Real Time Hybrid Testing of Autonomous Underwater Vehicle Docking to a Wave Energy Converter

1.1 Background/Objectives

Real-time hybrid simulation (RTHS) offers a promising pathway for evaluating coupled wave energy converter–autonomous underwater vehicle (WEC–AUV) systems in the laboratory, where mixed-scale physical interactions present significant challenges for conventional testing approaches. This study aims to develop and validate a RTHS testing framework that enables system-level evaluation of WEC-powered AUV docking under realistic ocean conditions by integrating wave tank experiments with numerical simulations.

1.2 Approach/Activities

The proposed RTHS testing framework combines wave tank measurements with real-time numerical simulation through a six-step procedure: (1) the modal-scale wave elevation at the dock location is predicted using wave measurements collected at an upwave location in the wave flume; (2) the full-scale wave condition is determined from the model-scale wave condition using wave distortion algorithms; (3) the full-scale wave force on the WEC is computed numerically; (4) the full-scale WEC/dock motion is determined based on the wave force and dock control algorithms; (5) the model-scale dock motion is obtained from the full-scale dock motion using dock motion distortion algorithms; and (6) the dock is physically actuated in the laboratory according to the model-scale dock motion.

1.3 Results/Lessons

Core methodologies—including wave and motion distortion, wave prediction, excitation force estimation, and control—were developed and experimentally validated in the large wave flume of the Hinsdale Wave Research Laboratory at Oregon State University.

- Wave and dock motion distortion algorithms were developed to match either acceleration or velocity amplitudes between model-scale and field-scale, enabling reproduction of both inertial and drag forces. Acceleration matching is suitable for the inertia force-dominant conditions; while velocity matching is for drag force-dominant conditions. The results show that the relative difference between the measured and analytical water accelerations ranges from -0.16% to 4.93% in the horizontal direction and 1.88% to 5.70% in the vertical direction. The difference between the measured and analytical water velocities ranges from -0.13% to 4.97% in the horizontal direction and 1.97% to 5.99% in the vertical direction.
- Wave prediction algorithms were developed to forecast wave elevation at the dock location. The accuracy, quantified by the coefficient of determination (R^2), ranges from 0.959 to 0.990 for regular waves and from 0.850 to 0.948 for irregular waves. In addition to limitations of the linear wave-based prediction method, the discrepancies are also attributed to measurement uncertainty and wave nonlinearity, as evidenced by differences between upstream and dock wave measurements ranging from 0.20% to 4.53% for regular waves and from 2.12% to 4.94% for irregular waves.
- The wave excitation force estimation force exhibits higher accuracy than the wave prediction method, with R^2 values ranging from 0.963 to 0.995 for regular waves and from 0.956 to 0.980 for irregular waves. This is attributed to the relatively limited influence of wave nonlinearity, particularly diffracted wave components on the excitation force.
- Based on predicted water particle velocities, the dock motion can be controlled to reduce the relative velocity between the dock motion and surrounding water velocity in the heave direction. Experimental results demonstrate that this relative velocity control strategy improves AUV docking performance compared to alternative control modes.