Hardware-in-the-Loop Testing for Autonomous Underwater Vehicle Docking in Dynamic Ocean Waves

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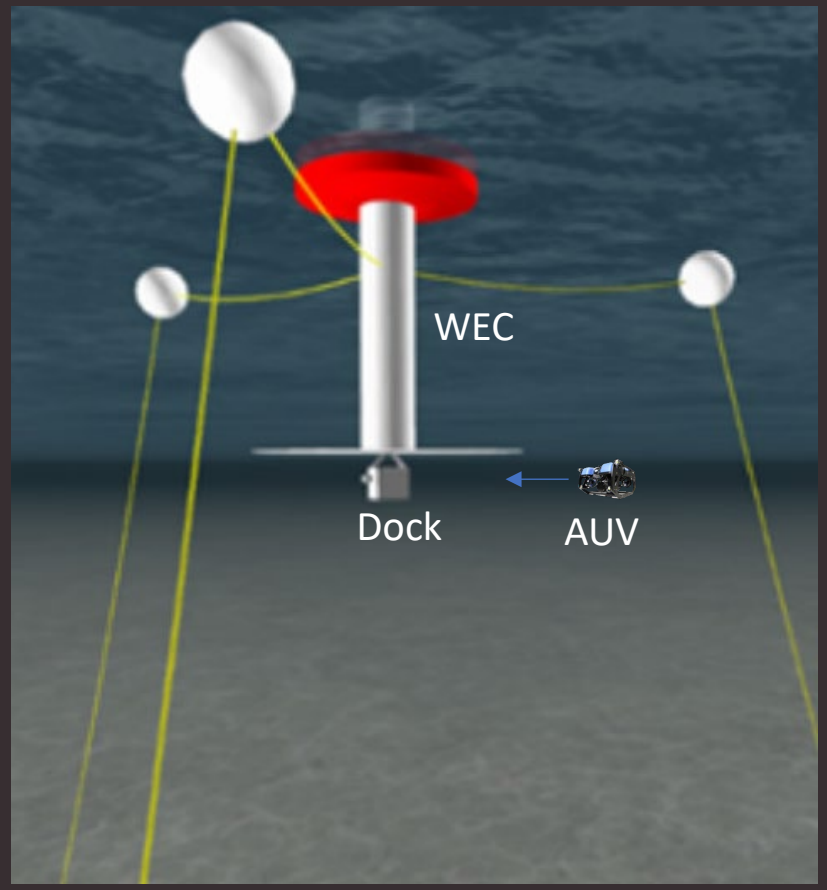
AUV powered by WEC

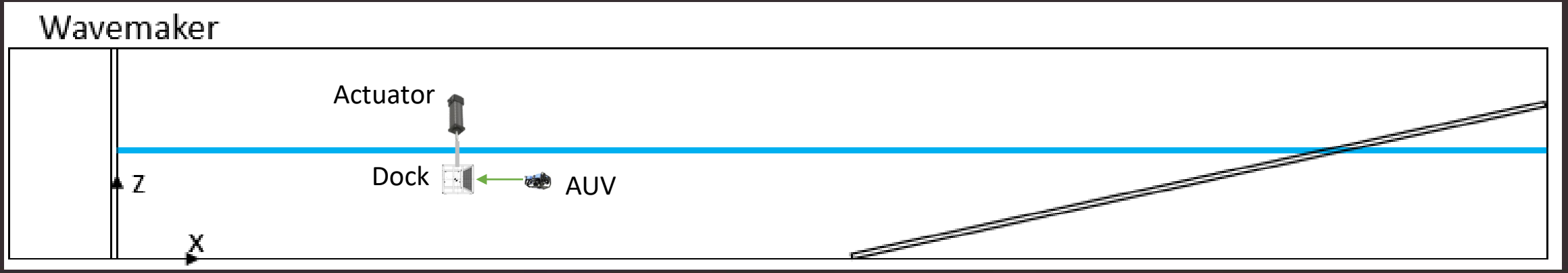
- Autonomous underwater vehicles (AUVs)
  - Wide range of maritime applications in ocean exploration
  - Range and duration are limited by battery capacity
- Wave energy converters (WECs)
  - Harvest ocean wave energy that is consistent and predictable
  - Charge AUV onsite enhancing AUV mission capacity
- Integrate AUV with WEC
  - Docking station attached to the WEC directly
  - Increased docking difficulty as AUV navigates and docks near the ocean surface, encountering significant wave force



Research Question

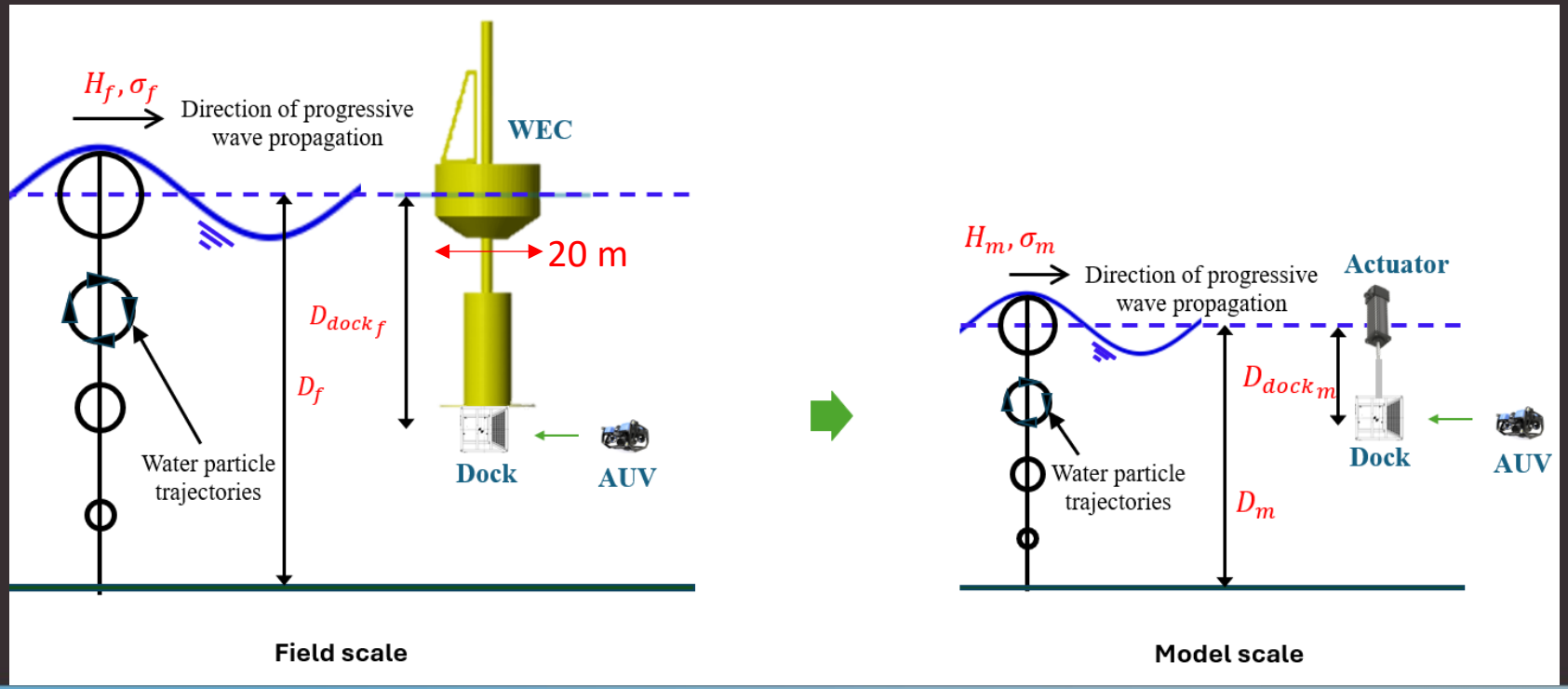
- This study investigated the experimental testing procedure of AUV docking on a WEC in the wave flume.

- How to test AUV docking through a mixed-scale approach with waves and dock motions synchronized in real time?



Mixed-scale Approach

- Testing AUV docking in the wave flume requires a mixed-scale approach
  - Full-scale AUV and dock, model-scale waves
  - Goal: replicate the wave-induced force on AUV and the dynamic motion of the dock in the laboratory



Wave Force on AUV

- Wave-induced forces on AUV calculated by Morison equation:

$$F = \underbrace{\rho C_m V \dot{u}_r}_{F_I} + \underbrace{1/2 \cdot \rho C_d A u_r |u_r|}_{F_D}$$

F_I is the inertia force, depends on water particle acceleration $\dot{u}_r$

F_D is the drag force, depends on water particle velocity u_r

Wave and Dock Motion Distortion (Inertia force dominant)

- **Inertia force dominant** scenario
  - Model-scale water acceleration = Field-scale water acceleration

$$a_{water_f}(\sigma_f) = a_{water_m}(\sigma_m)$$

  - Model-scale dock acceleration = Field-scale dock acceleration

$$a_{dock_f}(\sigma_f) = a_{dock_m}(\sigma_m)$$

- The following conditions are required for matching acceleration

$$\frac{D_{dock_m}}{D_{dock_f}} = \frac{D_m}{D_f} = \lambda \quad \text{(Froude scale factor)}$$

$$\frac{\sigma_m}{\sigma_f} = \lambda^{-0.5} \qquad \frac{H_m}{H_f} = \lambda \qquad \frac{A_{dock_m}}{A_{dock_f}} = \lambda$$

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Follow Froude scale law

Wave and Dock Motion Distortion (Drag force dominant)

- **Drag force dominant** scenario
  - Model-scale water velocity = Field-scale water velocity

$$v_{water_f}(\sigma_f) = v_{water_m}(\sigma_m)$$

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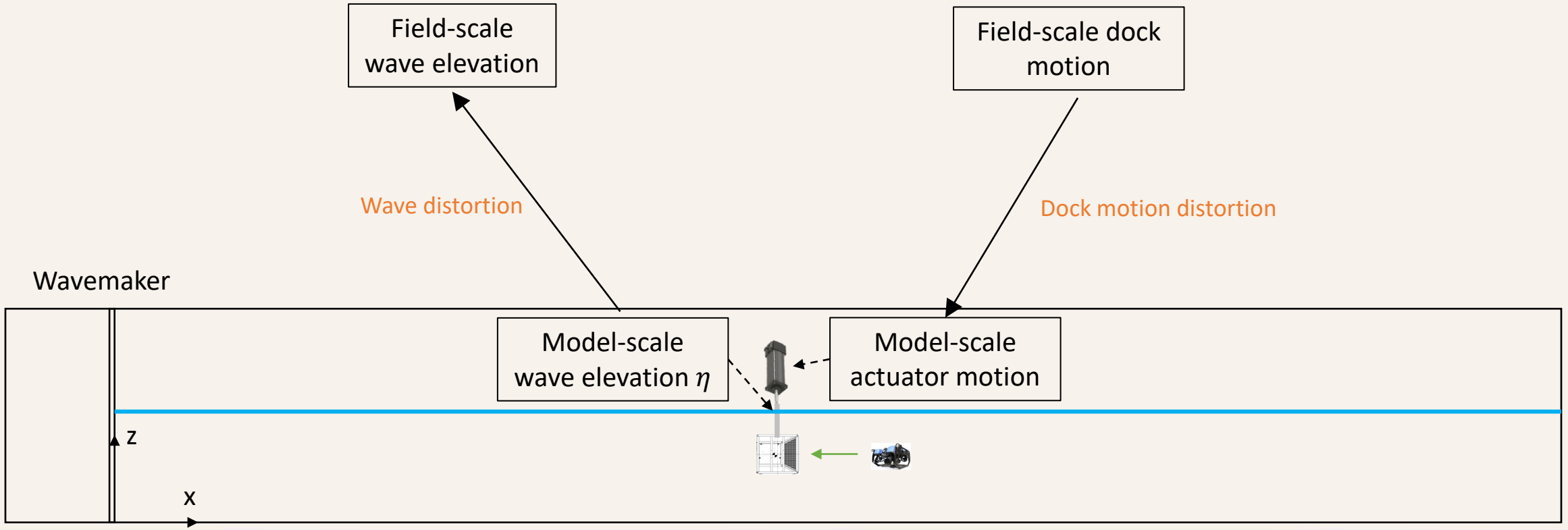
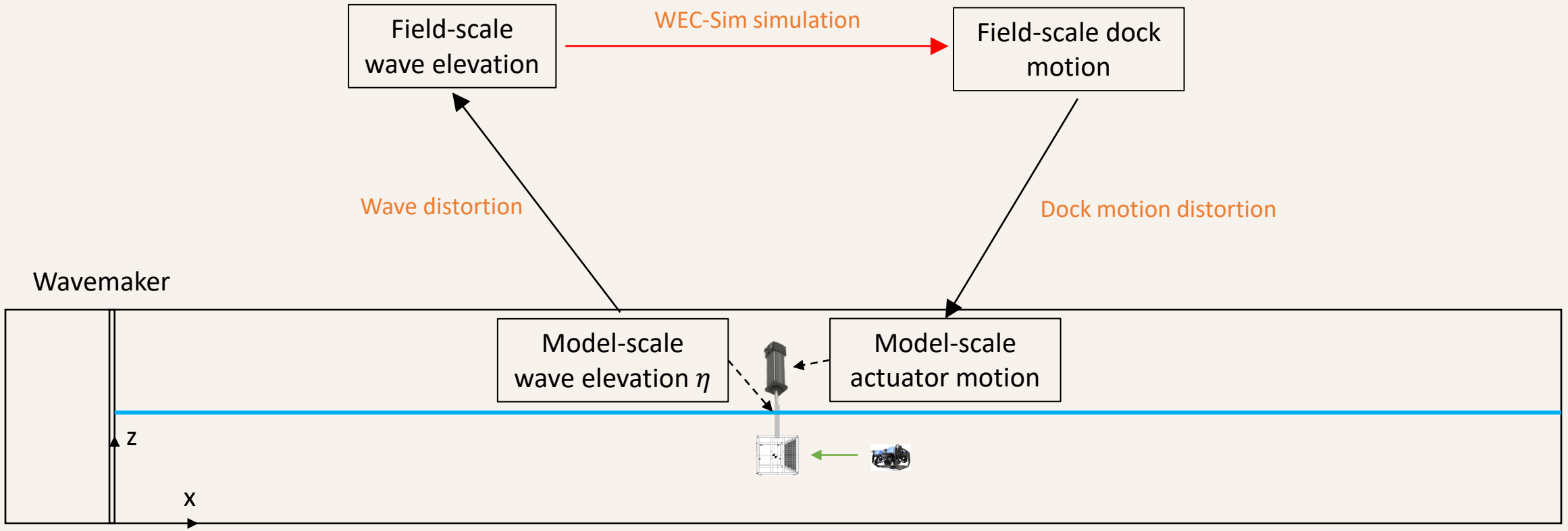
Not follow Froude scale law

Mixed-scale real-time testing procedure

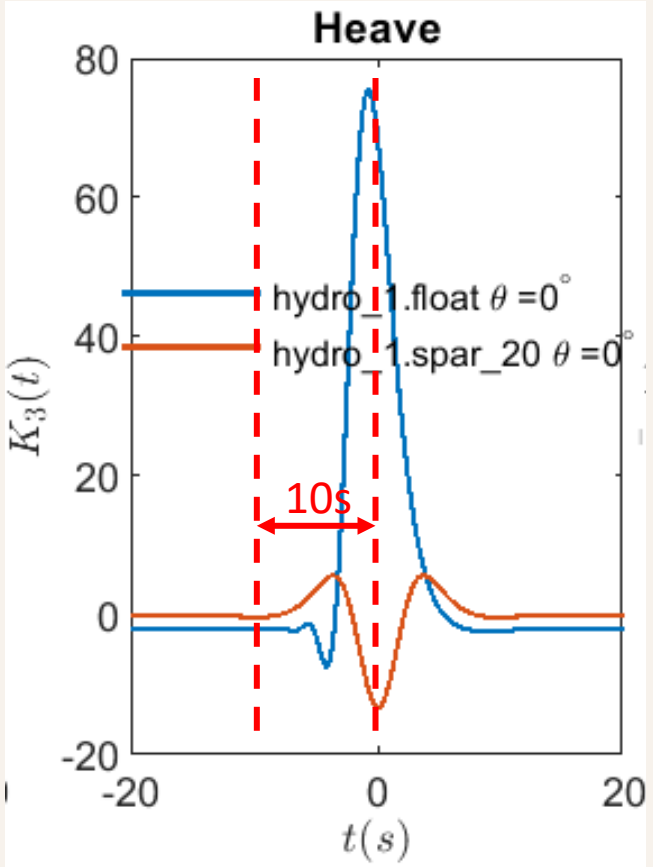


Mixed-scale real-time testing procedure



Non-causal Impulse Response h(t)

- Transfer function
  - H(f)=fft($F(t)$)/fft($\eta(t)$)
- Excitation impulse response function
  - h(t)=ifft(H(f))
  - 10 s of leading wave elevation for LUPA 20 m
- $F(t)$)=conv($\eta(t)$, h(t))



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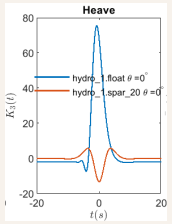


Field-scale wave elevation

WEC-Sim simulation

Field-scale dock motion

Wave distortion

Dock motion distortion

Wavemaker

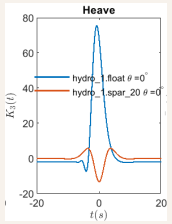
Model-scale wave elevation at the dock location

Model-scale actuator motion

z

x

Mixed-scale real-time testing procedure



Field-scale wave elevation

WEC-Sim simulation

Field-scale dock motion

Wave distortion

Dock motion distortion

Wavemaker

Model-scale upwave wave elevation

Model-scale wave elevation at the dock location

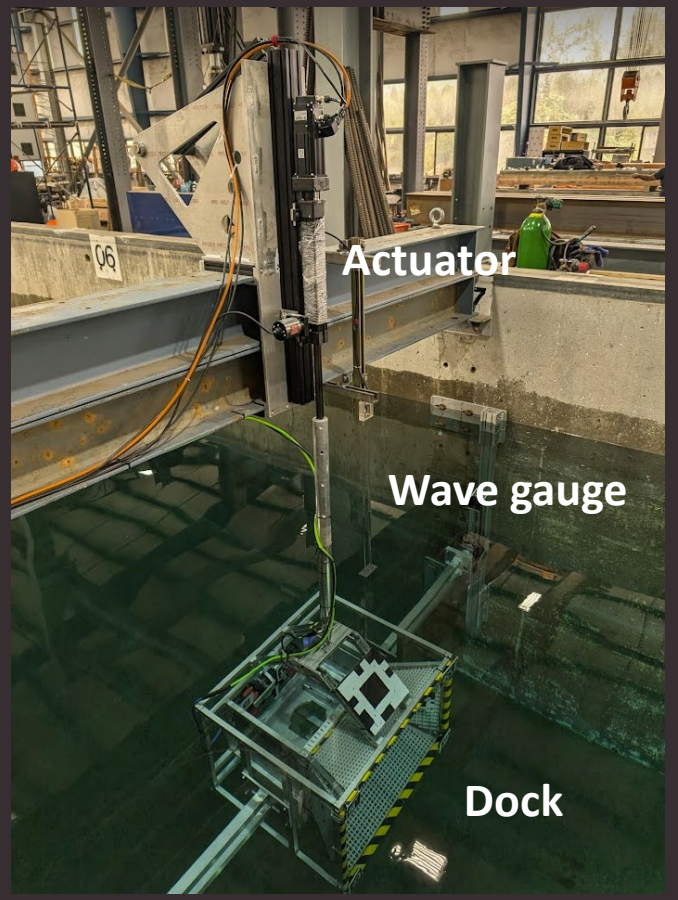
Model-scale actuator motion

z

x

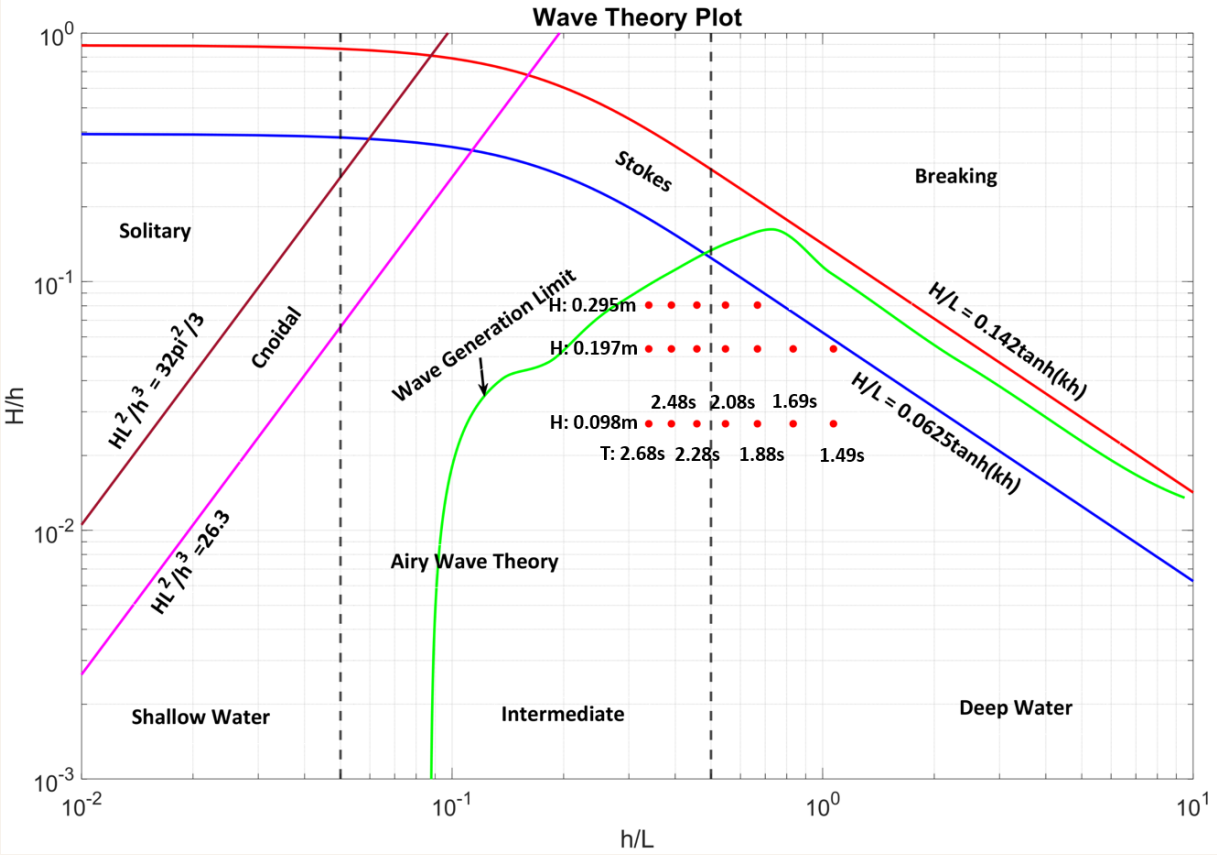
Laboratory Testing Considerations

- Large wave flume at O.H. Hinsdale Wave Research Laboratory
  - Water depth, wavemaker capacity
- Actuator
  - Stroke, velocity
- Wave gauge location



2024 WEC-AUV docking test

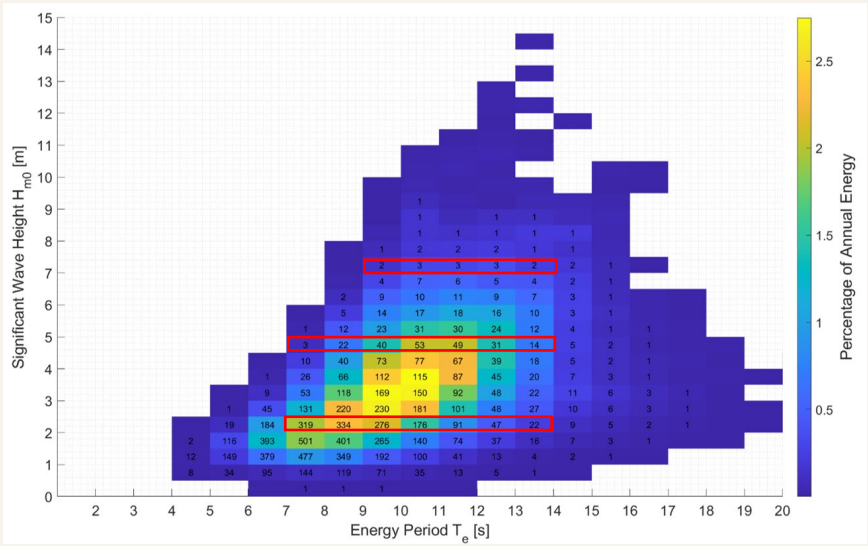
Model-Scale and Field-Scale Wave Conditions (acceleration matching)



Selection Of Model-scale Wave Conditions Within the Wave Generation Limit and Wave Breaking Limit

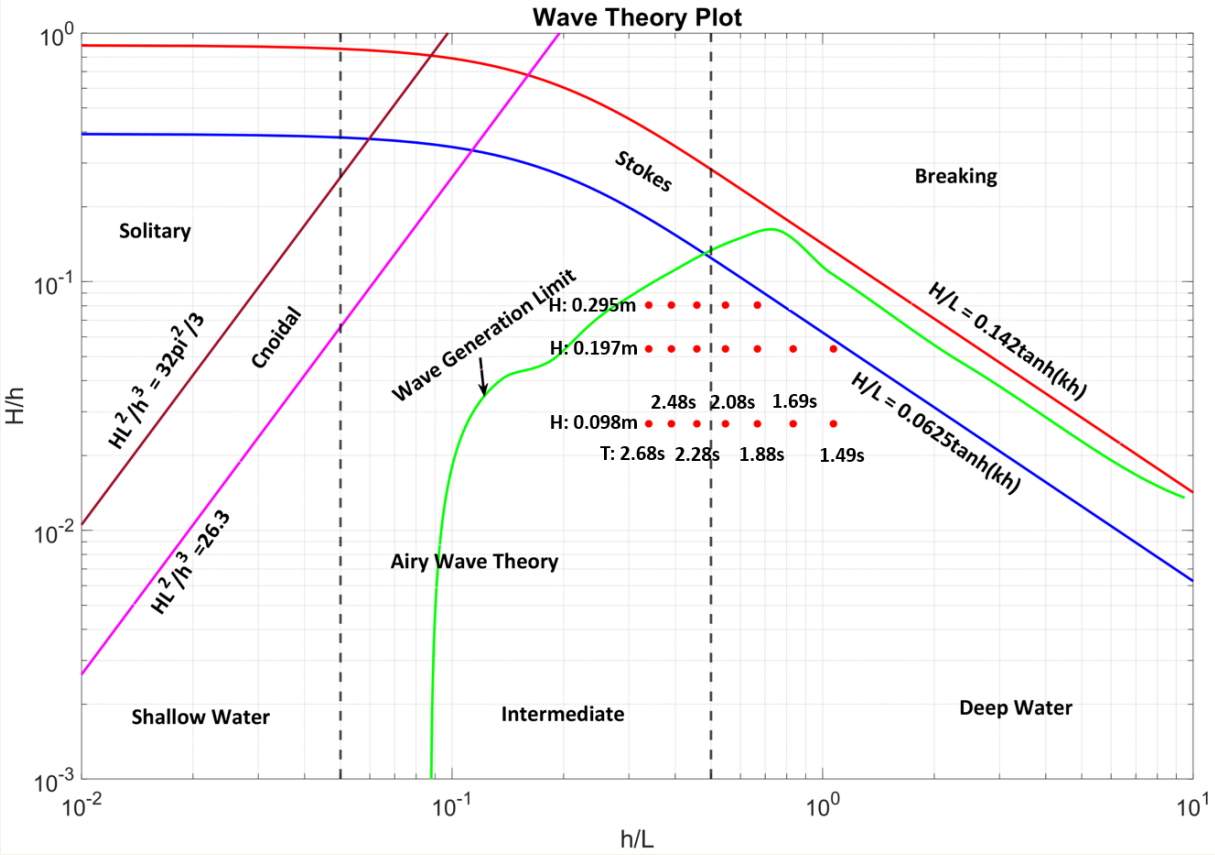
Corresponding field-scale wave conditions according to **water acceleration amplitude** matching criteria:

Wave height (m)	Wave periods (s)						
2.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5
5.0	7.5	8.5	9.5	10.5	11.5	12.5	13.5
7.5			9.5	10.5	11.5	12.5	13.5



Sea-state Histogram at the Targeted AUV Docking Site: U.S. PacWave Test Site

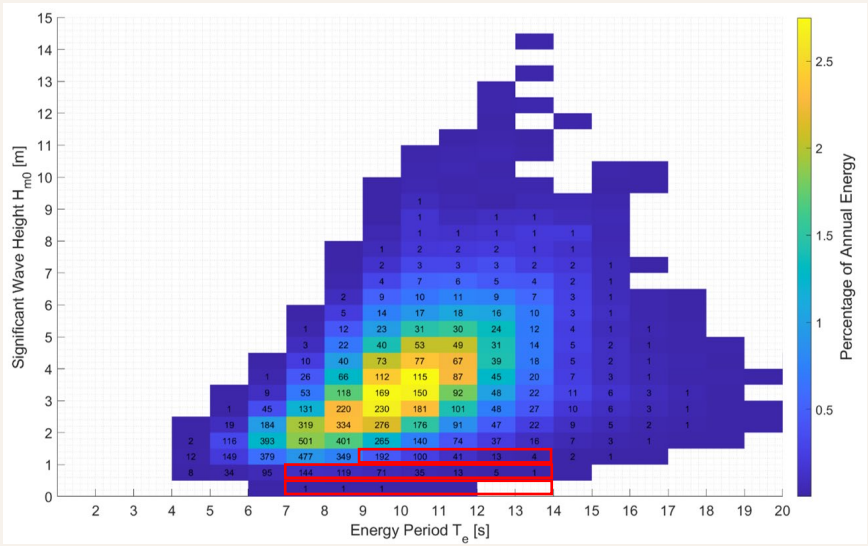
Model-Scale and Field-Scale Wave Conditions (velocity matching)



Selection Of Model-scale Wave Conditions Within the Wave Generation Limit and Wave Breaking Limit

Corresponding field-scale wave conditions according to **water velocity amplitude** matching criteria:

Wave height (m)	Wave periods (s)						
0.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5
1.0	7.5	8.5	9.5	10.5	11.5	12.5	13.5
1.5			9.5	10.5	11.5	12.5	13.5



Sea-state Histogram at the Targeted AUV Docking Site: U.S. PacWave Test Site

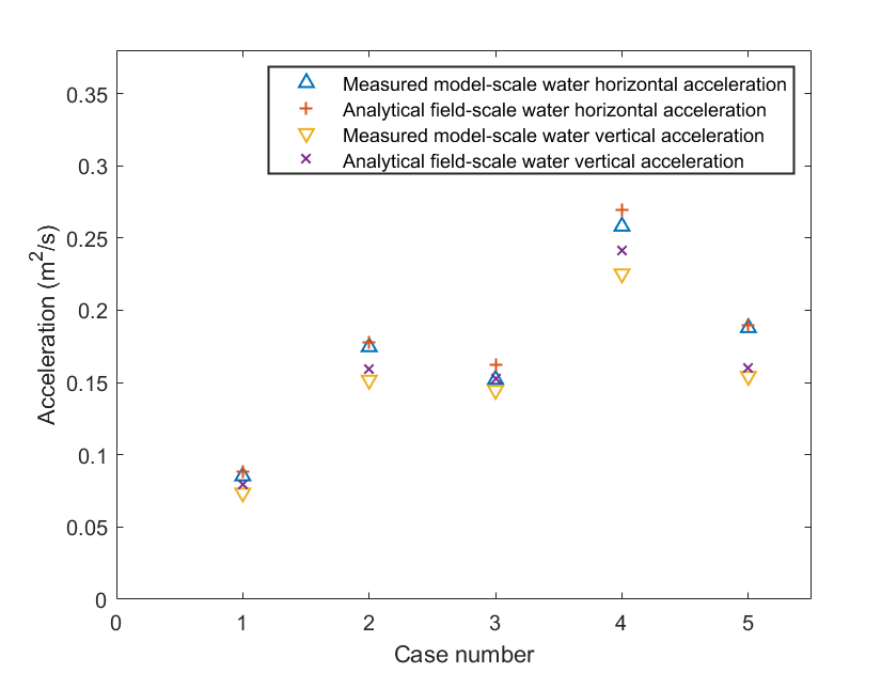
Validation of Wave Distortion Methods

- Five regular wave test cases were conducted in the laboratory to validate the wave distortion algorithms.

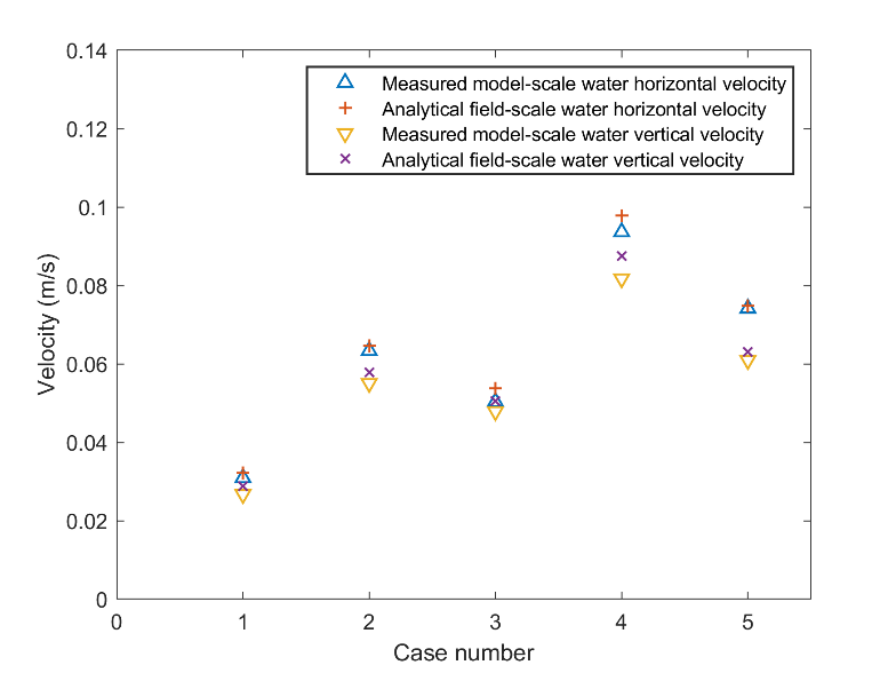
	Model-scale regular waves		Field-scale regular waves for acceleration amplitude matching		Field-scale regular waves for velocity amplitude matching	
Case #	Wave height (m)	Wave period (s)	Wave height (m)	Wave period (s)	Wave height (m)	Wave period (s)
1	0.098	2.28	2.488	11.50	0.494	11.50
2	0.198	2.28	5.028	11.50	0.998	11.50
3	0.198	2.08	5.028	10.50	0.998	10.50
4	0.298	2.28	7.567	11.50	1.502	11.50
5	0.198	2.48	5.028	12.50	0.998	12.50

Validation of Wave Distortion Methods (continued)

- Measured model-scale and analytical field-scale water particle acceleration and velocity in good agreements



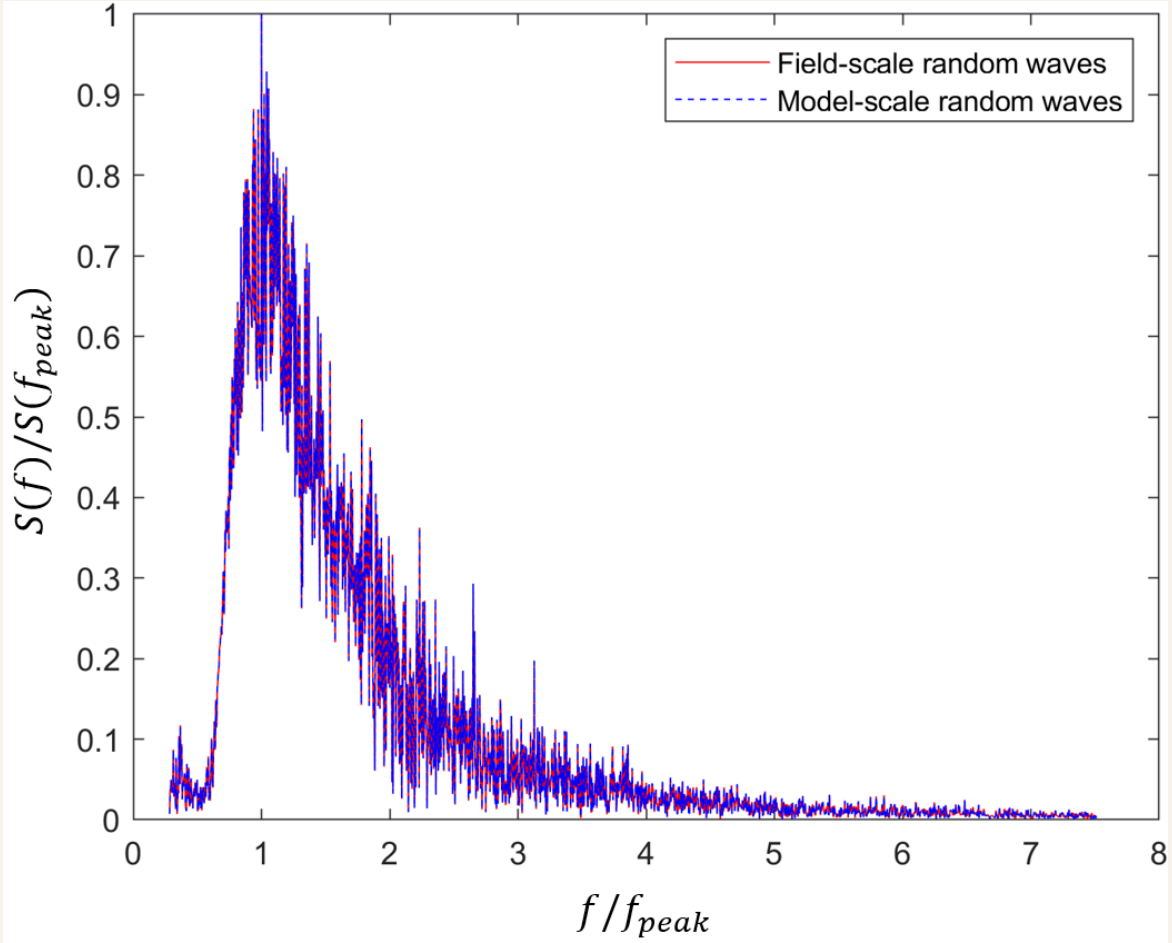
Comparison of water particle accelerations



Comparison of water particle velocities

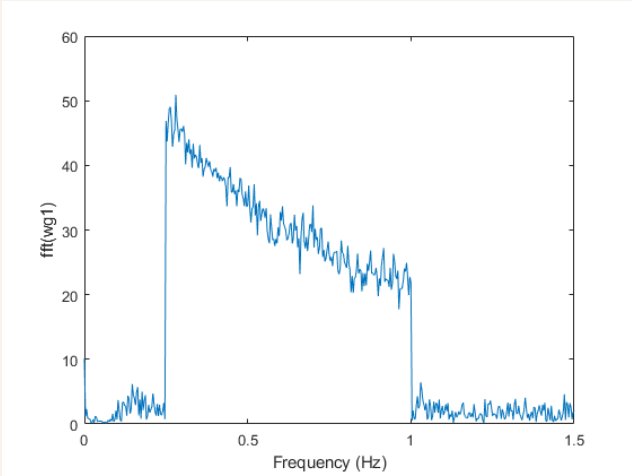
Random Wave Distortion Example

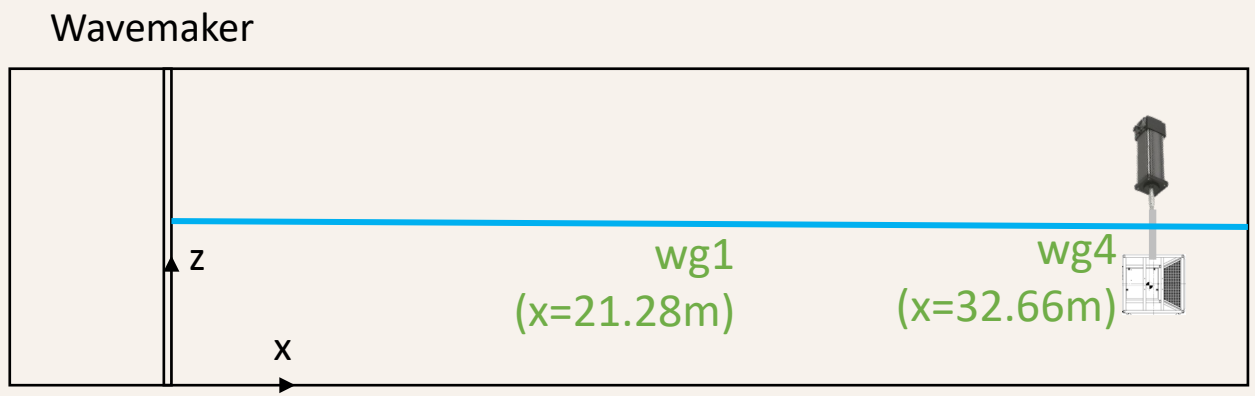
- Model scale random waves
  - Tp=2.28 s, Hs=0.198 m
- Field scale random waves (acceleration matching)
  - Tp=11.5 s, Hs= 5.0 m
- Model-scale random waves retain the same shape of power spectra density as the field-scale waves



Validation of Wave Prediction Method

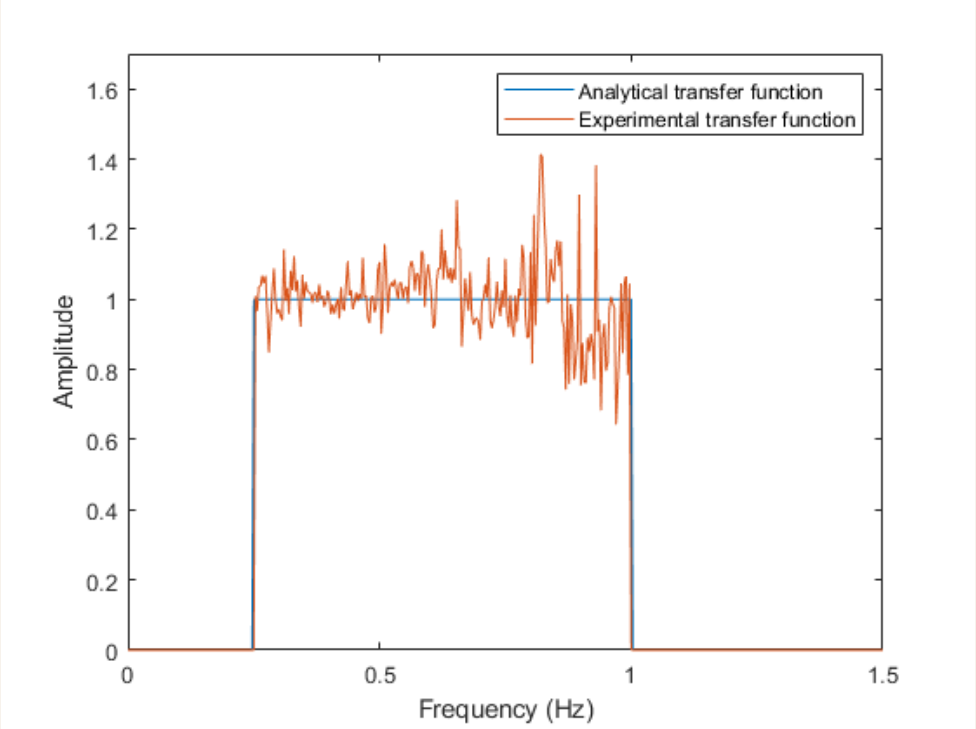
- Multi-sine waves
  - Wave period T (1 - 4 s)
- Wave gauge locations
  - Upwave wave gauge
  - Wave gauge at the dock
- Upwave time
  - 10 s (field scale) - > 2 s (model scale)
  - 2.2 s from wg1 to wg4 under T = 4 s

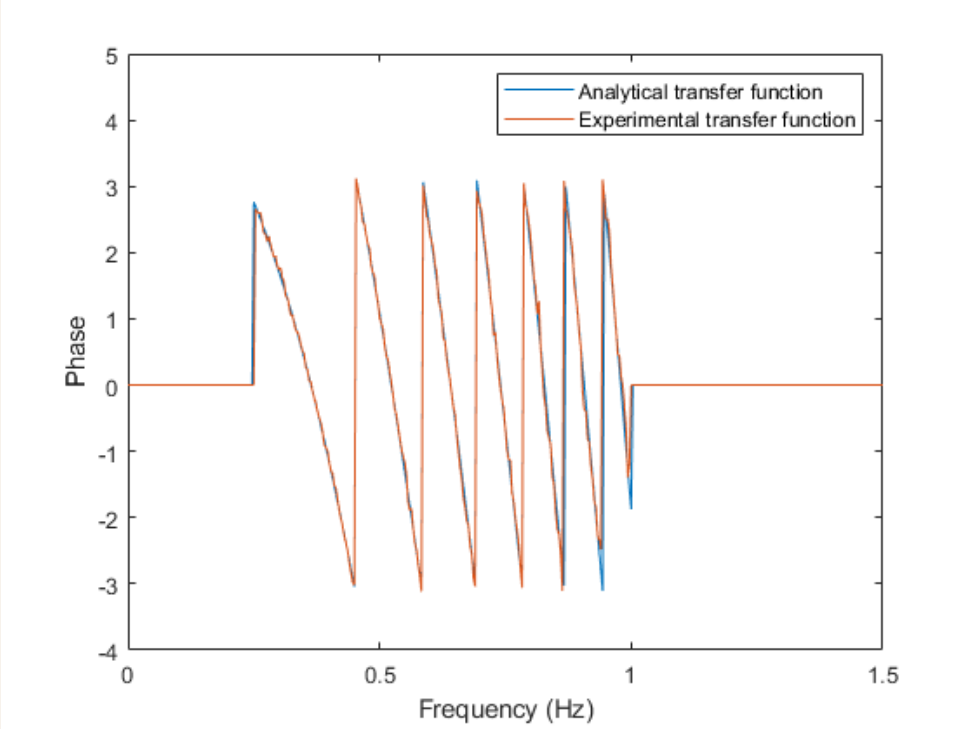




Validation of Wave Prediction Method (Continued)

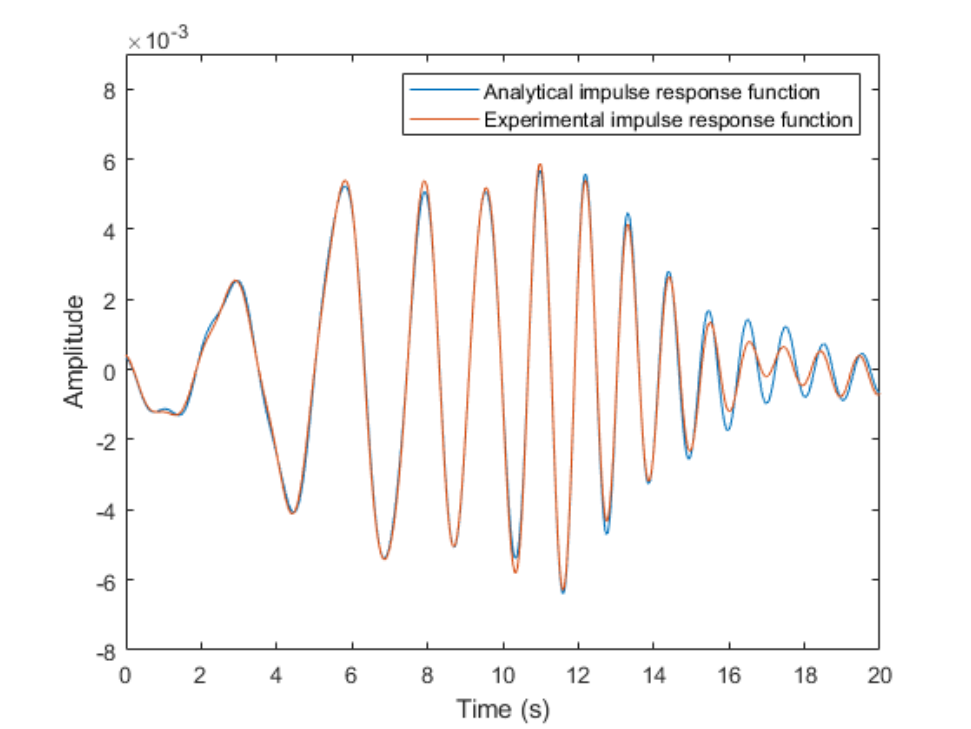
- Frequency domain transfer function from upwave wave elevation to near-structure wave elevation





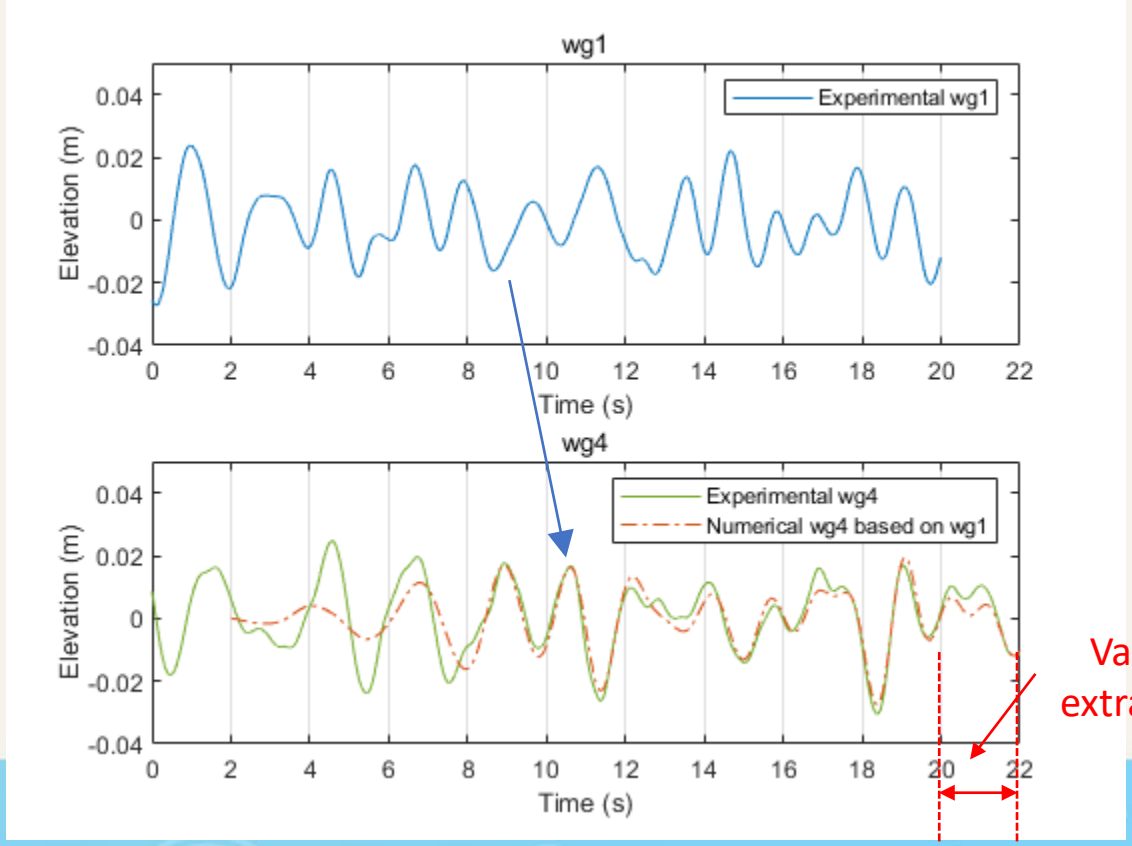
Validation of Wave Prediction Method (Continued)

- Time domain impulse response function from upwave wave elevation to near-structure wave elevation



Validation of Wave Prediction Method (Continued)

- The predicted wave elevation at wg4, based on wg1 wave elevation and impulse response, can provide extra 2 seconds of data



Summary

- 2024 WEC-AUV testing
  - Asynchronous testing
  - Validation of wave distortion method
  - Validation of wave prediction method
  - “Wave Distortion Methodology for Experimental Mixed-scale Testing of Underwater Vehicle Docking” OMAE Conference Proceedings 2025

- 2025 WEC-AUV testing (September 2025)
  - Real-time testing

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Wave Force on AUV

- Wave-induced forces on AUV calculated by Morison equation:

$$F = \underbrace{\rho C_m V \dot{u}_r}_{F_I} + \underbrace{1/2 \cdot \rho C_d A u_r |u_r|}_{F_D}$$

F_I is the inertia force, depends on water particle acceleration $\dot{u}_r$

F_D is the drag force, depends on water particle velocity u_r

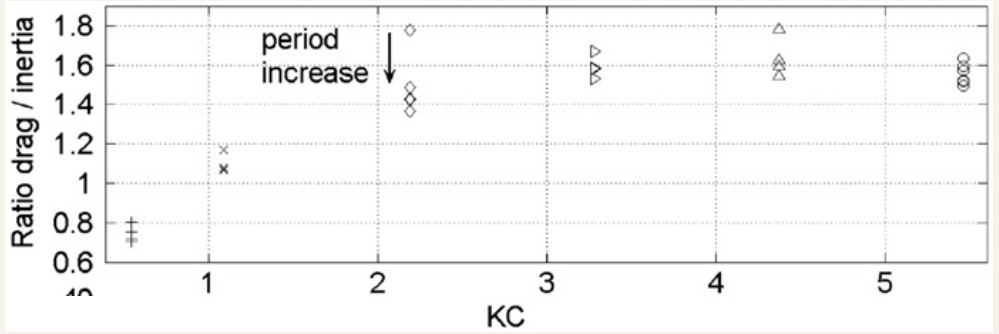
- The dominate wave force component is related to the Keulegan–Carpenter (KC) number

$$KC = UT/D$$

U is the maximum wave-induced particle velocity; T is the wave period; D is the AUV characteristic dimension

$KC < 1$: inertia force is larger than drag force

$KC > 1$: drag force is larger than inertia force



Avila, Juan Pablo Julca, and Julio Cezar Adamowski. "Experimental evaluation of the hydrodynamic coefficients of a ROV through Morison's equation." *Ocean engineering* 38.17-18 (2011): 2162-2170.