



Review

Real-time hybrid model tests of floating offshore wind turbines: Status, challenges, and future trends

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ABSTRACT

Offshore wind energy is being supported by more national policies. The complexity of the marine environment makes it more difficult to study the coupling performance of offshore wind turbines. Physical model testing is a research method, but there are still challenges such as scale conflicts and the reproduction of turbulent winds. At present, the issue of uncoordinated scaling laws cannot be solved well by increasing the wind speed, changing the blade chord length, or adjusting the airfoil. Recently developed real-time hybrid model (RTHM) test combining the merits of both numerical model and physical test is one of the most promising approaches to solve these problems. This paper systematically reviews the early history, current situations, and development trends of floating wind energy technology and model test methods. The research progresses of real-time calculations of numerical substructure, real-time loading of physical substructure, real-time signal acquisition and transmission are introduced. Finally, four future research trends are summarized, which can provide a reference for relevant numerical simulations, physical modeling, communication mechanisms, and error processing in future RTHM tests.

1. Introduction

1.1. Background

The development and utilization of offshore wind energy mainly rely on wind turbines, which are mainly made up of blades, nacelle, hub, tower, and foundation. The water depth varies from a few meters to thousands of meters, and the foundation types will change with different water depth. Due to the limitation of nearshore spaces, and the superiority of deep-sea wind power, the development of offshore wind energy has continuously moved from nearshore to deep-sea, which has led to a change from bottom-fixed foundations to floating ones (Ren et al., 2023). A mooring system is used to provide station keeping (Fig. 1).

The intensification of the global greenhouse effect has led to policy support from different countries for offshore wind energy, a new type of clean energy (Esteban et al., 2011; Grant et al., 2023; Yu et al., 2022;

Wang et al., 2023; Ma et al., 2022). Floating offshore wind turbines (FOWTs) are mainly used in deep-water areas, e.g., at a water depth of more than 100 m. The concept of FOWT was first proposed by Heronemus. (1927). FOWTs have gradually become the focus of researchers. The development history relating to most of the demonstration projects is shown in Fig. 2 and Table 1. Many prototype test projects of FOWTs have been and are being tested in the Norway site, such as SeaTwirl (2023), Siemens Gamesa (2023), TetraSpar Demonstrator (Thomsen et al., 2021), Unitech Zephyros, etc. (Vestheim, 2022). These projects provide support for the commercialization of floating wind turbines.

The global installed capacity of offshore wind energy is increasing year by year. In terms of cumulative installed capacity at this stage, the UK has the world's largest offshore wind energy market, accounting for 42 % of the world's total capacity, followed by China and Germany. However, China has been accelerating the development of offshore wind

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energy industry in recent years. In 2021, the new installed capacity of offshore wind in China reached 15.52 GW, representing 73.5 % of the world's new installed capacity. In the near future, countries around the world are also actively promoting the construction of FOWTs (Table 2).

The development trend of FOWTs is towards deep sea and large-scale (Perveen et al., 2014; Zhang et al., 2022a; Zhao et al., 2019; Zeng et al., 2023). The complex marine environment has led researchers to use different methods to study the structural performance of FOWTs (Peng et al., 2021; Zhang et al., 2022b; Feng et al. 2017; Ferčák et al., 2022; Ma and Liu, 2022; Qin et al., 2023). Numerical simulation software can be used to calculate the complex environmental loads on FOWTs. Generally, the blade element momentum method is used by engineering tools to calculate the aerodynamic loads on the blades. The hydrodynamic loads due to waves and currents are calculated using potential flow theory and the Morrison equation. With the improvement of calculation capacity and breakthroughs in key issues such as numerical integration algorithms and control, the reliability of numerical simulation results is gradually increasing. The theory used in numerical calculations usually simplifies the actual sea conditions, so it is necessary to use physical model experiments to simulate the coupling characteristics of offshore wind turbine structures. Adjust the parameters in the numerical model based on the experimental results to make it more accurate. However, in model tests in a wave tank, Froude's scaling law is usually used to maintain the ratio of gravity to inertial forces. The wind turbine blade airfoil with Froude scale will be in a completely different Reynolds number region from the prototype, which will inevitably make the aerodynamics unable to match the target (Canet et al., 2018; Robertson et al., 2013). One solution to solve the incompatibility between Froude's laws and Reynolds' number is to modify the blade design and develop a low Reynolds number airfoil design by adjusting the chord length and torsion angle of the blades to achieve thrust similarity (De Ridder et al., 2014b; Du et al., 2016). Although this method can reduce the Froude-Reynolds conflict, deformation in blade will lead to some defects, such as the mismatch of aerodynamic torque etc.

The concept of RTHM testing is shown in Fig. 3. By using actuators and measuring instruments to transmit data between numerical simulation and physical model results, the problem of scaling incompatibility can be solved (Chen et al., 2022).

The whole system of the RTHM test is divided into several actual physical models and numerical simulation substructures. Some parts that cannot be reproduced or simulated in the physical model tests due

to the contradiction between the scales of upper and lower structures can be replaced by numerical substructures. The real-time results are obtained from the numerical simulation, which are converted into electrical signals and sent to the controller via the communication program. The controller converts the electrical signal into command signals and sends them to the actuator and then applies the simulation results to the physical model. Physical model produces response or reaction under the action of loading device or moving platform. Sensors are installed on the physical model to obtain the required response or reaction and the monitored data is returned to the numerical substructure for iterative calculations in the next time step to form a closed loop. The RTHM test method can effectively solve the mismatch between the upper wind turbine scale and the lower foundation scale encountered in the physical model test of FOWTs. Therefore, the RTHM test is an inevitable development trend for the physical model test of FOWTs and its results can also provide references for numerical calculations and model tests, which are of great significance for practical engineering designs and applications.

1.2. Scope, novelty and target readers of the review paper

This paper presents an intensive review on the application of the RTHM test method in FOWT. The rapid development and commercialization of offshore wind turbines has placed higher demands on traditional physical test methods. Therefore, real-time hybrid test methods in fields such as civil have been introduced into offshore wind turbines. Due to different test places, there are two different RTHM test methods for FOWT: RTHM test in the wave tank and RTHM test in the wind tunnel test. The former focuses on the study of hydrodynamics, while the latter focuses on aerodynamics. But there are three main technical challenges in both: the real-time computing capability of numerical substructures, the loading and control of physical substructures, and the signal acquisition and data transmission in the test system. RTHM test can solve the problems of traditional test methods such as uncoordinated scaling laws, space constraints, and excessive costs, but there are also systematic errors, time delays, etc., which must be solved. This paper also analyzes the development and future trend of RTHM testing of FOWT and gives relevant suggestions.

This work will be of special interest to researchers working on structural design and safety of FOWT, blades, platforms, and physical model testing methods. The document will also serve as a benchmark for

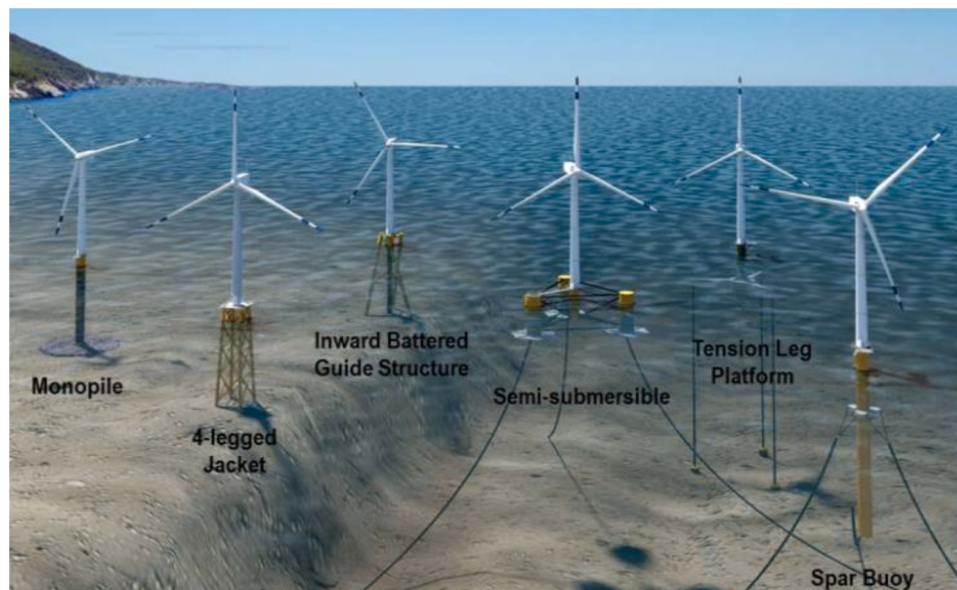


Fig. 1. Types of offshore wind turbines; Illustration by Josh Bauer, NREL; reprinted with permission (Smith et al., 2015).

industry practitioners to provide reference for numerical substructure real-time calculation, physical substructure loading control, signal acquisition, and data transmission, which will help them to carry out high-fidelity model tests.

2. History of model tests for FOWTs

Due to lack of prototype data, to study the system coupling mechanism of FOWT, it is necessary to correctly simulate aerodynamic, hydrodynamic and structural dynamics in physical model tests. To the mature reproduction of hydrodynamic load in wave basin, it is necessary to consider how to simulate the aerodynamic loads under the Froude's scaling law. The model tests are listed in Table 3.

Hywind project used geometrically matched-blades to conduct the physical model test of FOWT for the first time. The whole test scheme focused on the motion characteristics of FOWT under different sea conditions. Through the test results, the numerical simulation program integrated by Simo/RIFLEX and HAWC2 was verified (SINTEF Ocean, 2017; Torben et al., 2019). However, the aerodynamic equivalence lacks detailed descriptions.

Principle Power, Inc. used thrust disk instead of blades to simulate the equivalent aerodynamic thrust, and installed it on the WindFloat semisubmersible floating platform. A physical model test was carried out in the towing tank to study the motion/dynamic response (Roddier et al., 2010). The results of experiment reproduced the motion responses of FOWT (Roddier et al., 2009; Cermelli et al., 2009; Aubault et al., 2009).

Three different model tests were carried out for FOWTs by the University of Maine in MARIN tank: Hywind Spar, Pela Star, and DeepCwind Semisubmersible Platform (Martin et al. 2011; Goupee et al., 2014). The test technical details and some test data were disclosed in detail, which greatly promoted the development of model test technology for FOWTs

To reproduce the equivalent aerodynamic thrust, the GICON project redesigned the model-size blade using a low Reynolds number airfoil and installed it on the designed tension leg platform to carry out experiment in the wave tank (Adam et al., 2014; Grobmann et al., 2014). The dynamic motions of the FOWT were investigated under wind-wave conditions. Huigs et al. (2014) carried out physical mode tests on a Tri-floater in MARIN and added active blade pitch control. The average thrust level under dynamic wind conditions was improved and was close to that of a realistic situation (De Ridder et al. 2014a). However, the performance of the scaled controller was not perfect enough to fully meet the requirements of the full-scale system. On this basis, a physical mode test was performed in the wave basin in the EOLINK (Yu et al., 2017) project, where different gain-scheduling approaches were applied in the servo control to research the effect of aerodynamic load on FOWTs

Table 1

Division of different stages of FOWTs.

Theoretical research Phase 1970–1999	Design of concept Phase 2000–2008	Proof of concept Phase 2009–2016	Pre-commercial Phase 2017–2023	Utility-scale floating arrays 2024 and beyond
Combination of simulation and test Scientific funded	Design ranging from 10–100 kW Scientific funded	Prototypes ranging from 2–7 MW Research funded	Multi-turbine commercial machines 12–50 MW- financed with subsidies 14 projects totaling 229 MW	400 MW+ Capacity Competitive with Market conditions

coupling system.

Currently, there are three major problems of the physical model test for FOWTs: (1) The model-scale blades can only reproduce the aerodynamic thrust and neglect other relatively complex aerodynamic loads (e.g., aerodynamic torque). (2) Due to the space limitation of wave basins, large-scale model test cannot be carried out, resulting in insufficient consideration of system coupling characteristics (e.g., hydroelasticity). (3) The open spaces lead to relatively poor quality of the wind field, which cannot well simulate the turbulent wind, and the test method of active pitch control is difficult to realize.

To better reproduce the complex environmental loads on FOWT under real operating conditions in physical model tests, researchers have turned their attentions to RTHM tests.

3. History of RTHM test

The RTHM test in the field of marine engineering started late. The review of test systems in current section mainly refers to the existing advanced experience in automobile, civil engineering, and other industries. In civil engineering, the seismic model test of high-rise buildings, the loading path problem of the quasi-static method, the scale effect problem of the simulated shaking table test method, and the hardware-in-the-loop idea of electrical and mechanical components were introduced into the model test for the first time. The main development status is listed in Table 4.

In the 1970s, to solve the abovementioned test problems, Japanese researchers first proposed the hybrid test method. In this method, part of the structural system was excited by an actuator to obtain the restoring force in the structural dynamic equation, and the other part was simulated by a computer to obtain the inertial force and damping force of the structural system. The combination of physical tests and numerical calculations was used to carry out structural seismic tests, which solved

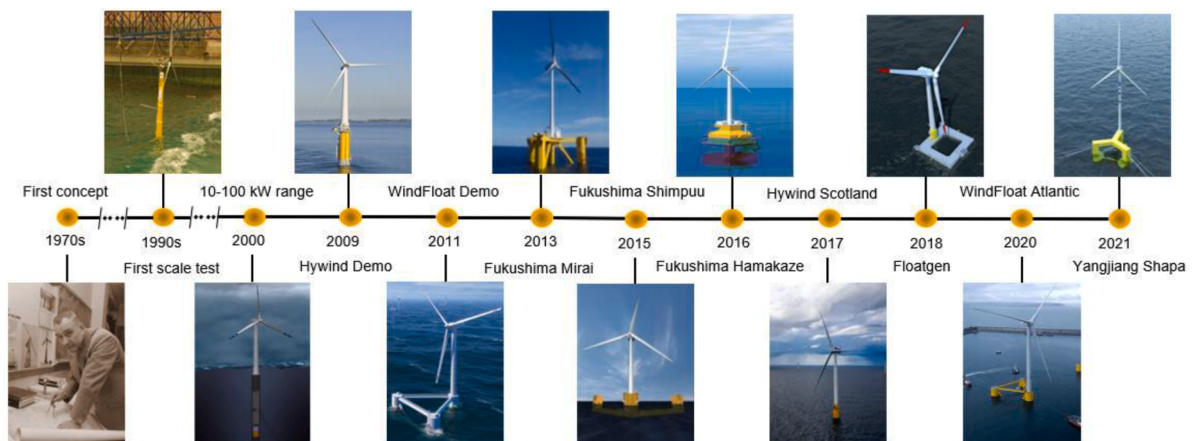
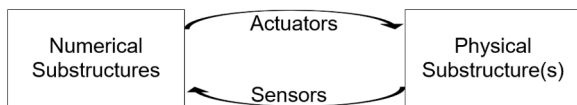


Fig. 2. Development of FOWTs.

Table 2

List of upcoming floating wind projects.

First Power	Country	Project	Total Capacity	Turbine Rating	Project Developer	Technology Developer	Concept	Turbine Supplier
2021/2022	France	Leseoliennes Flottantes de Groix and Belle-Ile	28.5 MW	9.5 MW	Shell/Eolfi,China Guangdong Nuclear	Naval Energies	Sea Reed	MHI-Vestas
2021/2022	France	Eoliennes Flottantes du Grofe du Lion	30 MW	10 MW	Engie,EDPR,Caisse des Depot	Principle Power	Wind Float	MHI-Vestas
2021/2022	France	EolMed Gruissan Pilot Farm	30 MW	10 MW	Quadran	IDEOL	Damping Pool	MHI-Vestas
2021/2022	France	Provence Grand Large	25.2 MW	8.4 MW	EDFEN	SBM Offshore	TLP	Siemens-Gamesa
2021/2022	Japan	Goto City	16.8 MW	2–5 MW	Toda Corporation	Toda Corporation	Hybrid Spar	TBC
2021/2022	Norway	Hywind Tampen	88 MW	8MW	Equinor	Equinor	Hywind	Siemens-Gamesa
2022	Ireland	AFLOWT	6 MW	6MW	EMES, SEAI, SAIPEM	SAIPEM	Hexafloat	TBC
2020	USA	Aqua Ventus	12 MW	12MW	University of Maine	University of Maine	VolturnUS	TBC

**Fig. 3.** Conceptual diagram of the RTHM test.

the contradiction problem of scaling in large-scale structural tests.

At that time, the hybrid test was loaded in a quasi-static way, and the loading rate was approximately 1 % of the actual rate. With the development of seismic and structural control technology, some rate sensitive elements (viscous dampers, rubber isolators, etc.) were widely used, which raised higher requirements for the loading capacity in the hybrid test method. To solve this problem, some scholars have improved the hybrid tests method by developing fast hybrid tests and continuous hybrid tests to reduce the waiting time of the loading device in the time step and improve the loading rate. However, due to the mechanical level defect of the loading device itself, real-time loading has not been achieved, and the resolution of related problems remains a challenge (Nakashima et al., 2018; Di et al. 2018; Di et al. 2019).

Nakashima et al. (1992) carried out a RTHM for the first time. Taking the damper at the bottom of a multistory building as the test object, the viscous damper was set as the physical substructure and the building was set as the numerical substructure, which was simulated as a linear single-degree-of-freedom (DOF) system, thus reduced the requirements for the loading capacity of the actuator. In this way, the loading device can be loaded in real time according to the actual load rate at the interface, and the seismic response test can be carried out. In the test, the speed-related structural characteristics were tested, which improved the accuracy of the test results. Since then, experts and scholars all over the

world have begun to carry out extensive and in-depth research on real-time hybrid tests, which are mainly divided into three aspects: solutions and calculations of numerical substructures, time-delay compensation of test systems, and accurate control of loading devices.

In terms of the numerical substructure solutions, real-time data exchange between the numerical substructure and physical substructure at the interface leads to requirements for the calculation time of each time step of the digital substructure. According to the traditional numerical integration algorithm of structural dynamics, the numerical

Table 4

Main development status of real-time hybrid test in civil engineering.

Researcher	Institution	Method	Contributions
Nakashima et al. (1992)	University of Kyoto	Linear single degree of freedom system	First published results of real-time hybrid test
Horiguchi et al. (1999)	Hitachi,Ltd	Energy balance method	First pointed out, time delay is equivalent to negative damping
Darby et al. (2002)	University of Bath	Study on coupling effect between multiple actuators	First published results of real-time hybrid test under multi-point input conditions
Wallace et al. (2005)	University of Bristol	Study on stability of delay differential equations by numerical methods	Using numerical method to calculate critical time delay for complex systems
Chen and Ricles (2009)	Lehigh University	Time delay compensation algorithm based on tracking error	Complete large-scale real-time hybrid test of multiple actuators

Table 3

Representative physical mode test projects.

Institution	Year	Project	Floater Type	Wind Turbine	Scale	Aerodynamic Equivalence
SINTEF Ocean	2006	Hywind (Nielsen et al., 2006)	Spar	2 MW	1:47	Geometry-matched Blades
UC Berkley	2009	Windfloat (Roddier et al., 2009)	Semi	5 MW	1:67	Thrust Disk
MARIN	2011/2013	DeepCwind (Martin et al. 2011; Goupee et al., 2014)	Spar, Semi, TLP	5 MW	1:50	Geometry-matched Blades/Performance-Matched Blades
MARIN	2014	GICON (Adam et al., 2014)	TLP	5 MW	1:37	Performance-matched Blades
MARIN	2014	Tri-floater (Huijs et al., 2014)	Semi	5 MW	1:50	Performance-matched Blades
SJTU	2016	SJTU-S (Duan et al., 2016)	Spar	5 MW	1:50	Geometry-matched Blades
IFREMER	2017	EOLINK (Yu et al., 2017)	Semi	12 MW	1:50	Performance-matched Blades
DTU	2020	KIER (Madsen et al., 2020)	TLP	10 MW	1:60	Performance-matched Blades
DUT	2020	TWWC (Ren et al., 2020)	TLP	5 MW	1:50	Performance-matched Blades
SJTU	2021	SPIC (Cao et al., 2021)	Semi	10 MW	1:64	Performance-matched Blades
SJTU	2021	SJTU-S4 (Jiang et al., 2021)	Spar	5 MW	1:50	Performance-matched Blades

substructure solution algorithm can be divided into explicit algorithms and implicit algorithms. Among them, the explicit algorithm is a conditionally stable algorithm that does not need to solve simultaneous equation, with a high solution speed and low difficulty in development. Therefore, it has been widely used in RTHM tests. Subsequent experts and scholars have also made efforts in the explicit algorithm, developed and applied the Newmark explicit integration algorithm (Wei et al., 2021; Chatzis et al., 2018), improved the Newmark explicit integration algorithm (Chang et al. 2010), and developed other new explicit integration algorithms (Huang et al., 2022). The implicit algorithm has good numerical stability, but it cannot be directly applied to the solutions of numerical substructure with two reasons. On the one hand, its iterative calculations take too long at each time step; on the other hand, the displacement mutation in the iterative calculations may affect the test accuracy and even damage the physical substructure. Generally, operator separation and other technologies were used to avoid the iterative calculations of the original algorithm and transform it into an explicit-implicit combination algorithm (Bayer et al., 2005; Jung et al., 2007). Another method is to divide the calculated time step into fixed steps and the iterations are carried out through the feedback of displacement response and the restoring force at each time step, therefore the implicit algorithm is suitable for real-time hybrid testing. Subsequent experts and scholars have also made significant contributions to the revisions of implicit algorithms and the development of new implicit algorithms (Bursi et al., 2010; Bursi et al., 2011; Wu et al., 2013; Abbiati et al., 2018).

In a RTHM test, the actuator will inevitably produce response delays after being commanded by the numerical substructure. These delays can be regarded as adding a certain amount of negative damping to the test system which leads to the loss in the precision of the test system. To eliminate this error, Horiguchi et al. (1999) first proposed a solution to the key problem of the hybrid model test delay. They predicted the simulation results of the next time step with Lagrange polynomial extrapolation and sent these results to the actuator as a command to drive the physical substructure model instead of using the results of the previous time step. The measured values are returned to the numerical substructure for iterative calculations. This process compensates for the delay of the loading device itself. Third-order polynomial extrapolation can provide a large stability range. Other experts and scholars have studied and improved the prediction compensation method and the prediction compensation function (Chen and Ricles, 2010; Lee et al., 2007; Wallace et al., 2005), but these methods are more suitable for the linear problem of stiffness. When the physical specimen enters the nonlinear stage, higher requirements are put forward for the accuracy of time-delay compensation. Darby et al. (2002) carried out in-depth research on this problem and found that the response time delay of the loading device is not a constant but has a strong relationship with the structural stiffness and excitation frequency. A compensation algorithm for adaptive estimation of time delay was proposed, and it effectively solves the compensation accuracy problem after the stiffness of the specimen enters the nonlinear stage.

In terms of loading device control, as long as the synchronization error of the loading device is zero, accurate control of the RTHM test can be achieved. However, the loading equipment used in civil engineering is generally hydraulic actuators or shaking tables (Tian et al., 2020), and there must be a certain lag in implementing the loading command signal. From the perspective of control engineering, an outer loop controller can be added to the loading device control loop to achieve zero synchronization error, which is a new idea for loading device dynamic behavior compensation. Wagg et al. (2001) introduced the adaptive minimum control synthesis (MCS) algorithm into a RTHM test and verified the feasibility of the algorithm through testing. Bonnet et al. (2007) proposed a multi-task MCS control algorithm suitable for multiple-DOF and multi-loading devices in a RTHM test.

The RTHM test has been gradually expanded to ocean engineering because it can solve the limitation of laboratory space (Chabaud et al.,

2013). For example, the physical model test cannot be carried out with full-scale mooring systems for deep water oil and gas platforms due to the big length of anchor chains in mooring systems. This problem can be solved by a RTHM test (Cao and Tahchiev, 2013). The advantages of RTHM test are significant, which have attracted the attention and research interests of some experts and scholars in the field of FOWT. The comparison and discussion are detailed in the following chapters.

4. State-of-the-art RTHM tests for FOWTs

4.1. Overview

In the model test for FOWTs, the gravity similarity dominates in the lower platform and the viscous similarity dominates in the upper wind turbine structure, resulting in an uncoordinated scaling contradiction. The RTHM test solves this problem well. Therefore, there are two ways to divide the substructure. One is the loading device and numerical substructures to reproduce aerodynamic related components and keep the tower, platform, and mooring as physical substructures. The whole test is carried out in a wave tank and called the RTHM test in the tank. The other is the loading device and numerical substructures to reproduce hydrodynamic related components and keep the tower and wind turbine as physical substructures. The whole test is carried out in a wind tunnel and called the wind tunnel RTHM test. The two test methods (Fig. 4) are described in detail as below.

4.2. RTHM test in the wave tank

The RTHM test in the wave tank calculates the aerodynamic load by developing a numerical substructure, and sends the load command to the actuator through a data transmission system. Therefore, it is possible to reproduce aerodynamic loads under different operating conditions on physical substructures. The motion generated by the physical substructure is measured and fed back to the numerical substructure through sensors. The feedback motions will participate in the calculation of aerodynamic load, thereby achieving the overall coupling effect of the structure. The whole RTHM test process is carried out in the wave tank. The advantage of this method is that it replicates the turbulent wind load in the experiment through numerical substructures and loading devices, which solves the complex scaling contradiction problem of the wind turbine blade. The test tactics are shown in Fig. 5. Table 5 summarizes relevant experimental projects, and different actuators are compared.

The current RTHM test system in the wave tank can be divided into three categories according to different loading methods: (1) cable-driven parallel manipulators (CDPMs); (2) fan; (3) actuator.

In the first method, the physical substructure is loaded by the parallel manipulator driven by tensioning cables, which can reproduce the multi-directional air load.

This method was used by Chabaud et al. (2018). The upper wind turbine was replaced by a numerical substructure. Through the wind field provided by TurbSim, the wind load was simulated and calculated by AeroDyn software. Six actuators with pulleys were connected to the square frame installed in the nacelle with thin wires. The aerodynamic loads of different degrees of freedom were calculated through numerical substructure, and then the thin was pulled line to reproduce the required aerodynamic load for the experiment (See Fig. 6). The experiment revealed technical details and simulation strategies, which have a driving effect on the implementation of hybrid test for FOWTs. The method was extended to the study of DeepCwind turbines (Hall et al., 2018; Luan et al., 2017; Jonkman et al. 2005; Hall et al., 2018). By setting up the forward and aft winch unit on stand, the cables are pulled to reproduce the X-direction thrusts at the hub, as shown in Fig. 7. There were some errors of platform surge motion, which may be that the steel cable restricts the movement of the platform. This method was introduced into the research of the mooring system (Vilsen et al., 2019; Vilsen et al., 2018; Vilsen et al., 2017). Taking the cylindrical buoy as

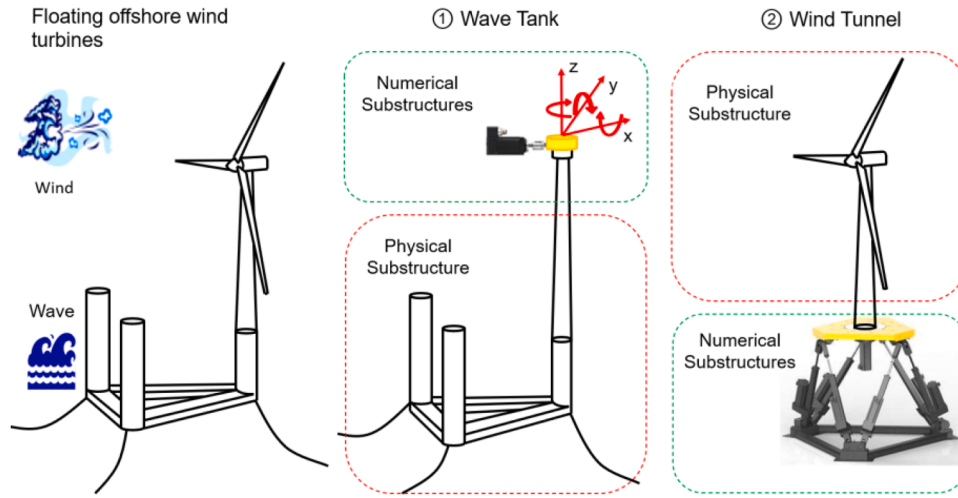


Fig. 4. Two hybrid model test methods.

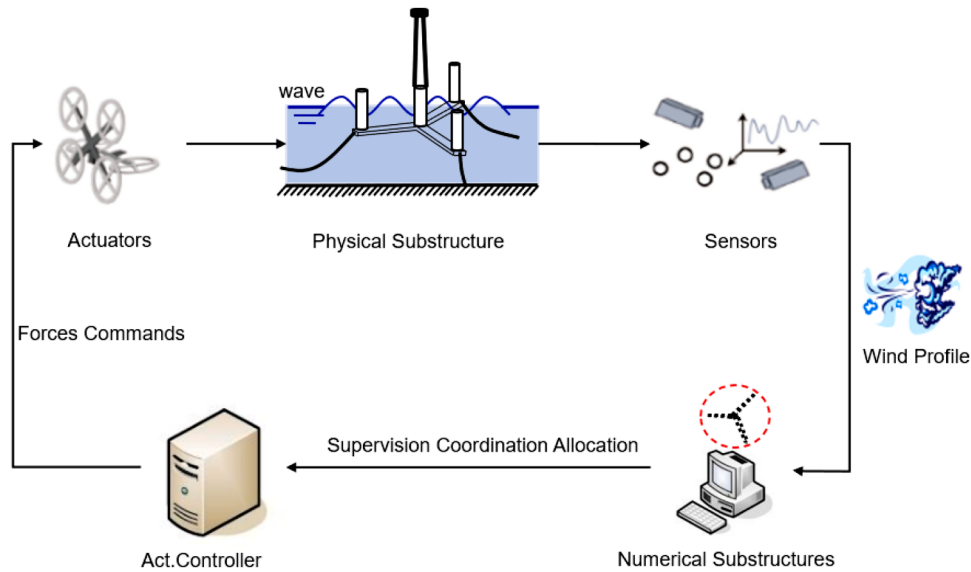


Fig. 5. Flowchart of RTHM tests in wave tanks.

Table 5
Comparison of actuators.

Actuation	Fx	Fy	Fz	Mx	My	Mz	Floater Type	Scale	Strengths	Limitations
Multi-DOF CDPMs	X	X		X	X	X	5 MW-CSC Semi (Sauder et al., 2016)	1:30	Low Time Delay	Unable-simulated Gyroscopic Effects
Single-DOF CDPMs	X						5 MW-DeepCwind Semi (M. Hall et al., 2018)	1:50	Low Inertia; High Sensitivity	Unable-simulated Torque
Multi-Fans	X	X		X	X	X	Semi (Urbán et al. 2019)	1:50	High fidelity; Low Time Delay	Complicated Control System
Ducted Fan	X						5 MW-DeepCwind Semi (Azcona et al., 2019)	1:45	Easy-to-construct Structure	Unable-simulated Torque
Ducted Fans	X					X	10 MW-Class Semi (Ha et al., 2023)	1:35	Easy-to-construct Structure; Low Time Delay;	Complicated Control System
Linear Actuators	X	X					SHIVER- monopile (Hendrikse et al., 2022)	—	High Sensitivity	Unable-simulated Torque

Notes: These force components (Fx...Mz) refer to the coordinate system in Fig. 4.

the physical substructure, the position and velocity of the buoy were returned to the numerical substructure for calculation, and the stress results of the mooring system were obtained. The cable tension of the mooring system was applied to the physical substructure through CDPM.

In the second method, the thrust is applied to the physical model

through the culvert fan or multi-DOF fans at the top of the tower. The multi degree of freedom fan loading system typically consists of several unmanned aerial vehicle rotor wings, which are controlled by electric motors (Urbán et al. 2019). Each small fan will generate corresponding thrust, four of which generate pure thrust along the horizontal axis, and

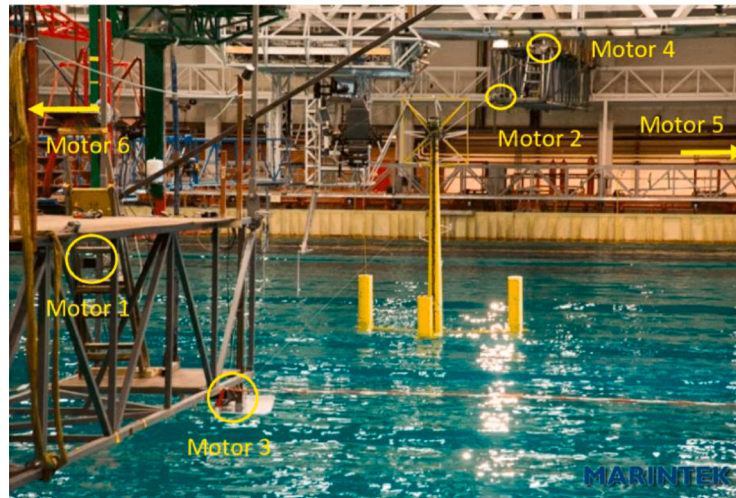


Fig. 6. 5 MW-CSC offshore FOWT hybrid model test; reprinted with permission (Chabaud et al., 2018).

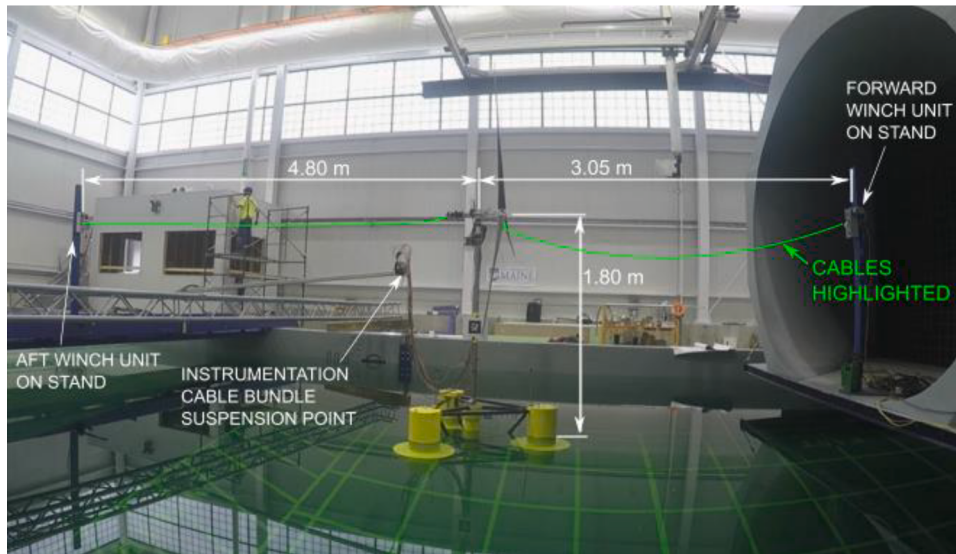


Fig. 7. Hybrid model test of DeepCwind semi FOWT; reprinted with permission (Hall et al., 2018).

two motors rotate to generate torque around the horizontal axis. Then, it can accurately recreate varied aerodynamic forces and torques exerted on wind turbines and mimic the aerodynamic load of wind turbines (Fig. 8). The following procedure is employed in the investigation of the MARIN tank (Azcona et al., 2019; Azcona et al., 2014): A duct fan was installed at the hub and a functional link was established between fan speed and hub thrust; reproduce the thrust generated by turbulent wind in the experiment by changing the fan speed (Fig. 9). The test results show that this method can reproduce the complex aerodynamics and can be performed for design evaluations (Ha et al., 2023), such as normal and emergency stops, faults, especially the influence of thrust, yaw moment and damping on the coupled system. Meanwhile, the typhoon effect and other extreme wind conditions can be particularly considered (Fig. 10).

The third method was introduced into ice load research through the linear actuator as the loading system (Hendrikse et al., 2022). A stress gauge was fixed at the thin wall of the rigid pile to measure the load at the ice action point, which was transmitted to the numerical substructure (Fig. 11). The measured ice load was combined with the virtual load (such as the wind load) to calculate the motion of the physical structure. Then, the actuator controlled the motion of the physical substructure to



Fig. 8. Schematic diagram of a multi-fan motor system; reprinted with permission (Urbán et al. 2019).

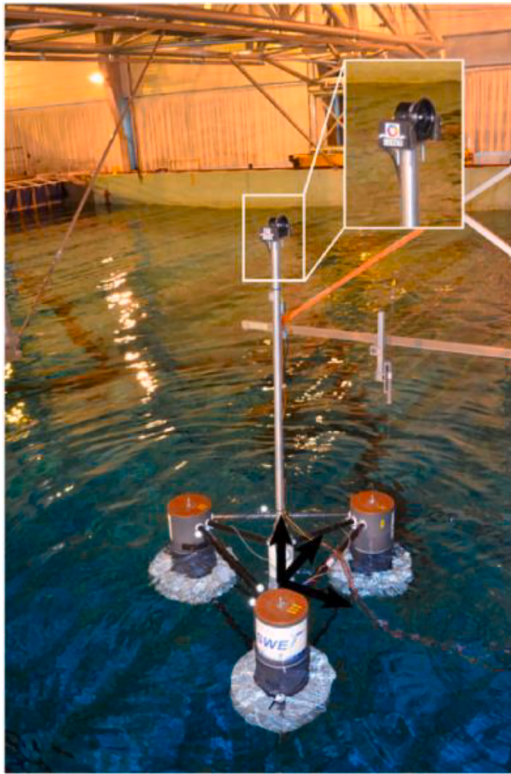


Fig. 9. RTHM test for 5 MW DeepCwind; reprinted with permission (Azcona et al., 2019).

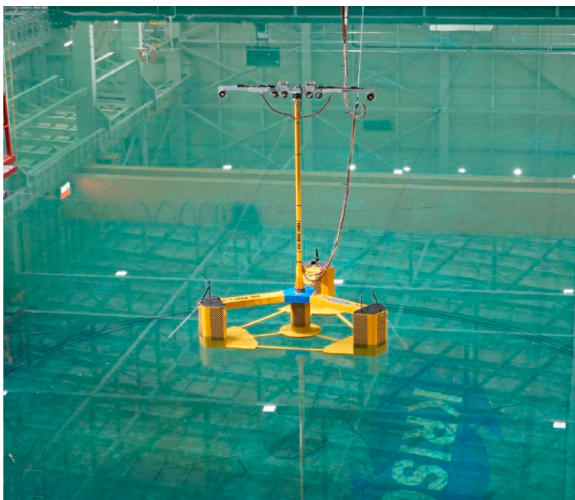


Fig. 10. RTHM test for 10 MW Class Semi; reprinted with permission (Ha et al., 2023).

form a closed-loop iterative calculation. This method can adjust the model parameters in the numerical substructure, and has excellent scalability.

The application of the RTHM test in the wave tank holds significant importance: to begin with, as an emerging frontier discipline, FOWT possesses highly intricate coupled physical characteristics of the wind and wave environments, and it lacks practical construction engineering experience. There exist certain approximate theories and empirical correction models in relevant to numerical simulations that necessitate a greater reliance on physical model experiments for verification. Scholars commonly express concern over how to accurately reproduce the marine environment, enhance the precision of experimental research on the

FOWT model, and guarantee the secure and stable operation of FOWTs.

Next, the floating platform is subjected to both hydrodynamic and significant aerodynamic loads on the wind turbine. Therefore, it is necessary to simultaneously take into account the effects of mooring system recovery force, hydrodynamics, and aerodynamics in the dynamic response analysis of FOWTs. Compared to fixed wind turbines, FOWTs exhibit larger motion responses, particularly the strong coupling effect between surge and pitch motion and aerodynamics. Crucial to guaranteeing the authenticity and reliability of FOWTs model tests is accurately simulating both aerodynamic and hydrodynamic loads.

Finally, the traditional physical model testing methods currently face various difficulties in reproducing aerodynamic loads due to the conflict between Reynolds and Froude scaling laws. Simulating turbulent wind loads in the wave tank is also impossible, thus it cannot address these challenges. The RTHM test has the potential to effectively address these existing issues and offer technical assistance for the advancement of offshore wind power.

4.3. RTHM test in the wind tunnel

The RTHM test in the wind tunnel replaces the lower platform with numerical substructures and keeps the upper wind turbine and tower as physical substructures. The force sensing system installed at the bottom of the wind turbine tower is used to measure the force of tower on the platform model in the wind field in real time. The wave file and hydrodynamic parameters are brought into the numerical substructure, and the virtual hydrodynamic loads are calculated by potential flow theory; then the measured aerodynamic and virtual hydrodynamic loads are transmitted to the platform's time domain motion equation to calculate platform response within time steps. The motion is achieved by motion actuators that change the position of the physical wind turbine model in the wind field to measure the new aerodynamic forces in the next time step. The cycle is repeated to realize the closed-loop data interaction. The whole RTHM test process is carried out in the wind tunnel. This test method pays more attention to aerodynamic effects of the wind turbine with the integration of platform motion. The test strategy is shown in Fig. 12.

Bottasso et al. (2014) carried out wind tunnel tests on a Vestas V90 3 MW wind turbine, which was scaled by a factor of 1:45 due to the limitation of the minimum cross-sectional size of the laboratory wind tunnel. The tests were performed under various working conditions, such as active control, tower pitch, and emergency shutdown. The test adopted some strategies of hybrid test by integrating the lower tower motion with the aerodynamic load and focusing on the aero-elasticity of the upper wind turbine blade. However, the two were not connected, thus it was not a RTHM test.

Bayati et al. (2012) carried out a series of studies on RTHM tests for FOWTs. To verify the results of the numerical simulations, a 2-DOF test device with a scaling factor of 1:25 was used to simulate the wave forces in the surge and pitch directions on a floating platform in a wind tunnel test with the real-time working mode of "hardware in the loop". To better realize the wave force simulation in the physical model, a six-DOF wave force loading platform was designed and studied, and its performance in terms of maximum displacement, force, and power was discussed (Bayati et al., 2014). To better simulate the nonlinear hydrodynamic force of waves in the RTHM test (Bayati et al., 2015), the influence of water depth on the potential flow of an OC4 semi FOWT was studied through DIFFRAC and ANSYSIM software developed by MARIN Research Institute in the Netherlands.

In the 1:75 RTHM test for a large DTU 10 MW FOWT (Bayati et al., 2016; Bayati et al., 2017b), the blade and electromechanical integration design was carried out, so that each blade could be controlled by a single pitch. Considering the first natural frequency of the blade and aiming at matching the horizontal thrust of the aerodynamics, the airfoil shape was determined to be the SD7032 airfoil through the optimization algorithm. The natural frequency of the model was verified by the finite

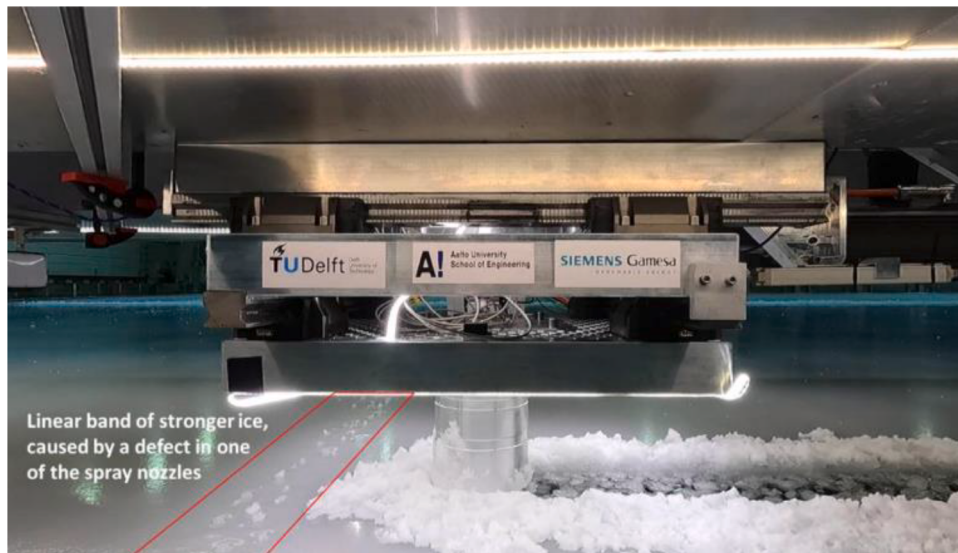


Fig. 11. Two-DOF ice load RTHM; reprinted with permission (Hendrikse et al., 2022).

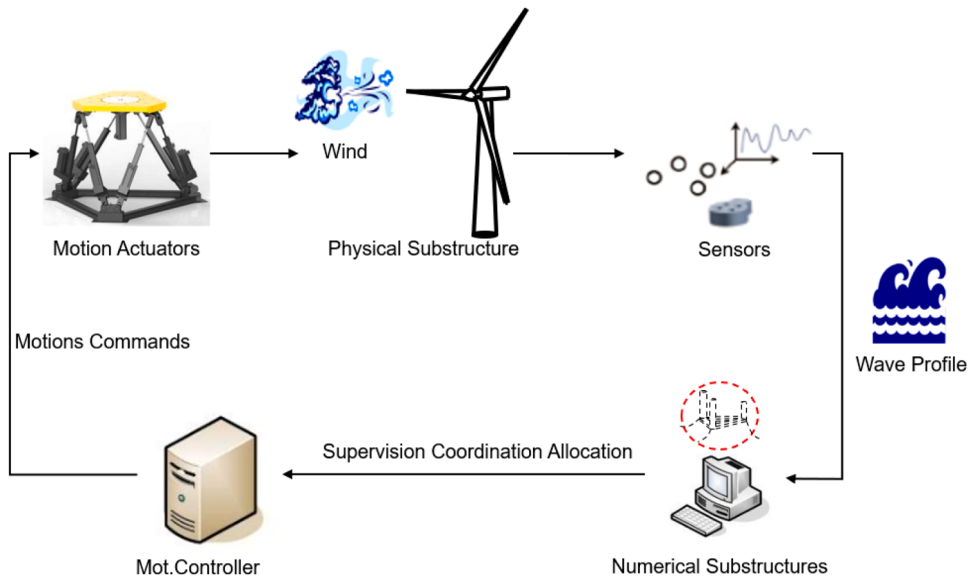


Fig. 12. Flowchart of the RTHM test in the wind tunnel test.

element method (Bayati et al., 2017a), and the aerodynamic performances of the blade with different speed scale factors were compared. The six-DOF RTHM test method and technical approaches were developed (Bayati et al., 2018a; Bayati et al., 2018b), and verified with the results of FAST software (Fig. 13). Then, the model was installed on a hydraulic servo braking platform (Belloli et al., 2020). Sinusoidal motions with different frequencies amplitudes and blade tip speed ratios were applied to the model, and the air wake characteristics under dynamic conditions were measured by a hot wire anemometer and particle image technology. Finally, in the Offshore Code Comparison Collaboration, Continued, with Correlation and unCertainty (OC6) project in 2022, the multidirectional coupling mechanism of wake energy, tip vortex and the lower foundation was investigated through the influence of tower top motion on the upper wind turbine under different operating conditions.

The application of the RTHM test in the wind tunnel holds significant importance. Wind tunnel tests primarily focus on examining the parameters and aerodynamic performance of the wind turbine blades. The Reynolds scaling cannot be fully reproduced in wind tunnels, however,

there exist multiple techniques to address the issue of low Reynolds numbers that arise due to this scaling conflict.

In the first approach, the wind speed is increased beyond the Froude-scaled value to compensate for the low thrust coefficient. A second approach addressing low Reynolds number effects is the placement of studs or other roughened materials as a turbulence stimulator along the leading edge of a blade. A third possible approach is to redesign the rotor blade sections to account for Reynolds number effects, or even more radical solutions such as changing the number of blades and the rotor diameter. This can involve the choice of laminar flow sections for the model scale rotor so that the model rotor design can simulate as closely as possible the correct full-scale mean thrust and torque coefficients at the model-scale Reynolds Number (based on blade chord), whilst still maintaining the correct mass properties.

However, all the aforementioned methods have their respective issues. Furthermore, traditional wind tunnel model tests are incapable of taking into account coupling scenarios. RTHM test simulates the motion response of the lower platform in waves through a shaking table. By paying closer attention to aerodynamic performance, model testing of



Fig. 13. Setup of the aerodynamic hybrid model test; reprinted with permission (Belloli et al., 2020).

the entire system can be achieved. The wave information can be easily modified in various numerical substructures. It has the ability to accurately capture the dynamic characteristics and responses of various wind turbine blades under environmental conditions.

4.4. Summary

The above two different hybrid test methods can be used to calculate the motion or force of the full-scale model in a numerical model and complete scaling from the actual scale to the model scale. Then transmit the scaled value to the physical model to effectively solve the problem caused by the Froude number and Reynolds number not being similar at the same time. The two methods can flexibly and conveniently change the structural shape of a floating foundation or wind turbine blade in the numerical model, so that the experimental conditions of different numerical models of the same physical model can be studied simply, effectively and economically. The difference is that the RTHM test in the tank needs to reproduce the aerodynamics with the help of the loading system, so the loading system is a force control system. The existing loading system has no uniform rules and cannot completely reproduce each force component of the aerodynamics, which requires targeted development by researchers. The RTHM test in the wind tunnel needs to reproduce the wave displacement with the help of a motion platform, so the loading system is a displacement control system, which has been mature and widely used in the civil engineering field. In addition, Specialist Committee on Hydrodynamic Modelling of Marine Renewable Energy Devices has expressed a keen interest in hybrid testing methods and issued guidelines for the advancement of this technology, which are published in the 7.5-02-07-03 series at the International Towing Tank Conference (ITTC) that deals with ocean engineering. The ITTC (2017) guidelines are relatively generic and do not provide detailed guidance on different aspects of the RTHM test. According to the specifications, the technical preparation level should be at TRL4, which is at the small-scale model testing stage. It is foreseeable that the hybrid model testing method is a new direction for the development of offshore wind turbine testing, which can solve many difficulties in traditional model testing, such as scaling conflicts, full-scale testing, turbulent wind replication, and complex shutdown condition testing. This will have broad application prospects.

5. Technical challenges of RTHM test of FOWTs

Based on the substructure analysis principle in structural dynamics, the RTHM test exchanges the results between the physical test and numerical calculations in real time to realize the real-time coupling and study the dynamic responses of the whole structure. Therefore, it is necessary to meet the real-time requirements in the whole test process, which poses technical challenges to three important components of a RTHM test: the solution for the numerical substructure, the loading of the physical substructure and data exchange between substructures.

5.1. Calculation capacity of the numerical substructure

In the RTHM test, the control signal of loading exerted on physical substructure comes from the real-time calculation results of the numerical substructure, which is unknown before the test. Therefore, the RTHM test requires that the numerical substructure meet the requirements of real-time calculations, i.e., it needs to run in the real-time environment and complete the whole calculation task within the specified time. In civil engineering, the xPC Target toolbox in MATLAB or the dSPACE real-time simulation system based on MATLAB/Simulink are generally used to build the real-time operation environment of numerical substructures. In FOWTs, the real-time environment built on the PC learns from the existing strategies in civil engineering. Most systems adopt the distributed real-time calculation method (Lu et al., 2020) or directly develop real-time modules on a PC and use the Linux operating system to run the numerical simulations. The real-time PC environment construction and calculation capacity of the numerical substructure in the RTHM test for FOWTs are listed in Table 6.

In the listed cases, some researchers did not adopt the strict real-time environment but chose a traditional PC equipped with Windows OS as the computing environment. This choice created systematic errors and the results of each time step calculated by the simulation software were not loaded on the physical structure in real time. However, the results of these research initiatives have little time-delay error because the wind itself is a kind of low-frequency load. Most FOWT tests studied the action mechanism of fully coupled systems, and there was little research on rate-sensitive elements (viscous dampers, rubber isolators, etc.). In addition, most of the items in Table 6 considered the wind turbine as numerical substructure and the platform as physical substructure. In this way, most of the dynamic loads at the tower base come from the structural vibration of the turbine rather than the direct transmission of aerodynamic forces. The real-time requirement of this coupling mechanism research is not high. When a Windows operating system meets the computing power requirements, it could be used to carry out a RTHM test.

Table 6
Comparison of real-time calculations with numerical substructures.

Operation Environment	Software	Time Step	Advantages	Disadvantages
Linux (Bottasso et al., 2014)	MATLAB/Simulink	0.004 s	Real Time	Difficulty in developing
dSPACE (Bayati et al., 2016)	MATLAB/Simulink	0.015 s	Real Time	Difficulty in Developing
Windows (Azcona et al., 2019)	AeroDyn	0.055 s	Simple Development	Non-real Time
Windows (M. Hall et al., 2018)	FAST	0.01 s	Simple Development	Non-real Time
Windows (Vilsen et al., 2017)	SIMA	0.01 s	Simple Development	Non-real Time
Linux (Urban et al. 2019)	FAST	0.01 s	Real Time	Difficulty in Developing

5.2. Loading and control of the physical substructure

The RTHM test puts forward high requirements for the real-time loading of the physical substructure. It is expected that the physical quantity at the interface of the numerical substructure can be accurately applied to the physical specimen in real time to realize real-time coupling between the physical substructure and the numerical substructure. If the real-time loading of the physical parameter at the interface is inaccurate, the physical parameter measured by sensors for the physical substructure will not represent the expected reaction value, which can lead to errors in the calculation of the next time step for the numerical substructure. The continuous accumulation of calculation errors leads to the distortion or even instability of the whole RTHM test system. Therefore, real-time loading of the physical substructure directly determines the success or failure of the whole test.

In the wind tunnel RTHM test, existing research has simulated the action of wave force on the 6-DOF platform and its motion response through a shaking table. This loading method has high accuracy for load reproduction, but it is difficult to develop (Bayati et al., 2014).

In the wave tank RTHM test, different loading devices are designed to exert the aerodynamic forces from different directions on the nacelle. Sauder et al. (2016) used the Behaviour Consider Sensitivity (BCS) method to design six actuators with pulleys that were connected to the square frame with thin wires (Bachynski et al., 2016; Berthelsen et al., 2016). Reproduce the calculated force command by pulling the square frame through multiple actuators. Hall et al. (2018) designed a winch system actuator by using a cable with large working space and small mass. Pulling the cable back and forth in the nacelle, air thrust is simulated in the X direction. Urbán et al. (2019) designed six-fan loading systems with the characteristics of high load, low inertia, and high efficiency and stability. In this loading system, four fans generated thrust along the horizontal direction, and two fans generated torque around the horizontal axis to simulate complex aerodynamics. The quantitative experimental data errors are summarized in Table 7 for reference.

5.3. Signal acquisition and transmission

Data acquisition refers to the process of automatically collecting signals from the tested components such as sensors. Data transmission ensures data communication among the numerical substructure, controller and physical substructure. In the process of the RTHM test, it is necessary to collect and store the acceleration, velocity, displacement, strain and other responsive quantities of the physical substructure in real time, send the interface feedback quantities to the numerical substructure in real time, and participate in the numerical iterative calculations to ensure the real-time calculation of the numerical substructure. At the same time, the results of numerical substructure calculations must be transmitted to the controller of the loading device in real time to ensure

Table 7
Quantitative experimental data error.

Physical quantity	Statistical value	Error	Research focus
Platform roll and pitch (Sauder et al., 2016)	Mean value	10 %	Feasibility Study on RTHM
Platform pitch (Hall et al., 2018)	Standard Deviation	−9 %	Validation of RTHM
Platform pitch (Azcona et al., 2019)	Mean value	1.1 %	Research on Low-frequency dynamics of RTHM
Thrust, torque and shear moments on the rotor (Urbán et al. 2019)	Mean value	2 %	RTHM allow the high-fidelity reproduction of wind turbine aerodynamics
Oscillation periods (Vilsen et al., 2019)	Mean value	2–5 %	RTHM testing is an extension to traditional hydrodynamic model-scale testing
Thrust and Yaw moment (Ha et al., 2023)	Root mean square	5 %	RTHM test exhibit good repeatability

the real-time loading applied on the physical substructure. If the real-time acquisition and transmission process takes too much time, error accumulation occurs, affecting the test results and even resulting in instability. The equipment for data acquisition and data transmission used in the RTHM tests for FOWTs are listed in Table 8.

Vilsen et al. (2017) used a sensor system in a traditional manner to measure the motion of the physical substructure. Because the integration of the measured acceleration into the velocity may lead to numerical drift, a nonlinear motion observation system coupled with an inertial measurement unit and a global navigation satellite system (Fossen, 2011) were selected to estimate the state of the whole physical substructure. The deviation of the acceleration sensor was improved in this way.

Sensors exhibit random errors such as background noise, which are detected in two ways. The first method measures these errors by repeated tests and ensures that they are below the critical limit. Another detection methods uses the energy standard at the interface between the numerical substructure and physical substructure proposed in the literature (Ahmadizadeh et al. 2009; Chang, 2010; Maghareh et al., 2014; Bachynski et al., 2015) to monitor the influence of these uncertainties.

Filters, both model-free and model-based, are the most used techniques to reduce the impact of noise in measurements. Both Sauder et al. (2016) and Hall et al. (2018) used low-pass filters to accomplish such a goal, and only the filter frequencies were different.

6. Time delay of RTHM test for FOWTs

In an ideal state, the results of numerical substructure calculations should be transmitted to the controller of the loading device at each time step. Then, under the real-time controller, the loading device shall accurately apply the load to the physical substructure in real time. Finally, the response at the interface is detected by the measurement system and fed back to the numerical substructure in real time to form a closed-loop.

However, in an actual test, due to the physical characteristics of the loading device itself, it is inevitable to have a certain response lag and not load the physical substructure in time (Maghareh et al., 2014; Tian et al., 2022). In order to counteract the effect of time delay, it is necessary to artificially compensate the delay of the system in the test.

In civil engineering, the main strategy is displacement prediction and compensation, that is, through the polynomial extrapolation algorithm, the value of advance time is predicted and input to the loading device as the control value. With the time delay, the loading device applies the value to the physical specimen at the right time. According to the assumption of time delay, prediction compensation algorithms are divided into two categories:

- (1) Fixed forward prediction methods, which assume that the time delay is fixed and known.
- (2) Adaptive estimation methods, which assume that the translation delay is not a constant and needs to be estimated and adjusted in real time during the experiment.

In addition, some scholars have also adopted a strategy different from displacement prediction for time delay compensation. Khansefid and Ahmadizadeh (2016) proposed the restoring force compensation method. According to the quadratic fitting curve of the measured displacement and interface force, the time when the loading device actually reaches the target displacement and the corresponding restoring force at that time are extrapolated and predicted, and then fed back to the numerical substructure. This method is adaptive and helpful to track the error and does not need to give the timing delay in advance. Li et al. (2017) proposed the virtual coupling method and introduced a virtual coupling element composed of a spring damper between the physical substructure and the numerical substructure. With this, the

Table 8

Comparison of the data acquisition and transmission systems.

Measure Object	Sensor	Frequency	Transmission	Advantages	Disadvantages
Position	OQUS Optical Measurement	100 Hz–250 Hz	Non-Real Time Network (Sauder et al., 2016)	Simple and convenient	Non-real Time
			TCP Communication (Hall et al., 2018)	Simple development	Large delay, Slow transmission
Angular Velocity Acceleration	Gyroscope Acceleration Sensor	600 Hz 250 Hz–600 Hz	CAN Open Communication (Azcona et al., 2019)	Low delay, Fast transmission	Difficulty in Developing
			Non-Real Time Network (Sauder et al., 2016)	Simple and convenient	Non-real Time
			Non-Real Time Network (Sauder et al., 2016)	Simple and convenient	Non-real Time
			CAN Open Communication (Azcona et al., 2019)	Low delay, Fast transmission	Difficulty in Developing
Thrust	Force Sensor	100 Hz–250 Hz	TCP Communication (Hall et al., 2018)	Simple development	Large delay, Slow transmission
			CAN Open Communication (Azcona et al., 2019)	Low delay, Fast transmission	Difficulty in Developing

virtual stiffness term and damping term are added to the transfer function between the restoring force and the external load. The virtual stiffness and damping are adjusted according to the restoring force to balance the performance of the system. It is suitable for tests with strong nonlinear behavior. These algorithms use an adaptive outer loop controller to replace time delay estimation and displacement prediction and minimize the overall synchronization error.

Different strategies mentioned above can be used as a reference in the RTHM test for FOWTs. Different technical methods are adopted to compensate and correct the loading device time delay, acquisition signal transmission time delay, background noise, etc., as detailed below.

Hall et al. (2018) described and compared different predictive delay compensation algorithms such as cubic polynomial and least square curve methods by considering the simulation time and communication efficiency of the numerical substructure. These methods were used for compensating the actuator delay. The delay of the optical recording sensor was 20 ms, plus the delay of the whole control loop, a total of 30 ms delay compensation was added to the value. The time delay caused by the delayed response of the loading device introduces false energy into the system which may lead to system instability (Sauder et al., 2016). To reduce the errors caused by the loading device, the simulation settings related to aerodynamic load were simplified by ignoring load components in some directions (gyroscopic moment and vertical aerodynamic load) for the numerical substructure. This limits the number of loading devices and reduces the working space for loading devices. The delay input of the numerical substructure and the time delay generated by acquisition and transmission are measured, and the total delay is 20 ms. The delay is compensated by the fixed forward prediction method based on the kinematic prediction delay compensation strategy. Assuming that there is a constant delay between the measurement force and the applied force, the delay is tested in advance, and compensation for the delay is realized by the compensation algorithm. The compensation is verified through the free attenuation test, proving that it does not cause false changes in the system energy.

Another way is to predict and compensate for the time delay caused by the measurement system, communication, calculation time, and inherent properties of the actuator (Vilsen et al., 2019). Polynomial identification is performed on a number of data points, and then polynomial extrapolation is performed before the last few data points to obtain the predicted position and speed in the next time step, which is introduced to the numerical substructure for calculation in advance to compensate for the system delay without introducing unacceptable noise. Azcona et al. (2019) addressed the time-delay problem by calculating the aerodynamic thrusts of the next time step in advance and then updating the aerodynamic thrust when sending the measured motion response of the physical substructure to the numerical substructure for calculation.

7. Development and future trends of the RTHM tests for FOWTs

7.1. Overview

Research on RTHM tests for offshore wind energy has made some progress, but it is far from mature (Sun et al., 2022). At present, the simulation ability of RTHM tests is limited, and there is still a long way from these tests to engineering applications. For the safe operation of FOWTs, the numerical simulation results and the physical phenomena should be verified, and the full coupling mechanism of FOWTs in a complex environment should be studied. The RTHM test needs a breakthrough in both numerical substructure simulations and physical substructure developments.

7.2. Numerical substructure

7.2.1. Promotion of computational efficiency

The computational efficiency of the numerical substructure needs to be improved. The higher the simulation fidelity is, the better, but this will also lead to higher computational costs. A great simulation should balance fidelity and computational costs.

To maintain the same simulation accuracy, faster computers or more efficient algorithms can be used. Real-time CFD is a good application. The computational efficiency of numerical substructures can be improved with the aid of cloud computing technology and more powerful computing machines. With the help of relevant experiences in civil engineering (Williams et al. 2007), we can adopt the RTHM test in the form of a distributed alliance, subdividing the numerical substructure into several parts, distributing them in different countries and regions, calculating them simultaneously, and returning the results to a central test base for reassembling. This is similar to the concept of parallel processing in computing. Improving the computational efficiency of the numerical substructure can greatly improve the ability of the RTHM test method.

7.2.2. Improvement of simulation fidelity

More accurate data should be input for the numerical substructure to obtain more accurate controlling commands for physical substructure. The upper turbine is used as the numerical substructure in the RTHM test in the wave tank. However, the calculation of the aerodynamic force is mainly based on the DNV or IEC standards, while wind field data are generated from the internal programming of the numerical software. There is still a gap between the simulated wind field and the actual wind field. There is uncertainty, and it is a lack of comprehensive data for the real wind farm. In addition, the numerical simulation of upper wind turbine requires more complex air wake and blade flexibility.

The lower platform and mooring system are used as numerical substructures in the RTHM test in wind tunnel. In the process of iterative calculation, it is necessary to consider the influence of more complex factors, such as high-order wave force, water viscosity, hydroelasticity,

etc. At present, existing theoretical calculation methods are simplified, therefore it is necessary to deeply study the theoretical calculation methods to improve the fidelity of numerical substructure simulation.

7.3. Physical substructure

7.3.1. Coupling between multiple DOFs and multiple loading devices

For of the physical substructure, it is necessary to study the multiple-DOF loading device (Albuérne et al., 2019; Botelho et al. 2015). For the loading device used in RTHM tests for FOWTs in wind tunnel, shaking tables are used to produce the multiple-DOF motion of the platform under wind load and wave load, but current research can only achieve a two-directional control for the six-DOF physical substructure in the test stage. The vibration table has the capability to simulate the surge and pitch motions of a FOWT scale model and assess how the structural motion affects the aerodynamics of FOWTs. The hybrid experimental loading device presents real-time challenges, necessitating substantial computational resources for running numerical models of the floating platform and mooring system, and for acquiring real-time feedback signals from the physical substructure of the tower to facilitate subsequent calculations. Developing a state-space model to address the coupled motion of wind turbine foundations is a practical solution that can improve computational efficiency and reduce the accumulation of errors. Moreover, the limitations in measuring aerodynamic loads during wind tunnel tests may introduce uncertainties into the dynamic response of floating platforms, which could result in cumulative errors during the iterative calculations of hybrid model testing techniques and ultimately lead to system instability.

When the tank test is adopted, several small fans, cable pulling and other loading methods are used to provide the multiple-directional aerodynamic loads, but there are errors in the test results, which put forward the universality and requirements for the multiple-directional loading device. To apply loads to the physical substructure using the cable pulling loading method, a winch device is necessary, which might limit the motion response of the floating platform. When using multiple small fans for loading, it is important to carefully consider the impact of their mass, given the requirement for lightweight rotor components under Froude scaling. Introducing rigid coupling among various actuators may introduce high-frequency errors into the experimental system, resulting in unnecessarily high-frequency vibrations. Therefore, it is crucial to utilize filtering technology during signal transmission in order to mitigate the accumulation of errors.

In addition, during the actual operation of FOWTs, the complex environmental loads are not uniformly applied. The division of the substructure and the accuracy of the multiple-DOF response in the RTHM test require that multiple loading devices operate at the same time (Wallace et al., 2004). Therefore, this will be a trend in the development of RTHM tests for the FOWTs in the future to deeply study the coupling effects between different loading devices, and to improve the design and manufacture of loading devices that can reproduce the actual complex loads.

7.3.2. The application of 3D printing technology

In the current physical model test, researchers have paid less attention to the material properties of the physical substructure itself when scaling, leading to the gaps in the hydroelastic effects, the substructure flexibility and other factors between the physical model and the real offshore turbine (Li et al. 2022). Moreover, the geometric structure or mass distribution of the physical model is not perfect, which leads to some differences caused by structural uncertainty. The corresponding specifications are proposed to buildup physical models to improve the product quality of physical models and carry out more accurate tests at similar scales. The application of 3D printing technology has been able to produce some elastic-plastic physical models, which is helpful to improve the physical model experiment technology (Song et al., 2023; Bandinelli et al., 2023). It will become a development trend of RTHM

tests for FOWTs in the future.

7.4. Potential applications of the RTHM test to FOWTs

In addition to the above development trends, the RTHM of FOWT also has the potential to solve some bottleneck problems in the existing offshore wind energy industry.

For horizontal axis wind turbines, there are several aspects:

- (1) To solve the wake effect problem (Sun et al., 2020), various aerodynamic wake models can be easily implemented in the numerical substructure. Based on the wake models, multiple actuators can be used to apply the aerodynamic forces considering the wake interaction between different physical substructures of a wind farm.
- (2) Some electronic and mechanical components must be added to the existing test methods to control the turbine (öschke et al., 2022). The method is relatively complex and difficult to achieve. Through a RTHM test, the wind turbine control strategy, such as individual pitch control, yaw control based on SCADA system et al., can be easily implemented in the numerical substructure without too much cost or effort compared with controls in the physical model.
- (3) For the deformation of long flexible blades and the hydro-elasticity of the turbine platform, it is very hard to achieve in the model scale. Instead, these materials elasticity can be well included in the numerical substructure. The load considering these factors can be obtained and applied to the physical substructure, and the RTHM test can be completed in a wave tank or wind tunnel.

In addition, the physical model test of the vertical axis wind turbine also has the same scale contradiction problem (Siram et al., 2022). The RTHM test method can be introduced to develop a specific loading device to simulate the aerodynamic forces exerted on the blade on the upper or lower parts of the tower to solve the scale problem.

8. Concluding remarks

This paper summarized the application of the RTHM tests in FOWT. The history and development of RTHM tests for FOWT was reviewed, typical test scenarios were discussed, and technical difficulties and main challenges in different applications were summarized. Some suggestions for the future development of the RTHM tests for FOWT are proposed.

- 1) The RTHM test of FOWT is an effective method to solve the scaling contradiction problem for the current physical model test. It can release laboratory space limitations and solve poor wind quality problems, which should be developed and widely applied to full-scale tests of mooring systems. With the use of this test method, only the critical components are used in the test as physical model, which significantly reduces test costs. Additionally, the model parameters of the numerical substructure can be directly changed to adapt to different objects and working conditions, expanding the test capability, which is more convenient, economical and efficient than traditional test methods.
- 2) There are two main methods of the RTHM test for FOWT. Reproducing aerodynamic loads using simulation software and loading devices is one method, which does not require a high-quality test site. The test is carried out in a wave basin with a focus on hydrodynamic analysis. The loading device adopts force control mode, which can effectively solve the problem of turbulent wind reappearance. Another is to use simulation software and a shaking table to reproduce the platform motion due to wave load, which requires wind tunnel site to conduct experiments and focus on aerodynamic analysis. The shaking table adopts the displacement control mode, which

is relatively accurate, and can effectively solve the problem of extreme wave recurrence.

- 3) RTHM testing for FOWT presents three technical challenges: a) Numerical substructure calculation, which requires high computational efficiency and construction of real-time operating environment. RTHM test in wave tank has low requirements for real-time control and is easier to implement. b) Physical substructure loading, which requires the design and manufacture of a displacement or force control loading system. Currently, there is no uniform form of loading device. c) Signal acquisition and transmission, which requires reducing the system error and time delay of the test. Filters, both model-free and model-based, are the widely used techniques to reduce the impact of noise in measurements. Different time delay compensation algorithms can be used to address time delay errors.
- 4) The development of RTHM testing of FOWT is late. Promoting computational efficiency and simulation fidelity, coupling between multiple DOFs and multiple loading devices, and the application of 3D printing technology will be the future development trends of RTHM test, which have broad application prospects in wake effect problem, wind turbine control strategy the deformation of long flexible blades and hydro-elasticity of the turbine platform.

This review paper will be of special interest to researchers working on RTHM testing and will serve as a baseline report for numerical substructure real-time calculation, physical substructure loading control, signal acquisition, and data transmission. This study makes four specific contributions:

- Presents an important review on the RTHM test of FOWT
- Analyze the time delay issues in the tests
- Provides tests guidance by analyzing three main technical challenges
- Useful suggestions for the defects and development trends of RTHM testing of FOWT are put forward

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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