CROSS-SECTORIAL LEARNING OF MODEL TESTING METHODOLOGIES ALIGNED TO TECHNOLOGY TRL

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ABSTRACT

This paper presents a state of the art review of Floating Offshore Wind Turbines (FOWT) tank testing in wave basins from the perspective of understanding how different test methodologies currently deployed can be correlated to the development stage of the design being tested. This approach was already adopted by the wave energy sector, however, for the FOWT sector this is not fully developed, and only briefly mentioned in guidance documents.

An open question in the application of aerodynamic loads within wave basin testing is, how complex does it need to be? For wave basin testing facilities, it is important to understand how a test program must be set up to meet the clients' requirements. The designs being tested may be at different development stages, i.e., different Technology Readiness Levels (TRL) and it is important to understand how the test configuration will impact the clients' objectives.

Three main tank test campaigns will be performed at FloWave Ocean Energy Research Facility using the UMaine VolturnUS-S reference platform developed for the IEA wind 15-MW offshore reference wind turbine. It will be used as a basis for the development of a staged development approach for the FOWT sector. In preparation for these tests, the present paper explores and evaluates the appropriateness, with relation to TRL, of different methodologies for including aerodynamic loads in wave basin testing of FOWT.

1 Acronyms

DLC	Design Load Cases
DOF	Degree of Freedom
FOWT	Floating Offshore Wind Turbine
FSRs	Froude-Scaled Rotors
MARIN	Maritime Research Institute Netherlands
MSWT	Model-scale Stock Wind Turbine
NREL	National Renewable Energy Laboratory
PKM	Parallel Kinematic Machine
PTO	Power Take-Off
SIL	Software-in-the-Loop
TLP	Tension Leg Platform
TRL	Technology Readiness Levels
TSR	Tip-Speed Ratio
WEC	Wave Energy Converters
WT	Wind Turbine

This is a peer reviewed, accepted author manuscript of the following research contribution: Leite, A., Davey, T., Dai, D., Pillai, A. C., & Bruce, T. (2023). Cross-sectorial learning of model testing methodologies aligned to technology TRL. In *Proceedings of the ASME 2022 4th International Offshore Wind Technical Conference* [IOWTC2022-93886] (Proceedings of the ASME 2022 4th International Offshore Wind Technical Conference, IOWTC2022). ASME. https://doi.org/10.1115/iowtc2022-93886

2 Introduction

The installation of wind turbines offshore, due to the steeper wind shear, higher wind speeds, and less competition for space compared to on land, needs to be economically viable and capable of competing with alternate technologies in the energy market. The cost of production and installation of fixed structures in deeper waters (i.e.>60 m), is not competitive [1].

A viable solution is therefore, the use of floating substructures, Floating Offshore Wind Turbines (FOWT), attached to the seabed by mooring lines and anchors. However, the motions of a FOWT exposed to the environmental conditions at sea will be different compared to their bottom-fixed or onshore counterparts, and further aspects need to be taken into account when designing these structures. Likewise, compared to traditional offshore floating structures, the inclusion of an operating wind turbine interacting with the atmosphere, requires considerations beyond traditional offshore engineering. For example, the coupled effects between the turbine and the floater will influence the performance of the turbine [2]. Aerodynamic loads will contribute to the damping of the system, the mean aerodynamic thrust loads will have an impact on the mooring loads and the mean torque on the rotor will generate heeling moments [3]. Additionally, gyroscopic moments for some types of floating structures may be significant, which may excite unwanted motions, for example yaw moments [3].

According to the IEC 61400-3-1:2019, Part 3-1: Design requirements for fixed offshore wind turbines design standards [4], an integrated load analysis is needed before the certification of the wind turbine (WT) in order to develop a cost-effective and safe FOWT [5]. This analysis is traditionally done through the use of numerical models.

However, there are still complex phenomena, including extreme wave loads, viscous loads (roll and yaw damping of ship-shaped floaters) and wave-current interaction effects on floating moored structures that are not fully studied or included in these models [6]. For those reasons, physical testing is an important approach that is used to validate the numerical models and compared to full-scale deployment at sea, it is often a simpler and cheaper way to test a design. It can also provide the motion response of the structure under uncoupled and controllable external loads which is not possible in sea deployment [7].

2.1 Physical Testing Challenges

When testing a scaled model, the mass and inertia properties must be accurately scaled, together with the structure's elasticity, external loads, and corresponding frequencies [8]. The main challenge in FOWT testing is the presence of both aerodynamic and hydrodynamic loads which scale differently. The Reynolds Number is commonly used for wind tunnel experiments which objective is to properly scale the aerodynamic loads. It corresponds to the ratio between inertial and viscous forces that should be maintained between the model tests and at full scale. Maintaining this similarity on wave basin testing is not practical since the wind velocity needed to be reproduced would be significantly higher than the full scale wind velocity and the forces would not be in proportion to the hydrodynamic and hydrostatic loads [7].

The Froude Number is appropriate for the scaling of free and moored floating structure tests since the ratio between inertial and gravitational forces is conserved and this will allow the capture of the wave loading correctly [8]. This similarity is commonly used in naval architecture and analysis of floating structures in wave tank testing due to the importance of wave loading in these structures. However, by maintaining Froude similarity the aerodynamic forces are greatly diminished by more than an order of magnitude which will impact on the turbine performance [9]. This impact increases the smaller the scale becomes.

Finally, physical testing in wave basins is primarily concentrated in wave loading on the structure which for FOWT may not be enough depending on the design phase of the model. Consideration of how to include aerodynamic loads must be developed. Certain techniques of model testing require the generation of a wind field over the wave tank. It is important that the testing facilities have the capability of generating a steady wind with low values of turbulence [10]. This is usually achieved by a set of fans which area must cover the total test area of the FOWT, including its displacement during tests [7]. Therefore, the wind generator system must be of considerable size in order to accomplish that which could become a challenge especially for smaller wave basin facilities [1].

The present paper reviews the current methods for simulating aerodynamic loads on the testing of FOWT in wave basins with the proposal of adopting a staged development approach that relates the tank test setup with the TRL of the model being tested. This is the first part of a continuous study to support the development of tank testing guidelines.

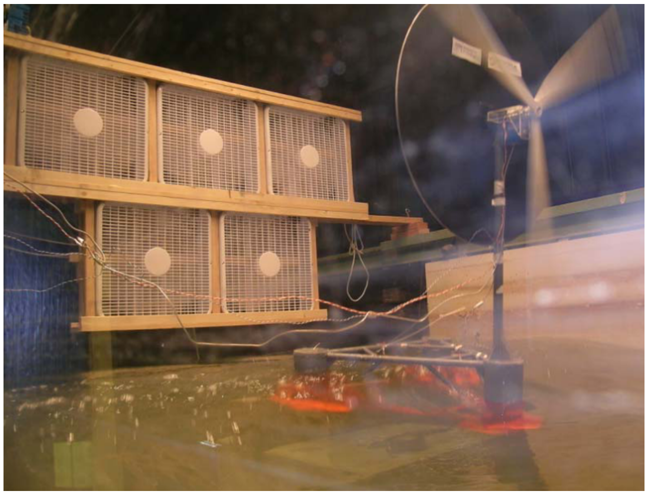

FIGURE 1. WindFloat model testing using a drag disk [2].

3 Aerodynamic Loads Simulation Methods in Wave Basins

3.1 Preliminary Methods

Different methods to simulate aerodynamic loads on the floating structure have been used in order to test operational and emergency conditions as well the inclusion of control strategies in the FOWT. However, an official protocol for physical testing of these structures has not yet been established [7].

One of the first approaches used to simulate aerodynamic loads on models, consisted of a static weight attached to a line connected to the nacelle [11]. This is a very rudimentary way of applying static wind load as it omits the motion response of the structure, wind variability, and gyroscopic effects. It should only be considered for rough estimation of maximum mooring offset [12].

Another method initially adopted was the use of a drag disk that simulates the mean static thrust on the rotor of a wind turbine. For the WindFloat project this was the method used together with a motor placed at the top of the tower behind the drag disk, spinning at Froude-scaled speed to simulate the gyroscopic effects. The model was then exposed to a wind field generated by a group of fans in the tank [2] as can be seen by Figure 1. Despite of being an easy method to design and deploy, a low turbulence wind generation system is needed and vortex shedding is created behind the disk. Control systems also cannot be simulated [8].

In order to mitigate some of the disadvantages employed in these methods more recent strategies are being adopted. These can be divided in two groups defined by Gueydon [10] as the "full-approach" and the "hybrid-method".

3.2 Full-Approach

The full-approach comprises the use of a wind turbine scaled model exposed to a generated wind field with the objective to correctly match the aerodynamic forces acting on the rotor. This means that the lift and drag coefficients for different values of tip-speed ratio (TSR) should match the full scale FOWT.

One of the two methods of the full-approach is the use of a geometrically scaled wind turbine, designated by Wen [13] as Froude-scaled Rotors (FSRs) which maintain the scaled mass and inertia properties of the full-scale prototype. One of the main projects developed using this type of turbine was done by the DeepCwind consortium in 2011 at the Maritime Research Institute Netherlands (MARIN). It included the testing of the three main floating structures, semi-submersible, spar and tension leg platform (TLP) with a geometrically Froude scaled version of the National Renewable Energy Laboratory (NREL) 5 MW reference wind turbine. The motions of the different platforms and performance of the turbine were studied for a range of different wind and wave conditions [14].

However, the low Reynolds number associated with Froude scaling for the model testing altered the lift and drag coefficients of the wind turbine significantly. This means that the turbine under-performed greatly and in order to match the thrust, considered the most significant aerodynamic load, higher values of Froude scaled wind speeds needed to be used [15]. Despite of geometrically representing the real wind turbine and being able to generate gyroscopic effects, the thrust can only be matched if the wind speed is increased while other aerodynamic loads, e.g. torque is still not matched.

In order to overcome these challenges, an alternative method was created within the full-approach strategy. It consisted of a model of a WT that is able to better match the performance of the full scale prototype. Referred to as performance-scaled WT, its blades are designed to match the performance of the full-scale prototype by changing the airfoil chord length and blade twist while maintaining the blade length, gross blade mass, and rotor operational speeds [15]. It will not resemble the prototype blade surface geometry, however, it will yield appropriate thrust when subjected to Froude scaled wind [7].

MARIN, following the tests using a geometrically scaled wind turbine in 2011, developed a model-scale stock wind turbine (MSWT) [16] that has comparable thrust performance as the full scale NREL 5 MW prototype for a TSR of 7. Other projects also made use of a performance scaled wind turbine [17, 18] and together with the MSWT developed by MARIN, it was concluded that the power coefficient under-performed and the matching of the thrust coefficient between prototype and model only happens for one or two operating points. This poses a challenge when testing control systems and unsteady aerodynamics of the FOWT [13]. When comparing both full-approach methods, Kimball [19] concluded that both WT configurations showed similar results on the platform pitch response for when the wind turbine is tested under operational conditions. Therefore, in case studies where the testing of active pitch control is not used and only the relative motion of the model exposed to thrust is important, the use of a geometrically scaled wind turbine is advised. On the other hand, if the testing of more realistic wind environment conditions is needed, the use of a performance scaled wind turbine may be necessary [19].

3.3 Hybrid-Approach

The hybrid-approach includes the use of the hybrid system also called Software-in-the-Loop (SIL), first developed by Azcona [20]. It consists of coupling a physical model and a numerical model in real time through the use of sensors and actuators [6], schematically represented in figure 2.

The physical model used can be a performance scaled WT exposed to aerodynamic loads in a wind tunnel [21] or a floating structure exposed to the hydrodynamic loads in a wave tank [6, 20, 22–24]. The actuator used in the former, is commonly a 6-DOFs parallel kinematic machine (PKM) capable of applying the output loads, generated by the numerical model, on the physical model. On the latter, the actuators diverge in terms of complexity, from a ducted fan [20,22] that can be expanded to a multi-fan system [8,23] to a more complex winch system [6, 24].

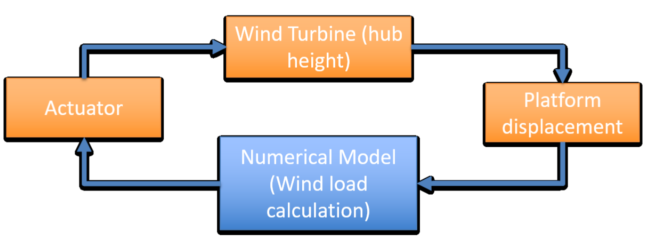

FIGURE 2. Basic principle of Software-in-the-Loop.

The way that these actuators differ from each other depends on the type of aerodynamic loads that they can generate. For example, using the ducted-fan only allows the application of thrust on the rotor while the winch system on a square frame allows the application of thrust, generator torque, horizontal tangential aerodynamic force, and aerodynamic moments [6]. Deciding which components of the load vector evaluated by the numerical model should be used in the physical model is important and it depends on the type of platform being tested and on the objectives of the test. However, the system must be able to cope with the increasing complexity by having a rapid rate of response on applying the forces calculated by the numerical model on the physical structure as well as receiving the input motions in real-time [6].

The main advantages of using a hybrid system are that a wind generation system is not needed; response of the structure to high frequency unsteady wind speed is captured [8]; different levels of complexity dependent on the desired result can be adopted; no need to build different rotors [21]; allows a test at relatively large scale due to the scale being dictated only by the hydrodynamics of the floater [5]; the impact of the turbine control system; blade elasticity on the thrust load may be modelled in the tests [5] and the possibility to investigate the response of the structure in operational and survival conditions, as well as in fault conditions [12].

The main disadvantages include the complexity and time consumption of the experimental study [5] and to the best of the authors knowledge, at present, no actuator is capable of applying the gyroscopic effects. This may be more significant for some type of structures than others, e.g. TLP. For a TLP, it will be insignificant as the pitch motions are small, therefore the pitch-yaw coupling related to the gyroscopic effects of a pitching rotor are likely to be negligible [5]. Lastly, the hybrid system relies on a non-physical component and it will only be as good as the numerical model used in the experimental study. The most used numerical model for this purpose is FAST, a coupled aero-hydro-servo-elastic dynamic simulator on on-going development that is only useful as long as its predictions continue to be verified by physical testing.

4 Staged Development Approach

Within the wave energy industry, a staged development approach is adopted, under the IEC TS 62600-103 [25] in order to de-risk the design and development of Wave

Energy Converters (WEC). The process from concept to multi-device commercial deployment is categorised into five stages. The first two stages of these (covering TRL 1-4) are the most informative when exploring laboratory scale testing. Stages 3-5 describe the move to the sea through a sub-system model (e.g. deployment in a nursery test site), solo device demonstration, and multi-device deployment.

When looking for transferable approaches to FOWT testing the key lesson may be the distinction between concept model testing in Stage 1 (TRL 1-3) and Design Model testing in Stage 2 (TRL 4). In the wave energy sector one of the key distinguishing features between these stages is the move to more representative power take-off and control, and more realistic simulated seaways. This is similar conceptually to the difference in complexity between the more rudimentary wind loading and drivetrain implementations for FOWT models, and the more complex hybrid approaches adopted by Azcona [20], Oguz [22] and Bachynski [33].

Wave energy testing is complicated by the fact that there is no archetypal wave energy device. Arguably the wind industry has seen convergence, perhaps in part due to the greater maturity of the technology. However, this maturity perhaps makes it more surprising that there is no standardised approach to exploring combined aerodynamic and hydrodynamic loading in the laboratory. A lesson that can be taken from the wave testing sector is that these standards need not be overly prescriptive, and can still provide adaption on emerging technologies. The IEC 62600-103 guidance [25] requires the production of a Design Statement, setting out the key objectives of the test programme and aiding in the process of setting priorities and resolving compromises in test design. A similar approach may allow for resolution when exploring differing requirements between the various FOWT platform concepts.

Currently, tank testing guidance documents and procedures for the FOWT sector do not describe which steps should be applied based on the TRL of the design being tested [12]. It only highlights, in a general way, the need of tank testing during the various experimental stages for novel floating concepts and provides a general idea of which environmental parameters should be considered in early and later stages of development. Furthermore, it is also stated that the rotor must be modelled for tests aimed at evaluating the system's global response, however, this may not be necessary for preliminary stages where different support structures deigns are tested [12].

Table 1 summarises the publicly published projects which performed tank testing of FOWT design in a wave basin as part of its concept development. A classification regarding the design TRL at the moment of testing is provided. The "present TRL" column indicates the TRL value at the time of the current publication, with only two designs currently on TRL 8, HYWIND and WindFloat. However, table 1 is based on published articles and also on testing experience from tank operators. Information on current developing projects from private developers which is not public, was not included.

From the analysis of the table 1, no correlation between the method used to apply aerodynamic load and the TRL of the model being tested exists. The method to apply aerodynamic loads is commonly chosen accordingly to the tank's capabilities and based on the objectives of the testing.

It is therefore proposed that the design of a tank test program should be driven by the maturity of the design, expressed in terms of Stage 1 (TRL 1-3) and Stage 2 (TRL 4) as shown in table 2. This design can vary in terms of complexity, depending on the way that the aerodynamic loads are applied especially within the Hybrid approach. It is expected that for Stage 1, concept model, a simpler setup, for example the use of a winch system to apply a constant thrust force in 1 degree of freedom will suffice. As stated in current guidelines [12], the mean wind thrust is the minimum requirement for modelling the presence of the rotor in a fully coupled test of a FOWT. This provides the generation of the correct aerodynamic overturning moments and mooring offsets which is theoretically ideal for initial development stages. Testing of control systems it is not proposed at this stage.

Progressing to more complex systems, for Stage 2 it is proposed the application of a dynamic thrust based on a look-up-table or by the full deployment of SIL in real-time. By using this approach, it is possible to introduce controlled aerodynamic loading and testing of control systems can be included. As referred by Antonutti [24], the use of a hybrid approach using a winch system as actuator, is the best compromise in order to test the coupled effects of the aerodynamic and hydrodynamic loads on the floating wind turbine.

At this stage, The inclusion of other forces from the wind load vector in more than one DOF could be investigated. For example, the representation of the gyroscopic effects to allow a more accurate representation of the aerodynamic coupling between the rotor and the support structure [12]. These considerations may be influenced by the type of model being tested, as observed by Høeg [34], the gyroscopic effects are more significant for a spar-type FOWT

TABLE 1. List of tank testing deployments with the corresponding technique used to simulate aerodynamic loads and the TRL value at the time of the testing and the TRL value at the present time.*

Design/ Project	Concept Model (Stage 1)			Design Model (Stage 2)	Technique(s)	Present TRL	References
	TRL 1	TRL 2	TRL 3	TRL 4			
HYWIND	X	X	X	X	Geometrically scaled	TRL 8	[26]
WindFloat	X	X	X		Drag Disk	TRL 8	[27]
TLP type OWT	X	X	X		Geometrically scaled	TRL 3	[28]
SPAR type OWT	X	X	X		Static weight/ Geometrically scaled	TRL 3	[11]
Dutch Tri-Floater	X	X	X		Geometrically scaled	TRL 4	[29]
WINFLO Floater	X	X	X		Performance scaled	TRL 5	[17]
Inverted conical cylinder	X	X	X		Geometrically scaled	TRL 3	[30]
GustoMSC Tri-Floater	X	X	X		Performance scaled	TRL 4	[18]
MERMAID Project	X	X	X		Performance scaled	TRL 3	[31]
Iberdrola TLP	X	X	X		Hybrid	TRL 3	[5]
Eolink OWT	X	X	X		Performance scaled	TRL 5	[32]

*This TRL classification is based on the articles referenced and on the authors' best judgement.

than for a semi-submersible or TLP.

As shown by Gueydon [10], within the software-in-the-loop, several actuators can be used to simulate different forces from the wind load vector. However, there's no comparison of what each application may bring to the results and how can it influence the platform responses. As stated by the author, comparisons between different testing techniques are needed to continuously improve tank testing results.

A study of the effects of limited actuation when using Software-in-the-loop was published by Bachynski [35], where a sensitivity analysis using numerical tools was performed. They removed step by step the gyroscopic effects; non-thrust aerodynamic loads: pitch moment, yaw moment, sway force, heave force; dynamic variation of generator torque and thrust directionality. It was concluded that the non-thrust aerodynamic loads had varied effects on the platform responses and significant couplings were observed between aerodynamic loads and platform responses.

The environmental parameters chosen for each stage are stipulated according to current guidance [12], where for earlier stages the characterisation of the frequency response is important and on later stages the accurate performance estimation is required. Also important to include the relevant IEC BS EN IEC 61400-3-1:2009 [4] design load cases (DLC) that are deemed necessary.

TABLE 2. Theoretical proposed set-ups for stages 1 and 2 for a Staged Developemnt Approach for FOWT.

Test Feature	Concept Model (Stage 1)	Design Model (Stage 2)
Wind Loading Application	Constant thrust winch system	Performance scaled/ Hybrid approach
Control	No controller	Control methodologies can be applied
Degrees of Freedom	1	≥ 1
Environmental Parameters	Long-crested waves and/or uniform wind; regular waves with/without regular wind; irregular waves with/without turbulent wind	Misalignment of wind and wave directions/ short-crested irregular waves

5 Conclusions

There are several methods that can be used to apply the aerodynamic loads on the testing of FOWT. Each method has its inherent advantages and disadvantages and its adoption depends on the capability of the tank testing facility as well as the objectives of the test campaign. Software-in-the-loop is a promising tool for wave tank testing facilities due to resolving the Froude-Reynolds scaling conflict, however it still relies on the capacity of the numerical model used and can become quite complex when run in real-time.

On the ongoing development of the tank testing of FOWT, understanding how complex a system set up needs to be in regards to its development stage can help tank test facilities and developers plan, in a informed way which requirements need to be met. Current procedures and guidelines for the testing of FOWT do not provide this information in a detailed and schematic way, as done for the wave energy sector. To develop this approach for the FOWT sector, more comparisons are needed between different testing techniques to continuously develop tank testing procedures and guidelines.

This paper highlights the need for FOWT testing guidelines to aid the TRL developments of FOWT and represents the first stage in an ongoing study that will include a set of tank trials using the UMaine VolturnUS-S reference platform developed for the IEA wind 15-MW offshore reference wind turbine.

Three main test campaigns are planned with increasing complexity in the application of aerodynamic loads which include: static mean thrust, dynamic mean thrust by implementing SIL and open development for either including more forces from the wind vector or change the type of actuator. These tests will be performed at FloWave Ocean Energy Research Facility located at the University of Edinburgh, which possess a 30 m circular concrete basin containing the 25 m diameter, 2m deep wave and current tank with fully independent direction control.

ACKNOWLEDGMENT

The authors are grateful to EPSRC and NERC for funding for the Industrial CDT for Offshore Renewable Energy (EP/S023933/1).

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