1:70-Scale Model Testing of the Reference OpenSource Controller (ROSCO) on the IEA-Wind 15MW Reference Wind Turbine Including Floating Feedback

Preprint

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ABSTRACT

This paper presents results from the Floating Offshore-wind Controls Advanced Laboratory (FOCAL) Experimental Campaign performed at the University of Maine's (UMaine's) Harold Alfond Wind/Wave Ocean Engineering Laboratory (W^2). The project involves four Froude-scaled test campaigns considering the International Energy Agency (IEA) Wind 15MW Reference Wind Turbine deployed on the VolturnUS-S semi-submersible platform with tuned-mass damper elements in the hull. The turbine employs real-time rotor torque and blade pitch control through the Reference OpenSource Controller (ROSCO), including the additional control strategies of ROSCO's thrust peak shaving and a floating feedback control loop. Results with the floating feedback control are considered in this paper and show a significant reduction in platform pitch motion and loads around the platform pitch natural frequency with minimal negative impact of rotor power quality.

KEY WORDS: Model Testing; Floating Wind; Controls; Wind Turbine; Wind Energy

INTRODUCTION

This paper presents testing results from the **F**loating **O**ffshore-wind and **C**ontrols **A**dvanced **L**aboratory (FOCAL) Experimental Program funded by the U.S. Department of Energy ARPA-e ATLANTIS program. The project aims to generate the first public floating offshore wind turbine (FOWT) scale model dataset to include advanced turbine controls, floating hull load mitigation technology, and hull flexibility to enable validation of FOWT engineering numerical tools. The experiments generated data for FOWT loads, motion, and performance, while operating in realistic wind/waves, and with advanced turbine and platform controls.

The FOCAL project involves four Froude-scaled test campaigns considering the International Energy Agency (IEA) Wind 15MW Reference Wind Turbine deployed on a VolturnUS-S inspired semi-submersible platform with tuned-mass damper elements in the hull. The turbine employs real-time rotor torque and blade pitch control through the Reference OpenSource Controller (ROSCO), including the additional control strategies of thrust peak shaving and a floating feedback control loop.

At full scale, the IEA-Wind 15MW Reference Wind Turbine is a three-bladed upwind design with collective blade pitch and a 240 m diameter rotor at a hub height of 150 m. The 1:70-scale turbine design employs Froude-scaling for mass and geometry while utilizing a performance-matched design for the rotor to generate proper aerodynamic forcing. Gueydon *et al.* (2020) present a summary of previous floating scale-model wind turbine testing, which generally aimed to reproduce the correct steady-state response of the rotor. This performance-matched design methodology focuses on designing a scale turbine that generates the correct rotor thrust, which is important to capturing mean loads on the system (e.g. Kimball *et al.*, 2014). The turbine designed for FOCAL expands on that methodology to also include capturing aerodynamic load sensitivities to changes in wind speed and blade pitch, which are important for dynamic loading and controller tuning (Goupee *et al*., 2017).

The first three test campaigns consider the rotor and hull independently, with the fully assembled system tested in the final campaign. In the first test campaign, aerodynamic performance of the turbine and controller is characterized on a rigid platform and presented by Kimball *et al.* (2022) and Mendoza *et al.* (2022). Campaigns 2 and 3 consider the floating platform in a variety of wave environments, using a scaled mass as a stand-in for the rotor topside, with the goal of characterizing hydrodynamic performance and the tuned-mass damper system. This paper presents initial results from Campaign 4, where the turbine is mounted to a flexible tower and deployed on the scale floating platform for a fully coupled wind/wave test campaign. The system is subject to a variety of wind and wave conditions representing operational as well as design driving environments. System dynamics and turbine characteristics are measured to determine global performance and assess the effect of the control strategies employed. This paper considers the performance of the floating system with the baseline ROSCO and the effect of the floating feedback control loop. Data from the test campaigns will be shared through the U.S. Department of Energy's Data Archive and Portal (DAP) (Robertson, 2023) upon completion of the project.

BASIN OVERVIEW

The scale-model testing is performed in the University of Maine's (UMaine) Harold Alfond Wind/Wave Ocean Engineering Laboratory. The facility includes a 30 m long x 9 m wide x 5 m deep wave basin with a 16-paddle directional wave maker and elliptical beach. The wind machine utilizes 32 individually controlled fans to generate winds up to 5 m/s with a test area 3.5 m tall x 7 m wide. The facility is shown in Figure 1.

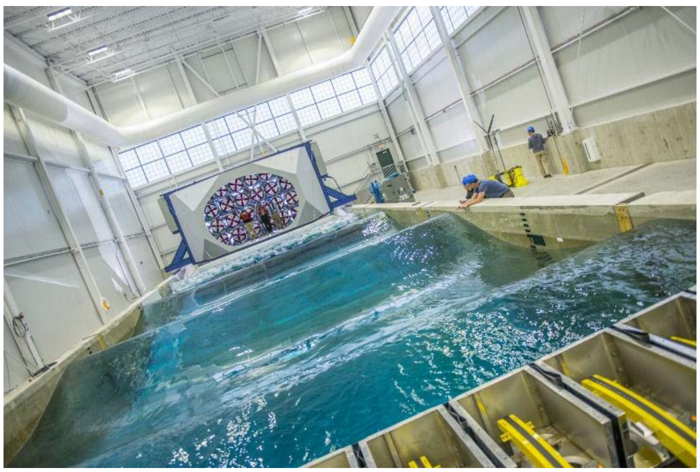

Fig 1. Wind/Wave Basin at UMaine

MODEL DESCRIPTION

The FOCAL experimental program considers a 1:70 Froude-scale model of the IEA-Wind 15MW Reference Wind Turbine (Gaertner *et al.*, 2020). As is typical for wind/wave floating wind turbine testing, the scale turbine design employs Froude-scaling for mass and geometry while utilizing a performance-matched airfoil design for the rotor to generate proper aerodynamic forcing. The design of the scale-model turbine has been presented in earlier publications from the FOCAL program (Kimball *et al.*, 2022). Unless stated otherwise, all results are presented at full scale using Froude-scale methodology (e.g. Martin *et al.*, 2014).

The hull is based on the VolturnUS-S (Allen *et al.*, 2020) semi-submersible platform and has been modified to include tuned-mass damper elements in the outer columns as well as measurement of internal hull loads. General characteristics of the floating turbine system will be more thoroughly documented in future publications, including the Campaign 4 Test Report that will be uploaded with the dataset. Main particulars of the hull and topside are in Table 1.

Table 1. General Model Dimensions, Mass, and Inertial Properties

Item	Unit	Value
Rotor Diameter	m	243
Hub Height	m	150
Rotor-Nacelle Assembly Mass	t	1,197
Tower Mass	t	641
System Draft	m	20
Platform Mass	t	18,656
System Pitch Inertia, Iyy at system CG	kg-m^2	4.936E+10

The system natural frequencies were measured from free-decay tests of the floating moored system to determine rigid-body natural frequencies and hammer tests to measure the tower first bending mode frequency. Results are summarized in Table 2.

Table 2. Floating System Natural Frequencies

Item	Period (s)	Frequency (Hz)
Surge	80.4	0.0124
Sway	79.1	0.0126
Heave	20.9	0.0478
Roll	31.0	0.0323
Pitch	31.4	0.0319
Yaw	50.7	0.0197
Tower – Fore/Aft 1st Mode	2.44	0.409
Tower – Side/Side 1st Mode	2.35	0.425

Mooring

The model is moored using three horizontal lines, each extending radially from one of the three platform legs. Each line is made from an extensionally stiff tendon in line with a linear spring. The resulting spring stiffness is 1.25E+05 N/m, and the system stiffness represents the linearized stiffness of the full-scale system. The full mooring system is described in the Campaign 2 Test Report, which will be made available with the dataset to the DAP upon completion of the project.

Instrumentation

The turbine and floating platform are fully instrumented, and all data are recorded with a National Instruments cRIO-9047 data acquisition system. Data are collected at 120 Hz (1,000 Hz model scale) and recorded to file at 24 Hz (200 Hz model scale). Additionally, a Qualisys motion capture system tracks reflective markers on the hull to resolve 6 degree-of-freedom (6DOF) motion of the hull. It is important to note that rotor thrust was not measured directly and was instead calculated from the tower top 6DOF force sensor, which is located between the tower top and the nacelle, see Figure 2. As such, this sensor measures all reaction loads from the nacelle. To calculate the rotor thrust force, the effect of gravity and nacelle inertial forces have been removed from the signal in post-processing using the values measured by the tower top accelerometer and the platform pitch inclination angle.

The data provided to ROSCO's control loop are the rotor torque, measured from the inline torque transducer located on the turbine's low-speed shaft; rotor speed, measured by the rotor's encoder; and platform pitch rotational velocity, measured by the hull-mounted accelerometer/inertial measurement unit (IMU). The rotor motor is coupled to the rotor and provides the ability to regulate rotor speed through application of positive or negative torque to the driveshaft. The torque set point calculated by ROSCO is thus implemented by controlling the rotor motor torque so that the torque measured on the torque sensor matches the set point provided by ROSCO. The ROSCO blade pitch set point is implemented via three independent servo motors in the rotor nacelle assembly, which each actuate one blade. For these experiments, the rotor was operated in collective blade pitch control, and each blade was controlled to follow the blade pitch set point defined by ROSCO. An overview of the system and primary instrumentation is shown in Figure 2.

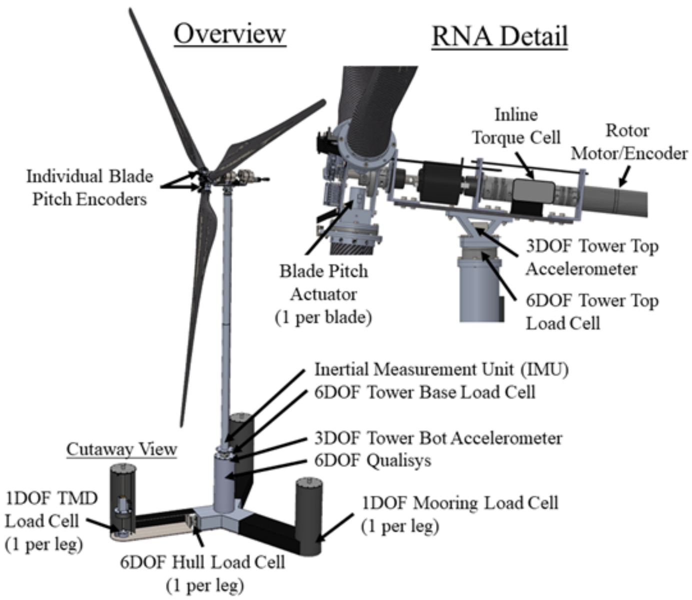

Fig 2. FOCAL Instrumentation Overview

ROSCO

Control of the turbine is accomplished through a real-time implementation of the National Renewable Energy Laboratory's ROSCO controller (Abbas *et al.*, 2022). The ROSCO controller is run at 120 Hz (1,000 Hz model scale) on the cRIO-9047 utilizing the bladed-style DISCON.IN input file. The general control strategy of ROSCO is shown in Figure 3, where ω_g is generator speed, τ_g is generator torque, β is blade pitch angle, v_{est} is estimated wind speed and $\Delta\omega$ is a controller set point shifting term.

The as-built properties of the turbine (e.g. performance, thrust, and torque coefficients (Cp, Ct, and Cq), rotor inertia, and filter settings) from earlier work were used to tune the ROSCO controller using the ROSCO toolbox, and the branch used by FOCAL is available on GitHub (NREL, 2021). Due to Reynolds number sensitivity inherent to these low-Reynolds-number turbines, the velocity difference between the rated and above-rated wind conditions was enough to warrant two different tunings depending on which wind environments were being considered. Details on the ROSCO tuning methodology, including Reynolds number effects, are to be presented in future publications. Measured rotor torque, rotational speed, and the current time from the experiment are passed to ROSCO at full scale at the cRIO loop rate of 8 ms (1 ms model scale) through the AVR-SWAP array. ROSCO then determines the appropriate blade pitch and generator torque set points, which are Froude-scaled down to model scale and implemented in the experiment.

The main control loops of the "ROSCO Baseline" (RO) controller are the collective blade pitch controller and the generator torque controller. This paper considers above-rated conditions, where the baseline controller uses a proportional-integral controller to regulate rotor speed through collective blade pitch actuation. Additionally, the "floating feedback" (FL), "pitch saturation" (PS), and "set point smoother" (SS) control strategies can be toggled on/off through the DISCON.IN input file. This experiment implemented the SS for all tests and selectively activated the FL and PS control loops to assess their impact on system performance. For more information on these control options, please see (Abbas *et al.*, 2022). Results from the FL control loop are discussed in this paper.

The FL control loop is used to decouple platform motion and generator speed variation, which occurs due to the negative damping problem in blade pitch control for floating wind turbines (Larsen and Hanson, 2007). In FOCAL, this feedback loop is considered with the above-rated wind and wave conditions. It uses the platform pitch rotational velocity and a tuned control loop gain to calculate a blade pitch increment, as shown in Figure 3. While ROSCO typically integrates the nacelle fore/aft acceleration or pitch rotational acceleration as the feedback signal, in FOCAL the platform pitch rotational velocity is directly available from the system instrumentation, so ROSCO is modified to take this input directly. ROSCO then filters the signal with a first-order high-pass filter and a second-order low-pass filter based on the input settings in the DISCON.IN file. The default settings were used for these filters with the high-pass frequency set to 0.0016 Hz and the low-pass frequency set to 0.034 Hz to include to the system pitch natural frequency. A Bode plot of the filter is shown in Figure 4. The design of this filter is critical to the performance of the floating feedback loop, as it modifies both the magnitude and phase of the feedback signal, which impacts the interaction between the blade pitch actuation and the platform global response. The platform pitch velocity is then used to compute a collective blade pitch adjustment, which is added to the collective pitch signal provided by the speed regulation control loop.

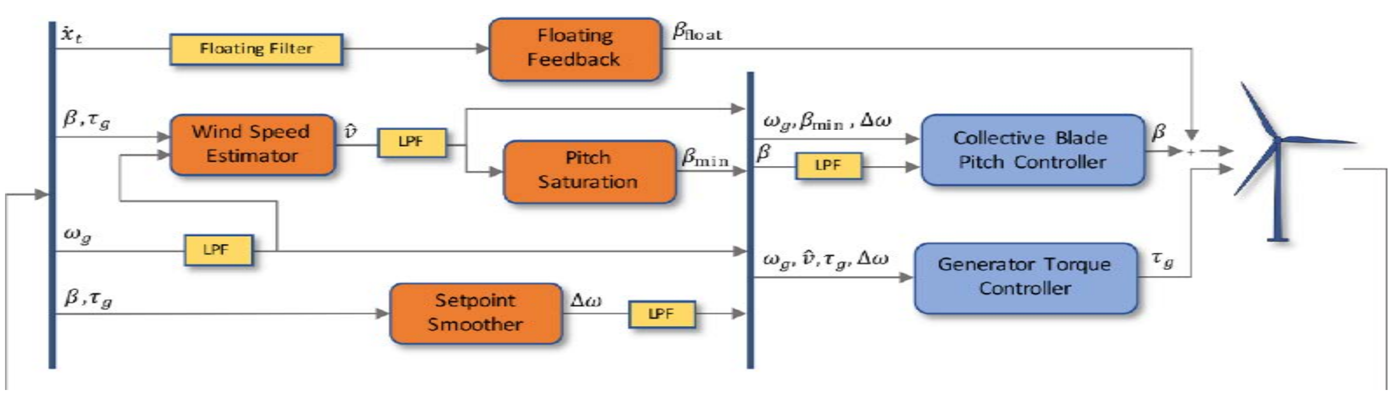

Fig 3. ROSCO General Control Strategy (Abba s *et al.*, 2022)

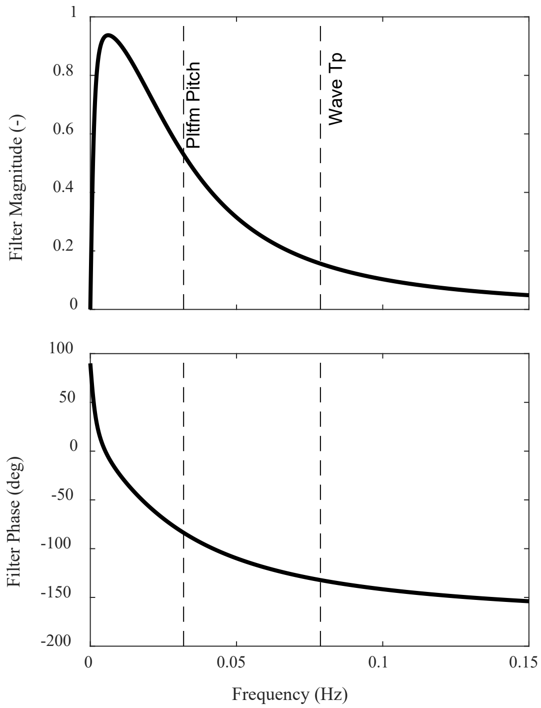

Fig 4. ROSCO FL Feedback Filter, Magnitude and Phase

TEST ENVIRONMENTS

Environments are informed by previous campaigns, namely, wind environments from Campaign 1 and wave environments from Campaigns 2 and 3. This paper focuses on the performance of the system in above-rated wind conditions with the corresponding wave environment.

Wind

The above-rated wind condition is realized through a time-varying wind field calibrated to be as uniform as possible over the rotor-swept area. Wind speeds were determined from prior turbine characterization work and include a 20% increase over Froude-scale conditions to help alleviate Reynolds number effects, which are common challenges with these model-scale floating turbine tests (Kimball, 2022). Anemometer surveys of the wind field are used to quantify spatial uniformity and wind shear while dwell measurements are used to quantify turbulence intensity. Parameters are in Table 3, where "Average U" is the average wind speed measured from three dwell measurements of the wind field, one at hub height at the rotor centerline as well as two at hub height at +/-70% of the rotor radius, respectively. The reported standard deviation is the average standard deviation from the runs. The power-spectral density results are shown in Figure 5.

Table 3. Wind Environment Characteristics

Wind ID	**Average U**	**Standard Deviation**	**Note**
AR2S	25.2 m/s	0.54 m/s	Above-Rated Wind

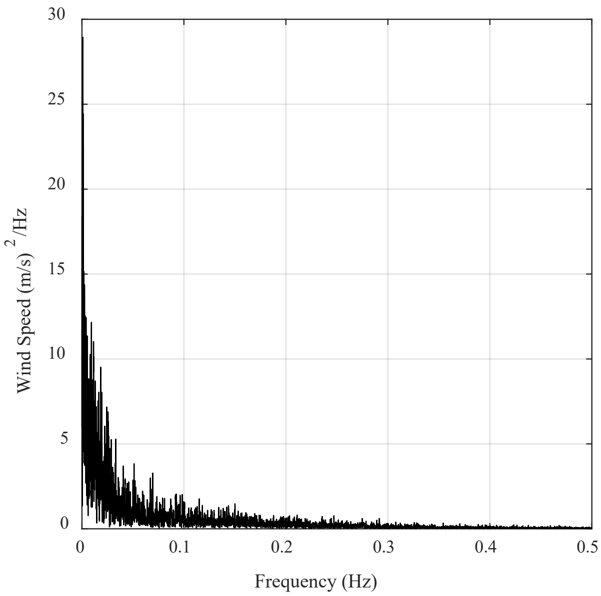

Fig 5. Wind Environment Power-Spectral Density

Waves

Corresponding to above-rated wind conditions, a JONSWAP spectral wave with parameters representative of a design load case (DLC) 1.6-style load case (ABS, 2020) is used. Multiple seeds are used to generate five instances of the wave environment, and five repeats are performed for the first seed. All wave conditions are long-crested waves with a head-on direction and no directional spread. Parameters of the wave environments are shown in Table 4, and the power-spectral density is shown in Figure 6.

Table 4. Wave Environment Characteristics

Wave ID	**Hs**	**Tp**	**Gamma**	**Notes**
I3 Seeds 1-5	8.1 m	12.7 s	2.75	DLC 1.6 Wave JONSWAP Spectra

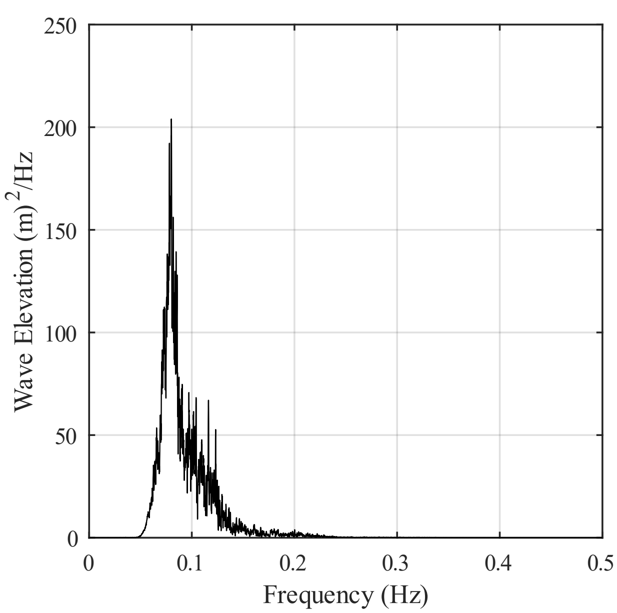

Fig 6. Wave Environment Power-Spectral Density

Test Matrix

To isolate the influence of wind and waves on the floating system, the system is first exercised under wind excitation only. In this configuration, the baseline RO controller is active and the turbine is floating on the moored platform. Next, the system is subject to wave-only tests with the turbine parked. Finally, combined wind/wave cases are run with the turbine operating either solely under the baseline RO control or with the additional FL control enabled. The subset of the test matrix considered in this paper is summarized in Table 5.

Table 5. Abbreviated Test Matrix

Wind	Wave	Control	Objective
AR2S	-	RO	Wind Only – ROSCO Baseline
-	I3S1	-	Wave Only – DLC 1.6 Wave
AR2S	I3S1	RO	Wind/Wave – Baseline RO
AR2S	I3S1	FL	Wind/Wave – FL

RESULTS

Wind Only

The aerodynamic performance of the wind turbine in fixed-bottom conditions with no waves was studied in Campaign 1 (Mendoza *et al*., 2022). In Campaign 4, the turbine was mounted to the floating platform and the system was subject to wind-only excitation. Results for the above-rated wind case are shown in Figure 7 and Table 6. In above-rated conditions, the rotor torque set point is the rated torque value of 1.87E+07 Nm, and ROSCO uses collective blade pitch control to regulate rotor speed to the rated rotor speed of 0.126 Hz. Results show that the rotor torque and speed are well regulated, with a coefficient of variation (COV) of 3.0% and 1.6%, respectively. Blade pitch actuation corresponds to the energy in the wind energy frequencies and has a COV of 1.7%. Note that rotor thrust, rotor speed, and rotor torque results here have been low-pass-filtered at 0.25 Hz using a third-order Butterworth filter to remove a 3P (0.38 Hz) excitation effect due to boundary effects of the wind field impacting the tip of each blade.

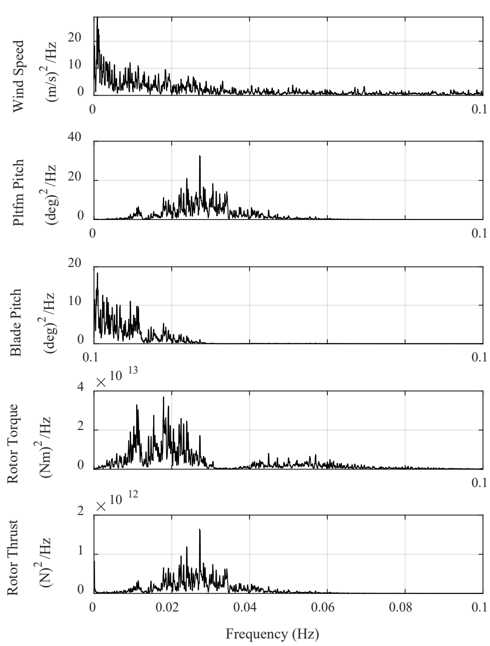

Fig 7. Wind Only – Platform and Turbine Responses

Table 6. Measured Values – Wind Only

Channel	Mean	Range	COV
Platform Pitch (deg)	5.2	2.7	8.2%
Blade Pitch (deg)	17.1	2.1	1.7%
Rotor Torque (Nm)	1.87E+07	4.28E+06	3.0%
Rotor Speed (Hz)	0.126	0.016	1.6%
Rotor Thrust (N)	1.07E+06	6.79E+05	9.2%

Wind/Wave – DLC 1.6

The next cases considered are an irregular sea state with the same above-rated wind condition. The wind/wave case is run five times with the baseline RO controller to establish repeatability of the test setup, wind/wave environments, and controller response. Statistics for the repeat RO cases are taken as the average of statistics computed from each individual run.

Under RO control, the blade pitch response is predominantly in the wind turbulence frequency range, and the rotor speed and rotor torque are well regulated with a COV of 1.9% and 3.8%, respectively. These results are similar to the wind-only case, indicating that the baseline controller is relatively insensitive to platform motion due to hydrodynamic forcing. With the floating feedback enabled, as shown in Figure 8, there is an increase in blade pitch actuation in the lower frequencies near the platform pitch natural frequency and extending into the wave energy region, starting to trail off after the wave peak frequency of 0.079 Hz, as would be expected based on the feedback filter discussed previously. The range increases by 24.8%, and comparing integrals of the PSD from 0 to 0.2 Hz indicates that there is 23% more energy when the FL controller is active.

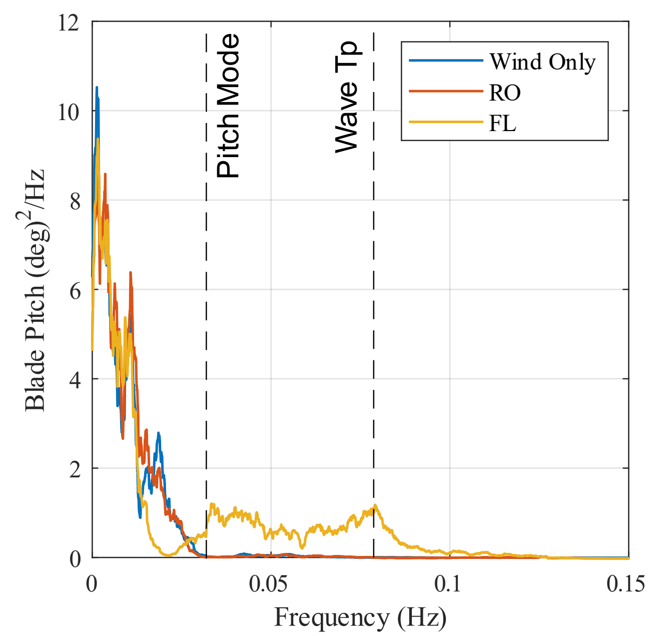

Fig 8. Blade Pitch Response with Floating Feedback

For the wind-only and RO cases, the platform pitch motion around the natural frequency is similar, indicating that the interaction of the wind and baseline RO controller excites the resonant platform pitch behavior in the absence of waves. When the floating feedback is enabled, the platform pitch response shows a significant decrease around the system pitch frequency while also increasing motion at frequencies between 0.03 Hz and 0.08 Hz relative to the RO controller. The increased motion is due to the ROSCO controller with the FL loop not having any information regarding the wave frequency and elevation, so it is unable to attenuate response at the wave frequency. The Bode plot of the filter shown earlier demonstrates that the filter magnitude at the platform pitch period is 0.6 and decreases to 0.2 at the wave peak period while the phase decreases from -85 deg at the platform pitch frequency to -130 deg by 0.079 Hz. This shows that while the magnitude of the feedback signal is being more strongly attenuated as the frequency increases, the phase is also becoming less effective for platform pitch control. Additionally, as shown in Figure 9, there is considerable platform pitch motion between 0.05 and 0.08 Hz, which corresponds to relatively strong feedback signals being considered by ROSCO. The tuning of the high- and low-pass filters affects how ROSCO behaves, and future work will consider further tuning of this filter to identify optimal settings. For the settings considered in FOCAL, comparing integrals of the power-spectral density of platform pitch shows that the energy present from 0 to 0.05 Hz is 33% lower with the FL controller than the RO baseline, and is 8% lower when considering all frequencies.

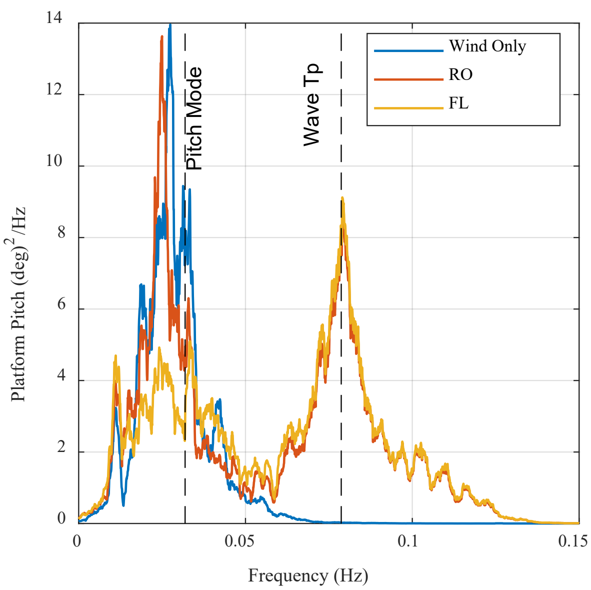

Fig 9. Platform Pitch Response with Floating Feedback

A comparison of statistics for key metrics is shown in Table 7.

Considering the tower base pitch moment, the wind-only and baseline RO controller show similar results below 0.05 Hz, corresponding to the platform natural pitch period as shown in Figure 10. When the FL controller is used, there is a significant reduction in tower base pitch moment around the platform pitch period of 0.0319 Hz while the higher frequency responses in the wave energy region and above are the same. Comparing integrals of the power-spectral density of tower base pitch moment shows that the energy present from 0 to 0.05 Hz is 40% lower with the FL controller than the RO baseline and is 7% lower when considering all frequencies.

Statistics for each of the five runs of the baseline controller were computed and then averaged for comparison with other runs in the table. It is notable that the range of the blade pitch and rotor torque increase by 24.8% and 13.3%, respectively, when the FL controller is used, corresponding to the increased blade pitch action. This increased blade pitch actuation results in a reduction in range of platform pitch by 11.3% and tower base pitch moment by 1.8%.

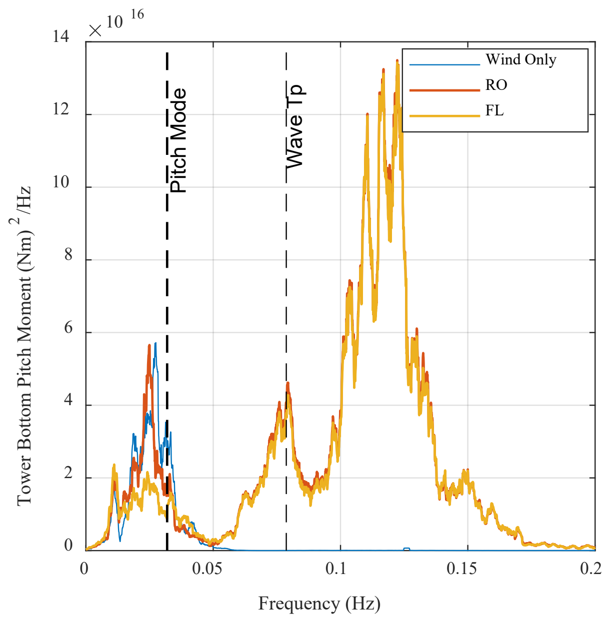

Fig 10. Tower Base Pitch Moment Response with Floating Feedback

Table 7. Comparison of Statistics for Key Metrics

	Wind Only			RO Controller			FL Controller			RO vs FL - % Diff		
Channel	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**
Surge [m]	8.7	5.1	0.74	9.6	12.0	1.61	9.9	12.2	1.59	2.7%	1.2%	-1.7%
Pitch [deg]	5.2	2.7	0.42	5.2	4.6	0.59	5.2	4.1	0.57	0.6%	-11.3%	-3.9%
Bld Pitch [deg]	17.1	2.1	0.30	17.1	2.0	0.31	17.0	2.5	0.36	-0.4%	24.8%	13.7%
Rotor Speed [Hz]	0.126	0.016	0.0016	0.126	0.016	0.0016	0.126	0.016	0.0016	0.0%	-7.2%	1.3%
Rotor Tq [MN-m]	18.7	4.3	0.57	18.7	4.5	0.63	18.7	5.1	0.65	0.0%	13.3%	2.9%
Thrust [MN]	1.07	0.68	0.10	1.16	1.87	0.25	1.15	1.95	0.26	-1.6%	4.1%	1.0%
TowerBot My [MN-m]	371.7	286.4	41.3	374.1	490.3	70.5	375.8	481.4	68.3	0.5%	-1.8%	-3.1%

CONCLUSIONS

Results from 1:70-scale model wind/wave testing for the IEA Wind 15MW Reference Wind Turbine on a VolturnUS-S-inspired semi-submersible floating platform are presented. The ROSCO controller is implemented in the loop on a real-time data acquisition and control system. Results from above-rated conditions are presented, showing the influence of the baseline blade pitch controller as well as a platform pitch floating feedback control loop, which demonstrated in the experiment a reduction in overall platform pitch motion and tower base bending loads, particularly near the platform pitch natural period.

The baseline ROSCO controller demonstrates the ability to regulate rotor torque and rotor speed in above-rated conditions through collective blade pitch actuation. The blade pitch response is primarily in the wind-energy frequency range, showing that the controller is responding to the turbulent changes of the wind field. It is observed that platform pitch motion is excited similarly in both wind-only and wind/wave environments with the baseline RO controller.

When the floating feedback control loop is enabled, the blade pitch controller takes into account the platform pitch rotational motion, and the blade pitch command shows significant activity around the platform pitch natural frequency as well as in the lower frequencies of the wave energy region. As there is significant platform pitch motion in these regions, this is consistent with the filtering of the platform pitch motion feedback signal, which passes through motion at the system pitch natural frequency and begins to attenuate the response at frequencies in the lower wave energy region. This blade pitch actuation results in a significant reduction in platform pitch motion around the platform pitch natural frequency as well as reductions in tower base bending moment and rotor thrust. While there is a moderate increase in platform pitch motion at the lower frequency wave energy region, the system responses are largely unaffected in the wave energy region and the FL controller shows an overall reduction in platform pitch motion and tower bottom pitch moment.

This work represents initial results from the FOCAL Experimental campaign. Future work will explore the additional environments, the effects of other ROSCO control parameters, the effect of the tuned-mass damper system, and further tuning of the floating feedback filters to adjust the interaction of ROSCO with the wave frequency energy range. All data from the experimental campaign will be uploaded to a publicly available repository upon completion of the work (Robertson, 2023).

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