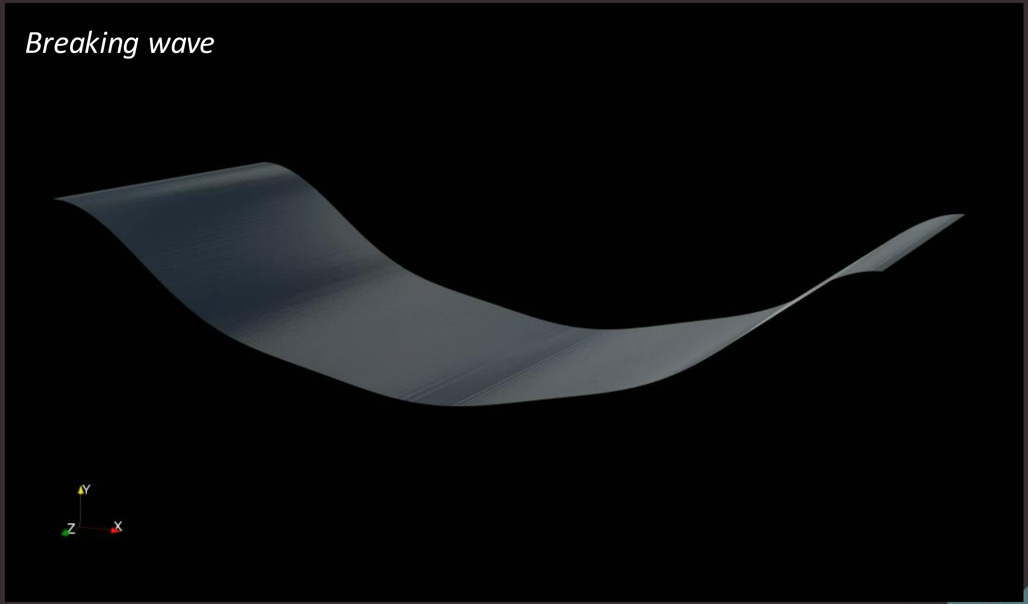
3-D dam break hitting a flexible plate



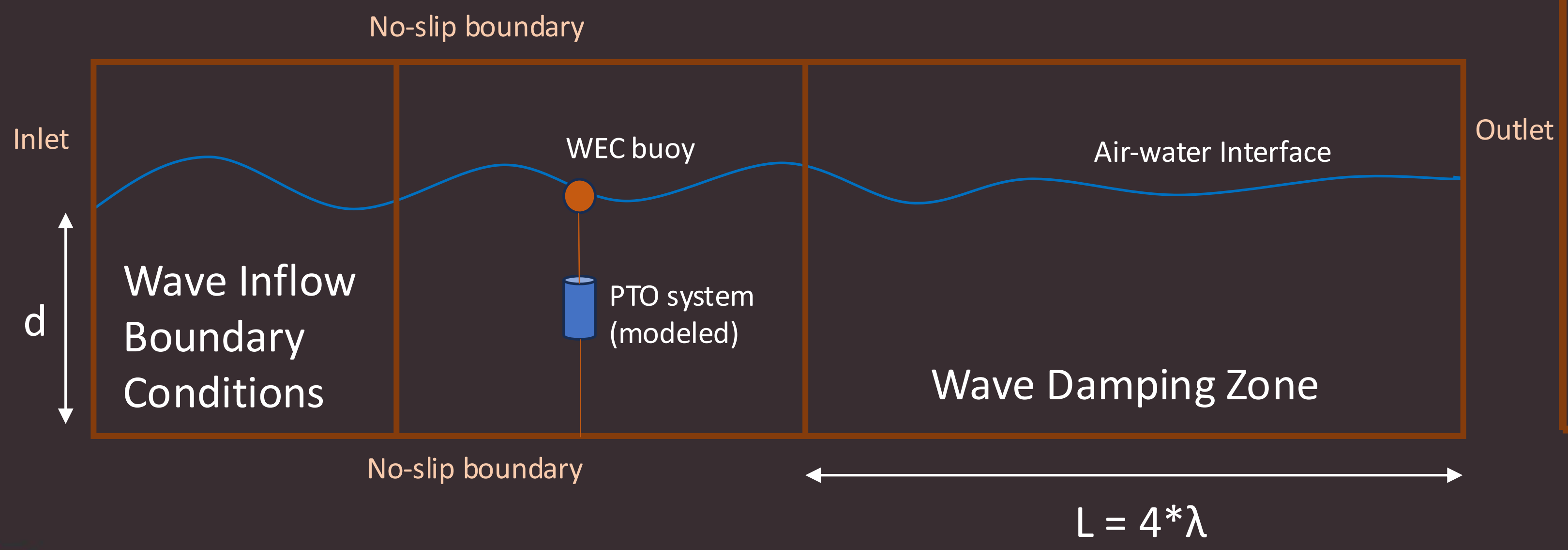
Kinematics of undulating batoid swimmers

Validation of Our Code

- Our lab’s wave and two-fluids codes have been extensively validated against established computational and experimental results
- Previous publications:
  - •Hao, X. & Shen, L. (2020), “Direct simulation of surface roughness signature of internal wave with deterministic energy-conservative model,” Journal of Fluid Mechanics, Vol. 891, R3.
  - •Yang, Z., Deng, B. & Shen L. (2018), “Direct numerical simulation of wind turbulence over breaking waves,” Journal of Fluid Mechanics, Vol. 850, pp.120-155.
  - •Zeng, Y., Xuan, A., Blaschke, J. & Shen, L. (2022), “A parallel cell-centered adaptive level set framework for efficient simulation of two-phase flows with subcycling and non-subcycling,” Journal of Computational Physics, Vol. 448, 110740.
  - •Gao, Q., Deane, G. & Shen, L. (2021), “Bubble production by air filament and cavity breakup in plunging breaking wave crests,” Journal of Fluid Mechanics, Vol. 929, A44.
  - •Hao, X., Wu, J., Rogers, J., Fringer, O. & Shen, L. (2022), “A high-order spectral method for effective simulation of surface waves interacting with an internal wave of large amplitude,” Ocean Modelling, Vol. 173, 101996.



Simulation Set-up



Parameter	Value
Water depth (d)	50 m
WEC depth from surface (h)	-1 m
WEC diameter (D)	2 m
CCC spring constant (k_{PTO})	3896 N/m
Damping coefficient (b_{PTO})	500 N*s/m
Wave height (H)	2 m
Wavelength (λ)	50 m
Wave period (T)	5.66 s
Density ratio $({}^{\rho_{WEC}}/_{\rho_w})$	0.98

- Fully resolved two-phase + rigid body simulation
- For expensive 3D runs, periodic boundary conditions and a smaller domain is generally used

3D Simulation of Point Absorber WEC

- Fully resolved, high fidelity CFD simulation of the WEC-wave interactions
- In this example, WEC motion restricted to heave only
- Note the turbulence when the WEC touches the surface

WEC Control

Damping PTO

- Doesn't require a controller
- Applied mechanically by the electricity generating mechanism

$$F_{PTO}(t) = -\beta V(t)$$

$$W_{PTO}(t) = -F_{PTO}(t) * V(t) = \beta V(t)^2$$

Complex Conjugate Control

- Simple
- Need to know impedance, which can be calculated from the no control case
- Can fine tune based on incoming waves

$$Z_i(\omega) = i\omega(M + m(\omega)) + B_v + R(\omega) + \frac{S}{i\omega}$$

$$F_{PTO}(\omega) = -Z_i^*(\omega)V(\omega)$$

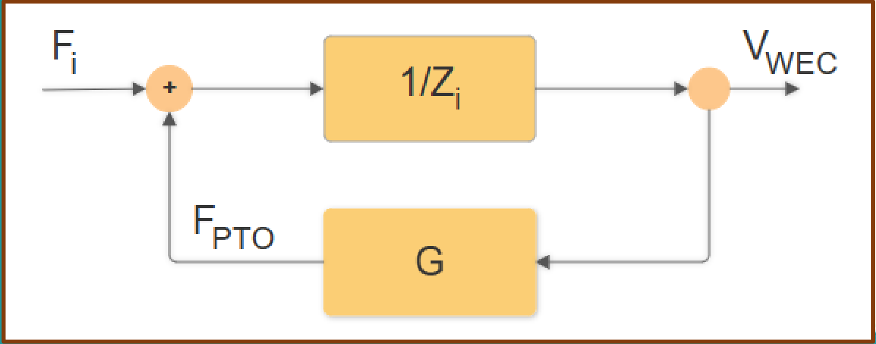
Sliding Mode Control

- Holds WEC above water when it is falling; extracts energy
- Holds WEC below water when it is rising
- More complicated, must estimate or know incoming wave

Sliding surface $= \dot{x} - \dot{h}_1 + \lambda(x - (h_1 + \alpha)),$

$$\begin{cases} \alpha = \varepsilon & \dot{h}_1 < 0 \\ \alpha = -w_{max} - \varepsilon & \dot{h}_1 > 0 \end{cases}$$

Block Diagram

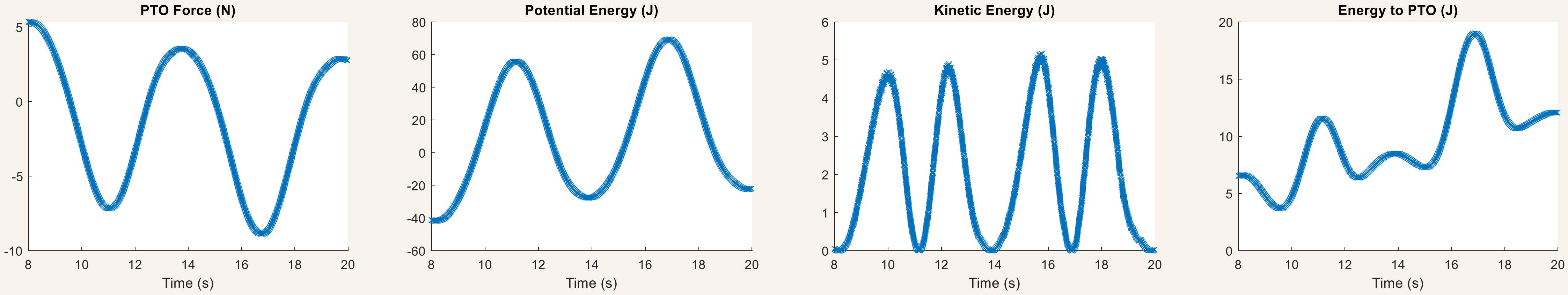


Legend

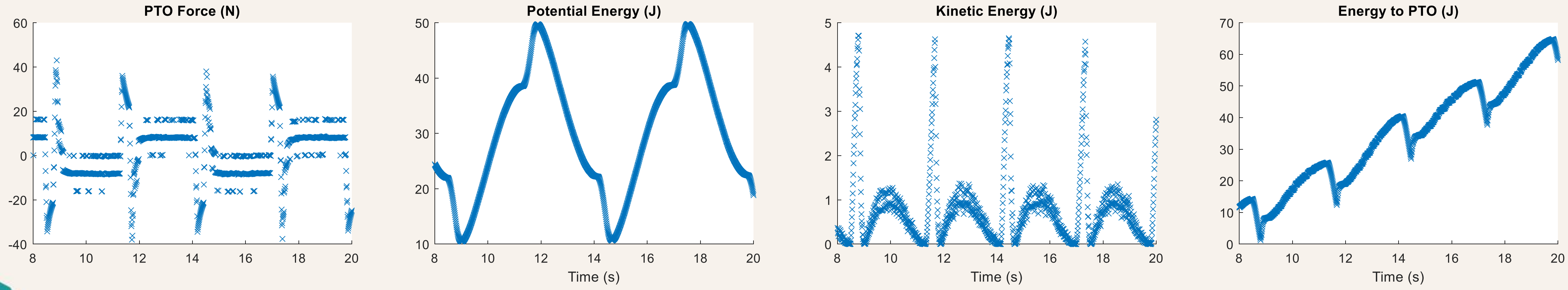
β	V(t)	M	m	B_v	R	S	h_1	λ	ε
damping variable	WEC velocity	WEC mass	added mass	hydro damping	radiation damping	hydro restoring coefficient	water height	control parameters	

Complex Conjugate Control vs. Sliding Mode Control

CCC

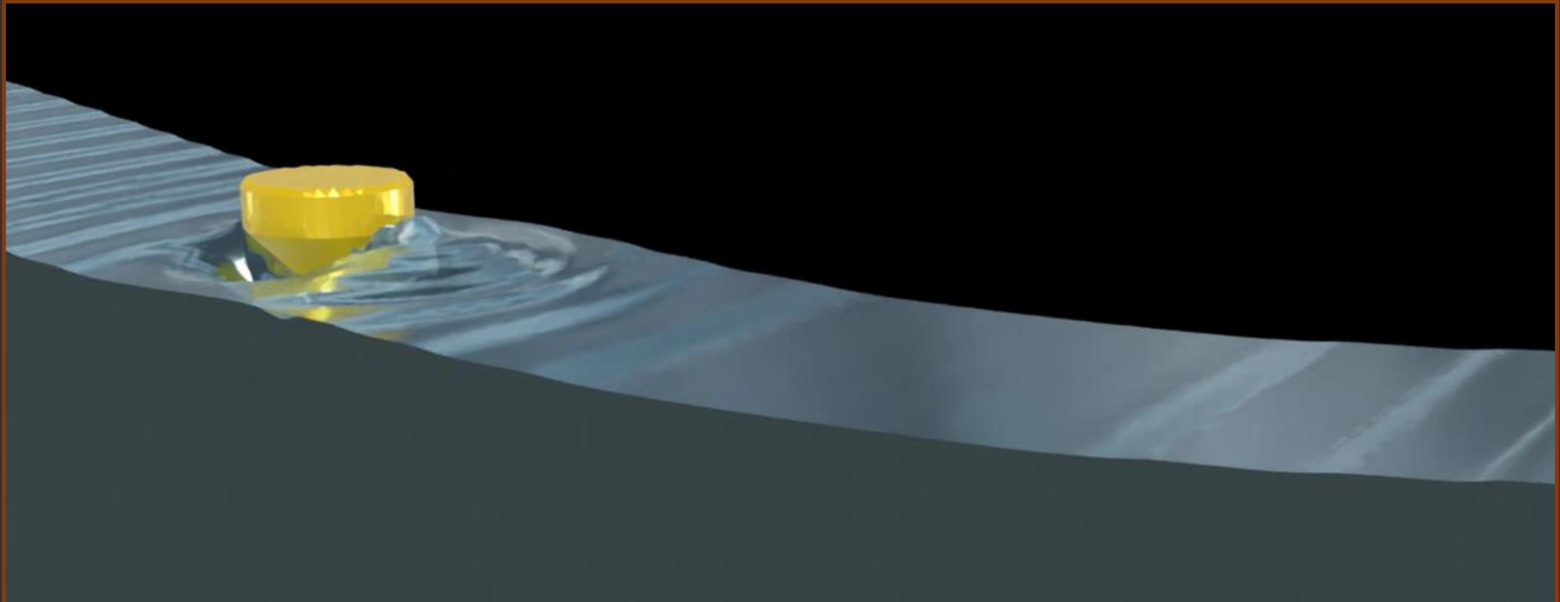


SMC

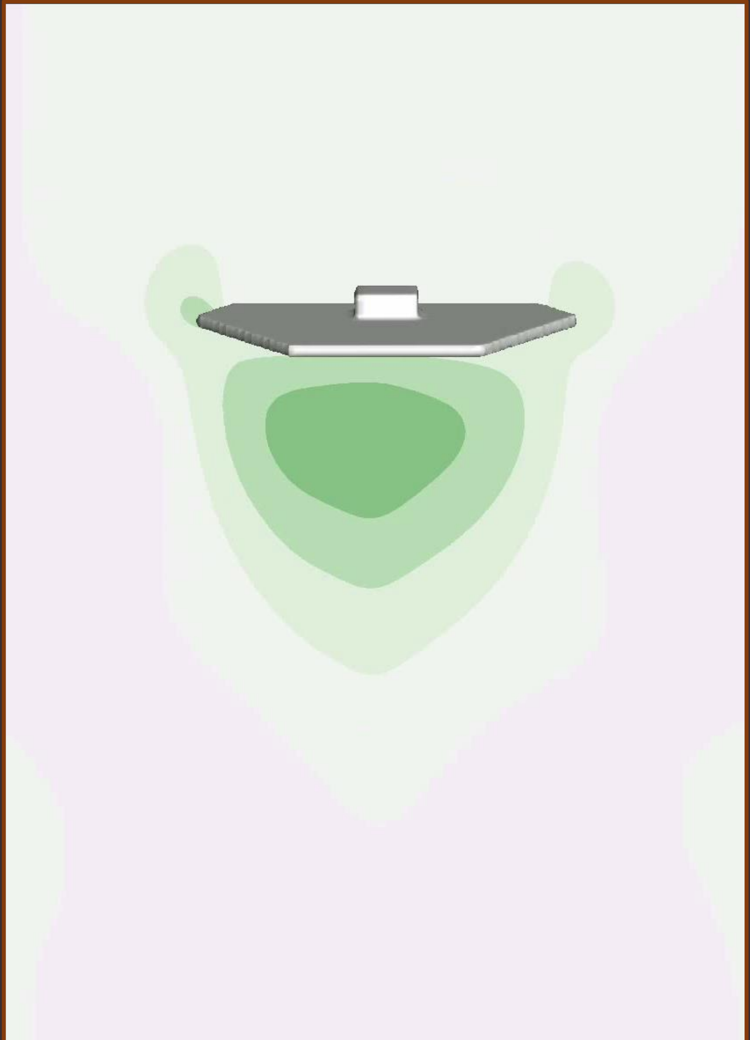


- In this test, SMC performs 4x better than CCC
- However, it requires knowledge of the incoming waves as well as a greater PTO force

Also explored: heave plates and different geometry



Wavebot microscale WEC simulation



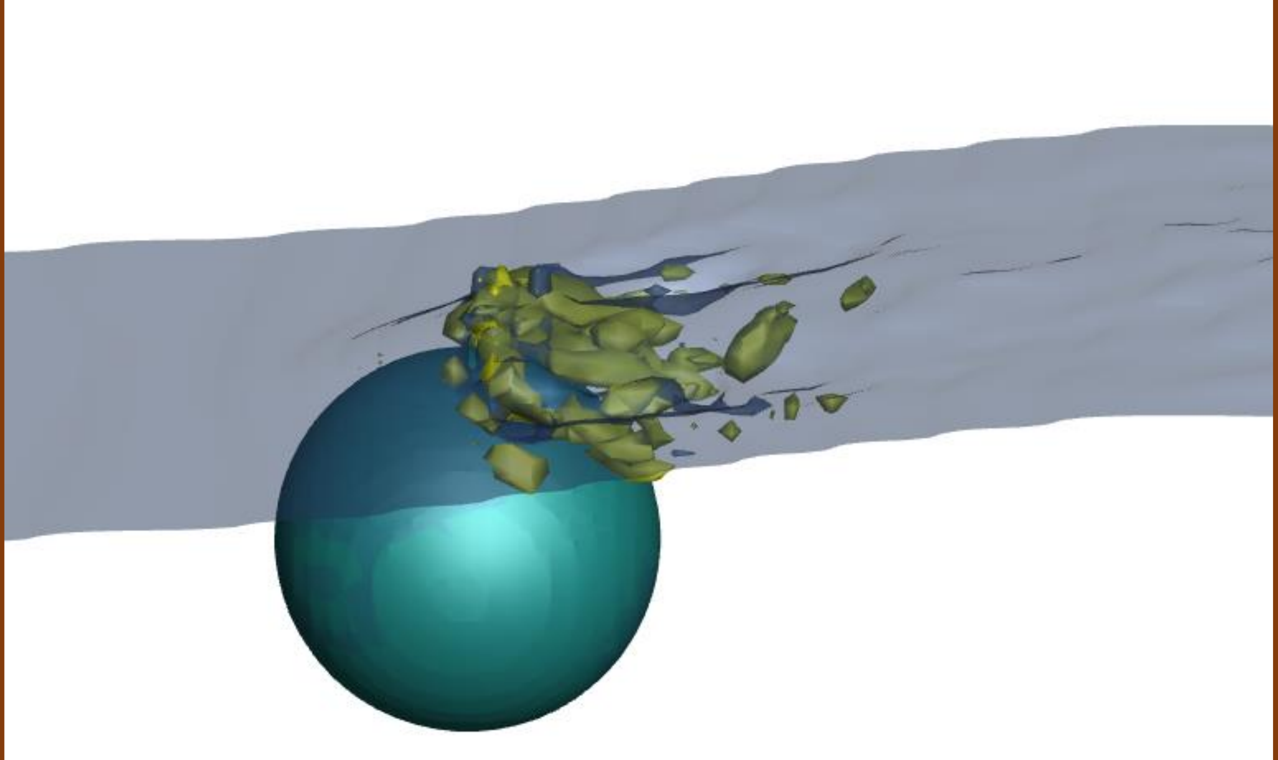
Heave plate added mass test

Collaborating with Professor Brian Polagye and Dr. Curtis Rusch on heave plate and microscale WEC simulations. See their work below:

Curtis J. Rusch, Ama R. Hartman, Benjamin D. Maurer, Brian L. Polagye, Influence of heave plate topology on reaction force, Ocean Engineering, Volume 241, 2021, 110054.

Future work: nonlinear effects in WEC CFD simulations

- Nonlinear effects such as wave breaking, bubbles, vortex shedding seen in WEC buoy and heave plate simulations
- Neglected by traditional WEC linear simulations
- Particularly relevant when the WEC breaks the surface
- Quantifiable by Force Partition Method



Yellow: Q-criterion iso-surface
Teal: WEC buoy
Clear: Air-water interface

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Thank You!
Questions? Comments?

Calculating power and efficiency

$$W_{PTO}(t) = -F_{PTO}(t) * V(t)$$

$$P_i = \frac{1}{32\pi}\rho g^2 H^2 T D$$

Force Partition Method

Kinematic
$$C_\kappa^{(i)} = -\int_B \vec{n}\cdot\frac{d\vec{U}_B}{dt}\phi^{(i)}dS - \int_B \frac{1}{2}|\vec{U}_B|^2 n_i dS$$

Vorticity
$$C_\omega^{(i)} = \int_{V_f}\left\{\left[\vec{\nabla}\cdot(\vec{\omega}\times\vec{u})\right]\phi^{(i)} + \vec{\nabla}\cdot\left[\vec{\nabla}\left(\frac{1}{2}\vec{u}_v\cdot\vec{u}_v + \vec{u}_\Phi\cdot\vec{u}_v\right)\phi^{(i)}\right]\right\}dV$$

Viscous
$$C_\sigma^{(i)} = \frac{1}{Re}\int_B(\vec{\omega}\times\vec{n})\cdot\left(\vec{\nabla}\phi^{(i)} - \hat{e}_i\right)dS$$

Potential
$$C_\Phi^{(i)} = \int_{V_f}\vec{\nabla}\cdot\left[\vec{\nabla}\left(\frac{1}{2}\vec{u}_\Phi\cdot\vec{u}_\Phi\right)\phi^{(i)}\right]dV$$

Boundary
$$C_\Sigma^{(i)} = \int_\Sigma\left\{-\vec{n}\cdot\frac{d\vec{u}}{dt}\phi^{(i)} + \frac{1}{Re}(\vec{\omega}\times\vec{n})\cdot\vec{\nabla}\phi^{(i)}\right\}dS.$$

Decomposition
$$C_i = C_\kappa^{(i)} + C_\omega^{(i)} + C_\sigma^{(i)} + C_\Phi^{(i)} + C_\Sigma^{(i)}$$

Flow Parameters	
$\vec{U}_B$	Velocity of rigid body
$\phi^{(i)}$	Velocity potential of moving body
$\vec{\omega}$	Vorticity
$\vec{u}$	Velocity
$\vec{u}_v$	Divergence-free component
$\vec{u}_\Phi$	Curl-free component

Helmholtz Decomposition

Laplace's Equation

- Can quantify nonlinear effects
- Time-consuming to implement