Results from the FOCAL experiment campaign 1: turbine control co-design

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Abstract. This paper summarizes the scaling approach and results from the first experimental campaign of the Floating Offshore-wind and Controls Advanced Laboratory (FOCAL) Experimental Program, which is focused on developing public data sets to support the validation of numerical models for floating wind control co-design. A 1:70 Froude-scale performance-matched model of the IEA Wind 15-MW reference turbine was designed, built, and characterized on a fixed base. The National Renewable Energy Laboratory's Reference Open-Source COntroller (ROSCO) was integrated into the scale testing to examine the impact advanced turbine and generator control strategies have on turbine performance and loads, enabling validation of control strategies for floating wind design optimization.

1. Introduction

The ATLANTIS research program ("Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control"), run by the U.S. Department of Energy's Advanced Research Projects Agency-Energy, is developing new and potentially disruptive innovations in floating wind technology by employing control co-design (CCD) methods. A CCD-based design approach considers the controller as a fundamental component of the floating wind system design from the start, rather than tuning a controller after the wind system design is already fixed. To effectively utilize a CCD approach, current numerical analysis tools, such as coupled aeroelastic-hydrodynamic software like OpenFAST and Bladed, must be improved to include new turbine and platform controls techniques and hull flexibility, and then validated with experimental data. These tools can then be used to optimize system and control design to improve performance and reduce loads and motion for a floating offshore wind turbine.

A primary goal of this project is to experimentally validate new control methods for floating offshore wind turbines. A critical element in developing advanced control methods is obtaining experimental data from systems (either full-scale or subscale) while operating under closed-loop control. To date, little experimental data are available in the public domain for floating systems—tests performed by Bredmose et al. [1] are one of the few. On the other hand, a number of studies (such as [2] and [3]) have reported experimental results for land-based systems.

The ATLANTIS FOCAL Experimental Program is generating the open-source data sets needed to address this CCD validation need. Four 1:70 Froude-scale experimental campaigns are being conducted in the University of Maine's Alfond Wind/Wave Ocean Laboratory (W2). The experiments use a scaled version of the IEA Wind 15-MW reference wind turbine [4] supported by the VolturnUS-S steel semisubmersible hull and consider the following: turbine control strategies for floating wind (Campaign 1), hull control of actuated masses (Campaign 2), hull flexibility and internal load measurement (Campaign 3), and combined turbine/hull (system-level) control (Campaign 4).

This paper presents the wind turbine design, scaling approach, and results from the first of these four experimental campaigns. Campaign 1 considers a fixed-base turbine and characterizes the turbine's aerodynamic performance in the model-scale test environment of the W2 facility as well as generates a data set to validate numerical modeling predictions of the turbine under active turbine controls. The paper presents an expansion of the turbine performance-matched methodology from previous work [5–7] to consider active turbine controls and to account for the known Reynolds number issues associated with the Froude-scale test environment.

2. Objectives

The objective of the FOCAL Experimental Program Campaign 1 was to run a series of scaled-model tests in a wind/wave basin to provide measurements to enable future validation of load reduction in a wind turbine using industry-based floating wind control methods. Toward this goal, Campaign 1 included:

- Designing and building a performance-matched 1:70 scale model of the IEA Wind 15-MW wind turbine and tower [4];
- Developing industry-representative turbine control methods of floating wind systems (including, for example, peak shaving and collective pitch control), scaling them for model testing, and implementing them through expansion of the existing IEA Wind 15-MW control system;
- Expanding the wind generation capabilities at the University of Maine's W2 facility to enable testing of the larger 15-MW turbine;
- Quantifying the steady-state loads and performance of the wind turbine;
- Quantifying the turbine dynamic response, including the sensitivity of the rotor thrust and torque, to changing generator speed, blade pitch, and wind speed;
- Assessing the impact of industry control methods on the loads and performance of the wind turbine.

3. Methodology

3.1 Scaling approach

As wind turbines reach larger and larger sizes, scaled testing is challenged by the large scaling ratios that must be used because of constraints on the physical dimensions of the testing facility. In the FOCAL project, a 1:70 scale ratio was used for testing a performance-matched model of the IEA Wind 15-MW wind turbine at the W2 laboratory (see figure 1). As shown in figure 2, the W2's wind machine is an open-jet wind generation source with 32 individual fans and a rectangular outlet width of 7 m and height of 3.5 m. With a full-scale rotor diameter of 240 m, a 1:70 geometric scaling is needed to fit within the height limit of the wind generation system.

The FOCAL program predominantly uses Froude-scaling, as is typical of floating offshore wind turbine model testing [5]. As discussed in [6], a performance-matched turbine is needed to impart the appropriate mean loads to the floating hull. This was done in the FOCAL project, wherein the turbine power coefficient, C_P, and thrust curves, C_T, of the IEA Wind 15-MW turbine were preserved as closely as possible by using low-Reynolds-number Selig Donovan SD7032 airfoils. Use of the low-Reynolds-number airfoils also addressed some, but not all, of the Reynolds number mismatch found in Froude-scaled test environments. The rotor blades were designed to be effectively "rigid" at model scale, as aeroelastic scaling would be prohibitively complicated and not directly supportive of the test objectives. The tower was also made to be rigid for this first experimental campaign to focus on the turbine performance and loads, but it will be flexible for future campaigns.

Figure 1. 1:70 scale model of IEA Wind 15-MW turbine.

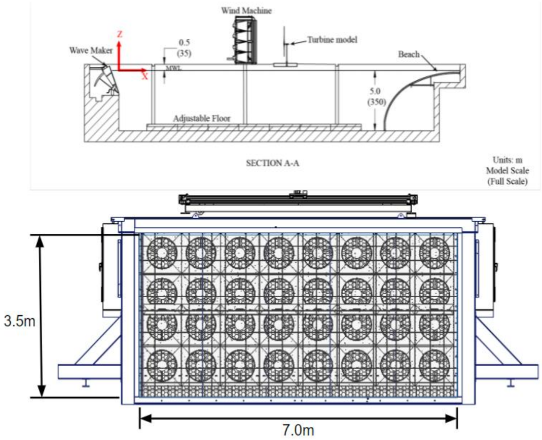

Figure 2. Schematic of W2 basin and wind machine.

The scale ratio of 1:70 was chosen based on the limits of the wind machine area relative to the turbine size. A higher scale ratio (smaller) turbine would make the scale model mass properties difficult to match the IEA15MW reference turbine values and a smaller scale ratio would put the tune swept area outside of the wind machine slipstream. At the top and bottom positions the turbine blade tip is only 3.6cm from the wind machine slipstream, but on the sides there is much more clearance due to the rectangular shape of the wind machine. Tip vortex interaction with the slipstream is possible at top and bottom, but this area is relatively small part of the swept area. In addition, the performance matched measurements of the turbine performance include this interaction effect and the resulting performance matched parameters are achieved on average, as this was the primary goal of the turbine scaling.

While a performance-matched scaling approach has been used successfully in several experimental campaigns [6] [7], the inclusion of active turbine controls in the FOCAL project required that additional factors be considered. As shown in [8], the larger sectional drag of the model wind turbine blades limits the ability to match performance by only changing the turbine geometry. To help overcome this, the experimental wind speed was increased by roughly 20% to impart more energy in the wind field (see wind speed adjustment factor below) while holding the scaled rotor rotation speed at Froude-scale to ensure the turbine blade-passing frequencies retained their appropriate relationship to other system frequencies (e.g., tower frequencies and rigid-body floater frequencies), which is important to controller design. The wind speed adjustment is also applied to other wind speed parameters, such as turbulence. This is particularly important when looking at the sensitivity of the turbine power and thrust to changes in wind speed. To this end, the target wind speed sensitivities were reduced by the same factor as the increased mean wind speed, ensuring that the effect of the wind speed increase is not double-counted. The adjusted wind speed is defined as:

$$U^* = U_{ms} \times WF$$

where U^* is the adjusted wind speed used in the rotor design, U_{ms} is the Froude-scaled wind, and WF is the wind speed adjustment factor. Changing the wind scale factor without modifying the turbine rotational speed will result in a different tip speed ratio (TSR) for the same operating point, which was taken into account during the design process. Tip speed ratio is not a direct design parameter as torque, thrust and wind speed are the controlled parameters in the test. Since the Rotor RPM is Froude scaled to the rated condition, the Tip speed ratio is computed from rated RPM, turbine diameter and wind speed. The controller then queries the turbine performance map at this TSR to determine the blade pitch to achieve the thrust or torque setting depending on the operating region. The turbine RPM is Froude scaled in order to ensure that the turbine forcing frequencies match the hull/waves frequencies during the floating system tests conducted in the future.

Water density corrections create a particular issue in preserving the balance between the hydrodynamic and aerodynamic loading. Because model basins use fresh water, and the full-scale IEA

Wind 15-MW reference turbine was designed for salt water (a difference in density of 2.5%), one typically includes this as a scaling factor when going from full to model scale. However, because the air density for the turbine does not change between scales, this creates an issue in getting the correct wind forces from the turbine, which drive the motions of the floating hull. Therefore, for the FOCAL project, the following approach was used:

- *Redesign of full-scale reference:* The full-scale IEA Wind 15-MW reference turbine was re-designed to sit in fresh water instead of salt water so that no water density scaling was needed.
- *Draft maintained*: To accomplish this without the draft changing, the turbine mass was decreased by 2.5%, while keeping the center of gravity the same.
- *Moment of inertia*: The hydrostatic stiffness was also decreased by 2.5%, resulting in a similar mass moment of inertia reduction.
- *Thrust*: To preserve the balance between wind and wave forces, the target thrust force was decreased by 2.5%.

3.2 Model turbine design

The focus of Campaign 1 was to ensure that we could accurately replicate the impact that floating wind turbine control strategies have on a full-scale design within the scaled wind/wave basin environment. Therefore, rigor was taken in ensuring the scaled turbine design retained the appropriate relationships between the control properties and dynamic response. The performance-matching objectives were to match the full-scale turbine in overall thrust (reduced by 2.5%, as discussed earlier), while having power and sensitivities to several key control parameters be reasonably matched. Performance targets were determined from the OpenFAST model of the IEA 15-MW turbine [9], and the sensitivities were obtained through linearization analysis using the frozen wake assumption and conditions specified in the turbine design. As such, the sensitivities are so-called open-loop responses because the controller action was not included in the linearization. This same process was used to quantify the performance and sensitivities of the design rotor for comparison.

The rotor design process follows the "Betz optimal rotor" as outlined by [10]. By making assumptions of no wake rotation, no drag, no tip loss, and an optimal axial induction factor of 1/3, the basic chord and blade twist distribution are defined. The resulting chord, *c(r)*, and blade twist, *φ(r)*, distribution along the blade are:

$$\phi = \left(\frac{2}{2\lambda_r}\right), c = \frac{8\pi r sin\phi}{3BC_l\lambda_r}$$

where $\lambda_r = \lambda(r/R)$, r is the radial location, R is the rotor radius, B is the number of blades, and C_l is the lift coefficient. These distributions are further adjusted during the design process to define the blade design. To assess the rotor design, the following process was carried out:

1. The target angle of attack was selected for the blade design. An angle of 6° was selected for the SD7032, as it represented a region of the airfoil performance where high C_l and low C_D were observed and was far enough from the stall region to ensure stable performance.
2. Chord and twist distribution were set by the Betz optimal equations, and chord distribution scale was adjusted.
3. Design optimization loop, Above Rated
    a. Evaluate the rotor performance using a blade element method analysis tool and scaled design conditions, including any wind speed scale factor.
    b. Calculate sensitivities using a perturbation approach and frozen wake.
    c. Adjust chord scale and wind scale factor until an optimal design is found.
    d. Prioritize thrust matching and $\frac{\partial Power}{\partial Blade\ Pitch}\ and\ \frac{\partial Thrust}{\partial Wind\ Speed}$.
4. Final Design
    a. Perform steady analysis in OpenFAST using final rotor design.
    b. Perform linearization with frozen wake assumption for sensitivities.

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Figure 3 shows the blade twist, blade chord, and blade pitch schedule as well as the predicted performance as a function of wind speed for the "Betz optimal" turbine. Note that all results are plotted using "Adjusted Wind Speed/WF" in order to plot the IEA Wind 15-MW turbine results against the scaled-up model results on the same axis. Note that without wind speed adjustment (*WF* = 1.0), the ability to performance-match both thrust and power was not achieved. The blade chord distribution was chosen to maintain constant lift coefficient (roughly) over the span of the blade. This chord distribution was then "scaled" in the optimization process to achieve the performance matching results shown in figure 4. To note: the "scaled" chord distribution is not a geo-symmetric scaling of the IEA15MW turbine.

The use of higher model-adjusted wind speed along with adjusted chord distribution provided better performance-matching for thrust and power. Figure 4 shows the results of this design process. A good match of all target parameters was found at an increased *WF* of 1.2 and a 0.6 chord "scale" relative to the baseline blade.

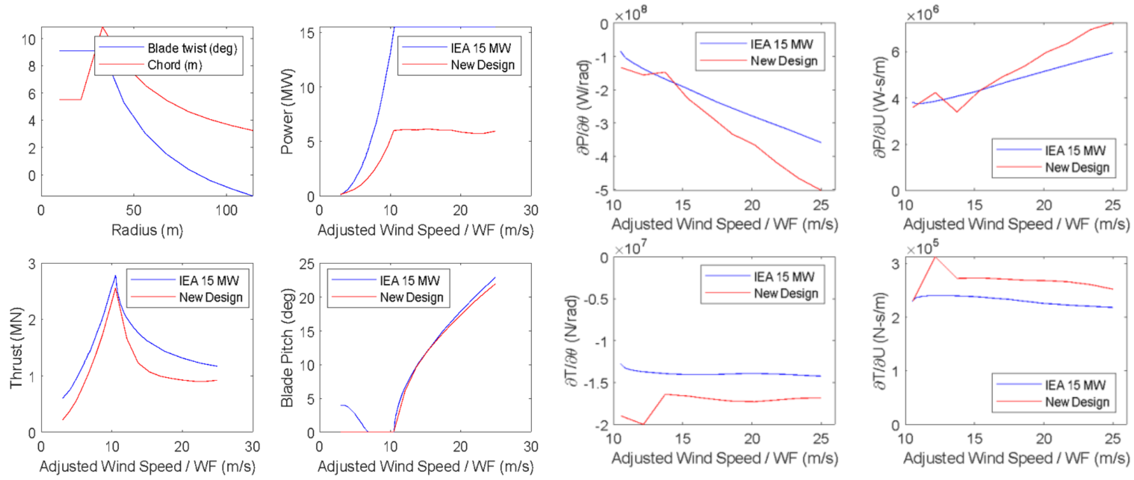

Figure 3. Betz optimal rotor—performance and sensitivity. Wind speed = 1.0 × U_{ms} (rated).

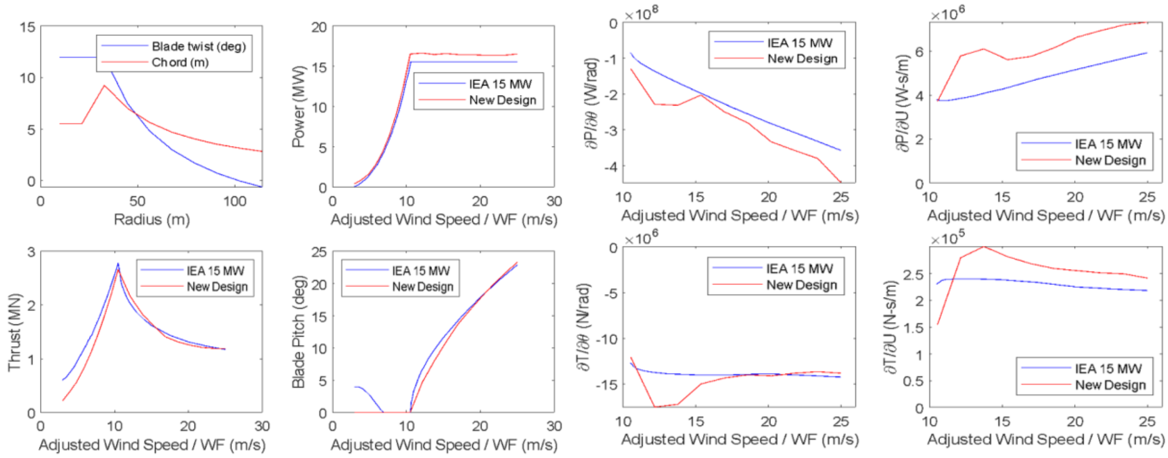

Figure 4. Turbine performance with 0.6 × chord and wind speed = 1.2 × U_{ms}.

Figure 4 results show a better thrust match at rated (10.59 ms^{-1}) and above-rated conditions while generating marginally more torque (power) than needed, giving some margin for losses in the as-built design. Note that the thrust curves in figure 4 include the additional thrust component due to the rotor weight at six degrees of tilt of the rotor. Figure 9 represents only the aerodynamic thrust as the weight component of the thrust was removed.

3.3 Model turbine and nacelle construction

To achieve better model scale performance at low Reynolds numbers, the scale model test blade was designed using an SD7032 airfoil, shown in figure 5. The turbine blade construction consisted of one layer of plain-weave carbon fiber infused with epoxy vinyl ester resin manufactured with a vacuum infusion process using high-density foam molds. The blades were infused in two parts in a modified butterfly configuration, and assembled with two foam spars and a mounting flange using a methacrylate adhesive, as shown in figure 6.

In order to achieve appropriate scaling of the blade weight, stiffness, and shape, the use of low-density, high-strength materials was required. The blades were evaluated for mass, center of gravity, and inertia, and final adjustments were made to the mass properties to achieve consistent properties. Average full-scale blade properties are shown in table 1, as are other key turbine characteristics. The model-scale blades were designed to be rigid as compared to the full-scale IEA 15-MW turbine, and the coning angle for the model was therefore 0°. The increase in wind speed shown in table 1 is due to the wind factor discussed earlier, and the reduced rotor torque comes from the measured airfoil performance. All values provided include the freshwater density reduction for the full-scale targets. The model including blade pitch control, which was implemented for collective pitch for Campaign 1 tests.

The validation data from this experiment is intended to validate numerical models of the scale model turbine under control, but the blade flexural effects were not scaled to match full scale values. The model blades were about an order of magnitude higher than the full scale blade at model scale with correspondingly higher natural frequencies. Scale model flexural properties for the blades has been collected and could be use in the validation of needed. These data will be part of the published FOCAL experimental dataset available to researchers and developers in the future.

Figure 7 shows the model turbine nacelle layout as implemented in the testing. The turbine instrumentation system used a National Instruments cRIO real-time platform and etherCAT communication to increase bandwidth with minimal cabling. An inline shaft torque sensor was mounted behind two shaft bearings. The slip ring was used to communicate with the pitch controllers mounted on the turbine hub, and a six degree-of-freedom load cell accelerometer was mounted at the base of the nacelle to measure the turbine thrust. The scaled turbine is capable of achieving the desired rotor speed and torque set points, as well as individual blade pitch control with blade pitch rate limits exceeding that of most commercial scale turbines.

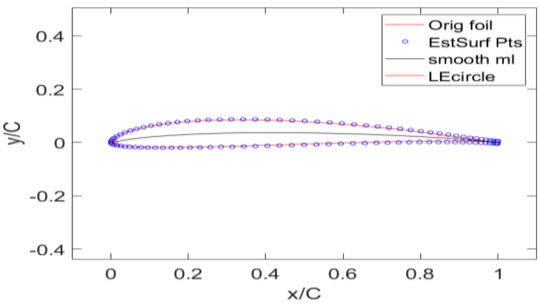

Figure 5. SD7032 blade section with thickened trailing edge.

Figure 6. Model blade as built, Stiffening foam spar placement shown in top figure

Table 1. IEA 15-MW turbine target vs. as-built model full-scale properties (freshwater density).

Quantity	Full-Scale Target	Full-Scale As Built	Model Scale As Built	Quantity	Full-Scale Target	Full Scale As Built	Model Scale As Built
Hub height (m)	150	149.8	2.14	Blade length (m)	117	115.9	1.655
Rotor diameter (m)	240	242.8	3.469	Blade mass (kg)	6.362E+04	8.081E+04	0.236
Shaft tilt (deg)	6	6	6	Blade CG (m)	20.48	37.73	0.539
Wind speeds (ms^{-1})	3-35	3.6-30	0.43-3.59	2nd mass MOI ($kg\text{-}m^2$)	1.44E+07	1.95E+08	0.1160
Rated rotor (rpm)	7.56	7.56	63.3	Total RNA mass (m)	9.91E+05	1.16E+06	3.396
Rotor Torque (Nm)	1.94EE+7	1.91E+7	0.796	Rated Thrust (N)	2.42E+06	2.42E+06	7.06

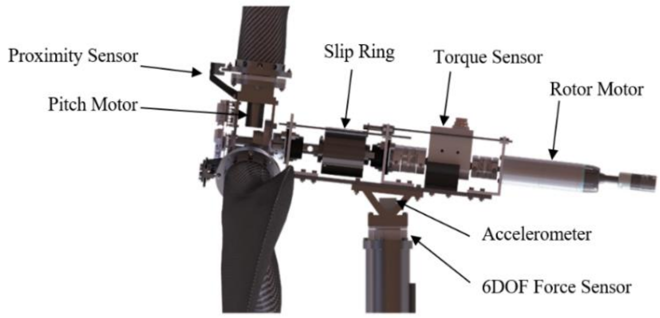

Figure 7. Model turbine nacelle configuration.

3.4 Controller design

Active turbine control was implemented in the FOCAL project using the National Renewable Energy Laboratory's (NREL's) Reference Open-Source COntroller (ROSCO) [11]. ROSCO was used to determine the rotor torque and blade pitch set points for the turbine performance and was tuned to give appropriate performance (experimentally measured thrust and torque data presented later in this paper) in the modified wind environment. The ROSCO controller formulation utilized by FOCAL is available via GitHub [12], and details on the ROSCO control strategy can also be found there. The general controller logic is shown in figure 8, 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.

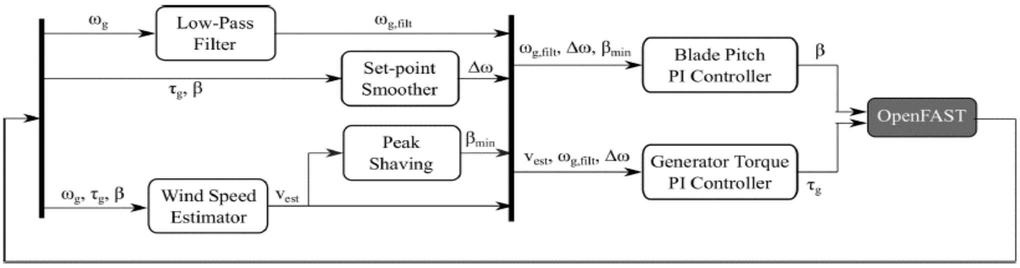

Figure 8. Rosco controller strategy.

To use ROSCO to control the model-scale turbine, we ran ROSCO in real time on our experimental system and replaced the OpenFAST block in the control diagram (figure 8) with hardware-in-the-loop communication with the operating model turbine using the following methodology:

- Model-scale wind turbine operating parameters of rotational speed, torque, blade pitch, and experiment time are Froude-scaled from model- to full-scale and input into ROSCO. This happens at the loop rate of the real-time system (2 ms).
- ROSCO determines collective blade pitch and generator torque set points, which are then Froude-scaled down from full- to model-scale and implemented in the scaled model.

The ROSCO control strategies considered in Campaign 1 are shown in table 2 and are representative of the types of simple control strategies employed by current commercial turbines. The thrust peak-shaving algorithm (T1), was not employed in Campaign 1, but will be included in Campaign 4 once the turbine is deployed on a floating platform. The transition controller is also called the set point smoother.

Table 2. Controller strategies for IEA Wind 15-MW turbine wind/wave basin experimental campaign.

Ctrl	Function	Op. Case	Actuation	Sensing
R1	ROSCO torque ctrl	Below rated (BR)	Generator torque (GT)	Rotor or generator speed (RS or GS)
R2	ROSCO pitch ctrl	Above rated (AR)	Collective pitch (CP)	RS or GS
R3	ROSCO transition ctrl	Transition (TR)	CP + GT	RS or GS
T1	Thrust peak-shaving	TR + near rated (NR)	CP + GT	RS or GS

4. Results and discussion

The tests conducted in Campaign 1 consisted of a series of controlled experiments with prescribed control actions (e.g., a step change or harmonically varying blade pitch angle) for a fixed turbine configuration, and the use of ROSCO to pass collective pitch and generator torque actuation for a variety of wind conditions. Each wind environment was characterized for each test wind environment in the rotor plane area. The turbine performance was then characterized to obtain the rotor performance maps used by the controller. The final validation data set focused on the impact of the controller on the turbine's aerodynamic response. The following is a summary of the tests performed:

- Steady-state performance curves for a variety of blade pitch and rotor speed settings;
- Sensitivity studies showing how changes in the blade pitch affect power and thrust;
- Studies of unsteady aerodynamics through harmonic variation of the blade pitch and wind speed;
- Parked performance;
- Controller validation across different wind speeds and types including dynamic and spectral wind fields.

Some of the core features of the controller that were examined include the use of a wind-speed estimator and a set point smoother (transition controller). This data set, in concert with full-scale targets for these responses from simulations, enables development and validation of robust control input and output mapping schemes that allow full-scale testing of floating offshore wind turbine controllers for wind-wave basin testing that produce the correct dynamic loading on the model-scale system.

4.1 Steady-state performance and performance-matching

The first set of tests performed quantified the steady-state response of the turbine for a variety of prescribed blade pitch and rotor speed set points. The set points were enforced directly through the rotor and blade pitch motor controllers without the use of ROSCO. Thrust and torque performance-matching was verified by running the turbine through the wind speed range, adjusting the blade pitch accordingly. Figure 9 shows the measured thrust and torque of the turbine ("FOCAL Experiment"), scaled to full-scale, as compared to numerical predictions of both the as-built turbine ("FOCAL OpenFAST") and the modified IEA Wind 15-MW reference turbine target ("IEA 15MW OpenFAST"). At and below the rated conditions, good performance-matching was achieved. The deviation above rated conditions is believed to be due to the blade performance changes from the increased wind speed effect on the blade section Reynolds number, which is not modelled in the numerical predictions

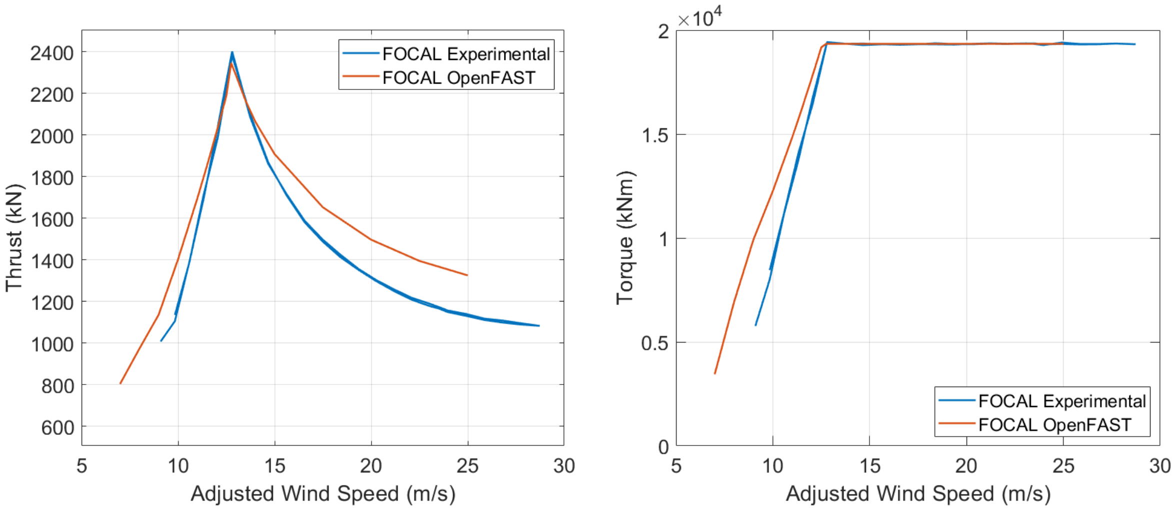

Figure 9. Turbine thrust and torque for performance-matched turbine vs. target performance.

. In the above rated region, the blade pitch was set to achieve the design power. Since the numerical model did not adjust blade drag and lift as the Reynolds number increased (due to higher wind speed) the predicted power would require more blade pitch (and more thrust) to bring the power up to rated, therefore the blade pitch predicted in the numerical model would deviate from the blade pitch setting in the experiment as commanded by the controller.

Rotor torque and thrust were measured and used to calculate the thrust coefficient, C_T = thrust/(0.5ρV^2A), and power coefficient, C_P = power/(0.5ρV^3A), curves as a function of tip speed ratio, TSR = Vwind/Vtip (see figure 10). The turbine data were used in the ROSCO toolbox tuning procedure to inform and tune the ROSCO controller used in subsequent tests.

4.2 Turbine performance under ROSCO control results

ROSCO control was exercised under a number of dynamic wind cases, including harmonic variation (designed to mimic the pitching motion of the system while floating), spectral turbulence, and extreme gusts.

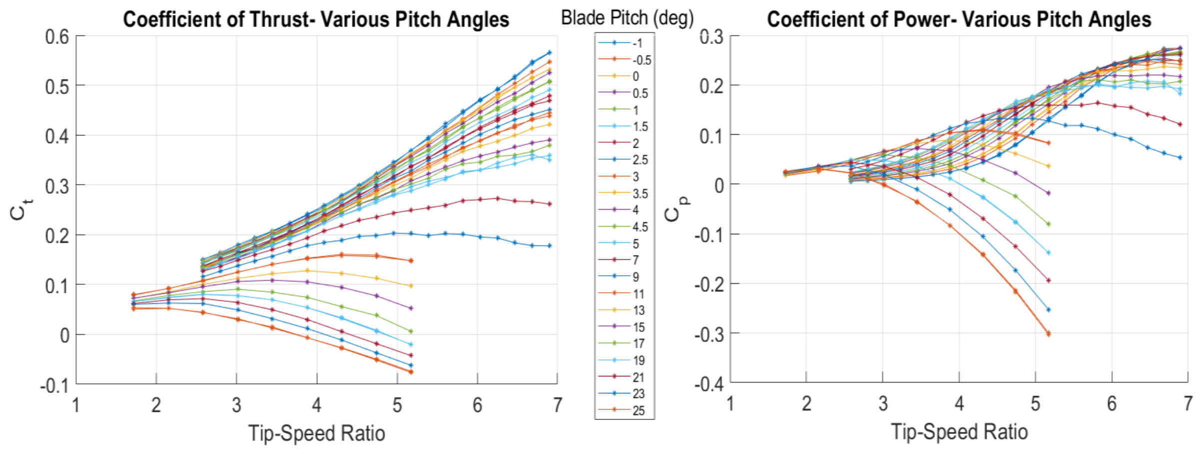

Figure 10. Measured 1:70 scale as-built IEA Wind 15-MW wind turbine C_p and C_t vs. TSR curves.

Figure 11 shows the control response to a large, sustained gust that carried the turbine from below-rated conditions, through the transition region, and into above-rated conditions, at which point the wind speed was held constant. The plot shows that in the below-rated conditions ROSCO controlled the rotor torque with a constant blade pitch. However, as the wind increased and the turbine moved into above-rated conditions, the blades were pitched out/to feather to reduce the excess load and maintain rated power. The turbine then reached a steady-state condition in the above-rated region. The initial overshoot was due to the pitch rate limit (part of the ROSCO controller), which places a limit on how fast the turbine is allowed to pitch the blades. Under normal conditions the turbine will not exceed the pitch rate limit; however, increasing this limit for model tests would give a better response in this step input case and help mitigate excessive loads on the test turbine.

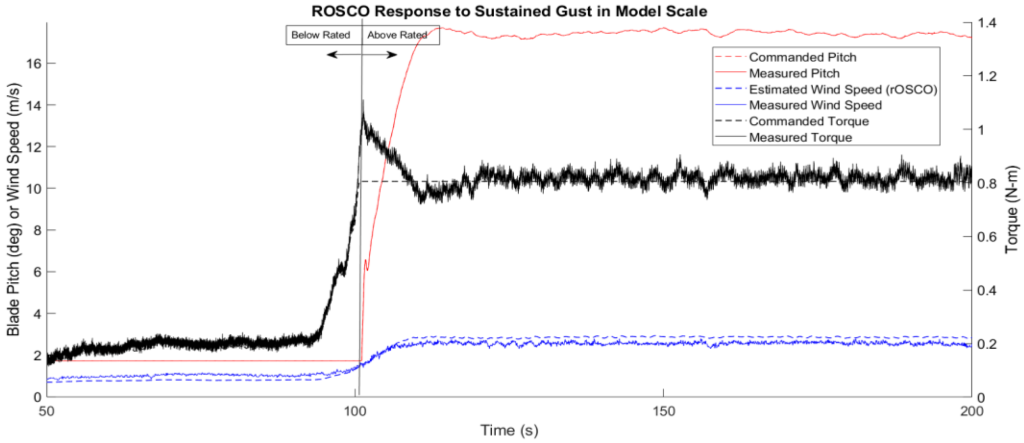

Figure 11. ROSCO response to a large, sustained gust case.

4.3 Dynamic load cases under ROSCO control results

A number of prescribed control cases were performed, including step and harmonic changes in blade pitch as well as linear and sinusoidal variation in wind speed. The responses from these load cases were used to assess the performance of ROSCO in a variety of different scenarios as well as evaluate aerodynamic effects on the scaled rotor. The final set of cases run were representative wind time histories based on design load cases for floating offshore wind turbines. Wind speeds in the below-rated, transition/rated, and above-rated operating ranges were run and included turbulence. Details on the wind environments, calibration procedures, and time histories will be included in the final data set. For each of these conditions, ROSCO controlled the turbine operation by defining rotor torque and blade pitch set points. In below-rated cases, ROSCO maintained a constant blade pitch setting and adjusted the rotor torque to maintain the *Cp*-maximizing TSR defined in the controller tuning.

The variations in the rotor torque set point are in response to the turbulence in the wind field about its mean value. As the wind speed increases, the turbine continues to accumulate loading and eventually reaches the rated power set point. At this point, the torque is fixed at the rated torque value of the generator. If the wind speed continues to increase, the turbine would start to generate more torque and subsequently more rotor speed than desired due to the fixed rated torque. Therefore, ROSCO implements blade pitch control to feather the blades and minimize the rotor speed error while maintaining a constant rotor torque. Figure 12 shows the active blade pitch control for an above rated dynamic wind case, with the ROSCO set points in red and the measured collective blade pitch in black. Corresponding torque, RPM and wind speed time series are also shown in Figure 12 for this test case. The torque is maintained at the rated torque by determining blade pitch at this TSR using the RPM and wind speed. The corresponding RPM time history plot shows that RPM is held relatively constant, but this is not directly controlled by ROSCO. The unfiltered torque history is plotted in the final plot of Figure 12. The mean torque at this condition is less that the rated thrust as depicted in Figure 9.

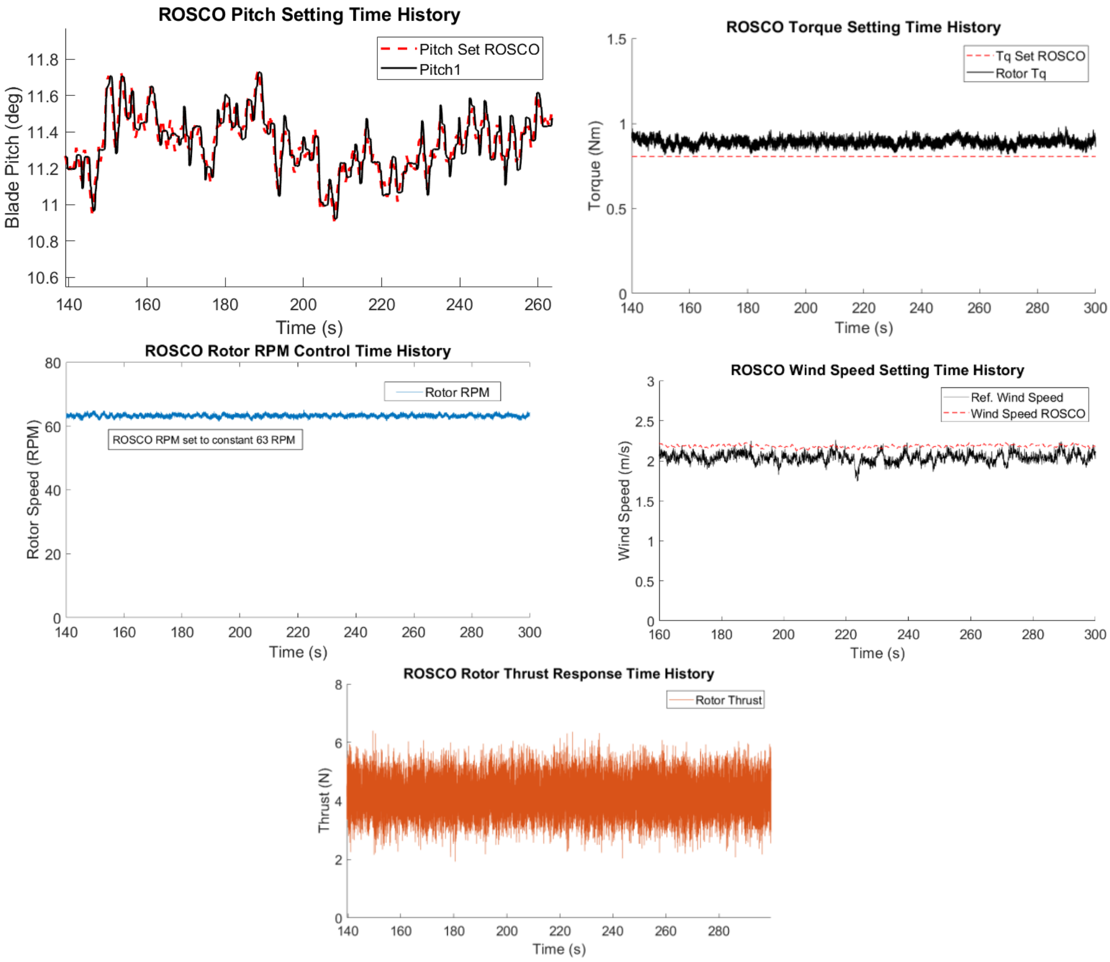

Figure 12. Model turbine data in dynamic wind under ROSCO control for torque, pitch and RPM and wind speed history and wind speed history vs. ROSCO wind speed estimation.

5. Conclusions

This paper provided a summary of the work performed to develop and execute the first of four experimental campaigns in the FOCAL project. The work included:

- Developing and implementing a performance-matched design methodology and experimental verification for scale-model turbine testing of the IEA Wind 15-MW reference wind turbine.
- Integrating, for the first time, NREL's ROSCO controller in scaled-model experimentation.
- Demonstrating implementation of control at model scale to represent full-scale performance.

The results of test Campaign 1 presented in this work will be used to further refine the 1:70 scale turbine model and ROSCO control in order to prepare for Campaign 4 on a floating platform. The data will also be used extensively in a cross-collaboration effort to validate numerical models. This validation data set and corresponding numerical models are valuable for controls co-design and can be utilized to develop the next-generation technology needed to revolutionize floating offshore wind through optimization and deep cost reductions. The FOCAL project is fulfilling this need by providing validation data to ensure that the offshore wind design tools can accurately represent the new features needed to advance floating wind designs to a commercially competitive cost level. FOCAL data sets will be made available to the public after the conclusion of testing in late 2022 through the U.S. Department of Energy's Data Access Portal, including model specifications, controller definitions, and test data.

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