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## Design and Validation of a Hybrid Model Testing Setup for Scaled Energy Converters in the NREL Wave Tank

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### Abstract

To capture the combined effects of wind, tides, and waves using real-time hybrid model testing, a system of winches was designed and integrated into the wave tank at the National Renewable Energy Laboratory. These winches provide the additional forces and moments caused by wind, currents, and moorings, which are not physically replicated in the tank. In the initial test of an open-source floating tidal turbine, five servomotor-driven winches apply forces on the device in four degrees of freedom: surge, heave, sway, and pitch. This system will expand the testing capabilities of the wave tank by enabling wind and tidal turbines to be tested, as well as reproducing more realistic loading on all marine energy devices. This paper discusses the motivation and methodology of the hybrid model testing system, in addition to sample results from preliminary testing with the tidal turbine prototype in the wave tank.

*Keywords:* real-time hybrid model testing, tidal turbine, wave tank testing, cable robot, OpenFAST

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### 1. Introduction

To ensure energy-producing devices in the ocean can operate reliably when deployed in open water, it is crucial to conduct laboratory tests that adequately recreate realistic operating conditions. This saves time and money by reducing the need to overdesign devices and enabling marine energy converters to be better optimized for their environment. The Sea Wave Environment Lab (SWEL) wave tank at the National Renewable Energy Laboratory (NREL) creates ocean waves in a controlled setting. Even though the SWEL wave tank can reproduce many different wave conditions in isolation, it cannot replicate a full ocean environment with wind or tidal currents. In general, it is challenging to find facilities that can adequately simulate multiple environmental loads concurrently. Hybrid model testing addresses this gap by integrating simulations with physical testing so researchers can perform lab tests that better represent deployment conditions.

Hybrid model testing uses numerical models and physical hardware in tandem to perform real-time tests on scaled prototypes. A numerical model calculates the scaled forces missing from the experiment, which are then recreated in the physical test setup using a set of actuators. Hybrid model testing has been used to test floating wind turbines and assess mooring systems for ocean structures [1, 2]. Although hybrid model testing expands the capabilities of experimental facilities by enabling more comprehensive loading conditions, its ability to recreate realistic ocean conditions is limited by the accuracy of the modeling software used in the loop. This study used a scaled model of the

RM1 open-source tidal turbine mounted on a floating platform [3, 4]. The following sections will detail the physical components installed in the SWEL wave tank, the controls system architecture, and the results of using this setup to test the RM1.

## 2. Implementation

### 2.1. Hybrid Model Testing Strategy

The hybrid model testing setup used in this study combines physical hardware attached to the SWEL wave tank with numerical modeling software. The hardware, a set of five winches, creates tension in cables attached to a floating prototype to re-create external forces that are not included physically. In this case, the winches simulate loads from mooring lines and tidal currents, including forces and torques from the turbine rotor. The real-time loads for the winches can be determined by simulating the floating tidal turbine in OpenFAST, NREL's open-source wind and marine turbine simulation tool, using its AeroDyn and MoorDyn modules. AeroDyn is a rotor aero/hydrodynamic module, and MoorDyn is a lumped-mass module that represents mooring system dynamics for floating structures [5]. An overview of the hybrid test setup is illustrated in Figure 1.

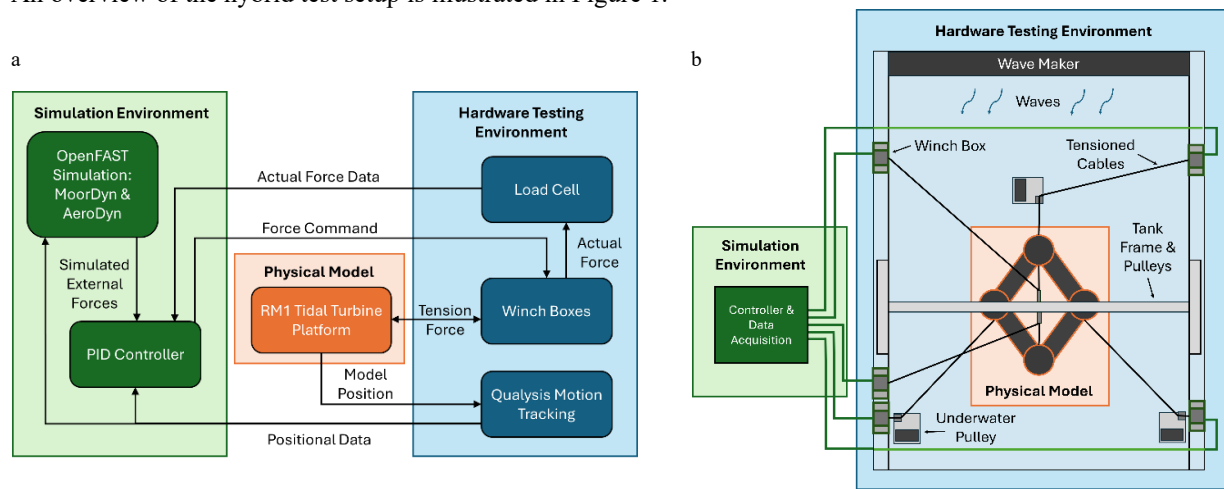


Fig. 1. (a) Overview schematic of hybrid model testing; (b) hybrid model test setup (aerial view of wave tank).

As shown in Figure 1(a), the floating prototype motion is recorded by a Qualisys optical tracking system and passed to the OpenFAST modules, which use the motions, along with knowledge of the inflow conditions, to calculate forces. These forces are then passed to a tension controller, which actuates the loads. The motions recorded by Qualisys, along with real-time tension data in each winch cable, are used as feedback for the controller. As integration with OpenFAST is still in progress, the hardware and motor controls were tested independently of the inputs from a numerical model, as discussed in Section 2.3. Design loads for the physical hardware were based on tension ranges in a prior study of mooring geometry optimization by Sharma et al. [6]. Figure 1(b) is an aerial view of the wave tank showing the layout of the physical hardware for hybrid model testing. The setup includes five winches, three underwater pulleys, and two above-water pulleys mounted on a frame over the tank.

### 2.2. Physical Component Design

The physical hardware in this hybrid model testing setup was designed to attach to the edges of the existing SWEL wave tank, generate up to 50 N of tension at each point of connection on a floating model, record the applied force for the control system, route the tensioned cables to the desired points on a floating model, and adapt to many configurations and cable angles. Additionally, components needed to resist corrosion either in damp air or fully submerged in chlorinated water.

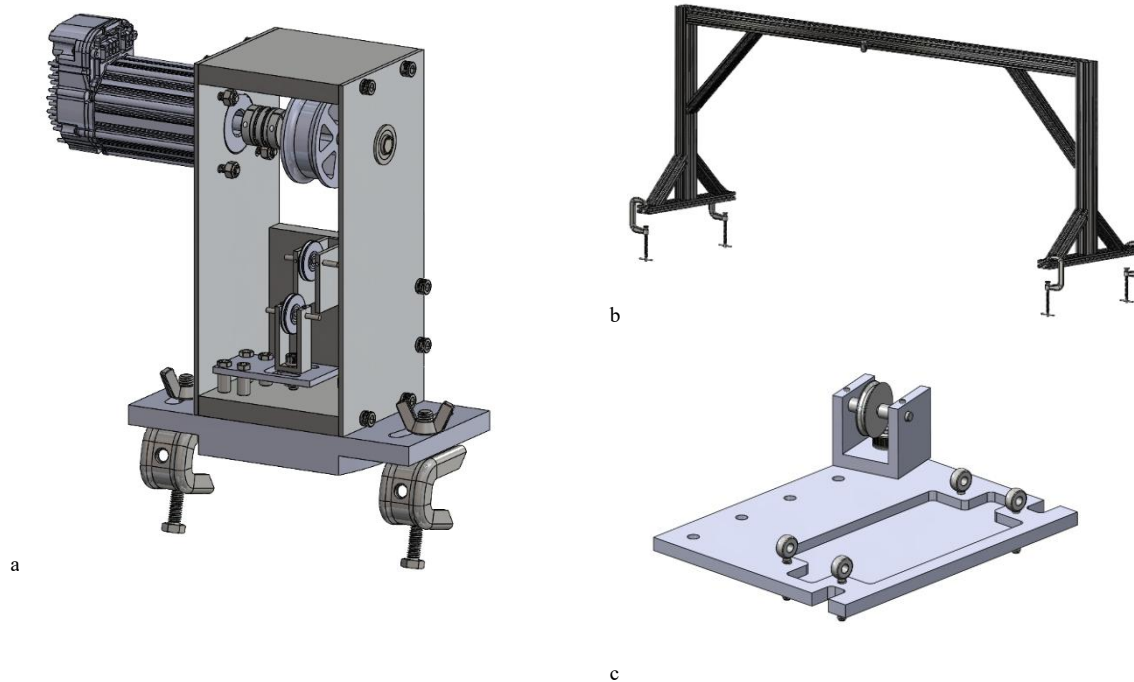


Fig. 2. (a) CAD of winch box and mounting block; (b) Tank frame and above-water pulleys; (c) Underwater pulley and base-plate.

Each winch box uses a servomotor to spool and unspool a cable drum to create the desired tension in a cable. This cable is routed through three pulleys inside the winch box and fed through an auxiliary pulley above or below the water's surface, shown in Figure 2(b) and (c). A load cell in the winch box provides tension feedback to the control system. Static tension testing of a single winch confirmed that the expected forces could be achieved by the winch motor. Tension control testing was performed on pairs of winches to tune the motor controls before testing all the winches and the floating turbine platform. One key parameter of the system is the placement of the winch pulleys and the line attachment points on the floating body. For the tension control system to work optimally, pulley positions need to be as accurate as possible, relative to their position assigned in the controller. By defining a global coordinate system through Qualisys, all above-water and body coordinates were found within  $\pm 2.5$  mm, and all underwater positions were found within  $\pm 20$  mm. Because the controller relies so heavily on the accuracy of these measurements, some future work includes using calibration routines and other measurement sources to improve the accuracy.

### 2.3. Controls

The controller for this hybrid modeling setup is adapted from [7] for use at SWEL. Initial simulation work was performed by [6] to determine the operating envelope for the RM1 tests in terms of maximum forces and the optimal placement of the tension lines on the model. The controller takes inputs from the Qualisys motion tracking system and the winch load cells and controls the motor velocities of the five winches. The net force of the winches produces a 4 degree of freedom (DOF) wrench on the body. The control system runs at 100 Hz and consists of four main parts: structure matrix, tension control, motion accommodation, and simulation. The structure matrix is the core of the controller. It relates the position of the body in the tank, which is measured by the Qualisys system, to the position of the winches. Through the matrix, a nominal pre-tension for each line can be computed, such that the pre-tension in the lines applies no net force on the body. Then, the desired wrench force can be added to those pre-tensions to compute the desired tension of each line. These desired tensions are the set point for the tension control. Tension control starts with a simple feedback proportional gain on the line tension of the winch. It is tuned to reach the set point as quickly as possible without oscillations. To speed up the rise time, a feedforward command is computed from the spring constant of the line. The tension controller by itself is not fast enough to accurately maintain the desired tensions while the body is moving, so a motion accommodation control is implemented as well. This part of the controller takes the incoming Qualisys positional data and computes the velocity of the body. From the velocity and structure matrix, the

change in length of the tension lines is determined and compensated for. This successfully accommodates the motion of the model and allows the tension controller to focus more on the stability of the desired tension rather than speed. With the first three parts of the controller, the winch system can apply a 4-DOF wrench on the body, accurately, in real time, regardless of its motion or position. The simulation part of the controller determines what that wrench force should be. In its simplest form, the simulation could be a stiffness matrix to approximate a mooring system or a constant thrust vector from a turbine. In a more complex case, OpenFAST modules can be run to simulate mooring lines, currents, turbulent inflow, or turbine control strategies. In all cases, the simulation takes in the position and orientation of the body from the Qualisys system and computes the expected loading, which it outputs as a 4-DOF wrench that the controller can apply to the body. The simulation is updated in real time with the controller to allow two-way coupling between the physical and numerical parts of the system.

### 3. Results

All aspects of the controller were tested individually, and the results presented here focus on the performance of the controller without simulation in OpenFAST. The tension controller by itself has a rise rate of  $\sim 23.8$  N/s with 0.1–0.6 N root-mean-square (RMS) error at steady state. The motion accommodation works well to account for large motions, but it does introduce some noise in the tension control. The full controller response to a step input and zero wrench leads to the same rise time, but now with an RMS error of 1.3 N at steady state, as shown in Figure 3.

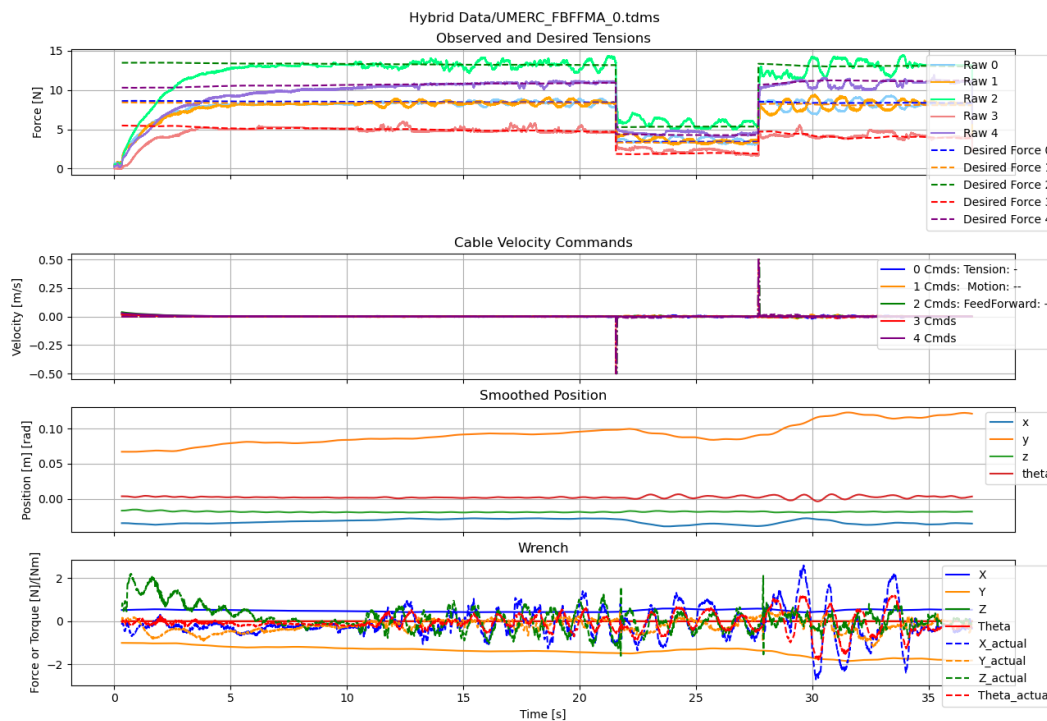


Fig. 3. Full control (feedback, feedforward, and motion accommodation) system response to step input and zero wrench.

One interesting result is the error in the applied wrench force on the body. By using the raw data from the test, the actual applied wrench force can be computed, and in this case the RMS error in the wrench is 1.4 N, very similar to that of the individual winches. This seems to suggest that there is little to no interplay between the winches at these forces. Additionally, the two other axes, roll and yaw, are not being controlled, but the winches can still apply a rolling or yawing moment to the body. The magnitudes of these moments are currently small enough that they are not a concern with this test, but this issue could be addressed by adding two additional winches to the setup, allowing for full control of all 6 DOFs. Additional tests for the controller's response to a wave case were also conducted.

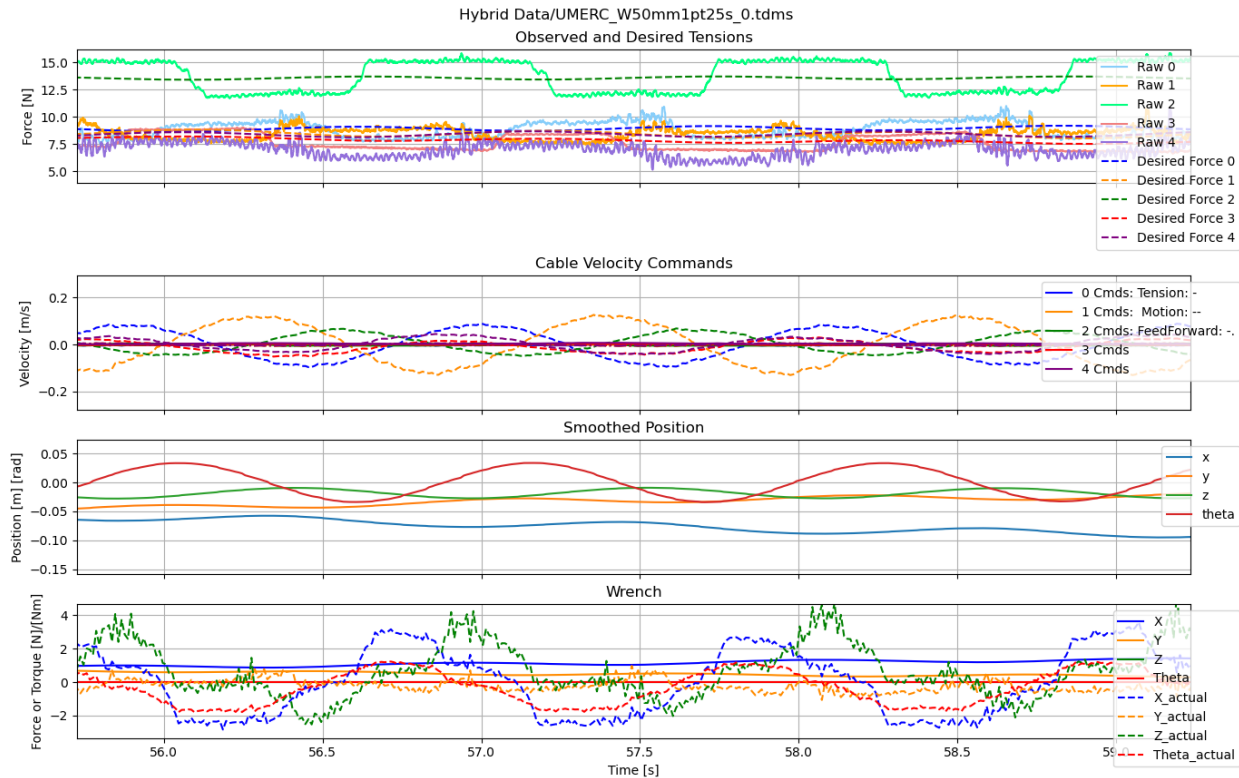


Fig. 4. System response to scaled waves propagated in the tank.

The objective of the wave case was to apply no net force on the structure as it moves with the waves. Only a small amount wrench in the x direction was used to keep the body in place in the tank. When testing with a regular wave period of 1.25 s and a wave height of 50 mm, the noise in the tension response became more regular and took on a square wave shape with a period that matched the waves. However, the relative magnitude of the error remained consistent, showing that the controller predominately allows the body to move freely in the waves. As the project continues, the controller will be improved to achieve the desired force as accurately as possible such that system global responses can be re-created within 5% of the expected values.

#### 4. Conclusion

A real-time hybrid model testing setup is being designed for the NREL SWEL wave tank to simulate external forcing that is present in an open ocean but cannot be created by the tank itself, such as loads from wind, currents, and moorings. This setup will expand testing capabilities at SWEL and other facilities. The system hardware has been constructed, tested, and deployed, and sample results from preliminary controller tests were presented in this paper. Ongoing work includes tuning and verifying all parts of the controller and integrating OpenFAST modules to simulate the full system response under combined loading.

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