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Real-Time Hybrid Testing of a Floating Offshore Wind Turbine Using a Surrogate-Based Aerodynamic Emulator

Physical modeling of floating offshore wind turbines (FOWTs) is challenging due to the complexities associated with the simultaneous application of two different scaling laws, governing the hydrodynamic and aerodynamic loading on the structure. To avoid these issues, this paper presents a real-time hybrid testing (RTHT) strategy in which a feedback loop, consisting of an on-board fan and control algorithm, is utilized to emulate the aerodynamic forces acting on the FOWT system. Here, we apply this strategy to a 70th-scale IEA Wind 15 MW reference wind turbine mounted on a version of the VolturnUS-S platform. Unlike other similar methods, which directly simulate the aerodynamic loads for the fan's control using an aerodynamic code running in parallel with the experiment, this example utilizes a surrogate model trained on numerical model data calculated in advance. This strategy enables high-fidelity numerical model data, or even physical data, to be included in the aerodynamic emulation, by removing the requirement for real-time simulation, and, therefore, potentially enables more accurate loading predictions to be used in the experiments. This paper documents the development of the real-time hybrid testing system in the Coastal Ocean And Sediment Transport (COAST) Laboratory at the University of Plymouth in the UK, including the hardware, software, and instrumentation setup, and demonstrates the power of the surrogate-based aerodynamic emulator based on numerical data calculated using OpenFAST. [DOI: 10.1115/1.4056963]

Keywords: hydrodynamics, ocean energy technology, wave mechanics and wave effects, wind energy

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Manuscript received January 12, 2023; final manuscript received February 16, 2023; published online March 16, 2023. Assoc. Editor: Hameed Metghalchi.

Introduction

Climate change is a global issue and a tangible threat to human existence as we know it. Most governments and leading international councils, recognize the importance of reducing "greenhouse" gas emissions, to minimize the anthropogenic impact on the Earth's climate system and stave off the more catastrophic effects of climate change. In most cases, replacing fossil fuel energy, with renewable energy sources, is a key part of the strategy to meet emissions targets, and for those countries with significant resources, offshore wind energy has been proven to be a promising and cost-effective solution. Despite this, with target deadlines fast approaching and forecasts suggesting a shortfall in the current climate action plan (not to mention the possible economic benefits associated with technological leadership in a globally important industry), significant research, development, and innovation are still needed in offshore wind.

To maximize the yield and minimize the levelized cost of energy, offshore wind developers are considering both larger wind turbines and sites further offshore, with deeper water, where the wind resource can be greater. However, there is considerable concern that the established foundation technologies, i.e., monopile foundations, and installation techniques, i.e., jack-up vessels, are not suitable for water depths much greater than 30 m (particularly for larger wind turbines). Therefore, a number of developers have proposed floating platform concepts to replace the traditional "bottom-fixed" solutions. In general, floating offshore wind turbines (FOWTs) can be deployed in any water depth, and can also overcome most seabed characteristics, greatly increasing the extent of feasible development sites. Furthermore, FOWTs offer possibly simpler, cheaper installation, and decommissioning, as well as potentially lower environmental impact, via their ability to be towed into position and secured with minimal seabed disturbance. However, the proposed FOWT and mooring coupled systems are significantly more compliant, compared to bottom-fixed examples, and therefore more susceptible to problematic excitation from aerodynamic and hydrodynamic loading. At present, this is a critical source of uncertainty in the design, performance, and survivability of FOWT systems and represents an unacceptable risk to potential investors.

To reduce uncertainty, the design process for offshore structures typically includes a significant amount of "modeling" (both numerical and physical) before deployment at sea. Numerical modeling has many advantages but, at least presently, still requires complementary physical modeling to provide confidence in the solution (particularly in more complex cases). Physical modeling, at laboratory scale, is standard practice in the development of offshore structures and an integral part of demonstrating technology readiness. However, physical modeling of FOWT can be challenging due to there being different scaling laws governing the hydrodynamic and aerodynamic loading. A review of physical and numerical modeling techniques for FOWTs can be found in Otter et al. [1].

Typically, for offshore applications, aerodynamic loading, at laboratory scale, requires Reynolds similarity, i.e., the ratio of the inertia forces and viscous forces should be constant. However, the hydrodynamic loading, for the same model, requires Froude similarity, i.e., the ratio of the inertia forces to the gravity forces should be maintained. The key issue when performing physical modeling of FOWT, at laboratory scale, is that these two conditions cannot be satisfied simultaneously. Severe "scaling effects," and behavior anomalies (compared to the full-scale system), can result from inconsistencies in the kinematic and dynamic similarity unless additional action is taken.

There are many proposed methods to tackle this issue; the majority involve some sort of "emulation," i.e., replacement of one of the load sources (either aero- or hydrodynamic) by an appropriate "emulator" to approximate the specific loads in the alternate scaled regime. For example, distorted, "performance-matched" blade geometries are used to include aerodynamic loading from an on-board turbine in Froude-scaled conditions in wave tanks with blown-wind generators. This strategy has many advantages, particularly as both aerodynamic and hydrodynamic loading is physically present. However, generating high enough quality wind fields, over a wave tank, can be very challenging and expensive, and achieving the correct mass properties of a scale-model turbine can prove near impossible.

An emerging strategy, known as "hybrid testing," is gaining popularity amongst FOWT researchers. A hybrid testing scheme only physically models one of the two loads, in an appropriately scaled experiment, whilst emulating the other using controllable "hardware-in-the-loop" (HiL). This means specialist, "single-environment" facilities can be used, without the need for costly installation of additional infrastructure, e.g., installation of blown-wind generators in a wave tank facility, as typically, only small, relatively cheap, mechanical components are required. Examples of hybrid testing range from fairly simple arrangements, such as systems of springs, masses, and pulleys to emulate wind loading on a floating structure in a wave tank, to multi-degrees-of-freedom parallel kinetic robots to emulate the hydrodynamic response of a wind turbine in a wind tunnel.

Clearly, the main drawback of hybrid testing is that the emulated part of the problem is not "resolved" in the physical experiments and, therefore, there is very little additional insight that can be gained about it from the experiments (effectively, all knowledge of the emulated part must be known *a priori* in order to implement the emulator). Furthermore, the emulated load is only as good as the emulator used in the hybrid testing and, in many cases, limitations in the emulator lead to questionably realistic loads being applied.

Development of hybrid testing strategies for FOWT is an active area of research. Recently, to overcome the limitations of "passive" emulation strategies (like springs, masses, and pulley systems), an extension to the hybrid testing paradigm is to include real-time feedback into the system, i.e. by controlling the HiL via "software-in-the-loop" (SiL) and enabling it to respond to real-time measurements recorded during the experiment [2]. This is known as "real-time hybrid testing" (RTHT) and yields a more sophisticated, and arguably more accurate, emulation than passive methods.

Materials and Methods

This paper details an RTHT system, for FOWT, developed within the Coastal, Ocean And Sediment Transport (COAST) Laboratory at the University of Plymouth, UK. The COAST facility includes a 30 m × 15.5 m wave basin (known as the Ocean Basin), with a moveable floor allowing for operating depths up to 3 m, ideal for physical testing of floating structures in various wave and current conditions. The RTHT system developed here is, therefore, one that emulates the aerodynamic loading on the FOWT via a hardware/software feedback loop (as opposed to a system where the hydrodynamic loading is emulated, in a wind tunnel facility for example). The system achieves aerodynamic emulation via a controller connected to a single on-board fan (the HiL) mounted rigidly to a Froude-scaled model FOWT platform and tower. During an experiment, measurements of the FOWTs position/orientation and motion state are fed into the software part of the feedback loop (the SiL). The output from the SiL is then used, via the controller, to update the force produced by the on-board fan. In this early-stage system, due to having a single fan, only aerodynamic thrust forces, in the fan's axial direction, can be included. Other components of aerodynamic loading, gyroscopic forces from rotating blades, and torque from the generator, cannot be included. Figure 1 shows a schematic of the RTHT workflow and an image of the system in the COAST Laboratory at the University of Plymouth, UK.

Similar systems are in development at many of the specialist hydrodynamics facilities around the world [1]. In many cases, advances have been made, with respect to the system hardware, in order to improve the aerodynamic emulation. For example, multi-

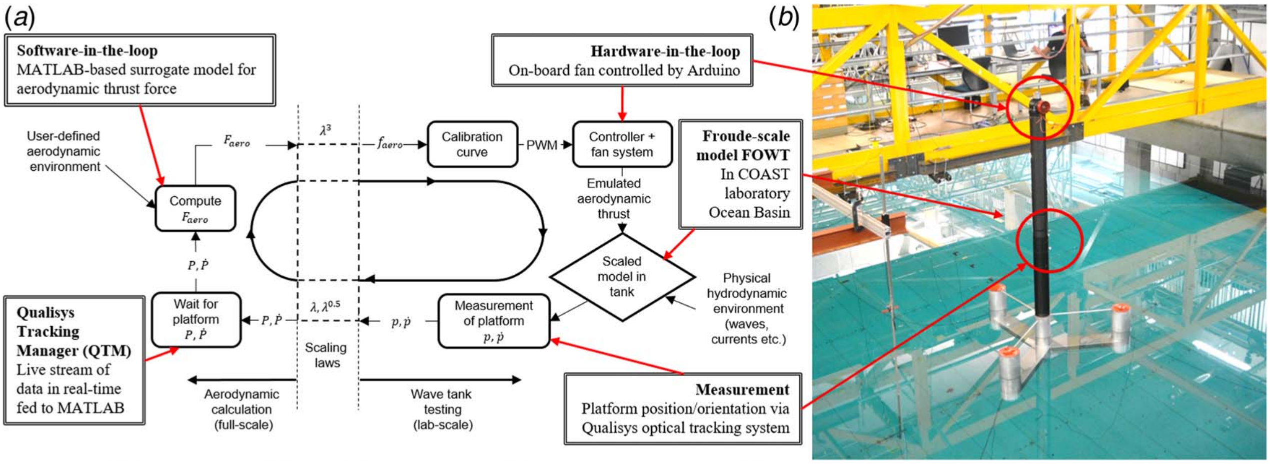

Fig. 1 (*a*) Real-time hybrid testing workflow (adapted from Ref. [3]) and (*b*) 1:70 Froude-scaled VolturnUS-S platform in the COAST Laboratory Ocean Basin at the University of Plymouth, UK

fan systems have been developed to enable additional components of aerodynamic loading, and generator torque, to be included [4]. However, despite a relatively basic hardware solution in the system reported here, the key difference between the approach taken in this work, and that used by others, is in the formulation of the SiL part of the feedback loop.

The computation of the aerodynamic loads, in most RTHT systems, is typically achieved using a numerical aerodynamic simulation tool running in parallel to the physical experiments. The position/orientation and motion state of the FOWT platform, at lab-scale (p and $\dot{p}$ respectively), are scaled-up to full-scale before being input into the simulation tool. The full-scale aerodynamic loads, F_{aero}, are then calculated, based on the full-scale position and motion state (P and $\dot{P}$ respectively), before being scaled back down to lab-scale. In addition to this, the use of an aerodynamic simulation code requires the sampling period of the tracking system to be scaled, in order to be consistent with the time-step in the simulation. Crucially, this process must be performed in real-time, as any delay in the calculation (or communication) could lead to highly spurious behavior as a result of the dynamic feedback loop in the RTHT system. Therefore, the simulation tools used are typically mid-low fidelity "engineering" tools, based on approximate solutions to the fluid-turbine interaction problem, but offering excellent computational efficiency. For example, a commonly used tool is the open-source, aero-hydro-servo-elastic code, OpenFAST, which includes the AeroDyn module to solve the blade element momentum (BEM) equations, as well as a number of unsteady aerodynamic models, to predict the aerodynamic load on a wind turbine. Developed by the National Renewable Energy Laboratory (NREL), OpenFAST also includes modules for solving the structural response of a wind turbine as well as the influence of the generator and power electronics (among other things). OpenFAST is also capable of simulating the motion response of a FOWT platform due to hydrodynamic excitation (although this function is effectively replaced by the physical hydrodynamic modeling in the case of this RTHT strategy). One alternative to OpenFAST is the Horizontal Axis Wind turbine simulation Code (HAWC), an aero-elastic code, based on BEM theory, developed by the Technical University of Denmark (DTU). Both tools are industry-standard aerodynamic simulation tools with a proven track record. However, for use in an RTHT system, the source code of these tools needs to be modified, to enable the feedback loop to be established, adding an additional overhead in the development of such a system. Furthermore, RTHT was never the intended use for these codes and so it is plausible to assume they are not optimized for this particular application.

As an alternative, in this work, a surrogate model has been developed to compute the aerodynamic loads, and replace the traditional parallel simulation as the "software" in the RTHT feedback loop. Using machine-learning (ML) methods, a surrogate model can be trained using data generated in advance of the experiments, relieving the requirement for real-time simulation. This strategy can enable high-fidelity simulation (or even physical) data to be used in the emulator and, if successfully implemented, can theoretically offer a real-time, high-fidelity solution to the aerodynamic loading, improving the performance of the emulator. Furthermore, provided an effective training process is established, such a data-driven approach could eliminate the dependency on specific simulation tools (which may limit the RTHT system usage in a commercial setting).

Surrogate Model Development. There are a number of possible ML approaches to generate data-driven, surrogate models, e.g., artificial neural networks, polynomial chaos expansion, or autoregressive with exogenous variables methods. In this work, a Gaussian process emulation approach (also known as kriging) has been taken [5].

Table 1 Full-scale incident wind and turbine parameters for each case considered

Datasets/Surrogate models	Mean wind speed (m/s)	Rotor speed (rpm)	Blade pitch (°)	Static thrust (N)
Steady 1	5.82	5.028	1.6	7.8328×10^5
Steady 2	6.65	5.00	0	1.0351×10^6
Steady 3	8.02	5.81	0	1.4656×10^6
Steady 4	9.00	6.52	0	1.8556×10^6
Steady 5	11.50	7.56	5.05	1.8629×10^6
Steady 6	13.14	7.56	8.7	1.4527×10^6
Steady 7	17.85	7.56	15.24	1.0256×10^6
Steady 8	25.0	7.56	22.7	7.6207×10^5

This paper documents an early stage in the development of the RTHT system in the COAST Laboratory – a "proof-of-concept". As such, a number of simplifications have been made to the problem in order to reduce the extent of the parameter space over which the surrogate model, and the system as a whole, must extend. These mark the initial stages in an incremental approach where increasing levels of complexity will be introduced, in future iterations, as experience is gained, understanding is improved and challenges are overcome. In addition to the single fan system being limited to providing only axial aerodynamic thrust, ignoring the other components of thrust, moments, and other system torques (such as that from the generator), a set of further simplifications have been made, as follows:

- Fixed rotor speed and blade pitch angle, i.e., turbine control system deactivated;
- Rigid tower and blades, i.e., structural response of the system assumed to be negligible;
- Steady wind, i.e., constant, non-time varying, incident wind speed;
- Uniform incident wind field, i.e., spatial variation in the wind field assumed to be negligible (including zero vertical velocity gradient or atmospheric boundary layer);
- Unidirectional, "aligned" wind and waves, i.e., no misalignment of turbine with respect to either the wind or waves.

Considering these simplifications, it is assumed that the critical variables, influencing the aerodynamic thrust, will be limited to the pitch angle of the platform as well as the velocity of the platform in the heave, surge, and pitch degrees-of-freedom. Therefore, the aim of the surrogate model, at this stage, is to predict the axial aerodynamic thrust from the values of these four variables only.

Generation of "Train-and-Test" Dataset(s). In this "proof-of-concept" work, all of the data used, for the training and testing of the surrogate model(s), have been generated from OpenFAST simulations of the full-scale International Energy Agency (IEA) 15 MW reference wind turbine (IEA-15-240-RWT) [6] and VolturnUS-S semi-submersible platform [7] (for which the OpenFAST aeroelastic model inputs are readily available via the IEA Wind Task 37 GitHub repository). To be consistent with the simplifications stated above, the OpenFAST model inputs have been modified to give a rigid structure; fixed rotor speed and blade pitch; uniform, steady wind, and; unidirectional, aligned wind and waves. Platform motion has been achieved, in the OpenFAST simulations, by including wave excitation based on an irregular sea state ($H_s = 9.7$ m, $T_p = 16.2$ s, $\gamma = 3.3$). In order to explore a range of environmental conditions, and operational regimes, multiple OpenFAST simulations have been run, with different incident wind and turbine parameters. The simulations are one hour in duration (at full-scale). A time-step of 0.025 s is used for all simulations. Each simulation yields a separate dataset which has been used to train (and test) a separate surrogate model for the specific conditions/parameters assigned. The specific parameters chosen (summarized in Table 1) are based on the controller regulation trajectory, from an OpenFAST simulation of the static wind turbine, with the control system operational (Fig. 2). Cases were selected in pairs (indicated by colors in Fig. 2) with approximately the same static thrust (but with one case below and one case above the rated wind speed of 10.59 m/s). Conditions in the center of, and at the transitions between, the minimum rotor speed, optimal tip speed ratio, and rated power regions were selected in order to cover the full range of possible operational scenarios. It is worth noting that, the specific values found/used differ slightly from those reported in the IEA-15-240-RWT documentation [6]. This is believed to be due to slight differences in the controller used in the case of a floating turbine.

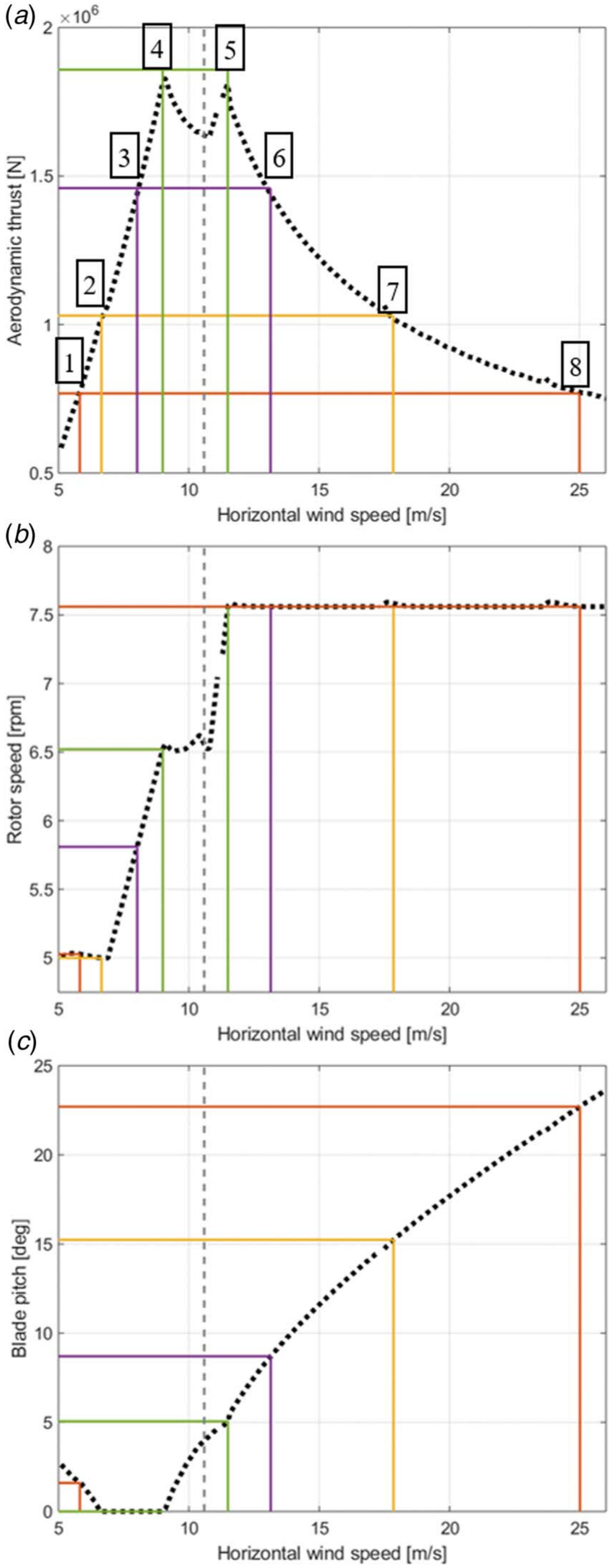

Fig. 2 Controller regulation trajectory for (*a*) thrust, (*b*) rotor speed, and (c) blade pitch showing the four pairs of select parameters (summarized in Table 1)

Training and Testing the Surrogate Models. A piece of software has been developed in order to train and test the surrogates. The software is written in the programming and numeric computing environment, MATLAB, and includes an algorithmic (Bayesian) optimization of the hyperparameters in the fitting of the Gaussian process regression models. The code produces a regressionGP data structure that can be used (without access to any special software, including MATLAB) to predict the thrust from the four input parameters.

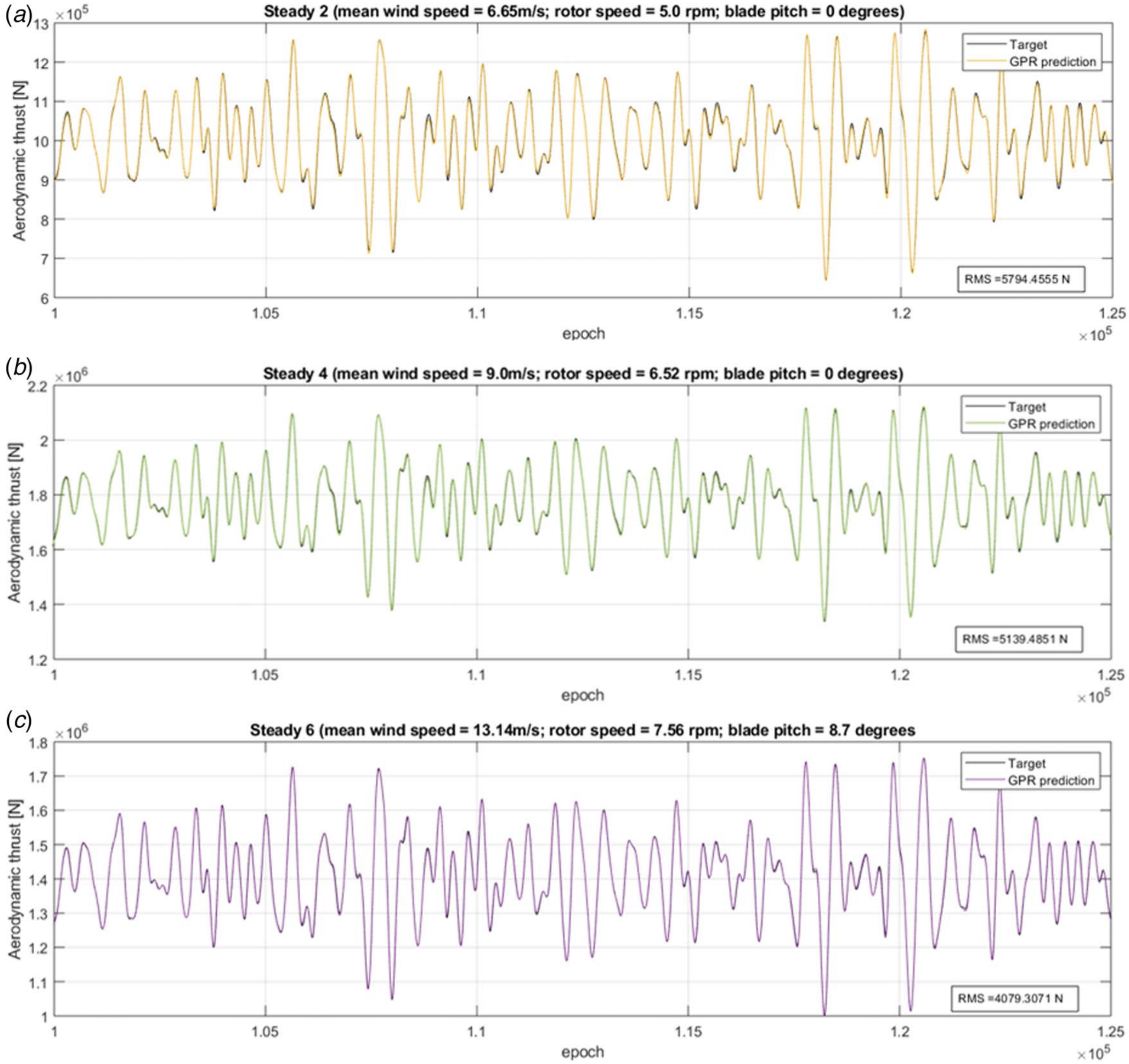

Fig. 3 Comparisons between the full-scale OpenFAST solutions (target) and the surrogate model predictions for a subset of the testing dataset for (*a*) case 2, (*b*) case 4, and (*c*) case 6

For each condition/dataset (Table 1), the output data from the OpenFAST simulation are split into two subsets. The first 50% of the dataset is used to train the surrogate model. However, the training dataset is first reduced by sampling every 100th point from the OpenFAST output as, in GPR models, the number of training data points strongly influences the execution time of the surrogate's prediction. The second 50% of the dataset is used to test the predictive capability of the surrogate. In this work, a root-mean-squared (RMS) difference, over the entire testing data subset, is used to quantify the quality of the surrogate's prediction. Figure 3 shows examples of the predictions from three of the surrogate models produced. It can be seen that the surrogate models perform very well, i.e., the "target" solution from OpenFAST and the predictions from the models are very similar. The RMS difference in each case is between 4000 N and 6000 N (approximately 3.5% of the standard deviation in the OpenFAST solution).

Hardware Solution (Controller + Fan System). The on-board fan used in the present system is a single ducted fan originally developed for model aircraft applications. The fan is controlled via an electronic speed controller and single-board Arduino micro controller connected directly to a desktop computer used to receive motion tracking data and evaluate the surrogate model predictions.

Using a cantilever rig and single-axis load cell, a calibration curve has been defined relating the achieved/desired thrust force from the fan, f_{aero}, to the pulse width modulation (PWM) used to control the fan's motor.

Scaled Model in Wave Tank. The physical model tested in the wave basin is a 1:70 scale model of the IEA-15-240-RWT and VolturnUS-S platform (Fig. 1). The model FOWT is based on the IEA Wind Task 37 reference documents [6,7] and is, therefore, consistent with the OpenFAST simulations, and the data, used to generate the surrogate models. However, the mass properties of the system have been adjusted, to account for fresh water in the basin, in order to maintain a consistent platform draft. As specified in the reference document for the platform [7], a three-point catenary chain mooring system is used to hold the platform on

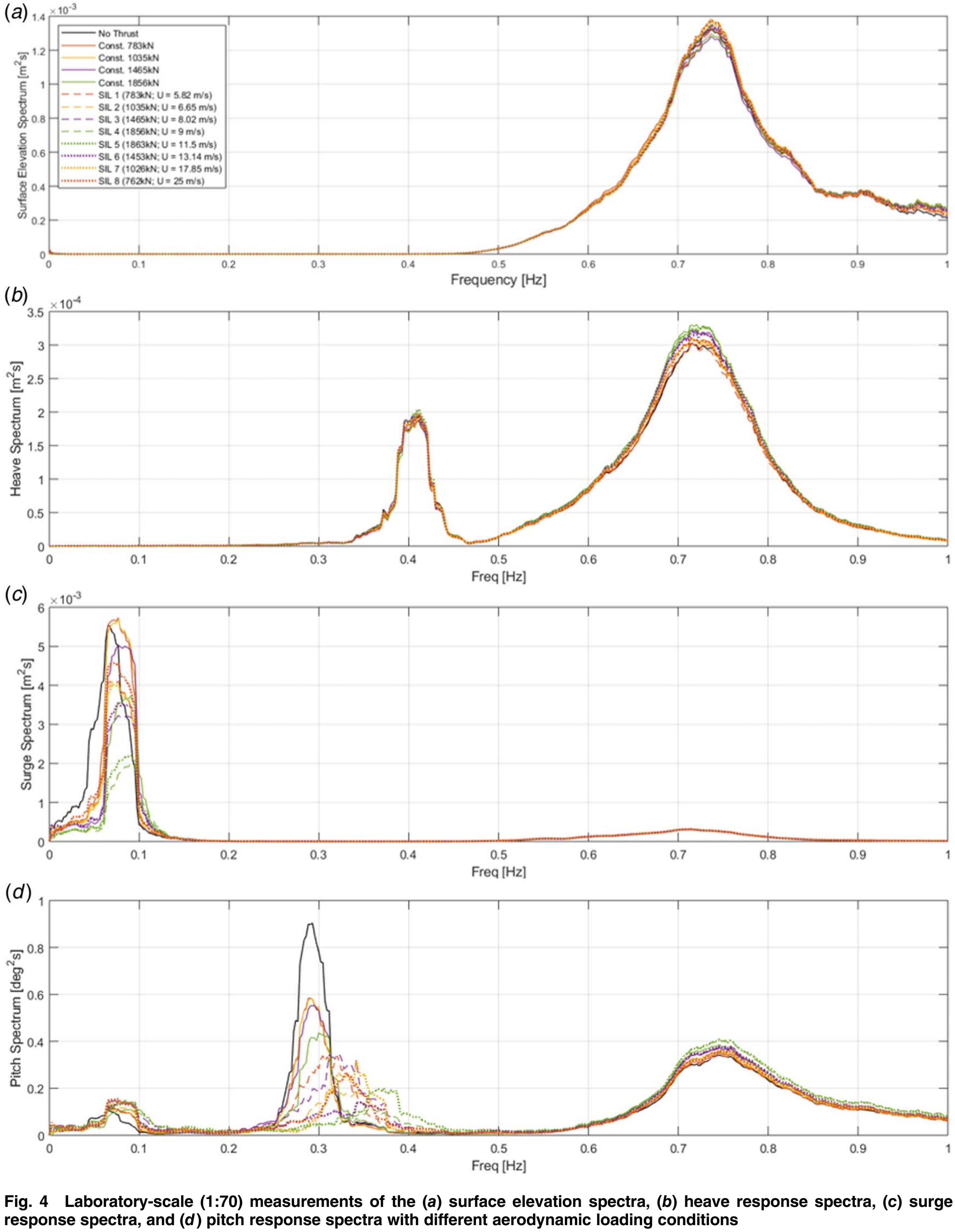

Fig. 4 Laboratory-scale (1:70) measurements of the (*a*) surface elevation spectra, (*b*) heave response spectra, (*c*) surge response spectra, and (*d*) pitch response spectra with different aerodynamic loading conditions

station. The water depth was set to 200 m at full-scale (again consistent with the reference documentation and OpenFAST simulations).

During an experiment, the platform position/orientation is measured using the Qualisys optical tracking system (at 128 Hz). The instantaneous velocities are then computed in real-time using a backward differencing algorithm and real-time filtering via a moving average filter. The platform pitch angle and heave, surge, and pitch velocities are then scaled-up to full-scale and input into the desired surrogate model. The surrogate model then predicts the instantaneous aerodynamic thrust force at full-scale. This value is then scaled down to model scale and converted into the appropriate PWM for the controller, via the calibration curve derived using the cantilever rig and load cell arrangement.

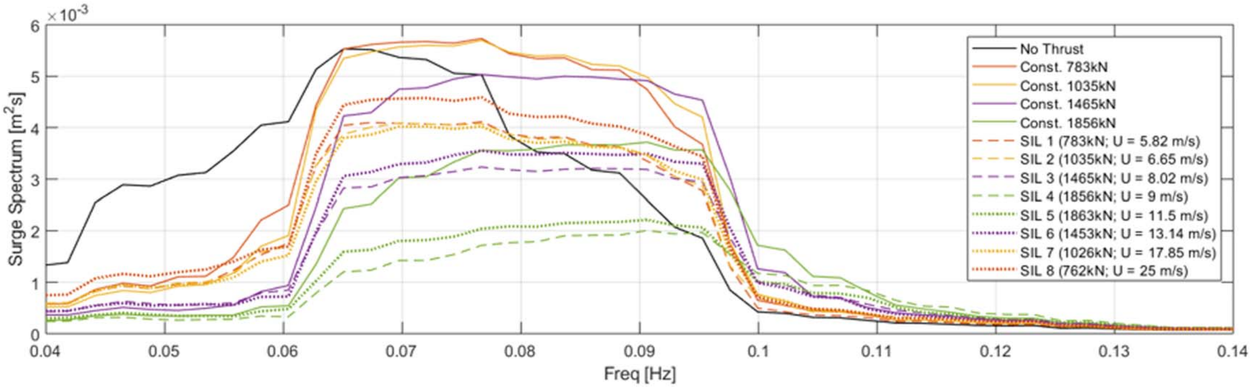

Fig. 5 Surge response spectra around the surge natural frequency of the system

Figure 1 shows the complete workflow for the RTHT system as well as an image of the 1:70 scale model in the COAST Laboratory Ocean Basin.

System Latency. Latency, in the feedback loop, is a key issue in RTHT systems. It is inevitable that some delay exists in the communication, calculation, and application of the aerodynamic loading and the consequences of this delay are an active area of research for those developing these systems. A number of factors influence this delay, including communication between the various pieces of hardware, execution time of the aerodynamic emulator, and response time of the fan.

From a series of bench tests, performed with the present system, the total delay in the feedback loop, i.e., the time between requesting a particular thrust and achieving the requested thrust, is estimated to be approximately 0.2 s. This is greater than desired, and considerable work/improvements are being made to reduce this as much as possible.

Despite this, according to numerical simulations, with artificially added delays, a 0.2 s delay does not have a drastic effect on the response spectra, in this case, but greater delays (∼0.7 s) can greatly influence the response of the system, particularly around the pitch natural frequency (greater system latencies appear to increase the energy present at the pitch natural frequency).

Results and Discussion

Figure 4 shows the lab-scale surface elevation spectra as well as the lab-scale response spectra, for heave, surge, and pitch motion, measured in a series of experiments with the model and RTHT system described above. Results are shown for cases with each of the surrogate models, and the entire RTHT system, active (SIL 1–8) as well as for cases with constant axial thrust corresponding to the four static thrust pairs (Const. 783 kN, for example). Also included are the measurements for a case with no thrust from the on-board fan. All cases have the same incident wave conditions (irregular waves based on the JONSWAP spectrum with lab-scale parameters: $H_s = 0.069$ m, $T_p = 1.37$ s, and $\gamma = 3.3$ (Full-scale: $H_s = 4.83$ m, $T_p = 11.46$ s)).

It can be seen (Fig. 4(*a*)) that the incident waves, in each case, are highly repeatable, i.e., very similar surface elevation spectra have been measured in each case. Therefore, it is assumed that the incident conditions are the same in each case enabling direct comparison between the response spectra.

Figure 4(*b*) shows that, in general, compared to the case with no thrust, the heave response of the model is not greatly affected by the aerodynamic loading, particularly around the heave natural frequency of the system (∼0.4 Hz) (regardless of whether it is constant thrust or actively adjusting based on the platform motion). However, the additional thrust does slightly increase the response of the system around the peak wave frequency (0.73 Hz) and the greater the thrust, the greater the increase. There is no obvious difference between the different loading conditions, i.e., constant or active. Nor is there any obvious difference between the below-rated and above-rated SIL pairs.

Figure 4(*c*) shows the surge response spectra. Conversely, to the heave response, around the wave frequencies the surge response is completely unaffected by the magnitude and type of aerodynamic loading. However, around the natural frequency of surge (∼0.08 Hz), the magnitude and type of aerodynamic loading strongly influence the response of the system. Figure 5 shows the surge response spectra, around this frequency, in more detail. It can be seen that, compared to the case with no thrust, the addition of aerodynamic loading creates a sort of square wave response, in this frequency range, i.e., narrower band response with very rapid

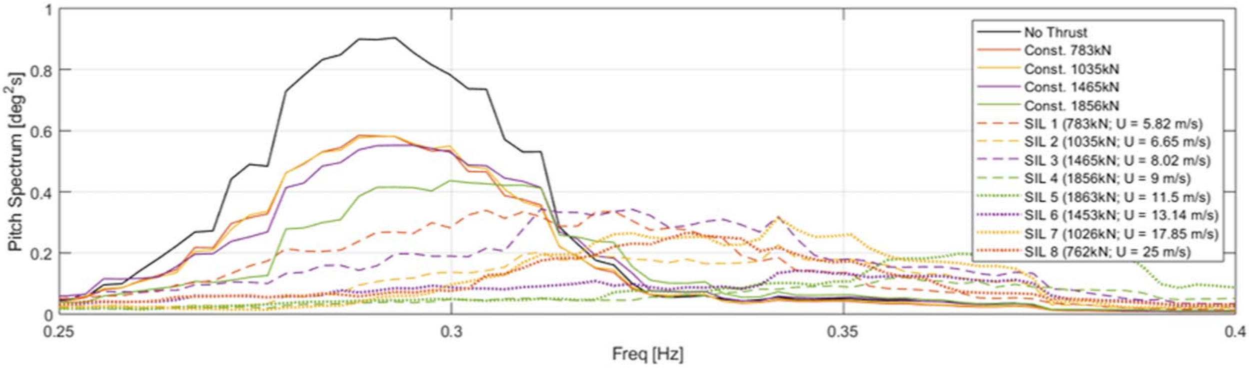

Fig. 6 Pitch response spectra around the pitch natural frequency of the system

increase/decrease in response in the frequency space, and the peak is shifted to a slightly higher frequency. The bandwidth of the response appears to be unaffected by the magnitude or type of thrust, but the amplitude of the response reduces with increasing thrust, and active SIL reduces the response more than constant thrust. There is also a suggestion that the below-rated SIL cases reduce the surge response, around the surge natural frequency, more than the above-rated cases.

Similar to heave, the pitch response, around the wave peak frequency, is enhanced, compared to the no thrust case, and this enhancement increases with increasing thrust. There is also a slight hint that active SIL increases the response, around these frequencies, slightly more than in the constant thrust cases. Some one-way surge-pitch coupling can also be observed in the pitch responses (i.e., pitch response around the surge natural frequency ∼0.08 Hz). The addition of aerodynamic loading appears to increase the pitch response around the surge natural frequency but also tends to shift the peak to slightly higher frequencies. There is no obvious trend, at these frequencies, with regard to the magnitude or type of aerodynamic loading. As expected, the most obvious effect of aerodynamic loading can be seen in the pitch response around the pitch natural frequency (∼0.3 Hz).

Figure 6 shows the pitch response spectra, around the pitch natural frequency, in more detail. It can be seen that aerodynamic loading dampens the pitch response around the natural frequency and that active SIL loading damps the response more than equivalent constant thrust. There is a hint that greater thrusts result in greater damping but this is not always the case. Constant thrust seems to retain a relatively narrow band response and a similar natural/peak frequency response to the no-thrust case. Active SIL loading, however, results in a much more broad-banded response and significant shift in the peak frequency to higher frequencies with a suggestion that the greater the thrust the greater the shift and spreading of the frequency response.

Conclusion

The initial stages, in the development of an RTHT system for FOWTs, have been presented. The system differs from existing RTHT methods by replacing the parallel simulation, in the aerodynamic emulator, with a surrogate model trained in advance of the experiments. To demonstrate the present methodology, the surrogate models in this work are trained using data derived from OpenFAST simulations only. In future iterations, however, higher-fidelity (or physical) data can be included in the training datasets, to enable more accurate emulation of the aerodynamic loading, without increasing the execution time of the emulator. For the simplified cases considered, the surrogate models are shown to accurately reproduce the aerodynamic thrust predictions from OpenFAST simulations. Bench tests reveal a system latency of ∼0.2 s. Considerable effort is being made to reduce the latency, but numerical simulations suggest this level of latency is acceptable in the case considered here. The developed system has been demonstrated for a 1:70 scale model of the IEA 15 MW reference wind turbine and VolturnUS-S platform in the COAST Laboratory Ocean Basin at the University of Plymouth, UK. Measurements, in irregular waves, with different loading conditions, show that the response of the system can change significantly when aerodynamic loading is included, particularly around the surge and pitch natural frequencies.

Acknowledgment

The authors acknowledge the continued support of the Engineering and Physical Sciences Research Council (EPSRC).

Funding Data

- Engineering and Physical Sciences Research Council (EPSRC) (Grant No. EP/T004177/1; Funder ID: 10.13039/501100000266).

Conflict of Interest

There are no conflicts of interest. This article does not include research in which human participants were involved. Informed consent not applicable. This article does not include any research in which animal participants were involved

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Nomenclature

p = lab-scale platform position
P = full-scale platform position
$\dot{p}$ = lab-scale platform motion state
$\dot{P}$ = full-scale platform motion state
f_{aero} = lab-scale aerodynamic force (N)
F_{aero} = full-scale aerodynamic force (N)
H_s = significant wave height (m)
T_p = peak period (s)
γ = peak enhancement factor
λ = scale factor

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