A virtual real-time hybrid simulation to study deep-water mooring dynamics of wave energy converters

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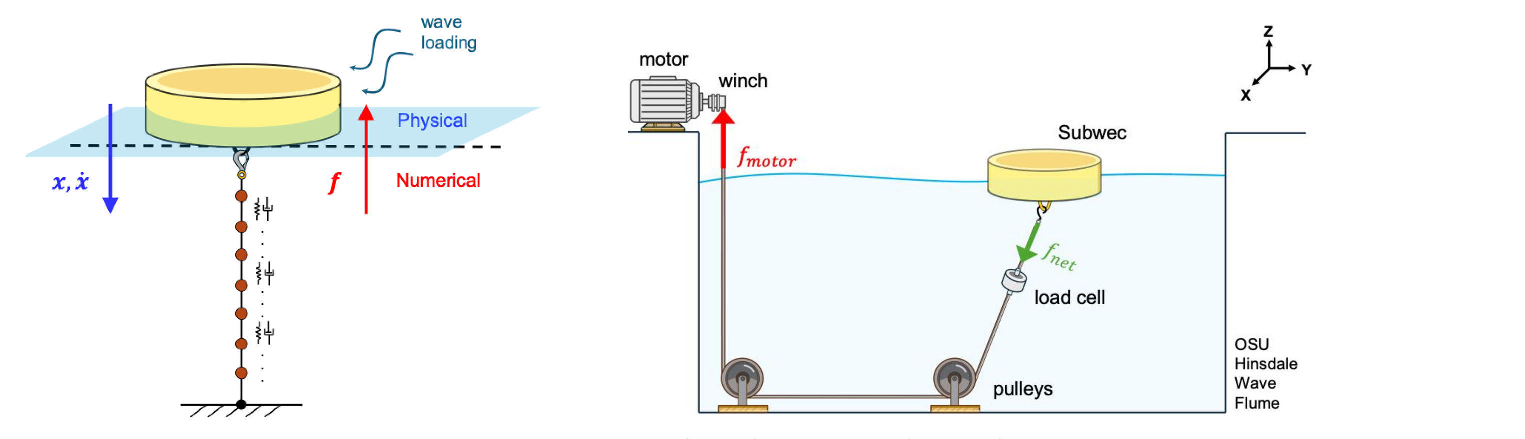
A dynamic motor model is derived and validated against experimental data. The model accurately captures system behavior, allowing for realistic simulation in a virtual environment.

INTRODUCTION

Wave flumes lack the depth to test deep-water wave energy converters & their full-scale mooring lines.

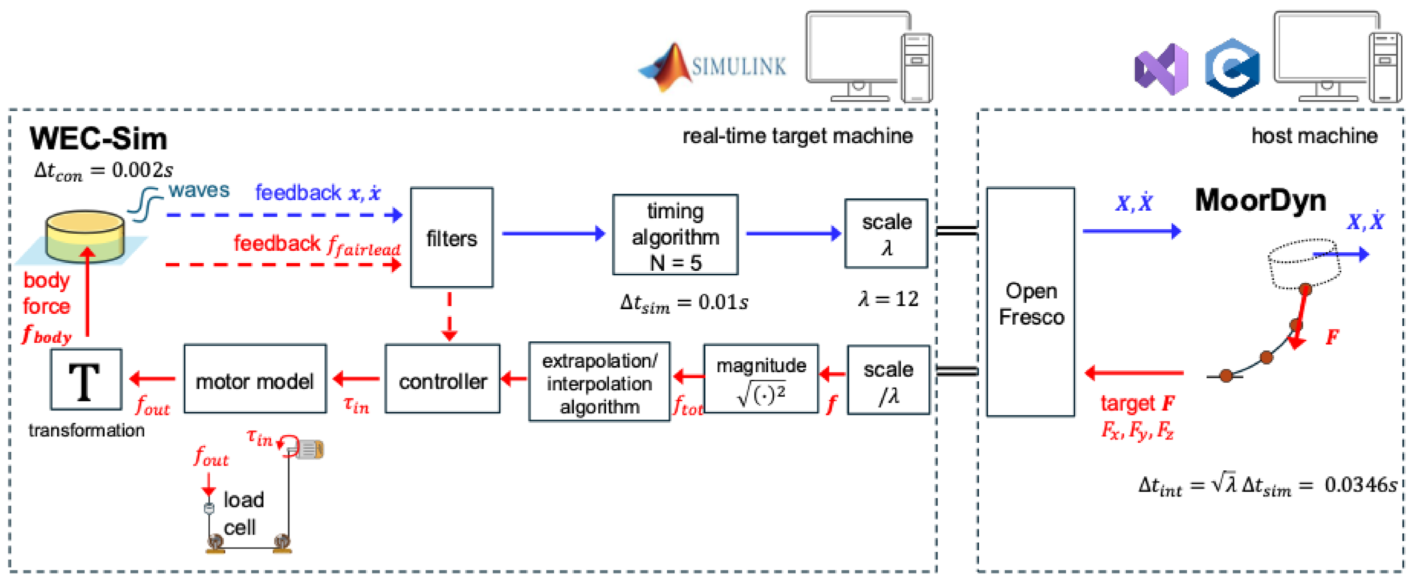


Partitioning in RTHS experiment — Physical experimental setup showing actuation system

Real-time hybrid simulations (RTHS) enable enhanced testing of deep-water devices by combining physical wave flume tests with actuator-imposed forces from numerically simulated mooring lines[1].

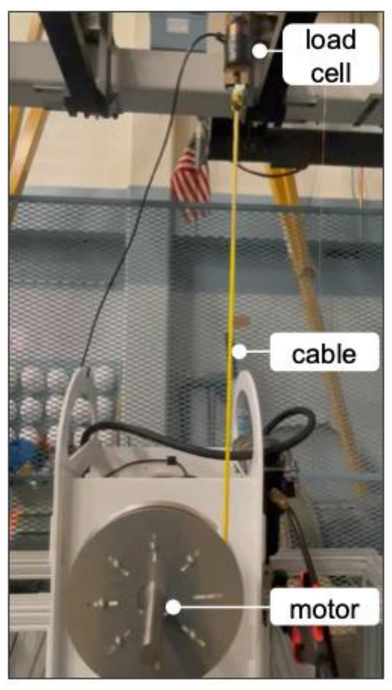
A virtual-RTHS with a modular, three-loop architecture, is developed to rehearse the experiment prior to flume testing.

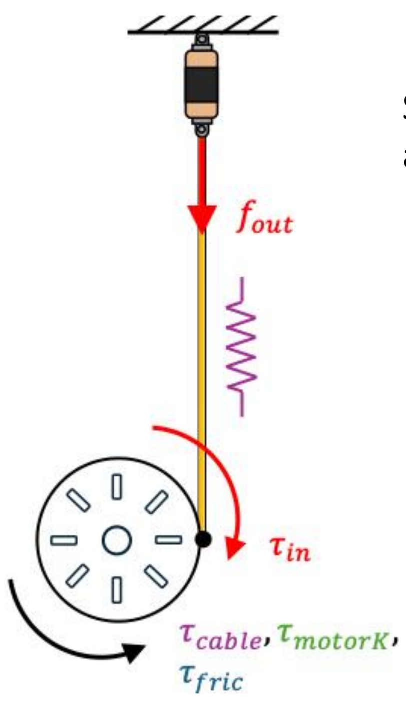
VIRTUAL HYBRID SIMULATION FRAMEWORK



The virtual-RTHS demonstrates the three-loop communications architecture and time synchronization algorithms behind the RTHS experiment. Here, the physical specimen is modeled in WEC-Sim[2], and the mooring line is modeled in MoorDyn[3]. Ordinary differential equations describing the motor's dynamics are used to model the actuation system.

MOTOR MODEL DERIVATION



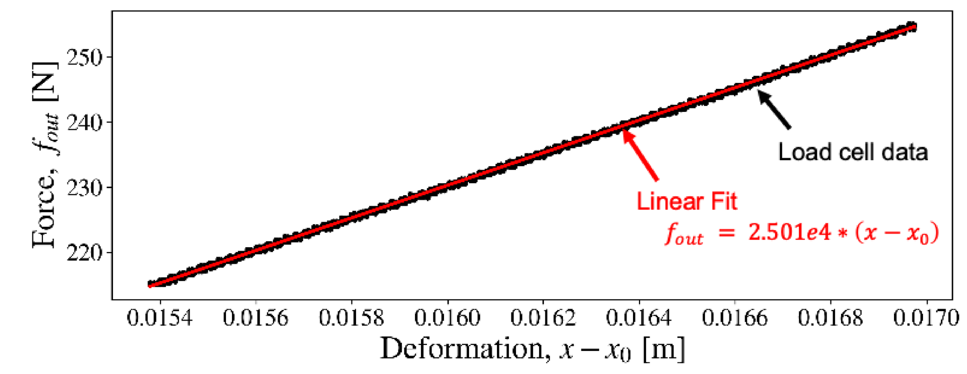


Schematic of experimental setup (left) and governing equations of motion (below)

$$I\ddot{\theta} = \tau_{in} - r \cdot k_{cable}x - r \cdot k_{motor}\theta - (\tau_c \operatorname{sgn}(\dot{\theta}) + b\dot{\theta})$$

A simplified experimental setup was developed to construct the numerical motor model. To model the dynamics, Newton's second law of rotation was used to obtain governing equations of motion at the motor relating to input torque, the stiffness of the cable and motor respectively, and friction.

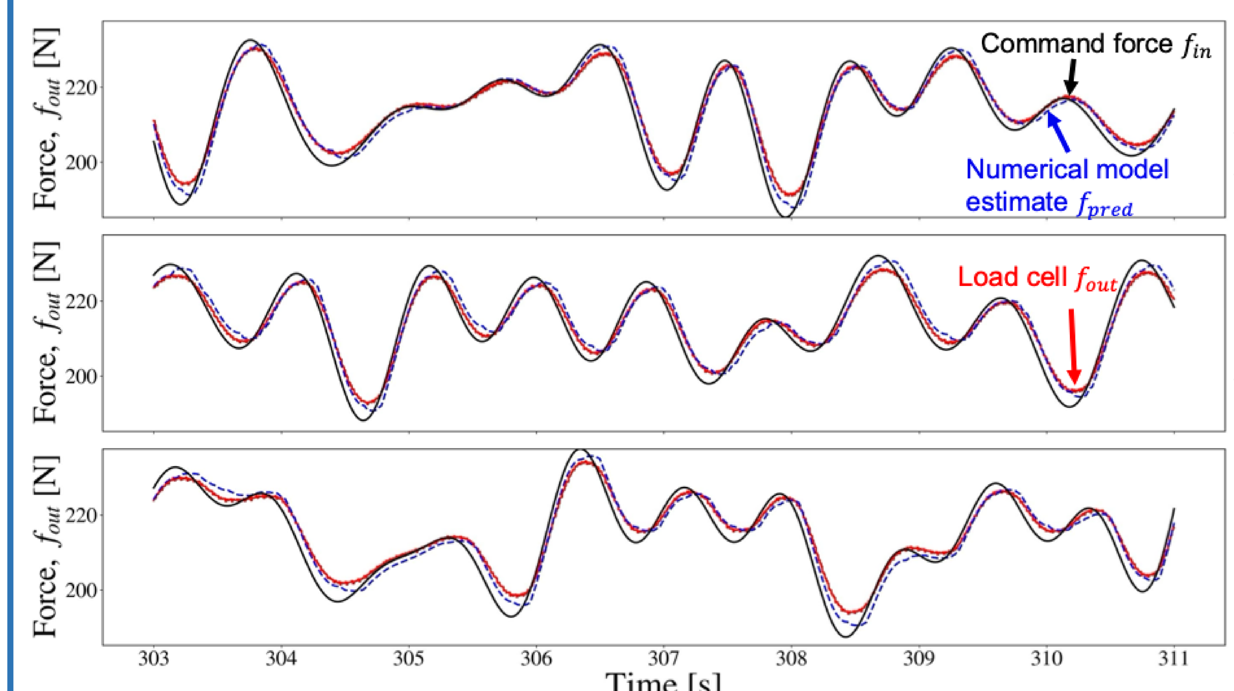
RESULTS & DISCUSSION



Force vs deformation at the cable from linear ramp tests

The cable stiffness k_{cable} is estimated from linear ramp tests at the motor, using the slope of the force-deformation curve beyond the pretension region. Experimental data from the load cell is shown in black, while the linear fit is in red.

The other parameters of the numerical model can be estimated using MATLAB System Identification Toolbox[4].



Sample time trajectory of multisine command force f_{in}, numerical model estimate f_{pred}, and load cell force f_{out}.

Table: Parameters estimated through system identification

Parameter	Value	Units
Total inertia I	0.0403	kg m^2
Viscous damping coefficient b	20.033	Nms/rad
Coulomb friction τ_c	0.401	Nm
Cable effective stiffness k_{cable}	369282.43	N/m
Motor rotational stiffness k_{motor}	0.974	N/rad
Pulley radius r	0.1143	m

The numerical model shows strong predictive capabilities.

The constant Coulomb friction τ_c serves to reduce peak amplitudes, while the inertia I models delay between command and output force.

Some discrepancy between estimated f_{pred} and actual force f_{out} can be explained by failing to capture rate dependencies with the simplified linear stiffness cable model or loose connections in the experimental setup. Some friction may also have a quadratic dependency with the motor's velocity.

CONCLUSION

A virtual hybrid simulation using a three-loop architecture is presented. The actuation system was modelled using governing equations of motion with nonlinearities such as friction. The parameters influence the results with varying sensitivities. The estimation was more sensitive to changes in parameters such as Coulomb friction τ_c and cable stiffness k_{cable}.

The virtual framework can contribute to designing hybrid simulations that virtually extend depth of wave facilities, facilitating more efficient testing and validation of deep-water devices. Future work will involve fine tuning the motor model and incorporating strain-rate dependencies under faster loading cases.

ACKNOWLEDGEMENTS

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