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REVIEW ARTICLE

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A review of modelling techniques for floating offshore wind turbines

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Abstract

Modelling floating offshore wind turbines (FOWTs) is challenging due to the strong coupling between the aerodynamics of the turbine and the hydrodynamics of the floating platform. Physical testing at scale is faced with the additional challenge of the scaling mismatch between Froude number and Reynolds number due to working in the two fluid domains, air and water. In the drive for cost-reduction of floating wind energy, designers may be seeking to move towards high-fidelity numerical modelling as a substitute for physical testing. However, the numerical engineering tools typically used for FOWT modelling are considered as mid-fidelity to low-fidelity tools, and currently lack the level of accuracy required to do so. Furthermore, there is a lack of operational FOWT data available for further development and validation. High-fidelity tools, such as CFD, have greater accuracy but are cumbersome tools and still require validation. Physical scale model testing therefore continues to play an essential role in the development of FOWTs both as a source of validation data for numerical models and as an important development step along the path to commercialization of all platform concepts. The aim of this paper is to provide an overview of both numerical modelling and physical FOWT scale model testing approaches and to provide guidance on the selection of the most appropriate approach (or combination of approaches). The current state-of-the-art will be discussed along with current research trends and areas for further investigation.

KEYWORDS

floating offshore wind, numerical modelling, physical testing, scale models

1 | INTRODUCTION

Floating wind energy is an emerging industry. Currently just three floating farms, Hywind Scotland (30 megawatts [MW]), Kincardine (50 MW) and Windfloat Atlantic (25 MW), are connected to the grid, and several other floating farms are in the construction and planning stages. While the industry is advancing at pace, the costs associated with floating wind are still significantly higher than for fixed offshore wind energy. However, significant price reductions are expected over the period 2021–2028, which could make floating economically competitive with the current price of fixed wind.[1]

To achieve these cost reductions, and for floating wind energy to establish itself as a reliable technology, high-fidelity design and modelling software are essential. Modelling of floating offshore wind turbines (FOWTs) is challenging due to the strong coupling between the aerodynamics of the turbine and the hydrodynamics of the floating platform. A variety of numerical and physical modelling approaches are currently in use, both independently and using a cross validation approach to de-risk the commercial development of concepts through the technology readiness levels (TRL).[2]

This paper informs the reader about the state-of-the-art of FOWT modelling, both numerically and experimentally, and attempts to aid in the decision of which methods and tools are most suitable for the design or research the reader may wish to perform. The paper builds on reviews of physical modelling approaches by Robertson et al,[3] Muller et al,[4] Stewart and Muskulus,[5] and Gueydon et al,[6] and numerical modelling approaches by Cordle et al[7] and Joao Cruz et al.[8]

The first part of this paper reviews the numerical methods and the leading software available for FOWT modelling. The second part reviews the methods employed to date in experimental campaigns of FOWT models, and the different methods to overcome the scaling mismatch caused by working in the two fluid domains, air and water. The focus of this paper will be on the modelling techniques required for the design stages up to TRL 4 (technology validated in a laboratory). The emphasis will therefore be on numerical and physical approaches used at an early concept-development stage and will not consider high-fidelity or component level analysis at the final design stages in detail.

Finally, in the third part gaps in the state-of-the-art are identified and recommendations for guidelines for the combined use of physical and numerical approaches in the FOWT development process are suggested.

2 | NUMERICAL MODELLING

A broad range of numerical techniques and software packages are available for the initial stages of the design process of a FOWT prototype. Some overarching aspects and contemporary directions are considered in this section. Traditionally, a numerical model of a new design is developed, and then validated using model-scale laboratory tests[9,10] However, in the drive for cost reduction of FOWT technology designers may be looking to use high-fidelity numerical tools in an effort to reduce reliance on costly and time-consuming physical tests, and also to reduce the uncertainty that simpler numerical models contain. On the other hand, when considering lifetime operations and maintenance aspects,[11] control,[12] or end of life decision-making,[13,14] lower fidelity models can be of significance. The competing needs and relevance of high-fidelity and low-fidelity models exist in a wide range of TRLs.[15]

2.1 | Computational methods

For numerical modelling purposes, the FOWT can be divided into roughly three categories (Figure 1): structural dynamics, hydrodynamics, and aerodynamics. Scaling aspects[4,6] of each of these categories and their requirements can differ significantly, and change based on the context of their uses, including control.[16] In this paper, turbine control will not be reviewed as a separate category since it requires an in-depth review of its own. The choice of numerical modelling method will generally be a trade-off between accuracy and/or fidelity, and computational efficiency with respect to the phenomena of interest and their acceptable performance levels. Accuracy is defined here as the deviation of simulated estimates

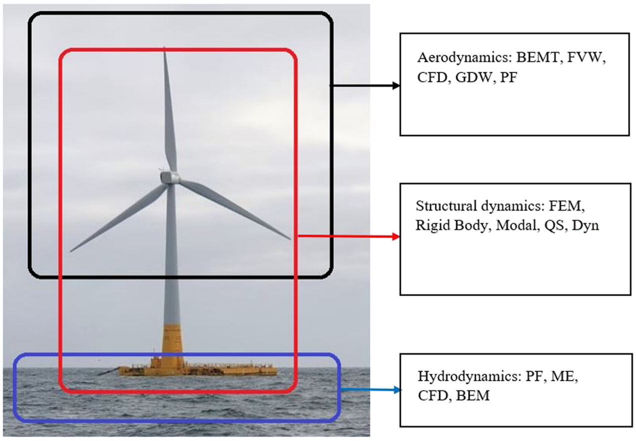

FIGURE 1 Numerical structure of the FOWT (photo: FLOATGEN, by A. Otter). Abbreviations are defined in Table 1

TABLE 1 Explanation of abbreviations of computational methods in Figure 1

Acronym	Category	Fidelity
BEM: Boundary Element Method	Hydrodynamic	Mid
BEMT: Blade Element Momentum Theory	Aerodynamic	Mid
CFD: Computational Fluid Dynamics	Aero-/hydrodynamic	High
Dyn: Dynamic method	Structural	Mid
FEM: Finite Element Method	Structural	High
FVW: Free Vortex Wake method	Aerodynamic	Mid
GDW: Generalized Dynamic Wake method	Aerodynamic	Mid
ME: Morison Equation	Hydrodynamic	Mid
PF: Potential Flow	Aero-/hydrodynamic	Mid
QS: Quasi-Static method	Structural	Low

from measured physical responses and is often presented as a statistical summary or in the form of metrics for direct comparison. On the other hand, fidelity describes the level of simplification of the underlying physics or phenomena of interest by the numerical model,[17,18] providing a level of confidence that said accuracy is indeed achieved during simulations. Computational efficiency is often reported as the amount of time required for a simulation to complete using standard computing equipment but estimates of the complexity of the problem in terms of floating-point operators are becoming more visible in the dynamical systems literature.

Overall, numerical models may be classified into three levels: low-, mid- and high-fidelity, where increasing fidelity leads to a higher demand on computational resources, reducing computational efficiency. The choice of fidelity level is a function of the objective of the simulation and the level at which such analysis and its accuracy is required. Typically, low-fidelity models are used during the initial stage of FOWT design for sizing analysis and optimization. Mid-fidelity models, or engineering-level tools, are used after the initial design stage for loads analysis of FOWTs to examine operational and extreme conditions. High-fidelity models are typically used during the final design stages for detailed investigations, especially to accurately obtain stresses on the structure. A multi-fidelity approach may also be used where elements of each fidelity-level model is used in the different stages of design. As an example, higher fidelity tools may be used to tune lower fidelity ones, or as checks for certain high-impact design conditions.

For brevity, the various computational methods will not be described in detail in this paper, as most can be found in standard texts. Instead, examples of numerical studies where low-, mid-, and high-fidelity approaches were used will be reviewed for the structure, hydrodynamic and aerodynamic categories. A detailed overview of computational methods relating to FOWT modelling can be found in Joao Cruz et al.[8]

2.2 | Software for FOWT modelling

There are several open-source and commercial numerical software packages for FOWT modelling. Some of the popular software packages are listed in the following sections.

2.2.1 | Low-fidelity

For the early design stages, simple low-fidelity frequency-domain models can be used to simulate linear dynamics of the FOWT. Although no commercial standalone frequency-domain solvers seem to be available for FOWTs, there are a number of examples developed in-house, for example, Hegseth and Bachynski,[19] Karimi et al[20] and Pegalajar-Jurado et al.[21]

2.2.2 | Mid-fidelity

Mid-fidelity software, often referred to as engineering tools, are used for global dynamics analysis, both in linear and nonlinear loads. The most popular engineering tools are listed below.

- FAST[22] is an open-source software developed as a research tool by the National Renewable Energy Laboratory (NREL) in the United States. Recently, it was re-named OpenFAST, with the idea of having a more community-driven development of the tool. OpenFAST is made up of several modules able to solve the coupled nonlinear aero-hydro-servo-elastic-mooring dynamics of FOWTs in time-domain only. The linearization of the underlying nonlinear system equations for OpenFAST is described in Jonkman et al.[23]
- HAWC2,[24] developed by the Technical University of Denmark (DTU), is an aero-elastic time-domain solver, which also includes a hydrodynamic model for FOWT modelling.
- SIMA,[25] developed by Selskapet for INdustriell og TEknisk Forskning ved norges tekniske hoegskole (SINTEF), comprises the hydrodynamic- and mooring modules SIMO and RIFLEX. Initially, it was developed for floating platforms in the oil & gas industry but now can also be used for FOWT modelling.
- Bladed,[26] developed by Det Norske Veritas (DNV), is an aero-elastic code which can be coupled with SINTEF's SIMA workbench for FOWT modelling.
- SIMPACK,[27] is a general multi body simulation tool with a dedicated wind simulator, which has an elastic module and interfaces with HydroDyn, AeroDyn (both FAST modules) and Bladed for coupled simulations of FOWTs.
- Both Orcaflex[28] and Flexcom,[29] hydrodynamic solvers for floating objects developed by Orcina and Woods Group respectively, can be coupled with FAST for a full time-domain FOWT analysis. Both these numerical codes were originally developed for the offshore oil and gas industry to model moorings, riser pipes and so forth.

Most of the engineering tools mentioned above require input from frequency-domain PF solvers, such as WAMIT, AQWA and Nemoh, for hydrodynamic coefficients to solve the radiation/diffraction problems.

The underlying numerical methods for the three main elements of FOWT design are detailed in Table 2 for the engineering tools discussed in this section.

Several studies have been conducted to compare engineering tools against each other, for example, Ormberg and Bachiynski,[30] which compared the aerodynamic results obtained by RIFLEX with those obtained by AeroDyn, and found comparable results.

However, the most comprehensive benchmark study to date is the Offshore Code (OC) Comparison Collaboration project. Most of the engineering tools mentioned in this section have been featured in the OC projects and were used by the participants to simulate the dynamic behaviour of a spar FOWT design similar to Hywind in the OC3[7] and OC4 projects, and the DeepCwind semisubmersible FOWT in the OC4, OC5 and OC6 projects.[31–33] Some important findings include the following:

- Similar results for the semisubmersible were found with potential flow and Morison-only solvers within the wave-frequency region, pitch variations were slightly higher with the latter.
- Significant difference in viscous drag loads is achieved with calculating the Morison drag terms for each member compared to approximation with a global drag matrix.
- Mean and slow drift caused by wave excitation varies significantly between the numerical codes when nonlinear hydrodynamics are included.
- Heave response is improved when dynamic pressure on heave plates is included in the Morison-only approach.
- There is significant difference for moorings with the Dynamic method compared to the Quasi-Static method, particularly in frequencies above the linear wave range.
- Response Amplitude Operators (RAO) are a good way of comparing the dynamic response of FOWTs between the different numerical codes, both with and without wind loads.

TABLE 2 Engineering tools used for FOWT modelling

Software	Hydrodynamics	Aerodynamics	Structure
FAST	PF + ME	BEMT + GDW/FVW	RB + Modal/FEM + Dyn/QS
HAWC2	PF + ME	BEMT + GDW	FEM + Dyn
SIMA	PF + ME	BEMT	FEM + Dyn
Bladed	With SIMA	BEMT + GDW	Modal
SIMPACK	With HydroDyn	AeroDyn/AeroModule	FEM
Orcaflex	PF + ME	With FAST	RB + FEM + Dyn
Flexcom	PF + ME	With FAST	RB + FEM + Dyn

Comparison between the engineering tools will only highlight their differences but cannot determine the accuracy of the simulations. To validate the numerical results,[32] the simulations of the DeepCwind semisubmersible were compared to experimental results measured in a test campaign at Maritime Research Institute Netherlands (MARIN).[34] Some important findings from this study include the following:

- Ultimate and fatigue loads were underpredicted compared to the experiments in varying degrees by all the numerical codes.
- The largest underpredictions were found at the low-frequency responses in pitch and surge due to inaccuracies in the nonlinear difference-frequency loads; codes that used second order hydrodynamics achieved the closest result, but still underpredicted loads.
- Differences in aerodynamics were masked by the differences in hydrodynamic loads; without an uncertainty assessment the researchers found it difficult to accurately quantify the differences in the results between experimental and numerical simulations.
- Some nonlinear loads could have been caused by the cables for the load cells on the model, for example.

In a separate campaign, Robertson et al[35,36] attempted to quantify the experimental uncertainty in order to get a reliable assessment of the accuracy of the numerical codes. For these tests a model of the DeepCwind semisubmersible was used, but only hydrodynamics were considered because that was the significant source of load under-prediction. Random uncertainty, that is, the differences in conditions across repeated tests, was negligible compared to the systematic uncertainty, that is, unknown bias in the waves and physical properties of the scaled model. Of course, these results are facility-specific (MARIN); however, repeatability was found to be excellent. The differences between experiments and numerical models were found to be larger than the uncertainties in the experiments. The level of underprediction of loads (around 20%) falls within the uncertainty assumptions for the FOWT design process, but improved accuracy will enable further design optimization to lower cost. In the next phase of the OC6 project, Robertson et al[33] investigated why the engineering tools all underpredict the response of the DeepCwind semisubmersible at the natural surge and pitch frequencies due to nonlinear hydrodynamic loads. Engineering tools were found to be missing some of the important physics needed to accurately predict the nonlinear, low-frequency loads. In comparison, high-fidelity CFD tools should be able to accurately predict the surge and pitch loads with high accuracy. Current efforts in the OC6 project are underway to validate the CFD tools using the same dataset and improve the engineering tools based on CFD results.

2.2.3 | High-fidelity

High-fidelity software is used for detailed investigations of local flow phenomena and stress hot spots in the structure, for example, as well as for increased accuracy, especially for extreme conditions. Although, no high-fidelity method software programmes have been developed specifically for FOWTs, there are nonetheless a number of both open-source and commercial software packages available for general engineering purposes that can also be used for FOWT design. Some of the popular software packages are listed in Table 3.

2.2.4 | Frequency-domain versus time-domain

Irrespective of the software of in-house developed codes, the question of time- versus frequency-domain simulations often needs to be considered. Linear frequency-domain simulations would typically fall in the low-fidelity category, due to the simple approximations of the underlying physics used in such models, and are used in the initial design stages. For example, Hegseth and Bachynski[19] developed a frequency-domain modelling approach and applied it to two types of spar FOWTs. Here, the platform was rigid, and the tower was a slender flexible beam. For long-term fatigue response, and short-term extreme response, the difference in results varied up to 30% as compared to the nonlinear time-domain models. On the other hand, for long-term effects and global-load assessments, especially from mid- to high-fidelity models, one needs to run computationally intensive time-domain analyses. Extensive time-domain simulations, though computationally expensive, tend to provide the most detailed estimates of the responses due to the coupled nature between the aerodynamics, hydrodynamics, structural dynamics, and control actions. Typically, the numerical results in the form of dynamic motions and loads are compared against experimental measurements using an

TABLE 3 High-fidelity software which can be used for FOWT modelling

Software	Computational method
OpenFOAM	CFD
Star CCM+	CFD
Ansys	CFD + FEM
Autodesk	FEM
Abaqus	FEM + CFD

error metric.[37] Such metrics are valuable for comparison and repeatability of different experiments, as well as investigating the performances of various experimental models at different scales, TRLs and repeated experiments, or experiments in different wave basins.

2.3 | Structural dynamics

The progression from lower to higher fidelity of the structural model of a FOWT is based on the type, range, detail and complexity of the responses it can capture successfully. In its simplest form, a low-fidelity model captures rigid-body motions[38,39] overall, or of its constituent rigid-body elements, and can be relevant for examining global stability, but are not appropriate for representing deformation responses. They are, however, particularly helpful for concept level, rapid and early designs or assessments of such structures. One can also sometimes choose to model parts of the system rigidly and others with flexibility.

Mid-fidelity models are typically defined through elements (e.g., beams, cables and joints) with linear and nonlinear properties.[40,41] They have been used to examine aerodynamic stability,[42,43] and estimate dynamic response related to deformation[44] and physical characteristics.[9] These models are often described via a set of differential equations and lend themselves to non-dimensional forms, enabling validation via scaled model tests. Such models can also, with numerical implementation, include additional aspects like damage via reduction of stiffness from chemical/physical processes (e.g., corrosion)[45] and marine growth.[37] These mid-fidelity models are also relevant for establishing or assessing safety in terms of fatigue and ultimate limit states (ULS) through analyses set out by standardized documents, for example, IEC[46] and DNV.[47] Early in the design process, a static analysis is used to assess loads, an overview of which may be obtained from Baltrop[48] and Journee and Massie.[49] At later stages, time-domain simulations are required to properly assess fatigue and extreme loads across a variety of operational, extreme and fault/start-up conditions.

Another common approach in structural dynamics is to use a modal approach, where certain flexible degrees of freedom are represented by their modes and mode shapes. This approach can be used for modelling the blades and tower in FAST, for example. At the highest level, FEM[50–52] is commonly used to represent one or all aspects of the design, including the platform, tower, blades and mooring lines. Many times, a mixture of fidelities is used for different components of the system depending on the purpose of the analysis and the relative flexibility of the different components. FEM models are associated with a large number of degrees of freedom (DOF), and to increase computational efficiency, dimension reduction is often attempted.[53] For linear analyses or linear approximations of these structures, a modal superposition approach often provides a good response estimate of a structure with state space models.[8,54] However, the success of such modal superposition driven dynamic models is related to careful choice of system parameters, assumptions about the physics of the systems and loading excitation. Deviations in reality from such assumptions will thus quickly lead to significantly higher errors, since the response information is represented by only a number of finite, generalized modal coordinates.

Reduced DOFs are also possible for certain cases by computing rigid body kinematics of various structural components and then combining them with pre-computed elastic properties to obtain deformation estimates.[38] The BEM[8] is another method that is often used in this regard, often with low-order meshing,[55] which is suitable for understanding the interaction between fluids and rigid structures.[56] Recently, there has also been an emergence of using finite volume method (FVM)[57,58] for significantly deformable structures,[59] in a Simo–Reissner format.[52]

Nonlinear dynamic characteristics of mooring lines and power cables,[60] and additional impacts on them over the lifetime,[61] are relevant and are part of a particularly active field of research, including interconnections and additional components like buoyancy elements and effect of ballasting. While traditional QS models, computed in terms of equivalence of relevant parameters of interest in each time-step, are used to assess mooring dynamics for computational ease,[62–64] they tend to underpredict the restoring force and is more noticeable for extreme sea states. They are also less useful for platforms that use catenary moorings and have natural frequencies close to peak wave frequencies. Dynamic analyses do not have these challenges and despite a higher computational demand, are becoming a natural choice since they match experimental results better[65] Computational efficiency in such approaches, including those in frequency-domain[66] are also being investigated.

Overall, the evolution of structural modelling has been in terms of allowing for complexity and detail to capture the widest range of phenomena, physical responses and stochastic aspects for various spatial and temporal scales through a range of discretization processes. Over time, the strong focus on computational ease has diminished in terms of its importance with the current expansion of capabilities in computing and the ease with which large scale computing facilities can be engaged for such analyses.

2.4 | Hydrodynamics

Numerical modelling methods for hydrodynamic problems have been mainly developed for the maritime[49] and offshore oil and gas industries[48] but can equally be applied to floaters and platforms of FOWTs.[67] The Potential Flow method, the Morison Equation, or a combination of the two, are used for the computation of first- and second-order wave excitations. These mid-fidelity methods generally deliver the required accuracy at reasonable computational efficiency but can have problems with complex geometries where the disruption of flow between members is not adequately addressed.

The PF method[49] is used to solve diffraction/radiation loads. Limitations of PF include viscous effects being ignored, and the oscillation amplitudes are assumed to be small compared to the cross-sectional area of the floating body.[68] Numerical tools based on PF theory use BEM. This method divides the floating body into panels, and hydrodynamic loads are found by integrating the dynamic pressure over the wetted panels. The submerged geometry is defined as the hydrostatic equilibrium in still water for frequency-domain PF solvers. Most time-domain-only PF solvers need to import a set of hydrodynamic coefficients pre-processed with a frequency-domain PF solver to define the panels of the submerged geometry of the platform.

The Morison equation is generally used for structures consisting of slender cylindrical members. It models inertial loads, and unlike PF, viscous loads, and can therefore be used to simulate structures in waves and currents. It is an empirical equation, originally developed by Morison et al[69] for fixed, infinitely long cylindrical offshore structures, but can also be used for FOWTs. A limitation of the Morison equation is that it ignores the alteration of the incident wave field by the floating body.

A mixed modelling approach of combining PF methods with ME is used when either method on its own will be unable to capture certain hydrodynamic effects, and is regarded as a computationally efficient alternative for CFD modelling.[70] This hybrid method could be useful for FOWT platforms consisting of large columns and slender braces, or for viscous drag effects resulting from severe sea states.

Complex flow problems are solved with high-fidelity CFD[71] models. CFD solvers are based on the Navier–Stokes equation and are generally used to solve specific nonlinear problems such as slamming loads due to extreme wave events and complex flow patterns such as vortex shedding around heave plates. CFD models are also used to tune model parameters for lower fidelity models[72,73] numerically rather than with decay tests from physical experiments.

Making direct comparisons between CFD models and PF + ME models[73–75] is nontrivial. The accuracy of the models will depend on a number of factors such as the load cases being investigated; whether steady state equations or transient equations are used for the CFD model; whether the hydrodynamic coefficients used are tuned; mesh characteristics and the competence of the user; and ensuring a converged solution for the CFD model. There are many components to the PF + ME solution that are needed for an accurate solution in some cases. Most significant is the calculation of the second-order PF solution, rather than just first-order. Other key components are wave stretching, which means that the wave forces are calculated above the water free surface, and the correct viscous damping in the model, especially if second-order PF loads are included.

Other alternatives, besides the PF + ME methods, to CFD are being investigated, for example, Chan et al[76] and Office of Energy Efficiency & Renewable Energy WETO.[77]

2.5 | Aerodynamics

The most challenging aspect regarding aerodynamics for FOWTs is the variation in relative wind velocity due to motions of the platform, both for horizontal axis turbines,[78–81] and vertical axis turbines.[82] This effect is referred to as dynamic inflow, or unsteady dynamics, and may cause an overshoot of rotor thrust loading, also referred to as negative damping. The efficient, mid-fidelity, quasi-steady BEMT models[83] were found to be incapable of capturing dynamic inflow effectively.[84] BEMT combines momentum theory and blade element theory and divides the turbine blades into smaller elements or strips. The aerodynamic properties for each element are calculated individually and the properties for the entire rotor are solved by integrating the values of each element. The quasi-steady BEMT models assume instant equilibrium of turbine wake. Some studies, for example, Henriksen et al,[85] Chen and Agarwal[86] and Ferreira et al,[87] suggest that by adding a simple dynamic inflow model, BEMT models can effectively capture dynamic inflow effects, while maintaining computational efficiency.

Higher fidelity models using PF and CFD based methods[88–90] are able to capture the effects of dynamic inflow, however, at the expense of lower efficiency. The UNsteady Aerodynamics for Floating Wind (UNAFLOW) project[91,92] studied the ability of numerical tools to capture unsteady aerodynamics of FOWTs in detail. In the OC6 Phase III project,[93] the UNAFLOW dataset will be used for in-depth comparison of the modelling approaches for aerodynamics of large motion. Other alternatives to study dynamic inflow, for example using machine learning,[94] are also being investigated.

Recently, modelling tools have been incorporating a mid-fidelity approach for aerodynamic modelling, the FVW method.[95–97] With increasing turbine rotor sizes, there is a greater need to accurately capture aerodynamic effects due to large blade deflections. The FVW method satisfies this need with a level of fidelity and computational efficiency between that of BEMT and CFD methods. The FVW method is a more detailed modelling method of the wake, which affects the aerodynamic loading on the rotor, and uses Lagrangian discretization of vorticity. FVW is introduced to the latest version of OpenFAST[98] and other industry tools.

Mitigating the effects of dynamic inflow is an important task of the turbine controller in addition to optimizing power production. Several studies, for example, Lackner,[99] Yu et al,[100] Savenije and Peeringa,[101] Fontanella et al[102] and Jonkman,[103] on turbine control for FOWTs can be found in the literature.

Another important consideration is the evolution of turbine wake[104–106] and the effects that it may have on FOWT dynamics, on downwind turbines, and on FOWT farm layout.

As mentioned before, the choice of which type of numerical method to use across the design stages is largely a trade-off between the available monetary budget and time budget on the one hand and the level of uncertainty and accuracy of the numerical model that are acceptable on the other hand. Other considerations may be what sort of load cases are to be investigated, what type of FOWT is being modelled, and what phase one is in for the design cycle—preliminary/early stages or detailed investigations/final stage.

3 | PHYSICAL MODELLING

Comparing numerical results with experimental results obtained in laboratory basins for validation is still considered an essential step in the design process by most designers of FOWTs. As turbine sizes continue to grow, consequently, the platform sizes of FOWTs continue to get larger. To accommodate the increasing dimensions of prototypes at model scale, and reduce the uncertainty of physical modelling, testing techniques of FOWTs in laboratories are evolving. The state-of-the-art of physical modelling techniques is outlined in this section.

3.1 | Scaling laws

Geometrical, kinematic and dynamic similarity between model scale and full scale is required[107] for the experimental validation of numerical models.

For geometrical similarity this means that all linear dimensions must have the same scale ratio, which is defined as

$$\lambda = L_F / L_M. \tag{1}$$

The subscripts *F* and *M* indicate full scale and model scale, respectively. The ratio between inertia and gravity is defined as

$$U^2 / g\,L, \tag{2}$$

where *U* is velocity, *g* is gravitational acceleration and *L* is physical length. The dynamic similarity requirement between model scale and full scale then is defined as

$$U_M / (g\,L_M)^{1/2} = U_F / (g\,L_F)^{1/2}, \tag{3}$$

which is also known as the Froude number.

The ratio between inertia and viscosity is defined as

$$UL / v, \tag{4}$$

where *v* is the kinematic viscosity. The dynamic similarity requirement between model and full scale is defined as

$$U_M L_M / v = U_F L_F / v. \tag{5}$$

This is known as the Reynolds number.

As the kinematic viscosity of air will remain the same for prototype and scale model, it becomes apparent that for a Froude scaled rotor with geometric similitude, the Reynolds number will be lower at model scale compared to the Reynolds number of the full-scale rotor. Consequently, the lift coefficient of the model scale rotor will be lower, and the drag coefficient will be higher compared to the full-scale rotor. As a result, the aerodynamic performance of the model scale turbine will be affected, causing a misrepresentation of wind load induced motion response of the FOWT. The focus for scaled turbines, however, is on the ability to emulate Froude scaled rotor thrust and torque. The following sections explain how this is achieved.

3.2 | Full physical testing

From Equations (1) to (5), it becomes apparent that either increasing the velocity of the applied wind or adjusting the turbine rotor geometry at model scale could compensate for the lower Reynolds number. Rotor thrust is the most critical aerodynamic load to impact on motion response of FOWT models. The simplest, and lowest fidelity, method to emulate thrust force is with a mechanical pulley system.[108] This method can only model steady thrust loads but cannot capture aerodynamic damping or the effects of turbine control. A simple method to emulate rotor thrust load with physical wind is using a drag disc instead of a scaled rotor. In combination with a Froude scaled rotating mass, the rotor gyroscopic loads can also be emulated.[109] The drag disc method (Figure 2) allows for varied thrust loads but like the pulley system will not be able to capture aerodynamic damping or the effects of turbine control.[110]

Increased wind velocity applied to a Froude scaled rotor can overcome the abovementioned limitations of the drag disc and achieve correct rotor thrust. However, maintaining rated rotor speed at higher wind velocities means the tip speed ratio (TSR) cannot be maintained.[111] As a result, rotor torque cannot be modelled correctly, and aerodynamic damping may not be captured correctly. If on the other hand correct TSR is maintained, the Eigen frequencies of the rotor and blade-tower passing frequency (3P frequency) and rotor thrust forces cannot be modelled correctly. Geometrically modified aerofoils to compensate for the low Reynolds number in a Froude scaled wind environment, are better able to emulate aerodynamic loads, and capture damping effects and blade pitch control effects while maintaining TSR. This is generally referred to in the literature as performance scaling of the rotor.[112–114] Roughened leading edges on the rotor blades, and slight increases of applied wind velocity, in combination with geometrically altered rotor blades can be applied to fine-tune the model thrust forces.

3.2.1 | Froude scaled rotor combined with higher than Froude scale wind velocity

Skaare et al[115] tested a 1/67 scale model of the Hywind FOWT (Figure 3) at SINTEF, Norway, in 2005. Their model used a geometrically adjusted rotor with two DC motors along with physically generated wind to control rotational speed of the rotor and blade pitch angle. The experimental results of this campaign were used to validate the integration of the two independent simulation software tools SIMO/RIFLEX (floater) and HAWC2 (turbine) to a coupled simulation tool for FOWTs.

Mortensen et al[116] tested a 1/35 model of a Tension Leg Platform (TLP) with a Froude scaled version of the NREL 5-MW reference turbine[117] and increased wind velocity. The numerical model was validated with the experimental results, which showed that dynamic response of the TLP was predicted correctly.

Bahramiasl et al[118] tested a 1/100 scale model of a TLP FOWT with a Froude-scaled turbine and increased wind velocity at Sharif University, Iran. As the applied wind failed to turn the rotor, an electric motor with variable speed was used to drive the rotor and aid rotation. Increasing the rotational speed of the rotor showed some damping effects caused by the gyroscopic moment. Furthermore, a shift of the peak of the RAO spectra of the platform in heave, surge, pitch and yaw occurred.

Li et al[119] tested a 1/50 scale model of the DeepCwind semisubmersible FOWT with a Froude scaled version of the NREL 5-MW turbine at Shanghai Jiao Tong University, China. Rather than controlling the rotor speed with an electric motor, the rotor was allowed to run freely, and the motor acted as a generator. The mechanical damping by the generator served to slow down the rotor speed and bring TSR closer to the desired rate resulting in improved aerodynamic damping compared to forced rotor speed control with an electric motor.

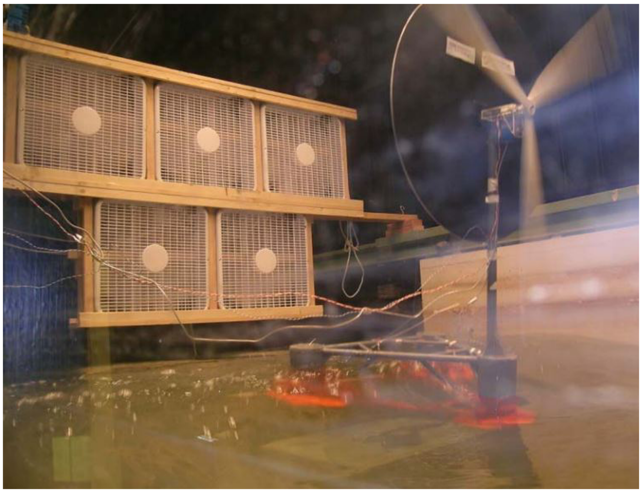

FIGURE 2 WindFloat model with drag disc and rotating mass[109]

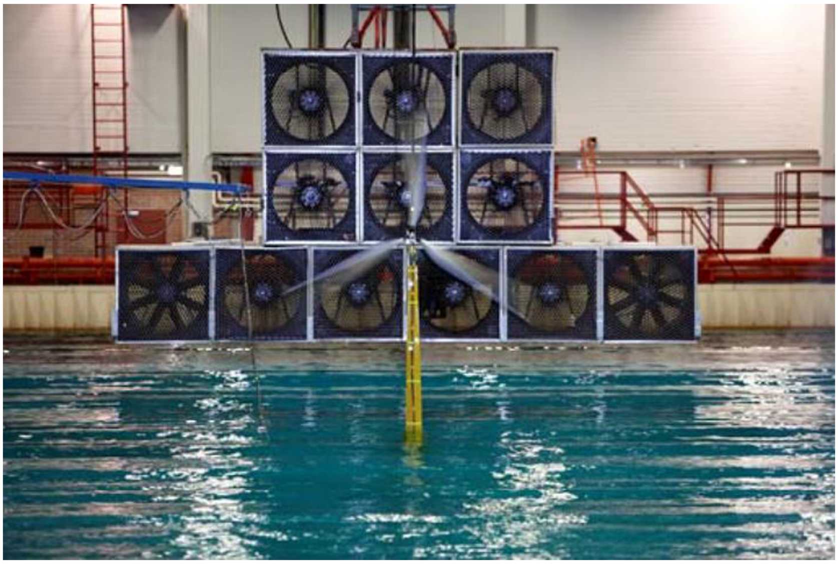

FIGURE 3 The Hywind model at SINTEF[115]

3.2.2 | Geometrically modified low-Reynolds aerofoils combined with Froude scale wind velocity (performance-scaled)

For the University of Maine led DeepCwind consortium, Goupee et al[3,120] tested 1/50 scaled models of a spar, semisubmersible and TLP platform at MARIN, the Netherlands, to compare the floater responses under similar conditions. Each platform was originally equipped with a geometrically scaled version of the NREL 5-MW reference turbine.

The DeepCwind team learned that geometrically scaling the rotor (based on a Froude-approach) was not the correct approach for scaled testing of FOWTs. The MARIN reference turbine was redesigned to create a performance-matched scaled model of the NREL 5-MW reference turbine. With this new turbine, the DeepCwind semisubmersible design was retested at MARIN in 2013, and this dataset was used for the validation study conducted in Phase II of the OC5 project.

The performance-matched MARIN reference turbine was also used by De Ridder et al[121] on the GustoMSC Tri-Floater model at MARIN. The results showed that the thrust coefficient of the model turbine was consistent with the thrust coefficient predicted by the CFD models, whereas the power coefficient found in the experiments is lower than the power coefficient predicted by the CFD models. To correctly model floater motions under combined wave/wind loads in laboratory basins, a correct thrust coefficient of the model turbine is essential, whereas the influence of the power coefficient is negligible.

Bredmose et al[122] tested a 1/60 scaled version of the DTU 10-MW reference turbine[123] with low-Reynolds aerofoils on the Triple Spar platform (Figure 4), a hybrid spar/semi-submersible platform designed for the INNWIND.EU project, at the Danish Hydraulic Institute (DHI), Denmark. The focus of this campaign was the effect of the blade pitch controller on the response of the platform. Experiments with wind-only loading revealed a clear instability at the natural platform pitch frequency due to aggressive blade pitch control above rated wind speed.

Madsen et al[124] also used the 1/60 scaled low-Reynolds version of the DTU 10-MW turbine on a model of the KIER TLP at DHI, Denmark. They also used three different kinds of controllers for blade pitch and found that use of the land-based controller resulted in high oscillations in blade pitch and increased surge response of the platform.

Koch et al[125] tested a 1/60 scale model of the DeepCwind semisubmersible FOWT with a low-Reynolds version of the DTU 10-MW turbine at Ecole Centrale de Nantes (ECN), France. To compensate for the higher mass of the turbine, ballast was added to lower the centre of gravity of the platform to the same level of the original design with the NREL 5-MW turbine. Free decay tests, wave only tests and wind only tests were performed, and all were found to be in good agreement with the numerical model.

Similarly, Ahn and Shin[126] adapted a 1/90 scale model of the DeepCwind semisubmersible for a low-Reynolds version of the DTU 10-MW turbine at the University of Ulsan, South Korea. Combined wave, wind and current conditions were modelled, where a steady current load was introduced by a mechanical pulley system. The introduction of current had a damping effect on the surge motion of the platform.

Ward et al[127] developed a model turbine with performance scaled aerofoils, a light-weight rotor nacelle assembly (RNA) and blade pitch control. Although the turbine has a fixed radius, the model turbine can be used for various turbine designs by adding weights to the RNA and varying the thrust load by pitching the blades. The concept was shown numerically to be viable. However, experimental results to validate their claims are not presented in the paper.

FIGURE 4 The Triple Spar model, left the visualization at scale and right the model in the basin at DHI[122]

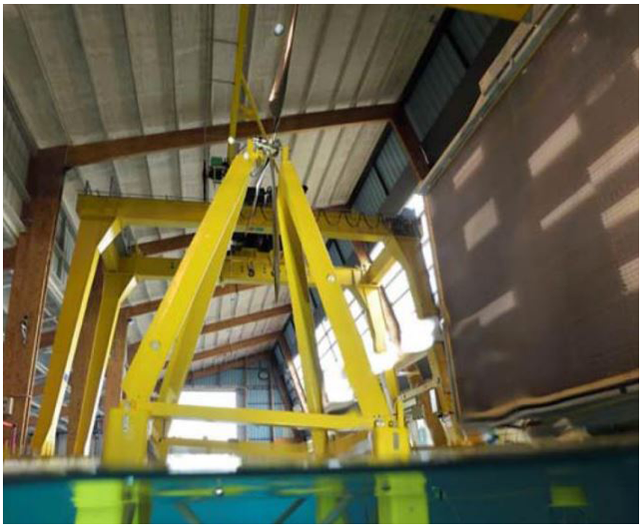

FIGURE 5 The Eolink model at ECN[70]

Connolly et al[70] tested a 1/50 scale model of the Eolink semisubmersible FOWT (Figure 5) with a low-Reynolds version of a 10-MW turbine at L'Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), France. The Eolink concept uses a pyramid construction to support the RNA with four pillars rather than the traditional single tower, and a single point mooring system for yaw alignment of the platform. Good agreement was found compared with the numerical results of Flexcom for most platform dynamics, however, the experiments showed that pitch response was overestimated by the numerical model.

Zhao et al[128] tested a 1/50 scale model of the WindStar TLP with a low Reynolds version of the NREL 5-MW turbine at Shanghai Jiao Tong University, China. An electro motor was installed on the turbine model to maintain TSR during tests with wind. They found that overall, the model showed relatively small motion responses and that wind and current had a damping effect on the surge and pitch response.

3.3 | Hybrid testing

Hybrid testing is the alternative to full physical testing of FOWT models. With this method, waves are still generated physically but the aerodynamic loads are replaced by a numerical substructure. The Froude/Reynolds mismatch is solved by calculating the aerodynamic loads at full scale and applying them to the physical model at Froude scale via one or several mechanical actuators. The two types of actuators most used in hybrid FOWT wave basin testing so far have been dynamic cable winches and propellers. The simplest, and lowest fidelity, hybrid method applies a steady load to the actuator to emulate steady thrust load. Aerodynamic damping and turbine control will not be captured by this method. Stochastic wind loads can be emulated by applying a time-series input which tells the actuator to vary the loads. This method will capture aerodynamic damping, however, synchronizing wave elevations and wind loads is challenging. Furthermore, turbine control effects are only emulated as the numerical simulation captures them; it is not possible to emulate turbine control effects that react to the actual motion of the platform with this method. Real-time hybrid testing is a more complex but higher fidelity method. With this method, physical modelling of the waves is combined with the numerical simulation of wind loads in real-time. The hydrodynamic module of the numerical code is replaced by the input of a motion tracking system, which records the spatial position of the platform for each time-step. According to the motion tracking data, the numerical code then calculates the aerodynamic loads acting on the turbine for the given wind velocity at full scale for each time-step. Finally, the aerodynamic loads are emulated by the actuator(s) at Froude scale and applied to the physical model and the process is repeated for the next time-step. This way, depending on the number of actuators, most aerodynamic effects can be captured (at least those that are captured by the numerical model), and waves and wind are perfectly synchronized. The diagram in Figure 6 shows a FOWT hybrid test setup for a wave basin developed at Centro Nacional de Energías Renovables (CENER), Spain, by Azcona et al.[129]

3.3.1 | Hybrid testing with propeller actuators

Azcona et al,[129] from CENER in Spain, were among the first researchers to use a propeller as an actuator for hybrid FOWT modelling. They have named their method Software-In-the-Loop (SIL). This method uses a single ducted propeller at hub height of the model. The diagram in Figure 7 indicates the hardware set-up of the SIL system.

The single propeller of the SIL system only emulates aerodynamic thrust, therefore the focus of their study was on platform pitch and surge response. Azcona et al used the SIL method to test a 1/40 scale model of the Concrete Star Wind Floater semi-submersible platform (Figure 8) at ECN, France. The turbine that was modelled during the experiments was a 6-MW turbine designed by Siemens. Azcona et al found that the

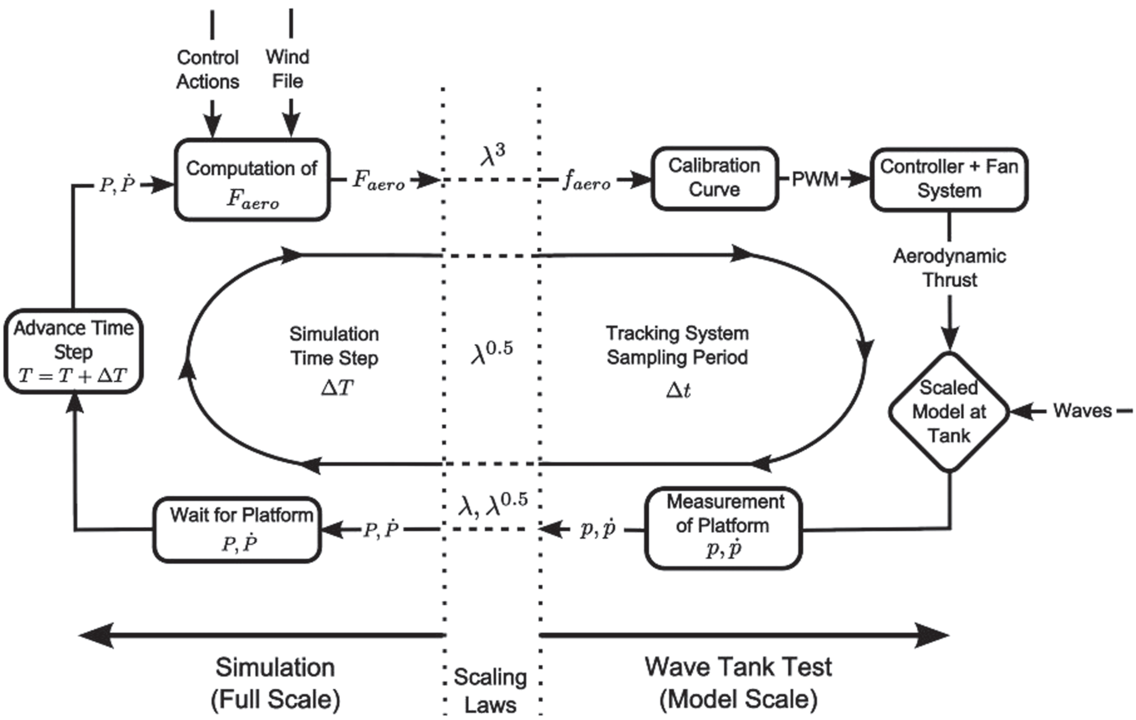

FIGURE 6 Diagram of the "software-in-the-loop" real-time hybrid test setup[129]

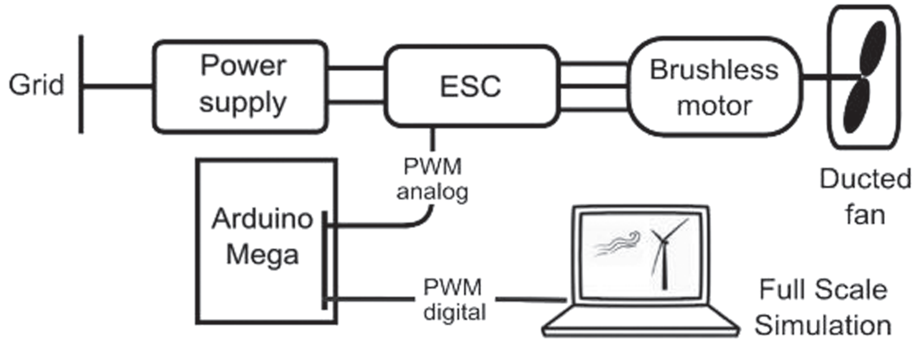

FIGURE 7 Hardware for the SIL setup[129]

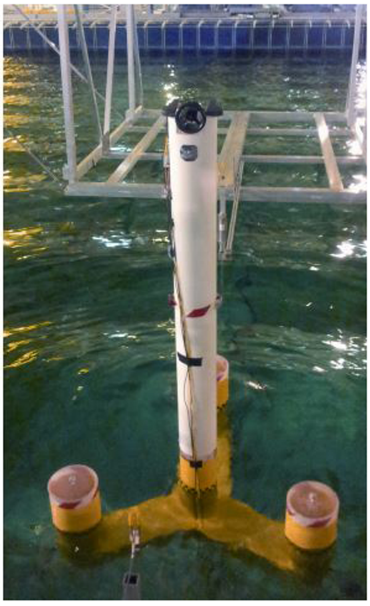

FIGURE 8 Full-scale CAD visualization (left) and model (right) of the OO-Star semisubmersible with ducted propeller[129]

platform surge and pitch response were closely matching the numerical models during static wind tests and free decay tests, demonstrating the ability of the SIL method to capture aerodynamic damping.

In a separate campaign, researchers from CENER applied the SIL method to a 1/45 scale model of the DeepCwind semisubmersible platform, also at ECN.[130,131] Second order hydrodynamics were included in the numerical models. Accuracy between experiments and numerical models had improved compared to the previous test campaign, when the second-order hydrodynamics were included in the numerical model. Best results were achieved for combined irregular wave and turbulent wind cases. In these cases, the aerodynamic excitations of the platform overshadow the second order hydrodynamic excitations for this type of platform.

Wright et al[132] fitted a ducted propeller on a 1/50 and a 1/30 scale model of a hexagonal braced TLP platform at IFREMER, France. Rather than using the SIL method, only steady thrust force was emulated. The aim of this study was to measure the difference in surge response in experiments with and without spring dampers in the mooring tendons. The results showed that the surge amplitude increased but mooring tension decreased with the spring dampers added to the mooring tendons.

Desmond et al[133] tested a 1/36 scale model of the SCDnezzy[2] (Figure 9), a semisubmersible FOWT design with two rotors and a single point mooring system, at Lir National Ocean Test Facility (NOTF), Ireland. Two ducted propellers were used to emulate steady wind loads and two stepper motors driving Froude scaled weights were used to emulate gyroscopic loads. Emulation of rotor thrust loads were found to have a significant impact on uncertainty, whereas the gyroscopic loads had limited impact.

Oguz et al[134] applied the SIL method to a 1/36 scale model of the Iberdrola TLP with the NREL 5-MW reference turbine at the University of Strathclyde, United Kingdom. The model was equipped with a single ducted propeller at hub height emulating aerodynamic thrust of the 5-MW turbine. The experiments showed that the platform response and tendon tensions were over predicted by the numerical models at the pitch- and surge natural periods.

Andersen[135] fitted a single propeller, using the hybrid method without real-time motion feedback, on a model of a generic semi-submersible model with three main floater columns and heave plates. The aerodynamic thrust loading was modelled using a turbulent wind time series of the DeepCwind semisubmersible FOWT, a comparable platform to the platform used in the experiments. This method is of lower fidelity and accuracy compared to the experiments by Azcona et al and Oguz et al using the SIL method.

A similar conclusion was found by Matoug et al.[136] Although the focus of their study was the comparison of the DTU 10-MW horizontal-axis wind turbine and the WindQuest 10-MW vertical-axis wind turbine on the same platform, they repeated their test cases, using the hybrid test method, with and without SIL. The experimental results with SIL matched the numerical results better than the test cases without SIL. A 1/42 scale model of the Nautilus semisubmersible FOWT was used for the experiments.

Using a single propeller with the hybrid method means the modelling of aerodynamic loads is limited to thrust load only, and although this is by far the most important excitation mode, other aerodynamic loads such as rotor torque, gyroscopic momentum and 3P tower loading are not captured.

Otter et al[137] developed a multipropeller actuator with six aerial drone propellers to emulate aerodynamic loads in multiple DOFs simultaneously (Figure 10). The device performs well for thrust and torque; however, it underperforms for aerodynamic pitch and yaw.

Meseguer and Guanche[138] developed a similar device, which also uses recreational drone technology, with six propellers. Their multipropeller actuator was used for an experimental test campaign of the TELWIND model FOWT[139] at Instituto Hidraulica Cantabria (IHC), Spain. Only constant wind loads were emulated during the tests.

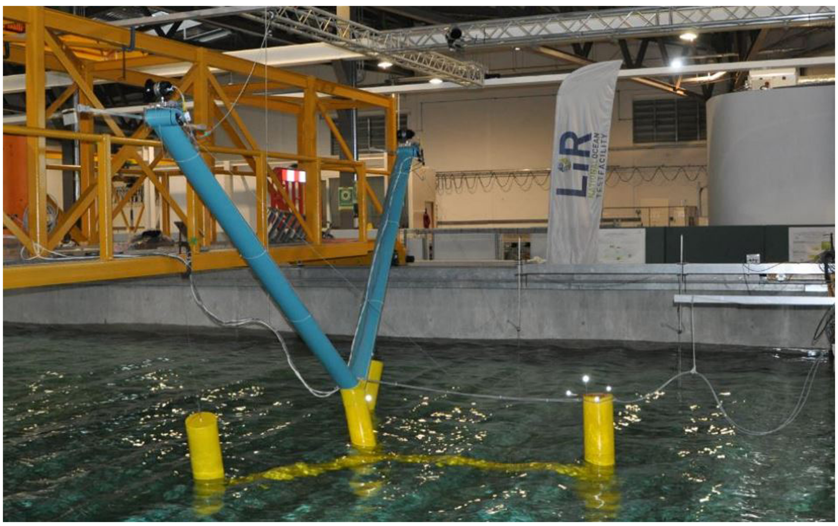

FIGURE 9 The SCDnezzy[2] model in the basin at Lir NOTF[133]

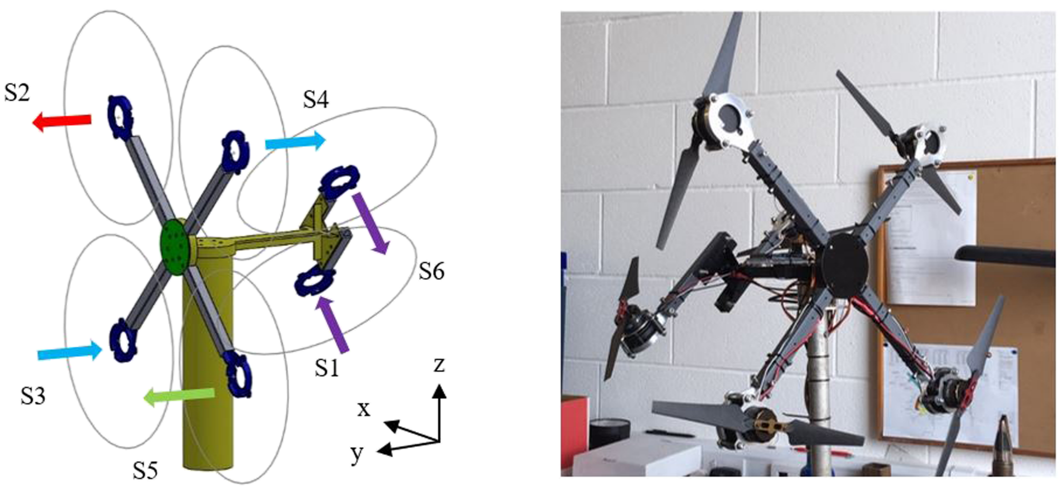

FIGURE 10 Multipropeller actuator, the arrows indicate the thrust direction of the propellers[137]

Recently, researchers from CENER have developed a multipropeller actuator with four propellers for multi-DOF emulation with SIL,[140] which was used on a 1/50 scale model of the DeepCwind semisubmersible FOWT for the Marine Renewable Infrastructure Network for Enhancing Technologies 2 (MaRINET2) project at MARIN.[102] The focus of their studies was on the testing of control strategies with the improved SIL for the NREL 5-MW turbine.

Kanner et al[141] applied hybrid testing to a semi-submersible model platform, based on the WindFloat platform, called MIST, at University of California Berkeley, United States of America. Rather than modelling a conventional horizontal-axis turbine, they modelled two vertical-axis turbines on the platform. The tangential force developed by aerofoils on vertical-axis turbines was emulated by two counter-rotating rods in the horizontal plane, each driven by a propeller at one end of the rod. The drive train of the actuators included a gearbox and generator, converting the mechanical power of the rods into actual electrical power. By controlling the generators during the tests, Kanner et al achieved limited yaw orientation of the platform to optimize power production of the turbines.

3.3.2 | Hybrid testing with dynamic cable winch actuators

Researchers from SINTEF, Norway, have performed a series of experiments[142–144] using real-time hybrid testing with a 1/30 scale braceless semi-submersible FOWT model[145] and the NREL 5-MW turbine. The researchers from SINTEF have named their method Real-Time Hybrid Model (ReaTHM) testing and use a square frame at hub height of the model connected with the winch cables. A comparison of the experimental results with numerical models is presented by Karimirad et al.[146] Figure 11 shows the model with the top frame. The arrows indicate the direction of actuation of each dynamic cable winch. An earlier quantification study[147] found the gyroscopic moments and heave response due to aerodynamic forces to be negligible for this type of platform. The SINTEF researchers therefore opted to emulate a limited number of aerodynamic loads. Waves and current, during the experiments were modelled physically. The numerical wind field was generated in TurbSim and the full-scale aerodynamic loads were calculated with AeroDyn.

Thys et al[148] used the ReaTHM test method at SINTEF to test a physical 1/36 scale model of the Nautilus semisubmersible platform with the DTU 10-MW turbine, as part of the LIFES50+ project.[149] An adjusted top frame and cable layout was used for this test campaign, and 3P frequency and first tower bending frequency were added in addition to the aerodynamic loads emulated on the 5-MW model platform.

Chabaud et al[150] compared the ReaTHM methods used for the test campaigns of the 5- and 10-MW model platforms at SINTEF and gave a theoretical overview of the allocation of tension for the actuation cables for the two methods. Where both methods provided similar results in

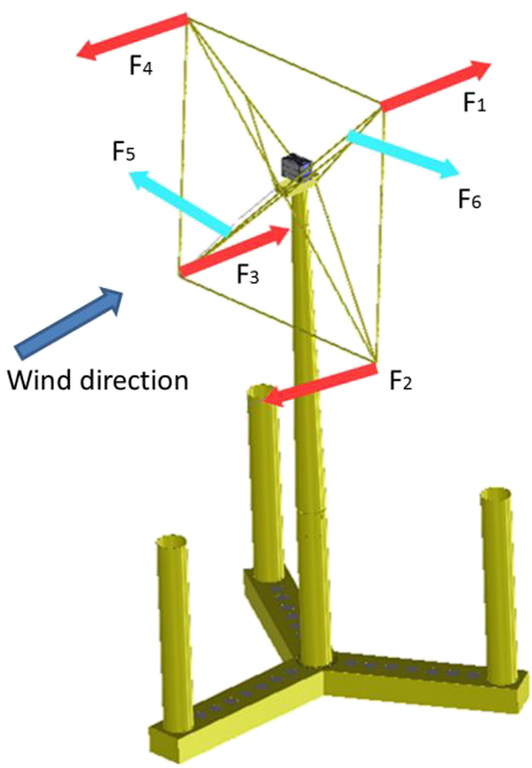

FIGURE 11 The semisubmersible model with top frame for the ReaTHM setup[142]

terms of accuracy, the method used for the 10-MW platform provided higher flexibility allowing for a higher number of aerodynamic loads to be included in the tests with the same number of cables and winches. However, the higher flexibility comes at the expense of higher cable tensions and a larger test area as the winches need to be spaced wider apart.

Hall and Goupee[151] used dynamic cable winches for hybrid testing of a 1/50 scale model of the DeepCwind semisubmersible platform, which was also equipped with a geometrically scaled rotor and low Reynolds adjusted blades. They validated the hybrid method by disconnecting the actuator cables and repeating the steady wind case with physical wind generated above the basin, at the University of Maine, United States America. In contrast to the SINTEF test campaigns, Hall and Goupee opted to simplify the test setup by only emulating the aerodynamic thrust in the hybrid tests using two rather than six cable winches. Using a windward and leeward winch cable connected at hub height allows for accurate control of aerodynamic thrust emulation. The results of the hybrid tests and full physical regular wind-wave tests matched closely, validating the hybrid approach. Hall and Goupee found that introducing wind turbulence in the hybrid experiments added a noticeable amount of excitation, accurately reproducing aerodynamic damping found with the numerical models, which was difficult to reproduce with the full physical wind-wave experiments.

Antonutti et al[152] used dynamic cable winches for hybrid testing with SIL of a 1/35 scale model of the Naval Energies semisubmersible FOWT with the Haliade 6-MW turbine at MARIN. Similar to the SINTEF campaigns, Antonutti et al used a cross-shaped metal frame with four front wires and one back wire. This enabled actuation in the surge, pitch and yaw DOFs. For operational and severe sea states, the experimental results were found to match the numerical results closely with combined wave and wind loads.

Some advantages and disadvantages of dynamic cable winches compared to propeller actuators are listed in Table 4.

3.3.3 | Hybrid testing in wind tunnels

Another approach to hybrid testing of FOWTs is to use SIL to numerically represent the hydrodynamics of the system, as opposed to the aerodynamics. This approach enables validation of aerodynamic forces in an environment with superior wind quality compared to wind generation over a wave basin, while allowing for examination of these aerodynamic forces under motion typical of a FOWT. This is particularly useful when studying the evolution of turbine wake of FOWTs, and how it may affect downwind turbines and farm layouts.

Schliffke et al[153] used a simple, 1/500 scale model of the FLOATGEN FOWT in a small wind tunnel at ECN, France to study unsteady aerodynamics and wake development. The model consisted of a porous disc at hub height mounted on a small rig to simulate regular surge motion of the platform. Results showed that the surge motions did not change mean velocities in the wake, however, turbulence intensity in the wake was modified.

Rockel et al[154,155] performed experiments with two performance scaled, 1/400 scale wind turbine models of a typical horizontal-axis wind turbine with 80-m rotor diameter in the wind tunnel at Portland State University, United States of America. In the first study the wake of a bottom-fixed model was compared with the wake of a FOWT model that was allowed to oscillate freely in the pitch DOF by mounting the model in a gimbal. In the second study both turbine models were used in tandem in the wind tunnel.

Bayati et al[156–158] used a Hardware-in-the-Loop (HIL) setup with a performance scaled, 1/75 scale model of the DTU 10-MW turbine on a 2-DOF rig to simulate surge and pitch motions of the OC5 semisubmersible FOWT in the wind tunnel of Politecnico di Milano, Italy. Platform kinematics were calculated and applied in real-time. The HIL setup uses load cells, dynamometers, accelerometers, linear variable displacement transducers, and a laser displacement sensor for a position feedback signal to update the numerical simulation of the platform motions for each time-step. The motion feedback combined with increased DOFs allows for a higher fidelity test setup compared to the abovementioned studies by Schliffke et al and Rockel et al.

In follow-up studies, Bayati et al[159–161] used a physical 1/75 scale, performance-scaled model of the DTU 10-MW turbine on a custom-designed 6-DOF robot, named Hexafloat, in the wind tunnel of Politecnico di Milano, Italy, rather than the 2-DOF rig. The platform hydrodynamics emulated by the 6-DOF Hexafloat were based on an ad-hoc model FOWT initially, and on the OO Star semisubmersible FOWT and the Triple

TABLE 4 Advantages and disadvantages of propeller vs. winches

	Advantage	Disadvantage
Propellers	• Effective simulation of thrust loads • Integrated on the model, small footprint on the test area • Simple control	• Difficult to effectively simulate aerodynamic moments • Source of high-frequency vibrations and, therefore, systematic uncertainty
Cable winches	• Effective simulation of thrust and aerodynamic moments • Low vibration levels, less systematic uncertainty	• Winches are land-based, large footprint on test area • Control of winches is complex compared to propellers

Spar FOWT for later tests. The applied wind velocity in the wind tunnel was increased by a factor of 3 to match the Reynolds number at full scale as closely as possible. The higher DOFs and addition of turbine control equipment allowed Bayati et al to also investigate turbine control routines. The results of the experiments with both the 2-DOF rig and Hexafloat showed close agreement with the wake measurements and platform dynamics found with numerical models.

Thys et al[162] performed scale model hybrid tests for the OO-Star and Nautilus FOWTs with the DTU 10-MW turbine in the wave basin at SINTEF and in the wind tunnel at Politecnico di Milano, Italy, for a comparative study. Wind tunnel experiments of the 1/75 scale model of the DTU 10-MW turbine in combination with the Hexafloat were first performed to validate the aerodynamic model. Next, the validated aerodynamic model was used with a 1/36 scale model of the platform and dynamic winch actuators to emulate wind loads in the wave basin for calibration of the platform and hydrodynamic model.

Arnal et al[163] used a 6-DOF Hexapod with a propeller actuator, rather than the wind tunnel, to simulate the NREL 5-MW turbine with the DeepCwind semisubmersible platform and the Hywind spar platform, and the DTU 10-MW turbine with the Triple Spar platform at ECN, France. They found that, at a scale of 1/30, high frequency aerodynamic loads could be emulated accurately with their system.

3.4 | Comparison of test methods: full physical versus hybrid, in laboratory wave basins

Generating physical wind in laboratory basins requires large wind generation installations and large amounts of energy to run said installations, making them expensive to operate. Furthermore, high-quality wind generation and accurate simulation of wind gradients and turbulence in the wind field are difficult to achieve other than in wind tunnels. A typical setup for an above-basin wind generation system consists of a bank of fans arrayed in several rows and columns, pumping the air through ducts with screens, honeycomb mesh, and nozzles over the basin. The screens and honeycomb mesh reduce the turbulence of the outflowing air, and the nozzle directs the flow to an area that can cover the rotor. Stochastic wind can be simulated by varying the revolutions per minute of the fans during tests, and vertical shear can be simulated by controlling each row of fans separately.[110] Accurately measuring and mapping the wind field is important to determine the best location for the model relative to the nozzle. This procedure is described for the MARIN wind setup in de Ridder et al[121] and for DHI in Madsen et al.[124] They showed that it is difficult to control the boundaries of the wind field and circulation of the airflow once it exits the nozzle. Inconsistencies in the screens and fan motors etc. can be mapped and accounted for during analysis of test results. However, the inability to control the airflow over the basin, unlike in wind tunnels, will decrease the ability of accurate repeatability of the tests, adding uncertainty in the test method.

An advantage of performance-scaled turbines on FOWT models in combination with applied wind generated above the basin is the ability to maintain the correct thrust coefficient and TSR in a Froude-scaled wind environment. This method also captures the effects of rotor gyroscopic moments, rotor torque and aerodynamic damping, and it is possible to implement turbine control. Another advantage is that it is likely that unexpected aerodynamic phenomena and hydrodynamic response, which are not captured with the numerical model, will be captured during the physical experiments. However, the low-Reynolds modifications make it difficult to also model the power coefficient and torque characteristics of the turbine accurately, limiting the scalability of blade pitch control and the ability to capture aerodynamic damping accurately.[149,151] Other disadvantages are the high costs of developing a modified model turbine, and the requirement of a bespoke scaled model turbine for each different design and scale.[110]

Hybrid testing in wave basins has the benefit that it does not require physical wind and current generation in testing facilities that do not have such capabilities. Furthermore, hybrid testing allows for the implementation of wind turbulence, turbine control strategy and aerodynamic damping, and any turbine type can be simulated regardless of the scale, making it far more versatile and cheaper compared to full physical testing (Figure 12).

However, a hybrid test setup is a complex system; fidelity of the test method and accuracy of test results can be influenced by a number of factors such as the force actuation and motion tracking.

The accuracy of wind emulation will depend on the type and number of actuators. However, the mechanical actuators are easier to control than physically generated wind.[151] Careful calibration of the actuators and quantification of actuator inaccuracies provides high experimental repeatability, as was found by Meseguer and Guanche[138] and Bachynski et al.[143]

With hybrid FOWT testing, the hydrodynamic module of the aero-hydro-servo-elastic tool used for the numerical substructure is de-coupled, and instead the motion response data of the physical model received from the motion tracking system is used as the hydrodynamic input to calculate the next simulation step, as described in Section 3.3. The motion tracking system will therefore require high accuracy of position measurements. Furthermore, it will require a high sampling rate and must be able to operate in a wet environment.

A certain amount of system latency during hybrid testing is unavoidable. Each step in the hybrid testing loop - simulation, actuation, motion tracking and feedback - causes a system delay. An appropriate simulation time-step at scale for hybrid modelling must be determined. Within this time-step the actuator must have sufficient bandwidth to deliver the required load at the right frequency, and the motion tracking sampling rate must be high enough to feed the position data back to the numerical code to calculate the required actuator load for the next time-step. To keep the latency at acceptable levels within each time-step, the actuator will have to emulate the required loads faster than the numerical simulation takes to calculate the loads for each time-step. It becomes apparent then that the computing system will require high processing power.

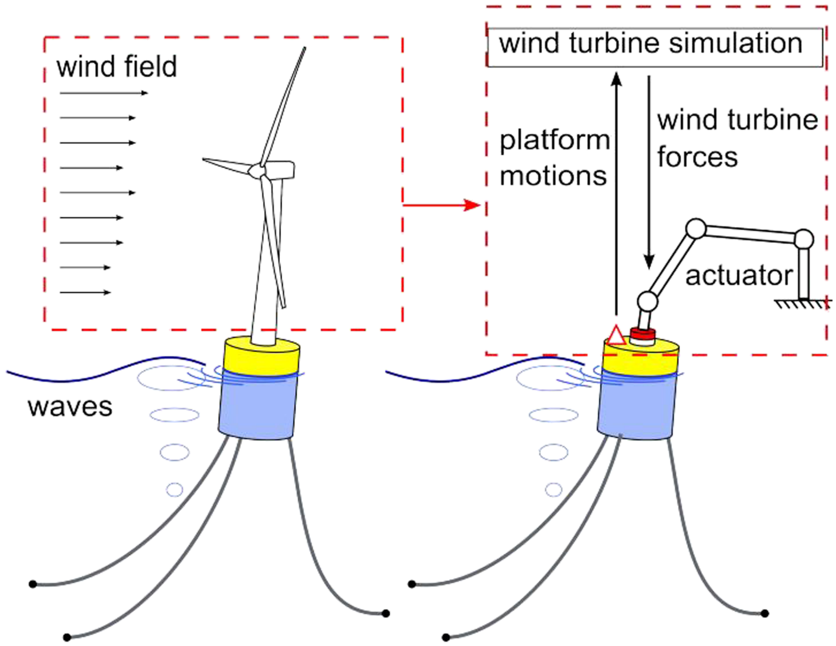

FIGURE 12 Full physical testing (left) vs. hybrid testing (right)[164]

In the design of the experiments, the appropriate time-step, number of actuators etc. used for hybrid modelling will depend on the modes of interest to be investigated. Sensitivity studies, for example, Hall et al[164,165] and Bachynski et al,[147] will give an indication of the required actuation forces and number of actuators, tolerance levels of inaccuracy and latency. A higher number of actuators will increase the fidelity of the hybrid test method, as the three-dimensional wind field can be represented more accurately. However, a higher number of actuators will result in a more complex system and a higher level of uncertainty.

Another disadvantage of hybrid testing compared to full physical testing is that aerodynamic phenomena which are not captured by the numerical model, will not be simulated during the experiments. As a result, the potential hydrodynamic response of the platform to said phenomena may not be captured either. One example is dynamic inflow; this effect cannot be captured effectively by quasi-steady BEMT tools, but the more computationally intensive PF and CFD solvers are capable of capturing this effect. This has implications for hybrid testing of FOWTs. It means that unsteady dynamics might not be captured during hybrid testing when the computationally efficient quasi-steady BEMT tools are used to compute the aerodynamic loads for each time-step. Consequently, the resulting platform motion response and blade pitch control effects from dynamic inflow effects may not be captured either. As mentioned in Section 2.5, BEMT models can be corrected by adding simple dynamic inflow models. However, such improved BEMT tools have not been applied during hybrid tests to date. Furthermore, the actuators used in hybrid test experiments need sufficient bandwidth to replicate any control strategy designed to counter the effects of dynamic inflow. Of course, the same is true for control equipment used during full physical experiments.

A comparative study was performed by Gueydon et al[166] with a 1/50 scale model of a TLP FOWT and the NREL 5-MW turbine at MARIN. Combined wind, wave and current tests were first performed with the full physical method and then repeated with a real-time hybrid method using dynamic cable winches and SIL. Both methods showed comparable results up to 0.55 rad/s. Above this frequency the dynamic cable winches used in these tests were not able to deliver demanded thrust without a significant delay and Gueydon et al found it problematic to accurately assess the tendon tensions. They concluded that for FOWTs that respond to high frequency, such as TLPs, the use of winches for hybrid testing may not be adequate.

Both the performance scaled full physical method and the multiactuator hybrid method can be considered high-fidelity test methods. The level of fidelity is likely somewhat higher for the full physical method, however, as aerodynamic loads which are not captured by the numerical model are still likely to be captured during testing, unlike during hybrid testing. The choice of test method will therefore be a trade-off between budget and fidelity/uncertainty. The advantages and disadvantages of full physical testing and hybrid testing are summarized in Table 5.

4 | DISCUSSION

The state-of-the-art of numerical and experimental modelling approaches available for the design of FOWTs cover every aspect of aero/hydro/servo/elastic modelling. However, there are still inconsistencies in accuracy between the different numerical codes, as shown in the OC5 project

TABLE 5 Advantages and disadvantages of the full physical methods and hybrid methods

	Advantage	Disadvantage
Full physical modelling	• Models aerodynamic thrust, torque and gyroscopic moment • Captures aerodynamic damping • Turbine control can be implemented	• Requires expensive and bulky wind generation equipment • Difficult to generate high quality laminar steady wind • Difficult to generate stochastic wind with good repeatability • Requires unique turbine model for each turbine design and scale • Rotor often requires the aid of an electric motor to reach correct TSR
Hybrid modelling	• Depending on number of actuators it is possible to emulate thrust, torque and gyroscopic moment with good repeatability • Captures aerodynamic damping • Turbine control can be implemented • Stochastic wind loads can be implemented without great difficulty • Versatile, can be used for any type of turbine or scale • Requires less space and considerably cheaper than wind generation system	• System latency • Multiple actuators required to emulate all aerodynamic loads, adds complexity and uncertainty • Phenomena not simulated with the numerical model will not be captured during testing

and studies by Roberston et al.[31,32] Additionally, a level of uncertainty in experimental methods is unavoidable.[35,36,137,161] The applicability of an approach will be case dependent. The configuration of the FOWT design and the goal of the analysis will dictate fidelity and type of modelling approach that is warranted. The design process for a FOWT is a multistep process. Eventually, a detailed loads analysis is needed at the component (member) level. However, typically, the global analysis is used with simpler models, and then, a detailed analysis focuses on a few load cases and perhaps a few points in the structure.

In the continuing drive for reduction of levelized cost of energy (LCOE) of FOWT technology, platform designers may seek to replace some of the physical test stages in the design-to-prototype process with high-fidelity numerical modelling. The authors would caution against such an approach. Numerical modelling tools show some limitations in accurately modelling the physics of floating wind designs for some conditions and configurations (as discussed in the IEA Wind Task 30 – OC projects[32,33]), and there is also a lack of sufficient measurements to validate their capabilities in realistic ocean conditions. The limited deployment of full-scale FOWTs to date has resulted in only a few publicly available data sets, for example, Cermelli et al,[167] ORE Catapult,[168] of dynamic response and fatigue life. The continued upscaling of turbine sizes is another factor in the drive for LCOE reduction. However, turbines of that size, and the impact of environmental loads on their components,[169] have not been tried and tested yet. High-fidelity tools, such as CFD tools, have greater accuracy but are cumbersome tools and still require validation. Therefore, the authors believe that the traditional approach, of combining numerical modelling with scale model testing, is still the preferred approach for FOWT engineering.

As Gueydon et al[6] highlighted, improved accuracy of numerical tools and concise quantification of uncertainty for experimental tools can be achieved if "hydrodynamic testing facilities engage with more critical comparisons of results obtained from all available FOWT testing techniques," and validation of both numerical and experimental tools would also benefit from the inclusion of test data from full-scale prototypes in real ocean-conditions. However, it should be considered that while full-scale turbines continue to get larger, the full physical test method will become increasingly impractical. As rotor diameters continue to grow, either the flow field of wind generators over wave basins will have to get larger too, or researchers will have to work with ever-smaller scales, which will exacerbate the scaling difficulties and increase the significance of sensor uncertainty. The authors are of the opinion that hybrid testing will become the preferred experimental method for FOWT modelling as bulky and expensive wind generation equipment is not needed, nor is it necessary to construct a physical model of the turbine rotor for each new test campaign in wave basins. Instead, the actuator emulates the wind loads, which (a) it can do cheaper and (b) it can do for any turbine at a wide range of scales, making hybrid testing more versatile and more practical than the full physical method. The same could be said for hybrid tests in wind tunnels. Although the turbine is a physical model in this case, hydrodynamic loads are emulated by the actuator and any type of platform at any scale can easily be simulated.

To improve the fidelity and accuracy, identifying the limitations and quantifying the uncertainty of hybrid systems will therefore be essential. Comparative studies such as Hall and Goupee[151] and Gueydon et al,[166] for a wide variety of platform types and load emulation systems are strongly recommended. Testing the same platform with the full physical method and the hybrid method, at a scale that is practical for the test facility involved, will help to identify the limitations of both systems.

Unsteady aerodynamics can be pronounced for FOWTs due to platform motions and large blade deflections, particularly with large rotor diameters. Sensitivity studies could reveal whether the effects of unsteady aerodynamics are noticeable and determine whether the effects should be emulated during hybrid testing. For example, Lupton et al[170] found that the effect of blade deflections on platform response is limited. This might suggest that blade deflections could be ignored during hybrid testing if platform dynamics are the quantity of interest. However, if for example structural dynamics of the tower are a quantity of interest, the effect of blade deflections should be included in the hybrid tests. The question then is whether the real-time simulation software used during hybrid testing can capture this effect, and whether the actuator is able to emulate it. The majority of the experimental campaigns mentioned in Sections 3.3.1, 3.3.2 and 3.3.3 used FAST as the real-time simulation software during hybrid testing, FAST is a CPU-efficient tool, that is, simulation time is fast enough to keep latency at an acceptable level for each time-step, and therefore a suitable real-time engineering tool for hybrid testing. AeroDyn, FAST's aerodynamic module, uses a combination of BEMT and GDW to model dynamic inflow. However, with the introduction of the FVW based module, named cOnvecting LAgrangian Filaments (OLAF), to OpenFAST, the effects of unsteady aerodynamics may be captured more accurately during hybrid testing. Furthermore, it may improve computational efficiency of the real-time numerical simulation during hybrid testing. However, this has not yet been tested in practice. Tentative steps, for example, Chen et al,[171] are being taken to replace the real-time simulation tool with an Artificial Neural Network (ANN) to predict wind loads. The use of ANN has the potential to improve computational efficiency during hybrid testing.

Furthermore, the majority of FOWT test campaigns focus on combined wave and wind loads. Although several studies found in the literature mention the addition of a current during testing there is little mention of the resulting effects of current. However, some numerical studies, for example, Chen and Basu,[172] suggest there is significant impact of current on mooring tensions and fatigue loads. Therefore, further experimental investigation of the effects of current on the dynamic response and fatigue life of FOWTs is recommended.

Finally, the structural dynamics of FOWTs are generally investigated numerically and several examples can be found in the literature where the tower elasticity is modelled physically. However, the elasticity of the platform is generally not considered for physical experiments. Scaling effects will mean the physical modelling of platform elasticity is challenging and, in most cases, modelling the platform as a rigid body will give acceptable results for FOWT dynamics. However, as turbine sizes continue to get larger, platform sizes will follow a similar trend. As a result, platform structural dynamics could become more influential and should not be ignored during experimental modelling.

The research trends and gaps observed through this review are summarized here.

- As turbine sizes continue to grow, full physical testing of FOWTs at scale will become impractical. Comparative studies between full physical testing and hybrid testing, for the same platform under the same load conditions, are limited, for example, Hall and Goupee[151] and Gueydon et al.[166] More comparative studies for different kinds of platforms and different types of actuators are desirable to identify the limitations of both methods.
- Studies of unsteady aerodynamics for FOWTs have increased in recent years, both numerically, for example, Lee and Lee,[81] and experimentally, for example, Belloli et al.[161] However, mention of computationally efficient real-time simulation tools to capture this effect during hybrid testing in wave basins is lacking in the literature.
- The effect of current on platform dynamics, mooring tensions and fatigue life found experimentally is also lacking in the literature. Numerical studies suggest the effects could be significant, therefore further experimental investigation is desirable.
- As turbine sizes, and consequently, platform sizes continue to grow, structural dynamics of the platform could become more influential on overall FOWT dynamics. However, results of platform structural dynamics during scale model FOWT experiments are also lacking in the literature.
- The use of both numerical and experimental tools is generally good practice for the validation of any design, but in the case of FOWT modelling is essential. The confidence in numerical models only is not yet at an acceptable level due to the inaccuracy of the engineering tools and the limited availability of FOWT prototype data in real ocean conditions with which numerical models could be validated.
- There is, however, an ongoing drive to improve fidelity and computational efficiency, particularly of engineering tools, for example, Lemmer et al.[38]

After all this information the reader might ask, "So, what is the best modelling technique or tool to design a FOWT?"

The best choice will generally be case-specific, and the likelihood is that several techniques and tools will be used over the course of the design process. However, recommendations are provided here, which can serve as a guideline for the choice of modelling technique and tool. The first consideration will be the available budget of the designer or researcher; in general, the higher the fidelity of the method, the larger budget requirements will be. This is valid for both numerical and experimental methods. Another major consideration is the stage of the design process. For numerical modelling, the standard practice is as follows:

- Low-fidelity tools are used at the early design stages and for sizing purposes. Typically, linear frequency-domain models with high computational efficiency and fast simulation times are used. A few examples are mentioned in Section 2.2.1.
- Mid-fidelity tools, referred to as 'engineering tools', are used at the more advanced stages for global dynamics analysis of the FOWT design under operational and extreme conditions. Typically, these tools use nonlinear time-domain models. Accuracy of these tools will generally be higher compared to the low-fidelity models, yet efficiency is lower. Some popular choices of engineering tools are summarized in Table 2.

- High-fidelity tools are used at the final stages of the design and for detailed investigations. These tools use complex nonlinear time-domain models, and their accuracy is considered higher than that of the low- and mid-fidelity tools. However, computational efficiency is low for these tools. Some popular examples are mentioned in Table 3.

For scale model testing, the consideration will be between choosing either full physical testing or hybrid testing. The recommendations are determined by answering the following set of questions:

1. Does the test facility have equipment to generate the required environmental loads?

- Yes: Full physical is the preferred method
- No, or partially: Hybrid is the preferred method

2. Can the investigated phenomena be captured numerically?

- Yes: Hybrid is the preferred method
- No: Full physical is the preferred method

3. Is the scale of the model practical to handle for the test facility?

- Yes: Both methods can be used
- No: Hybrid is the preferred method

Next, if the choice falls on the hybrid method there are some more distinctions to be considered:

4. Are aerodynamics or hydrodynamics the focus of the investigation?

- Aerodynamics: Hybrid testing in wind tunnels is the preferred method
- Hydrodynamics: Hybrid testing in wave basins is the preferred method

5. For wave basin testing, what type of actuator is most suitable?

- Thrust loading only: A simple, on-board propeller actuator is most suitable
- Thrust + aerodynamic moments: Dynamic winch actuators are most suitable

5 | CONCLUSION

This paper gives an overview of the modelling methods for FOWTs. The first part reviews numerical modelling methods and software. The choice of computational method and software will generally be a trade-off between accuracy and computational efficiency. A computational method is considered efficient if it is able to complete a simulation within a timeframe that is acceptable for the user's purpose using standard computing equipment. Low-fidelity and computationally efficient methods, such as linear frequency-domain solvers, are used at the initial design stages of FOWTs for sizing purposes. Mid-fidelity methods are used for global dynamics analysis of FOWTs. Long time-domain simulations of FOWT dynamics are performed with engineering tools, coupled hydro-aero-servo-elastic solvers using computationally efficient methods such as PF and BEMT. Code-to-code comparisons and uncertainty assessments have shown that, despite representing the state-of-the-art, accuracy of the majority of numerical engineering tools needs improving. In particular for the prediction by engineering tools of low-frequency hydrodynamic loads and motion response to hydrodynamic loads in the surge and pitch DOFs of FOWTs. High-fidelity methods are used at the final design stages and for detailed analysis. Specific load cases, such as slamming events due to non-linear waves, are best modelled with high-fidelity methods such as CFD. The main disadvantage of high-fidelity software is their low computational efficiency. High- fidelity software is also used for the tuning of hydrodynamic coefficients used with mid-fidelity engineering tools.

The second part gives an overview of physical test methods, which are used to validate and calibrate the numerical models. Physical test methods can be classified in two categories: full physical testing and hybrid testing. A review is given of experimental campaigns for both methods, and the advantages and disadvantages of both experimental methods are outlined. The choice of experimental method is a consideration between test facility, budget, and uncertainty associated with the respective test methods. The full physical method with performance scaled turbines can model all aspects and phenomena of the FOWT, such as aerodynamic damping, for example. It also has the potential to identify unexpected aerodynamic phenomena which are not captured by the numerical model, but may have an effect on overall dynamics of the FOWT. For example, dynamic inflow is not effectively captured by quasi-steady BEMT. However, the full physical method is expensive and requires a dedicated physical model for each turbine design. The hybrid test method is cheaper and more versatile than the full physical method. It does not require bulky wind generation equipment and any type of turbine at a range of scales can be simulated with the same actuator when used in wave basins. With hybrid tests in wind tunnels, it is the hydrodynamic loading which is emulated and any type of platform at any scale can be simulated without the need for a dedicated scale model platform.

The final part identifies trends and gaps in current FOWT related research, such as a desire for more comparative studies between the full physical and hybrid test methods, and the improvement of the accuracy of numerical engineering tools. Recommendations on which modelling method or tool to use, both numerically and experimentally, are provided in the discussion in Section 4.

Several factors, such as the accuracy of numerical tools, limited availability of prototype data in real ocean conditions, and the continued upscaling of turbine sizes, contribute to the fact that the traditional modelling approach of numerical modelling validated by physical scale model testing remains essential for FOWT designs.

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Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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