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A review of aerodynamic and wake characteristics of floating offshore wind turbines

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ABSTRACT

Wind-generated electricity has effectively promoted the net-zero carbon emission plan, and gradually developed to the deeper ocean, which leads to the emergence of rotating equipment with both rigidity and flexibility: floating offshore wind turbines (FOWT). This review presents crucial determinants for the FOWT's power generation, namely aerodynamics and wakes, which are strongly coupled to the hydrodynamics of the floating platform. The selection of different platforms leads to unique performances, and technology and cost are direct constraints for global floating projects. In the experimental study, the scale model based on some similarity criteria is used to reflect aerodynamic characteristics of the prototype under the multi-degree of freedom motions, but with the contradiction between the Froude number and Reynolds number. Wave basin and wind tunnel are two typical research forms, but the premise is the model scaling to obtain similar dynamic thrust and power. Besides, a cyclic pitch control method is discussed, which is expected to effectively reduce the fatigue load of the spindle and gears. As for the numerical simulation, Blade Element Momentum, Computational Fluid Dynamics, Free-Vortex Wake and Boundary Element behave in different calculation capacities and costs. The power, thrust and wake are obtained under specific platform and motion conditions, and the calculation results lack comparisons and verifications. It is necessary to ignore the extremely limited power increase caused by pitch and surge motion in the design process, to make the platform more stable for dynamic performances and significantly reduce fatigue loads. As a review article, this paper could provide a meaningful reference for those engaged in the aerodynamics of FOWT.

1. Introduction

Wind energy utilization is considered a useful way to realize the plan of net-zero carbon emission before 2050. In recent years, offshore wind resource has been developed rapidly, followed by FOWT as an emerging concept. The FOWT with a water depth greater than 50 m or 50 km further from the coast is gradually becoming the focus of the future wind turbine industry. However, technology maturity and cost reduction are at odds and they are the most direct limitations for the final commercial operation. For instance, the floating platform draws on the design of offshore oil and gas production platforms and this application resists the

wind load to improve stabilities. Instead, the wind turbine utilizes the wind load to stabilize the power generation. Therefore, there is always a contradiction between the turbine and the platform, so how to make a compromise between the two is a hard problem to be solved at present. Nevertheless, power generation by offshore wind, especially in the deep sea, is an inevitable trend.

Fig. 1 shows statistics and forecasts of the new installed capacity of global onshore and offshore wind power from 2010 to 2025. Although the world experienced novel coronavirus pneumonia in 2020, the installed capacity of wind turbines exceeded 93 GW, with a year-on-year increase of 53%, including more than 6 GW offshore, of which China accounts for the main proportion, showing incredible toughness and

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Nomenclature:

A	amplitude of the platform motion
c	chord
Cl	lift coefficient
C_P	power coefficient
C_T	thrust coefficient
D	diameter of the rotor
E	young's modulus
f	frequency of the platform motion
F	objective function
Fr	Froude number
g	acceleration of gravity
I	section moment of inertia
k	normalized weight value
Kl	slope of curve
L	length
n	number of tip speed ratio
P	weight function
R	radius of the rotor
Re	Reynolds number
t	time
TSR	tip speed ratio
U	velocity of the water
U_{rel}	resultant velocity
U_w	inflow velocity
V	correlative velocity in scale
x	polynomial coefficient
Δ	constant
ω	rotor angular velocity
θ	twist
ν	kinematic viscosity coefficient
$\lambda(^*)$	scale of relevant parameters
$(^*)_L$	lower limit of relevant parameters
$(^*)_m$	quantity pertaining to the model
$(^*)_{opt}$	optimal value
$(^*)_p$	quantity pertaining to the prototype

$(^*)_U$	upper limit of relevant parameters
AD	Actuator Disc theory
Barge	Barge Platform
BE	Boundary Element
BEM	Blade Element Momentum theory
CFD	Computational Fluid Dynamics
DNS	Direct Numerical Simulation
DNV	DET NORSKE VERITAS
DS	Dynamic Stall
FAST	Fatigue, Aerodynamics, Structures, Turbulence
FEM	Finite Element Method
FOWT	Floating Offshore Wind Turbine
FWW	Free-Vortex Wake
GDW	Generalized Dynamic Wake
GWEC	Global Wind Energy Council
HIL	Hardware-In-the-Loop
IEC	International Electrotechnical Commission
LES	Large Eddy Simulation
MBS	Multibody System
ME	Morison's Equation
MIL	Model-In-the-Loop
NREL	National Renewable Energy Laboratory
PF	Potential Flow
QS	Quasi-static
RANS	Reynolds Average Navier-Stokes
RBM	rigid body motion
Semi-Sub	Semi-Submersible Platform
SIL	Software-In-the-Loop
Spar	Spar Platform
TBD	To be determined
TLP	Tension Leg Platform
UD	User Defined
WBG	World Bank Group
WinDS	Wake Induced Dynamic Simulator
GW	gigawatt
MW	megawatt
TW	terawatt

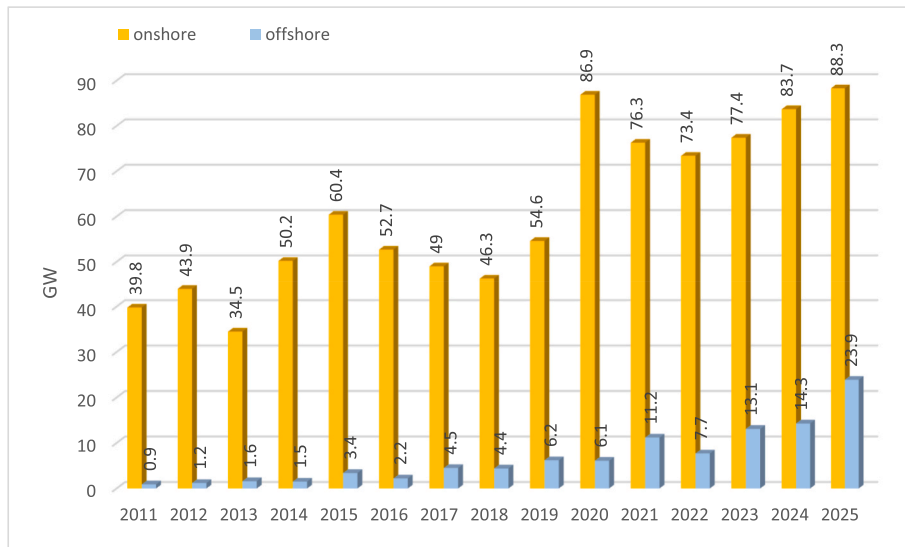


Fig. 1. Global annual cumulative installed wind capacity 2010–2025 (Fig. 1 was reproduced based on the data reported by GWEC [1]).

survivability [1]. The longer delivery period of the project made the offshore industry better able to survive despite the supply chain disruption and logistics challenges [2]. If a good situation continues, World Forum Offshore Wind predicted that the global offshore capacity would exceed 200 GW by 2030 and 1400 GW by 2050 [3]. Wind Europe pointed out that to achieve the decarbonization goal of Europe within the specified time, it was necessary to increase the offshore installed capacity to five times the current level in the next five years, of which the number of FOWT would be more than 100 GW, accounting for one-third of the total [4]. Global Wind Energy Council (GWEC) also announced that it was expected offshore wind power would increase by more than 70 GW in the next five years, with a Compound Annual Growth Rate of 31.5%, accounting for an increase from 6.5% to 21% [1]. These positive prospects benefit from the following aspects.

1. The levelized cost of energy of offshore turbines is decreasing [5].
2. Offshore wind plays a leading role in the global energy transformation and zeros carbon target.
3. Many countries attach importance to the construction of offshore turbines.
4. The exploration of FOWT promotes the possibility of deep-sea wind energy utilization [6], and so on.

According to the latest analysis of World Bank Group (WBG), the exploitable potential of global offshore wind power is 71 TW, as shown in Fig. 2. As long as 1% of them is developed, 10% of the global power demand can be met [7]. It also can be seen that more than 70% of the technical potential is located in deeper waters suitable for FOWT. In order to make full use of wind energy, the construction trend of wind farms “from land to sea, from shallow to deep, and from fixed to floating” is inevitable. However, there are still several key scientific problems for FOWT to be solved.

FOWT is the largest combination of the marine floating platform and flexible rotating equipment in the world. The operation is interfered with the wind, wave and current, and the platform behaves with six degrees of freedom of motion. The aero-hydro-servo-elastic mechanism of the turbine-floater-mooring system shows the coupling of kinematics-mechanics-electromagnetics in the time-space-frequency domain. Compared with the hydrodynamics of floating platforms and the structural dynamics of the mooring system, the aerodynamics and wake characteristics of the upper wind turbine directly determine the quality

of power generation, and they are quietly different from that of the fixed wind turbine in the complex ocean environment. The most remarkable is the large amplitude and low frequency of dynamic performances caused by the platform motions. Therefore, whether the traditional aerodynamic and wake research methods and design concepts of fixed wind turbines apply to FOWT, especially after considering the multi-field coupling and the integration model, and how to study the aerodynamic and wake, are still interesting and worthy research directions.

Generally speaking, FOWT’s two states are more concerned: operation and survival [8–10]. Similarly, the focus is also on aerodynamics through experimental and simulation studies under the two stages. On this basis, relevant design corrections and control technologies can be carried out to ensure more stable outputs and better aerodynamic performances. Different from fixed wind turbines, the combination structures and external inputs of FOWT are too complex, and the model system needs to be simplified to a certain extent. In the experiment, the hydrodynamic effect is weakened to better reproduce the aerodynamics, and the components of the wind turbine model system are often physically equivalent by some similarity. In the simulation, the mathematical model is often derived from the idealized assumption, and the motion characteristics of the platform are often imposed forcibly. These settings have changed the inherent natural attributes of FOWT, and until now, people are looking for a high-fidelity research method under the real-time coupling mechanism to more accurately capture the dynamic aerodynamic and wake performance.

This review focuses on the complex aerodynamics and wake characteristics, and summarizes how to make effective research without specifications and standards, or more accurately, how predecessors carried out theoretical analysis and experimental tests, which has laid a solid foundation for FOWT research. This paper proceeds as follows: the next section outlines platforms and projects; the third section discusses experiments; the fourth section offers simulations, and the last section concludes. Note that the whole article is about horizontal axis wind turbines because of the limitation of length, although there are also many interesting researches on vertical axis wind turbines.

2. Platforms and projects

In this section, the structural classifications and motion characteristics of different floating platforms are described, and their effects on the aerodynamics of each platform are briefly discussed. Then the completed and ongoing floating projects are summarized to have a comprehensive understanding of FOWT’s current situation.

2.1. Floating platforms

Although 6.1 GW offshore turbines were installed worldwide in 2020, which was the second best year of installation in history, more capacity is still required to meet the level of the net-zero carbon plan. Based on this, turbines need to be transferred to deeper and farther areas to capture wind resources in a wider range. This would lead to a sharp increase in the cost of fixed wind turbines, which is no longer applicable, but the appearance of floaters that rely on the design of ocean oil and gas platforms.

Typically, there are four platforms: Spar Platform (Spar), Semi-Submersible Platform (Semi-Sub), Tension Leg Platform (TLP) and Barge Platform (Barge) [11], which can be seen in Fig. 3. In different regions, it is necessary to comprehensively consider the extreme climate and installation depth below the waterline, and select appropriate platforms to capture the wind energy to the greatest extent based on ensuring the stability. There are nearly 50 design forms at present, of which 62% are Semi-Subs and 20% are Spars. Almost 78% of the concepts are used to accommodate a single turbine, and 80% prefer reinforced materials to concrete because of their shorter manufacturing time and more coordinated appearance [4]. With the continuous growth of the blade size, the reported length has reached 107 m and the capacity is

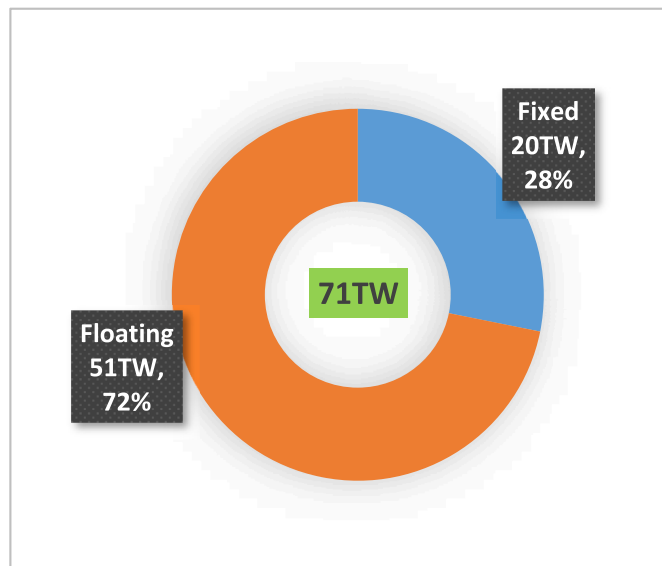


Fig. 2. Global offshore wind resource capacity (Fig. 2 was predicted based on the data of WBG [7]).



Fig. 3. Four typical platforms [21].

12 MW [12], which requires the platform to have unique shape and support to maintain stability, which also brings high difficulties for assembly, transportation, installation, component mobilization and so on.

From the above, more forms of floating platforms and larger blades will provide more different motion characteristics for upper wind turbines. They include three translational degrees of freedom: surge, sway and heave, and three rotational degrees of freedom: pitch, roll and yaw, which can be seen in Fig. 4. Pitch and surge, as typical ones, will strongly affect the aerodynamics and wake of wind turbines in different ways. Considering that the movement of the platform makes the airflow around the rotor superpose an additional velocity to the inflow, the dynamic aerodynamic and wake characteristics of the wind turbine are

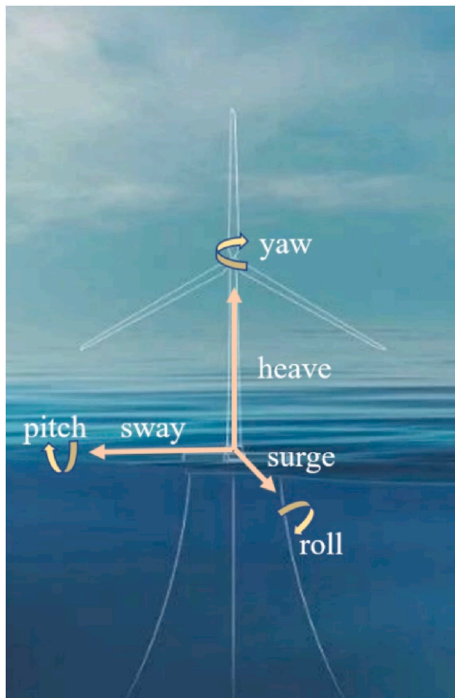


Fig. 4. Six degrees of freedom of FOWT motion (Fig. 4 is reproduced from the picture provided by DET NORSKE VERITAS (DNV) [22]).

greatly affected by the time-varying flow field. For instance, time-variant wind speed will cause the aerodynamic force to show a circular hysteresis effect with the tip speed ratio, which is the dynamic stall. In addition, large pitch or surge movements will cause the wake of the wind turbine to be disturbed by its flows. As a result, the dynamic power, load and wake performances of the FOWT will also be interesting and different from that of the fixed wind turbine. It is necessary to clarify the motion characteristics of different platform structures, to show their impact on the aerodynamic and wake performance of upper wind turbines.

The various platform features and their impacts on aerodynamics are concisely outlined here:

Spar platform is the simplest structure with a cylindrical shape, which is filled with dense materials to keep the center of gravity below the floating center, so as to keep it stable. It is usually pulled by three catenaries arranged at equal angles to keep it running in a safe area. The catenary is anchored to the seafloor, and the horizontal distance between the anchor and fairlead is 450–1200 m. The foundation can be assembled on shore and then towed to the sea with relatively high technical maturity. There has been a commercial project using the Spar platform: Hywind, which has brought considerable benefits [13].

The significant advantage of the Spar platform is that the draft is deep, generally within 70–90 m, and some people even estimate that it is much higher than this. It also results in smaller heave characteristics, but the roll and pitch motions are strengthened. For the survival condition, the wind turbine on the Spar platform has a greater potential danger of overturning. Therefore, it is necessary to make control strategies as early as possible. Under operating conditions, the fluctuation of aerodynamics is more severe because of the large pitch or roll motion. The frequency of pitch motion is consistent with the frequency of regular waves, and so is the dynamic response of the thrust and power. Besides, the large pitch angle of the platform will significantly reduce the wind area of the rotor, so the average power will be reduced. At the same time, the large amplitude pitch motion promotes the interaction between the wind turbine and its wake, which affects the aerodynamics of the rotor.

Semi-Sub platform is usually composed of three columns providing buoyancy through support links, and the wind turbine on them can be installed in the center or on one of the columns. The structure is generally anchored to the seafloor with six catenaries or taut mooring lines, and the horizontal distance between the anchor and the fairlead is 450–1200 m. The distribution of catenaries occupies a larger sea area

and has the potential danger of collision with ships. Because of the large platform and shallow draft, the components can be assembled on shore and towed to the destination, which greatly saves the installation cost.

Barge platform is made of steel or concrete, and the buoyancy provides the stability of the system. It also needs facilities such as a catenary to locate. The installation depth and assembly method are relatively flexible. Due to its large waterline area, Barge platform can ensure that it will not overturn under the combined action of wind and wave. In addition, it also has the advantages of a simple structure, low construction and installation cost, and a promising development prospect.

Semi-Sub and Barge platforms show better stability for their large waterline area, and the amplitude of the pitch motion is weaker than that of the Spar platform. However, pitch and surge motion are still the main factors affecting aerodynamics. Fluctuations in the thrust and power are displayed as frequencies consistent with the platform motions. In addition, it is worth noting that recently, the concept of multi rotors or multi wind turbines installed on a single platform has been carried out. It is inferred that the cost can be reduced and more power can be obtained. However, due to the closer distance between the rotating planes, the wake will be mixed with more indescribable flows, so their impact on the power and aerodynamic load of the wind turbine becomes complicated.

TLP platform has a small volume and is light weight, and its uniqueness lies in that gravity is less than buoyancy, which requires tension tendons in a tight state to provide sufficient pressure. The tension of the tendon is mainly to balance the vertical gravity and buoyancy, The vertical load is large and the heave motion is small, and the surge motion amplitude is large under the effect of wind induction. When the platform moves forward and backward continuously, its speed is mixed with the inflow, so the flow at the wind turbine is periodically changed, and the aerodynamic load of the wind turbine will fluctuate, accompanied by the dynamic stall effect. The motion frequency of the platform is so close to the wave frequency, and the vibration frequency of the upper wind turbine is easy to couple with the motion of the platform, which will lead to resonance and reduce the service life of the whole system. The installation accuracy of this structure is difficult to control and the economy is not good enough. As a result, there is no floating wind turbine using the TLP platform at present.

Different platforms behave in different motion responses, which has been supported by many experiments and simulations [14–20]. Aerodynamics depends on the specific platform rather than just the given wind and wave conditions, which directly determines the power generation and benefits of floating projects.

2.2. Floating projects

This part roughly describes the existing and ongoing floating projects, to have a better understanding of the development of FOWT, although it is irrelevant to aerodynamics and wake. In general, the concept of FOWT was put forward in the 1970s and paid attention to in the 1990s [23]. It was not widely explored until the 21st century and gradually moved to the prototype test and commercial operation stage. Most scientific researchers are to summarize the universal conclusions and apply them to specific wind turbine designs, and the ultimate goal is to improve technology maturity and reduce the cost. Fig. 5 shows the prototypes and capacities classified by countries, of which the United States accounts for 38%, Europe accounts for 34%, and the rest are almost Japan. With the completion of the first floating project Hywind [24], which can be seen in Fig. 6, countries have started the pace of floating wind farms in the deep sea. U.S.A, Europe and Japan are in a leading position, and their FOWT by Spar and Semi-Sub platforms are already in power generation, TLP is still under exploration [25]. China installed its first 5.5 MW FOWT by the Semi-Sub platform based on DNV and International Electrotechnical Commission (IEC) design specifications on July 10, 2021. So far, there are 11 floating projects and 74 MW installed capacity, of which 62 MW is in Europe. By 2022, there will be

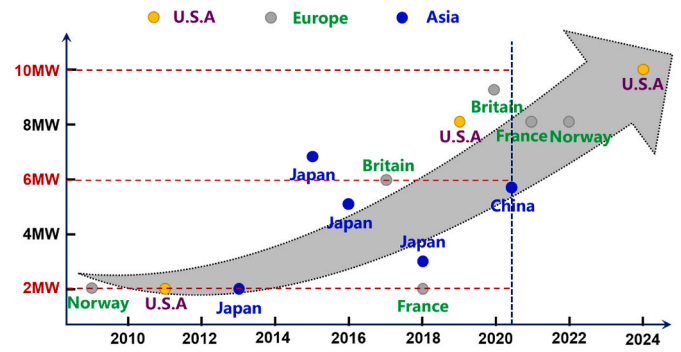


Fig. 5. Global floating prototypes (Fig. 5 was reproduced based on the data reported by GWEC [1]).

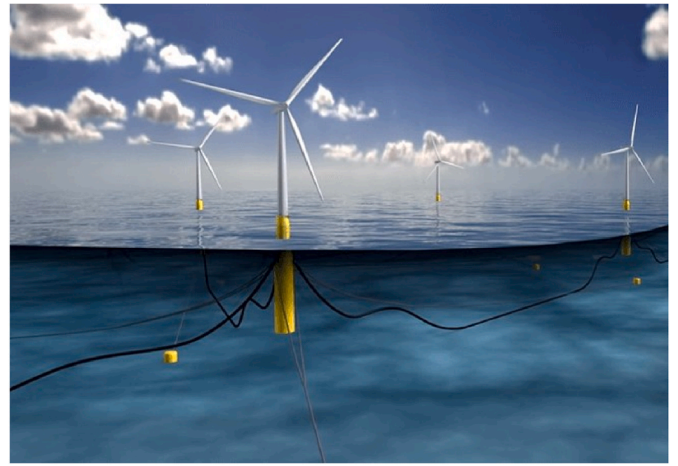


Fig. 6. The world's first floating wind farm: Hywind Scotland [24].

350 MW floating projects in Europe, accounting for 45% of wind power generation. Table 1 lists the global floating projects with different platforms as the classification standard. Soon, FOWT is bound to become the mainstream of offshore wind energy utilization.

Although FOWT relies on the platform to ensure stability, aerodynamics is still the key to evaluating the power generation of floating wind farms. Therefore, it is necessary to accurately evaluate the thrust coefficient, power coefficient and wake characteristics under complex degrees of freedom motions, whether through experiments or simulations, and these will be described in later chapters.

3. Experiments

The most direct and effective way to explore the aerodynamics and wake of FOWT is to monitor the operation data of the full-scale turbines in the marine environment. But the equipment is too huge, and the design and manufacturing require the cooperation of departments for a long time, so it is not efficient or even feasible. Instead, the model experiment in the wave basin or wind tunnel is a short-term, low-cost and effective way, and the results can be compared with the numerical simulations.

It is known that model experiments are used to reflect some characteristics of the prototype, such as aerodynamics, to guide the design of large FOWT. Therefore, it is very important to design a model wind turbine with similar aerodynamic characteristics to the prototype. This process includes similarity criteria, design process and experimental methods, which will be discussed as follows.

Table 1
Global floating projects [4].

	Technology designer/ developer	Concept name	Country	Material	Demonstration and construction period	Units installed and cumulative capacity (MW)	
Semi-Sub	Principle Power	WindFloat	US	Steel	2011–2015	4 (27.2 MW)	
	Naval Energies	Semi-submersible	France	Hybrid	2022–2025		
	Mitsubishi Heavy Industries	MHI 3 column V-shape	Japan	Steel	2016	1 (7 MW)	
	Mitsui Eng. & Shipbuilding	Compact semi-sub	Japan	Steel	2013	1 (2 MW)	
	GustoMSC	Tri-Floater	Netherlands	Steel	TBD ^a		
	Aqua Ventus Maine	VoltumUS	US	Concrete	2022		
	SAIPEM	HexaFloat	Italy	Steel	2020–2030		
	Nautilus	Nautilus	Spain	Hybrid	2021		
	Dolfines	TrussFloat	France	Steel	2022–2025	1 (0.17 MW)	
	EOLINK	EOLINK	France	Hybrid	2022	1 (0.2 MW)	
Barge	UoU, Mastek, Unison & SEHO	UOU 12-MW FOWT	South Korea	Steel	2020–2025		
	IDEOL	Damping Pool	France	Concrete	2018–2025	2 (5 MW)	
	SAITEC	SATH	Spain	Concrete	2020–2025	1 (0.03 MW)	
	Spar	Equinor	Hywind	Norway	Hybrid	2001–2024	6 (32.3 MW)
		TODA Corporation	TODA Hybrid spar	Japan	Hybrid	2016–2021	1 (2 MW)
	JMU	Advanced Spar	Japan	Steel	2016	1 (5 MW)	
	Stiesdal	TetraSpar	Denmark	Steel	2020		
	SeaTwirl Engineering	SeaTwirl	Sweden	Hybrid	2020	1 (0.3 MW)	
	ESTEYCO	TELWIND	Spain	Concrete	TBD		
	TLP	SBM Offshore & IFP Energies Nouvelles	Inclined-leg TLP	France	Steel	2022	
GICON GmbH		GICON-SOF	Germany	Steel	TBD		
Iberdrola		TLPWIND	Spain	Steel	TBD		
X1WIND		X1WIND	Spain	Hybrid	2020-TBD		
Hexicon		Hexicon	Sweden	Steel	2021–2025		
FLOW Ocean		FLOW	Sweden	Steel	2021		

^a To be determined.

3.1. Scale effect

When it comes to the similarity between models and prototypes of FOWT, a remarkable contradiction between the Reynolds number and Froude number and a “scale effect” problem caused by the difference of the Reynolds number appear. They are all needed to be concerned with the design of the model wind turbine to reflect the aerodynamics of the prototype.

In the scaling design, the most important thing is to ensure the mechanical similarity between the prototype and model, including geometric similarity, kinematics similarity, dynamical similarity, structural stiffness similarity and so on. Only in this way, it is convincing to use the reduced model to reflect the performance of the prototype. The so-called “scaling” means that the prototype is scaled to a specific proportion according to certain design principles. This proportional value is called the “scale ratio”, and it is determined according to the operating conditions of the experimental environment. For a specific wind turbine, it is determined according to the size of the wind tunnel or wave basin, operating parameters and measuring devices.

$$\lambda_L = \frac{L_p}{L_m} \quad (1)$$

$$TSR = \left(\frac{\omega R}{U_w}\right)_p = \left(\frac{\omega R}{U_w}\right)_m \quad (2)$$

Eq. (1) and Eq. (2) are the similarity in geometry and kinematics, that is, the scale of the length and the tip speed ratio, which is to ensure that the system excitation frequency and tower shadow effect are the same between the model and prototype. Where, λ_L is the length scale, the subscripts p and m represent the prototype and model respectively, L is the geometric feature length, TSR is the tip speed ratio, which means the velocity ratio of rotation at the blade tip to the inflow, ω is the rotor angular velocity, R is the blade radius, and U_w is the inflow velocity.

$$Re = \left(\frac{cU_{rel}}{\nu}\right)_p = \left(\frac{cU_{rel}}{\nu}\right)_m \quad (3)$$

$$Fr = \left(\frac{U^2}{gD}\right)_p = \left(\frac{U^2}{gD}\right)_m \quad (4)$$

As for the dynamical similarity, if the model is used to reflect the power, aerodynamics and wake, the Reynolds number similarity should be considered first, that is, flow similarity. However, FOWT operates in the marine environment, gravity and buoyancy are also the main loads, not just the viscous and inertial force. Therefore, the similarity of the Froude number is also an important criterion. The two can be seen in Eq. (3) and Eq. (4). Where c is the chord length of the airfoil, U_{rel} is the resultant velocity, which is the combined velocity of the inflow and the rotation, and ν is the kinematic viscosity coefficient of the airflow, U is the velocity of the flow, g is the acceleration of gravity, and D is the diameter of the rotor.

The tower is the support to transfer loads, and its natural frequency needs to avoid the excitation frequency of the upper rotor, and the tower belongs to a flexible component. Therefore, the tower of the model and prototype need to meet structural stiffness similarity [26], such as Eq. (5), so as to ensure that the natural frequency and deformation are the same.

$$\frac{(EI)_p}{(EI)_m} = \lambda_L^5 \quad (5)$$

where E and I are young’s modulus and section moment of inertia of the structure respectively.

With the increasing length of blades and limited size of the test environment, the scale ratio will usually be more than 100 times. In this way, the Reynolds number of the model will be two orders smaller than that of the prototype. The lift coefficient and drag coefficient of the model airfoil change greatly, so do the aerodynamics of the rotor. It can be deeply understood through Eq. (6).

$$Re = \frac{cU_{rel}}{\nu} \approx \frac{cR\omega}{\nu} \quad (6)$$

Here, it is reasonable that the resultant velocity is simplified to the

rotation velocity. If the scale ratio of 1/100 is taken as an example to illustrate that the Reynolds number cannot be similar, the following reason will be useful.

The scale of the length is generally determined according to the size of the wind tunnel or wave basin, so this value cannot be changed. If the Reynolds number wants to be unchanged from the prototype to the model, the rotating speed of the model must be increased 10,000 times to the prototype, which is absolutely impossible. Moreover, the endless rising rotating speed will also bring serious compressibility.

The above analysis shows that the Reynolds number difference is congenital and cannot be changed. In other words, the flow field will cause great deviation, which is the so-called "scale effect". Considerable similarity criteria have been proposed to solve this significant problem, which will be reviewed in the next section.

3.2. Similarity criterion

There are two environments for the model experiments of FOWT: the wave basin and the wind tunnel. In different tests, the selection of the similarity criterion is important for aerodynamic research.

The wave basin can provide waves and currents, and the model of the wind turbine and platform maintain stability by their own gravity and buoyancy of water. Therefore, the similarity of the Froude number is adopted for almost all tests, and then the hydrodynamics of the prototype can be obtained [26–28]. The aerodynamics of the prototype is reproduced by the design of model blades with a similar thrust, which will be clarified in the next section. Eqs. (7)-(12) show the complete similarity criterion of the Froude number. Among them, the length scale is the basic scale. Once it is determined, the scale of other parameters of the model wind turbine can be derived depending on the similarity of the tip speed ratio and the Froude number. From these formulas, it can be concluded that the wind speed in the wave basin test is low, and the amplitude of the motion of the model platform is small and the frequency is large. The thrust coefficient of the prototype can be well reflected, but due to the serious deviation of the optimal tip speed ratio of the model, the power coefficient and dynamic aerodynamics are usually lacking in accuracy.

$$\lambda_L = \frac{L_p}{L_m} \quad (7)$$

$$\lambda_{TSR} = \frac{TSR_p}{TSR_m} = \frac{(\omega R/U_w)_p}{(\omega R/U_w)_m} = 1 \quad (8)$$

$$\lambda_V = \frac{U_p}{U_m} = \sqrt{\lambda_L} \quad (9)$$

$$\lambda_\omega = \frac{\omega_p}{\omega_m} = \frac{1}{\sqrt{\lambda_L}} \quad (10)$$

$$\lambda_A = \lambda_L \quad (11)$$

$$\lambda_f = \frac{f_p}{f_m} = \frac{(U/A)_p}{(U/A)_m} = \frac{1}{\sqrt{\lambda_L}} \quad (12)$$

where V , A and f are the correlation velocity, amplitude and frequency of the platform motion, respectively. The velocity scale of Eq. (9) is calculated from Eq. (4).

The wind tunnel is more suitable for the aerodynamic and wakes research of FOWT models because of its excellent wind quality. Eq. (13)-Eq. (18) show the complete similarity criterion widely used in the wind tunnel [29–32]. It can be seen that the velocity scale is also defined as the basic scale, not just the length scale in the wave basin, which makes the inflow velocity is adjustable and the operation settings flexible. Meanwhile, the velocity proportional method is proposed to determine the parameters of the platform motions, that is, the ratio of the motion velocity to the inflow is the same between the model and the prototype.

In this way, when the velocity of the platform motion with the same proportion of the inflow is added to the air on the rotor surface, the velocity triangle of the model and prototype, as well as the lift and drag of the airfoil, will change in the same state, so will the aerodynamic performance. From these formulas, it can be known that the motion amplitude of the model platform is small. The wind velocity of the experiment is changeable, so the rotating velocity of the rotor and the motion frequency of the platform can be controlled.

$$\lambda_L = \frac{L_p}{L_m} \quad (13)$$

$$\lambda_V = \frac{U_p}{U_m} \quad (14)$$

$$\lambda_{TSR} = \frac{TSR_p}{TSR_m} = \frac{(\omega R/U_w)_p}{(\omega R/U_w)_m} = 1 \quad (15)$$

$$\lambda_\omega = \frac{\omega_p}{\omega_m} = \frac{\lambda_V}{\lambda_L} \quad (16)$$

$$\lambda_A = \lambda_L \quad (17)$$

$$\lambda_f = \frac{f_p}{f_m} = \frac{\lambda_V}{\lambda_L} \quad (18)$$

$$\left(\frac{Af}{U_w}\right)_p = \left(\frac{Af}{U_w}\right)_m \quad (19)$$

Eq. (19) describes the velocity proportional method to calculate the frequency of the model platform [33]. In this case, the motion frequency of the model depends not only on the prototype, but also on the mutable velocity scale. Such the flexibility of the frequency seems to be somewhat inappropriate, especially in the similarity of dynamic fluctuations of the aerodynamics. However, most of the papers have no relevant arguments. Considering this, a newly dynamic similarity criterion is proposed as follows.

There are three basic scales in the new similarity criterion for the wind tunnel model test: the scales of the length scale, tip speed ratio and velocity, and this makes the applicability of the model experiment improved again. More importantly, the similarity of tip speed ratio change rate is proposed to ensure the aerodynamic performance between the model and the prototype is the same, as shown in Eq. (26). That is to say, under a certain motion, a relative inflow superimposed by the wind and platform motion causes the model wind turbine to be in a dynamic tip speed ratio. The change rate of this tip speed ratio of the model to the time should be consistent with that of the prototype. Then the resulting dynamic aerodynamic loads and flow fields caused by the change of the angle of attack of the airfoil, such as the dynamic stall and wake interferences, can be similar. The whole criterion is expressed by Eqs. (20)-(25). Eq. (24) describes the frequency scale and it is calculated by Eq. (26) of the change rate relationship of the tip speed ratio. The frequency of the model platform is relatively small and the amplitude is large. As the dynamic tip speed ratio and angle of attack of the prototype are better regenerated, the more accurate aerodynamics such as power and thrust fluctuations can be captured, and it will contribute to the design and load evaluation of the large FOWT.

$$\lambda_L = \frac{L_p}{L_m} \quad (20)$$

$$\lambda_{TSR} = \frac{TSR_p}{TSR_m} = \frac{(\omega R/U_w)_p}{(\omega R/U_w)_m} \quad (21)$$

$$\lambda_V = \frac{U_p}{U_m} \quad (22)$$

$$\lambda_{\omega} = \frac{\omega_p}{\omega_m} = \frac{\lambda_{TSR}\lambda_V}{\lambda_L} \quad (23)$$

$$\lambda_f = \frac{1}{\lambda_T} = \frac{1}{\lambda_{TSR}} \quad (24)$$

$$\lambda_A = \frac{A_p}{A_m} = \frac{(U/f)_p}{(U/f)_m} = \lambda_{TSR}\lambda_V \quad (25)$$

$$\frac{d(TSR_p)}{d(t_p)} = \frac{d(TSR_m)}{d(t_m)} \quad (26)$$

where T is the period of the platform motion, and t is the time.

After the similarity criterion is determined, the next step is to design and build the physical model of FOWT, which is still the basis of the wave basin or wind tunnel experiments.

3.3. Model scaling

From the previous section, the scale effect seriously affects the reliability of model experiments. Several similarity criteria are proposed considering the contradiction between the Froude number and Reynolds number to make the aerodynamics of the prototype, especially the thrust, reappear accurately. Then a series of designs of the FOWT models in the wave basins or wind tunnels are carried out and introduced here.

The earliest scale model was the DeepCWind project funded by the U. S. Department of Energy's in 2007 [34]. The 5-MW wind turbine of the National Renewable Energy Laboratory (NREL) under three platforms was tested at a scale of 1/50. Due to only the geometric similarity, the velocity of the model was far lower than the requirements, and the aerodynamic performance was not obvious. Then the generator was improved and the wind velocity was increased immediately to a certain extent [35], but the power was very limited and still unconvincing. Although the model blade shape represented the full-scale structure, it should increase the torque output, match the full power and thrust coefficient curve, and closely match the change of the airfoil lift relative to blade pitch if possible [36]. This would ensure that the overall forces on the model structure were maintained in the Reynolds and Froude scale and help to maintain the effect of the damping forces due to the change of the inflows or the overall structure movements. Based on the poor performance of the geometrically similar blades, it is necessary to give up the geometric similarity and replace it with the matching of the aerodynamic performance, while maintaining an appropriate proportion of mass and inertia characteristics. In this case, the blade geometry is modified and the required aerodynamics, especially the thrust, is obtained at a low Reynolds number [37], and this method is called "blade reconstruction", which has been widely used until now [38].

Hansen et al. [39] designed an early FOWT model with the TLP platform at a scale of 1/200. The rotor was scaled by the Froude similarity to match the thrust of the prototype and to meet the maximum power at the low Reynolds number, and this was the basis for model designs. Then most of the wave basin experiments adopted this design concept, that is, the thrust similarity was mainly guaranteed between the model and the prototype, and it can be seen in Eq. (27) and Eq. (28). On this basis, Shanghai Jiaotong University used a quartic polynomial of the chord and a quadratic polynomial of the twist to fit their radial distributions. The eight coefficients of the polynomial were used as optimization variables, and the thrust coefficient was still the target [27]. The mathematical model of the chord and twist is shown in Eq. (29). The results of the wave basin test showed that the thrust coefficient of the model was in good agreement with the prototype, but due to the deviation of the optimal tip speed ratio, the power differs significantly. Considering this, Bayati et al. [40] reduced the blade of the DTU-10MW wind turbine by 1/75 on the basis of similar thrust coefficients and used it in the wind tunnel experiment. The principle was that the lift coefficient of the model blade and its change rate with the angle of attack was

the same as those of the prototype, as shown in Eq. (30). Because the aerodynamics was mainly dominated by the lift and its dynamic properties under the operations. For other wind tunnel tests, such as the one conducted at Iowa State University in 2016 [41], the reconstruction principle was that the proportion of the platform and hub motions between the model and prototype was consistent, so the relative tip speed ratio caused by the platform movement could also maintain similarity. Bottaso et al. [42] developed an aeroelastic scaled model, which was characterized by the active single-blade pitch angle and torque control. Then the non-aerodynamic and non-standard experimental verification of the aeroelastic performance was carried out in the Politecnico di Milano wind tunnel. The limitation of the model was that the power coefficient could not be matched, but the optimal tip speed ratio was the same. The thrust coefficient matched well, but the wake velocity was seriously insufficient. In view of the above results, the similarity of the power coefficient should also be added to the objective function, which is shown in Eq. (31) and Eq. (32). The key is that the model should maintain the approximate flow state with the prototype, that is, operate at the scaled tip speed ratio. Through the scale of the tip speed ratio, the thrust coefficient of the model can be equivalent to that of the prototype. The power coefficient of the model is low, but it can maintain the same shape as that of the prototype in the specific tip speed ratio range, so it can be approximated by adding a constant.

Min

$$F = P \quad (27)$$

S.t.

$$\begin{cases} P = \sum |C_T(TSR) - C_{Tp}(TSR)| \\ c_{Li} \leq c_i \leq c_{Ui}, \theta_{Li} \leq \theta_i \leq \theta_{Ui} \end{cases} \quad (28)$$

Where F and P are the objectives and weight function of the optimization, C_T is the thrust coefficient, c and θ are the chord and twist along the span of the blade, and subscripts L and U represent the lower and upper ts.

$$\begin{cases} c_i = x(1)(r/R)^4 + x(2)(r/R)^3 + x(3)(r/R)^2 + x(4)(r/R) + x(5) \\ \theta_i = x(6)(r/R)^2 + x(7)(r/R) + x(8) \end{cases} \quad (29)$$

where the x is the polynomial coefficient.

$$\begin{cases} c_i = \frac{c_p \cdot Kl_p}{\lambda_L \cdot Kl} \\ \theta_i = \theta_{ip} - \frac{C_p^0}{Kl_p} + \frac{C_p^{\theta}}{Kl_p} \end{cases} \quad (30)$$

wherein, Cl and Kl are the lift coefficient and the slope of its curve to the angle of attack in the linear area, respectively. The superscript 0 represents the angle of attack at zero degrees.

$$\text{Min } F = P_1 + P_2 \quad (31)$$

S.t.

$$\begin{cases} P_1 = \sum |C_T(TSR) - C_{Tp}(TSR \cdot \lambda_{TSR})| \quad TSR \cdot \lambda_{TSR} = [TSR_{Lp}, \quad TSR_{Up}] \\ P_2 = k \left(0.593 - \frac{\sum C_p(TSR)}{n} \right) \quad TSR = [TSR_{opt} - \Delta, \quad TSR_{opt} + \Delta] \\ c_{Li} \leq c_i \leq c_{Ui}, \theta_{Li} \leq \theta_i \leq \theta_{Ui} \end{cases} \quad (32)$$

where, Δ is a constant, k and n are the normalized weight factor and the number of tip speed ratios in the given interval, respectively. The subscript opt represents the optimal value, and 0.593 is the Betz limit of the theoretical power coefficient.

The blade reconstruction based on similar performance scaling is still important to obtain experimental models now, but there are also some

other novel means. A typical one is the Model-In-The-Loop (MIL) test that integrates the real-time simulation and experiment, including Hardware-In-the-Loop (HIL) and Software-In-the-Loop (SIL) [43], which is to solve the contradiction between Reynolds number and Froude number and obtain a more accurate scaled model. The flow chart is shown in Fig. 7. In the wave basin, the rotor is replaced by some equipment that can produce the same aerodynamic force as the result of the simulation [44]. The numerical model of aerodynamics takes the displacement of the platform as the input, integrates it in real time, determines the load, then the physical replacement transmits the load to the platform. In turn, the platform motion echoes and acts as an input to the numerical model of aerodynamics through the feedback mechanism [45]. This method can overcome the various inaccuracies of the actual model blade in generating aerodynamic loads. In detail, the duct fan was used to replace the rotor in the SIL test, loads of the nacelle and tower were obtained from the synchronous simulation, and the platform displacement was fed back in real-time by the acquisition system [46]. Elsewhere, the drag pool was also used to generate relevant loads of the wind instead of traditional fans to eliminate the interference of the turbulence and non-uniformity, and the results well verified the feasibility of this treatment [47]. Often, these methods were mainly used to explore the coupling mechanism of aerodynamics and hydrodynamics under different control conditions and platform motions [30]. Compared with the model test of the blade reconstruction in the wave basin, the hybrid system showed some newly dynamic aerodynamics [48]. As for the wind tunnel, the system is also divided into physical and numerical substructures. The aerodynamic load is output by the model wind turbine with the blade reconstruction and measured by the force measuring device installed on the top and foundation of the tower, and it is used as the input of the numerical subsystem of the hydrodynamics, combined with the real-time integration of the force of the platform and mooring system. Then the platform motion is calculated, and the model wind turbine is driven by the excitation actuator, such as a six degree of freedom platform [31]. Due to the high-fidelity aerodynamic loads and platform motions, the hybrid test in the wind tunnel is regarded as the most accurate way to reflect the dynamic performance of the prototype. However, the real-time experiment and simulation has not been effectively solved until now.

Model experiments can be applied separately to the wind, wave, or current conditions to study their impact on the aerodynamics, which cannot be achieved under the actual operating conditions, and can be used as the comparative verification data of simulations. In this section, two widely used physical modeling methods are summarized: the full

approach, in which each part needs to be scaled according to the similarity criterion; The simplified approach, which designs special devices to simulate aerodynamic or hydrodynamic loads [49]. There are two difficulties in the simplified approach of the hybrid test: the integration of the software and physical data acquisition system and the load transfer ability of the exciter. The full approach needs to consider a large number of variables, which is helpful for researchers who do not understand the performance thoroughly and will produce some new phenomena or mechanisms. However, all loads need to be scaled in the same way in the model design, and there is no standard for the scale of the lift and drag of the airfoil, which is very important in the aerodynamics of the wind turbine. Low Reynolds number airfoils are often selected. The chord is lengthened to meet the similarity of the flow conditions and the blades are thickened to reach the strength requirements. Table 2 lists the scaled model tests and aerodynamic design methods.

In model experiments, the similarity criterion and model scaling is the key premises, which are related to whether the aerodynamic performance of the whole system is representative and whether the

Table 2
FOWT experimental scaled setup [30,31,39,42,45–47,50–55].

Experiment Name	Scale	Aerodynamic Setup
Spar at NRM (2009)	1/ 22.5	Steady Force
WindFloat (2010)	1/105	Actuator Disk + Rotating Mass
DeepCWind (2011/2013)	1/50	Full Rotor (Froude/ Performance-Scaled)
Tension-Leg Bouy (2011)	1/100	None
Beyond aerodynamics Test (2014)	1/45	Full Rotor (Performance -Scaled)
NREL 5 MW Scaled TLP (2014)	1/200	Full Rotor (Froude-Scaled)
Tension-Leg Bouy (2014)	1/40	None
80 m diameter horizontal axis turbine (2014)	1/200	Blade Element Momentum Theory Based
Concrete Star (2014)	1/40	Ducted Fan
MARINTEK Braceless (2015)	1/30	Novel Actuator
INNWIND.eu Model Test (2015)	1/60	Ducted Fan and Froude-scaled Rotor
NREL 5 MW Scaled CSC (2016)	1/30	rotor-nacelle-assembly (RNA) model
OC4 semisubmersible 5 MW wind turbine (2018)	1/45	Ducted Fan
H-rotor VAWT model (2018)	1/100	Aerodynamic similarity
NREL 5 MW Scaled (2018)	1/50	Full Rotor (Froude-Scaled)
NREL 5 MW Scaled (2019)	1/40	Multi-fan system
2-DOF hybrid HIL (2017–2020)	1/75	Full Rotor (Performance-Scaled)

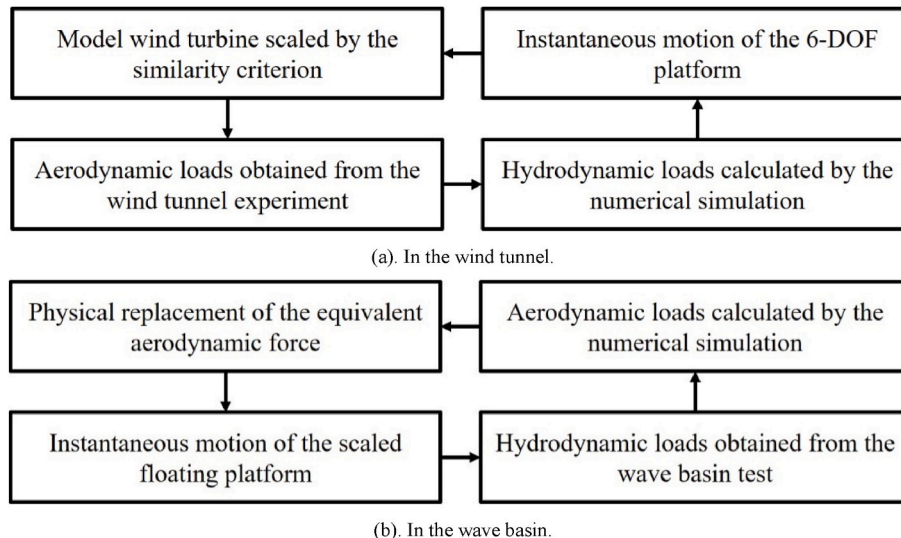


Fig. 7. MIL of the wind tunnel experiment and the wave basin test.

obtained effect can really be coupled to other parts as a standard. In the integrated design of the large FOWT, although the hydrodynamics of the platform determines the stability, the wind turbine capture wind energy to maintain sufficient power outputs. Therefore, aerodynamics is important enough to be quantitatively evaluated in wave basins and wind tunnels, and it will be discussed next.

3.4. Wave basin tests

The basin for aerodynamic tests provides the wind, wave and current environment after meeting the requirements of accommodating the scaled model of the wind turbine, floating platform and mooring system. Regular or random waves with different directions, frequencies and heights are provided by the wave makers of three main forms: air type, shaking plate type and punching box type. A wave elimination bank must be installed on the opposite side of the wave generator in the basin to eliminate incoming waves and avoid interference caused by wave reflection. The current pump can provide scaled currents with different velocities. Fig. 8 shows the marine engineering basin of MARIN in the Netherlands.

There are two keys for wind generation in the wave basin: steady wind and wind with low turbulence intensity. The widely used wind-making equipment is a regularly arranged fan array, which can produce relatively stable inflow. Since there are no wall restraints of the wind tunnel and professional wind detection devices, the quality of the airflow is not guaranteed and is easy to dissipate. In order to accurately obtain the aerodynamics, a larger multi-fans system was proposed. Using the system, the thrust error was less than 0.5%, the fastest change rate could reach 35 N/s, and up to 96% of wind energy could be reproduced [55]. Besides, because the undisturbed steady and uniform flow field cannot be generated in the wave basin, a towing test of the model wind turbine could also effectively avoid the spatial difference caused by wind [47].

Aerodynamic performances in the wave basin are often studied under the coupling with the hydrodynamics. Wake is generally not concerned due to the inaccurate inflow. When measuring the torque of the main shaft in the high frequency and large amplitude of the platform motion, great attention should be paid to the selection of the sampling frequency of the torque sensor. It may not meet the requirements, resulting in no obvious power fluctuations, although the average value is measured accurately. In the research of Sant et al. [56], the measured time-averaged power coefficient deviated from that of the fixed turbine. Although this deviation was small, it was considered to depend on wave conditions and mainly occurred at and above the optimal tip speed ratio. No matter what waves, there was no difference in the time-averaged power coefficient at a low rotor tip speed ratio. More research focused on the accurate reflections of thrust performances of the prototype and



Fig. 8. Marine engineering basin of MARIN [57].

the safety assessment under extreme load operations. Fig. 9 shows some typical wave basin tests worldwide.

In general, the challenges of wave basin tests are the similarity of the aerodynamics in the Froude number scale, the impact of oversimplification of the rotor and inflow on the accuracy of experimental results, and how to solve the scale effect. Therefore, some people turn to wind tunnel experiments, which will be explained in the next section.

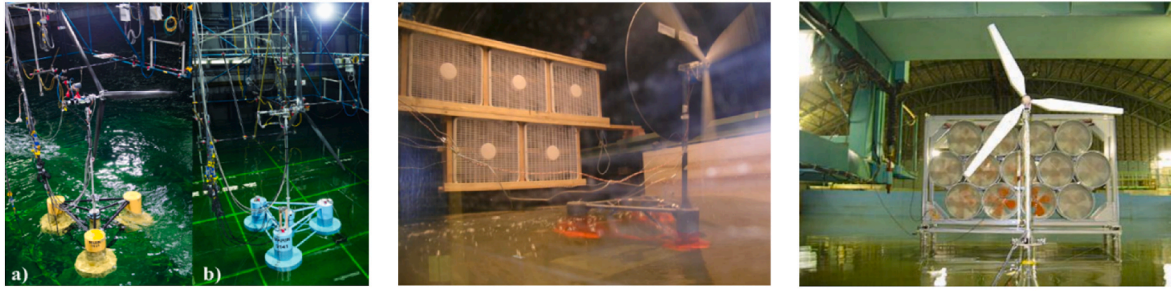
3.5. Wind tunnel experiments

Due to the limitation of the wave basin experiment, the whole system can be tested in the wind tunnel, and it's installed on a robotic platform that can realize the movement of certain degrees of freedom. The motion of this device can be applied by single or multiple degrees of freedom, and can provide unbiased velocity, amplitude and phase. In the MIL test, the hydrodynamic problem of incompatible Froude number is avoided by the numerically calculated platform motions to better present the real aerodynamic performance. Then the measured power, load and displacement need to be verified reliably, whether using the comparison of prototype data or simulation results [32,58]. Fig. 10 shows motion platforms with a single degree of freedom, two degrees of freedom, three degrees of freedom and six degrees of freedom.

The simplified methods mentioned above are mainly to explore the motion response under air-water coupling because they do not have a complete wind turbine structure. However, in the aerodynamic experiment, it is necessary to install a model wind turbine with similar aerodynamics to obtain accurate thrust, power and wake. The active and passive driving mode of the motor in the nacelle is applied: the active mode is that the rotor is controlled by the servo motor; The passive mode is that the rotor and the generator are driven by the wind, the motor provides resistance torque, and the rotation is adjusted by the variable electronic load. The wake under the two modes was discussed [59], and the results showed that the velocity, intensity and higher-order statistics of the wake were an acceptable consistency. A high tip speed ratio increased the instability of wake turbulence intensity. From the instantaneous angular velocity characteristics of the rotor, it was concluded that the active driving mode was more stable.

Compared with fixed wind turbines, the wake of FOWT is more complex, and its influence on the power generation of itself and downstream turbines is obvious, but previous work is limited. Surge motion significantly changes the wake, and the fatigue load will increase exponentially. At the same time, it will affect the mixing process of wake turbulence and the arrangement in the selection of the turbine site. The "wake reduction frequency" was also defined to evaluate the instability level of the system [52], and it was concluded that the surge motion amplitude was independent of the wake. Under pitch motion, the vertical flow velocity and the reduced velocity in the mainstream would lead to greater loads and less available kinetic energy of downstream wind turbines [54]. In the model experiment of two wind turbines, the pitch motion led to a long distance between the wind turbines to recover the wake and to obtain the sufficient power, but its ability to suppress fluctuation was expected to reduce the fatigue load [60]. The existing wake models are almost developed on the basics of fixed wind turbines and they need to be improved, especially considering the additional velocity and the displacement of pitch or surge motion. In addition, attention should be paid to the optimal layout when selecting the site of a floating wind farm, to reduce cost and increase power generation.

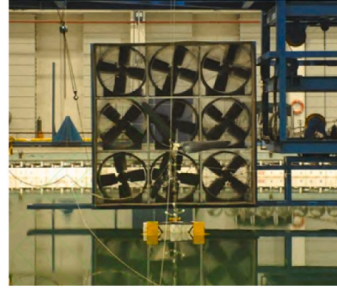
After the dynamic characteristics of aerodynamics and wake are obtained, some new control strategies are expected to be applied to improve the stability of the power and loads, while resisting the platform motion and its adverse effects. They are mainly focused on the yaw and pitch. For example, the tuning mass damper was installed in the FOWT nacelle [61], the stability of the power generation was extremely high, and the pitch, surge motion and lateral displacement of the tower top were significantly reduced by the mass adjustment. From perspective of the mechanical transmission, a cyclic pitch control technology



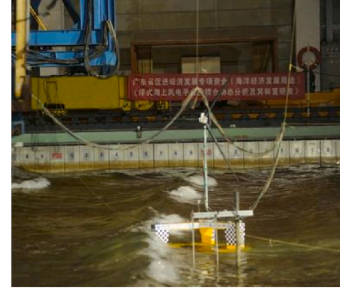
(a). DeepCwind project in MARIN.

(b). WindFloat project in America.

(c). NRMI project in Japan.



(d). Basin test in Shanghai Jiaotong University.



(e). Three Gorges pilot project in China.

Fig. 9. Typical wave basin tests worldwide.

and device were also given [62,63], which was used for aerodynamic load reductions and power efficiency improvements. Specifically, the cyclic pitch action is completed by the swash plate, connecting rods and control and driving equipment. The principle can be shown in Fig. 11. By controlling the horizontal displacement, inclination and azimuth of the swash plate, three control parameters can be realized: the average pitch angle, pitch amplitude and pitch phase. The controller drives the swash plate for horizontal displacement, then the connecting rods drive the collective pitch. On the other hand, the controller drives the swash plate to tilt to a certain azimuth, then the connecting rods drive the cyclic pitch. The wind tunnel experiment and simulation results showed that at the optimal tip speed ratio, different pitch phases and amplitude showed little effect on the average value of power coefficients and thrust coefficients, but the yaw moment and pitch moment changed linearly with the change of pitch amplitude, which suggested that the torque could be controlled by adjusting the amplitude and phase of the cyclic pitch. It was important to reduce fatigue loads, improve stability and reduce the cost of the operation and maintenance, and solve the lack of existing control technologies suitable for FOWT [64].

As a new electricity generation equipment formed by the integration of the wind turbine and floating platform, FOWT has gradually become the research hotspot in the field of wind power and offshore engineering in recent years. Aerodynamics and wake have been quantitatively analyzed by model experiments, and they are useful for evaluating the performance of FOWT. Besides, numerical simulations will also prove the correctness and reliability of the model test results, and this will be introduced in the next chapter.

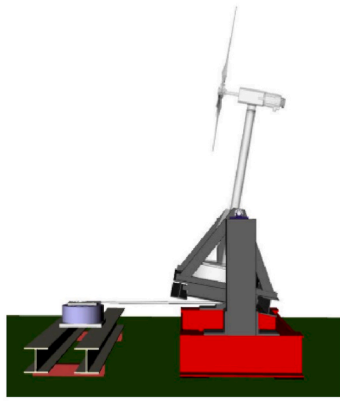
4. Simulations

There are three main factors affecting the FOWT aerodynamics: blade design, control method and platform motion, but the root cause is the change of the flow structure around the rotor. Among them, the blade design can be adjustments of the airfoil, chord and twist, and the setting of protrusion structures to forcibly change the airflow state, etc. These have been done on fixed wind turbines and achieved remarkable

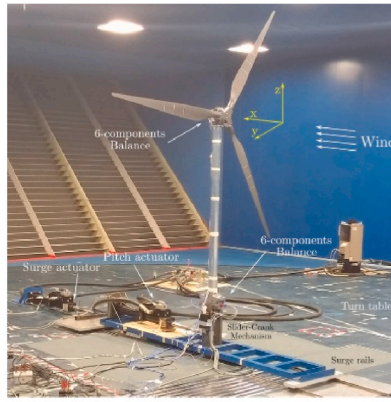
results [65,66], which certainly can also be extended to FOWT. The control methods include blade pitch control, yaw control, operation and shutdown control, etc., but obviously they are mostly designed for traditional fixed wind turbines and not all effective for the FOWT, and even have negative effects. There is not much exploration into the aerodynamic controls of FOWT [61,67–69], because it needs to be based on the motion data of the system, which is also unproven. Compared with the above two aspects, the platform movement is the stronger factor affecting the unsteady aerodynamics, because it directly interferes with the inflow and makes the wind turbine in a complex mixed wake of itself and others. Only by clarifying the dynamic performance in the moving state can the relevant control and design be carried out. In this part, numerical calculations of aerodynamics, power and wake under complex motions will be discussed.

4.1. Coupled algorithm

It is widely known that the platform moves aperiodically and non-linearly in six degrees of freedom during the operation, which is caused by the instantaneous coupling of the wind, wave and current. This involves the aerodynamics of the wind turbine and the hydrodynamics and structural dynamics of the mooring system and floating platform. In aerodynamic simulations, the unilateral load application is incorrect, but a cyclic process to solve the force, power and wake on the basis of the coupling of multiple fields, and feed-back to the whole system as data in turn. Therefore, coupling codes applicable to FOWT are integrated by several subset modules, which are almost the existing engineering calculation models, as shown in Table 3. It can be seen that the fully coupled model includes aerodynamics, hydrodynamics, structural dynamics and mooring, in which each part is coupled into Newton's formula to solve dynamic performances. Analyses in frequency and time domains are mainly performed. Frequency analysis can obtain aerodynamic fluctuations of the rotor, but cannot capture nonlinear properties under transient loading forces. In the time history analysis, the motion equation is solved by the time marching scheme to predict the status of FOWT at any time [70].



(a). Single degree of freedom (pitch).



(b). Two degrees of freedom (pitch and surge) [52].



(c). Three degrees of freedom (pitch, surge and heave) [41].

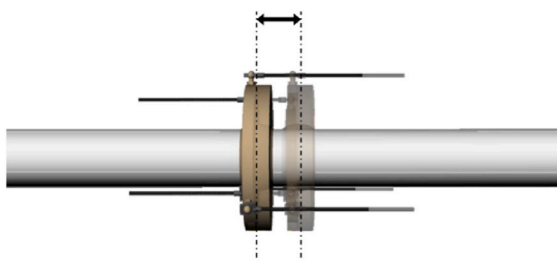


(d). Six degrees of freedom.

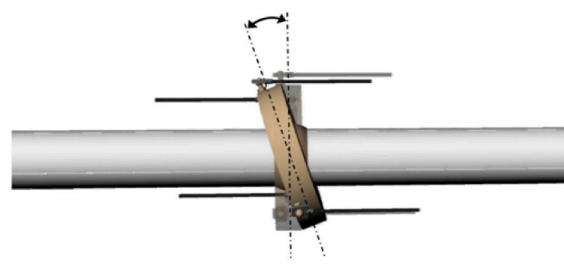


(e). Six degrees of freedom [30].

Fig. 10. Motion platforms with different degrees of freedom.



(a). Collective pitch control.



(b). Cyclic pitch control.

Fig. 11. Collective pitch and cyclic pitch control [62].

Table 3
FOWT multi-field coupling simulation codes.

Code	Institution	Aerodynamics	Hydrodynamics	Structural dynamics	Mooring
FAST	NREL	BEM/GDW + DS	Airy + ME, Airy + PF + ME	Modal/MBS + FEM	QS
GH.Bladed	GH	BEM/GDW + DS	Airy + ME	Modal/MBS + FEM	UD
ADAMS	MSC + NREL + LUH	BEM/GDW + DS	Airy + ME, Airy + PF + ME	MBS	QS/UD
SIMO	MARINTEK	BEM	Airy + ME	MBS	QS/MBS
HAWC2	RISO-DTU	BEM/GDW + DS	Airy + ME, Airy + PF + ME	MBS + FEM	QS/UD
3DFloat	IFE-UMB	BEM/GDW	Airy + ME	FEM	FEM/UD

Notes: BEM: Blade Element Momentum; GDW: Generalized Dynamic Wake; DS: Dynamic Stall; PF: Potential Flow; ME: Morison's Equation; MBS: Multibody System; FEM: Finite Element Method; QS: Quasi-static; UD: User Defined.

In the process of the aerodynamic simulation, multiple models can be selected, and they are developed based on fixed wind turbines. Most codes lack the ability to simulate the aerodynamics of long flexible blades and a high tower with large motion velocity, and how to couple models of other parts rather than simply stack is a difficult problem. In addition, new code needs to be developed to optimize and correct the defects caused by the existing coupling methods. Due to the complex structure of the wake, the formation of the tip vortex, the calculation accuracy of high Reynolds number flows and the blade model based on the dynamic grid need better algorithms and more computational resources. Some researchers have used open source codes to model and calculate the aerodynamics and wake under different floating platforms, mooring systems and wind-wave conditions [17,71], which enhances the flexibility and portability for FOWT simulations, but the results need to be compared with the results of wave basin or wind tunnel tests.

Fatigue, Aerodynamics, Structures, Turbulence (FAST), as a FOWT solver of full coupling codes, has been developed by NREL [72], and is relatively mature and open to the public. It focuses on the calculation and verification of aerodynamic and hydrodynamic loads and the coupled system behavior [73]. However, it also has limitations, which is reflected in that it can only model the viscous resistance of equal diameter cylinder at the platform centerline, and the quasi-static mooring line model is used, which cannot capture the dynamic characteristics of mooring lines, and does not simulate the dynamic interaction between water and mooring lines, mooring lines and seabed [36]. In addition, the linear diffraction model is applied, which cannot capture the average drift force, differential frequency excitation and sum frequency excitation captured by the second-order model. As for aeroelastic analysis, Fig. 12 shows the flow chart. The time-series inflow and parameters including airfoil information are input to the Aerodyn module, and then aerodynamic performances such as power and other loads in this module are analyzed coupled with the hydrodynamic and structural modules under the FAST environment. The non-viscous momentum theory with generalized dynamic wake and dynamic stall is used, but there are still a series of defects, which will be discussed in the next section.

4.2. Aerodynamic calculation methods

There are four methods mainly used for numerical simulations and analyses of the aerodynamics and wake: Blade Element Momentum (BEM) theory, Computational Fluid Dynamics (CFD) method, Free-Vortex Wake (FVW) method, and Boundary Element (BE) method [74]. Table 4 lists parts of calculation software using different methods.

BEM method was proposed by Betz and Glauert based on the momentum balance theory of the rotating disc and flow tube [70]. It is now widely used in the aerodynamic load calculation of fixed wind turbines. The blade is divided into some uncorrelated elements. The axial and radial induction factors distributed on the ring are iteratively calculated on each element, which can be seen in Fig. 13, and then the aerodynamic loads are superimposed on the whole blade. Relevant engineering corrections are added, such as the wake inclination, tip loss and so on [75]. Based on the assumption of static equilibrium wake, complex flows cannot be accurately calculated [76]. Computational costs of the

Table 4
Aerodynamic calculation methods and software [76].

Aerodynamic Calculation Method	Software Using This Method
BEM	FLEX5, FAST, HAWC2
CFD	EllipSys 3D, ACL, ANSYS
FVW	GENUVP, AWSM
BE	MATLAB, COMSOL

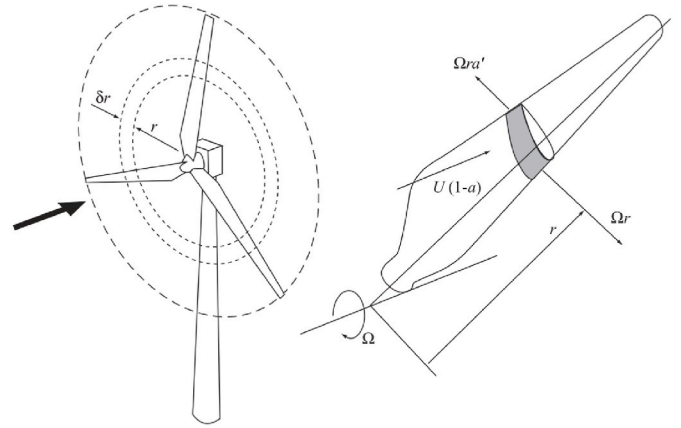


Fig. 13. An annular ring swept out by the blade element in blade element theory [86].

transition model, dynamic grid and turbulence model limit the application of this theory. In addition, for FOWT, the vibration of the platform will increase the computing complexity, and the wind turbine will be in the wake generated by itself [77]. The computational capacity of BEM remains to be argued.

CFD method can accurately and visually obtain flow information on the basis of solving the Navier-Stokes equation, and it needs to make a trade-off between the algorithm, grid and calculation accuracy, and needs a great cost, including time and capacity [75]. There are still some aspects to be improved. For example, it is necessary to give an appropriate turbulence model and obtain an approximate numerical solution through discretization. Large Eddy Simulation (LES), Direct Numerical Simulation (DNS), Reynolds Average Navier-Stokes (RANS) and other methods can be used to numerically calculate the turbulent field near the rotor, but the authenticity of the flow on the blade surface needs to be verified because the calculation is usually carried out under the assumption of ideal incoming flows and boundary conditions. The turbulence model has insufficient accuracy in calculating the transition position and other information, and relies on the correction of empirical parameters. It is time-consuming and depends on the experience of mesh generation [78]. Structured grid is more convenient to control the position of nodes and obtain a grid suitable for the distribution of grid nodes on the blade surface. Besides, the factors of platform motions should also be added for comprehensive calculation. It is difficult to establish the numerical model of wind-wave-current coupling in the same computational domain, and the transfer between the aerodynamic

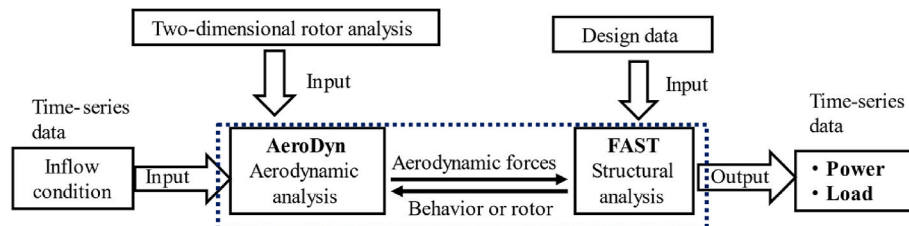


Fig. 12. Aeroelastic analysis flow in FAST.

load of the runner and the hydrodynamic load of the platform also needs to consider the corresponding structural calculation.

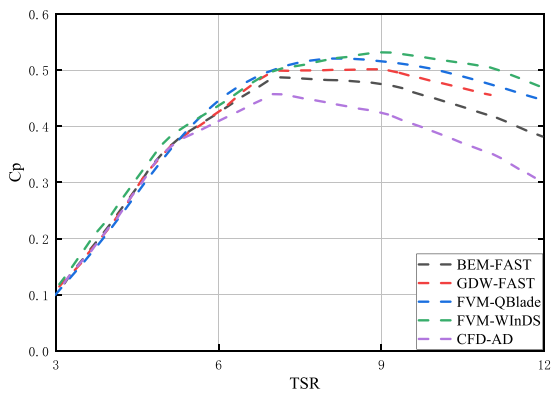
FVW is proposed based on CFD method. The three-dimensional rotation effect and dynamic stall model are taken into account. The aerodynamic performance, flow field characteristics and dynamic effect are calculated with the actual vortex structure around the blade, and the calculation accuracy and time are compromised [76]. Under the assumption of incompressibility and potential flow, the aerodynamic model is simplified as the incoming flow, attached vortex and free vortices. The free vortices are formed by vortex filaments drawn from the trailing edge of the blade, and they are composed of the trailing vortex and detached vortex, which are used to simulate the temporal and spatial changes of the attached circulation respectively. Compared with BEM, it can directly determine the vortex induced velocity of the blade element, rather than the average induced factor, and it is more efficient than CFD [79]. The reliability has been widely confirmed.

BE method is based on the potential theory and is suitable for solving steady, inviscid and irrotational incompressible flows [80]. The blade surface is discretized into multiple flat or curved panels, on which singularities such as the point-source, point-vortex, dipole and their combinations are attached. Some functions are used to determine singularities along the element, and aerodynamic performance information such as the velocity and pressure are calculated by solving boundary condition equations [81]. Different methods based on the geometric shape of elements, the type of boundary conditions and the form of the singularity distribution are applied to the different steady or unsteady aerodynamical analyses, such as the Panel method, Vortex Lattice method, etc. This method is relatively simple and universal for the aerodynamics and wakes calculation of low-speed flows, but the integration in the nonlinear domain will produce strong singularity, which makes it difficult to solve. Besides, it can also be used to study the effects of sudden changes in inflow, pitch angle and yaw angle on the aerodynamic loads and flow fields of the flexible rotor [82,83].

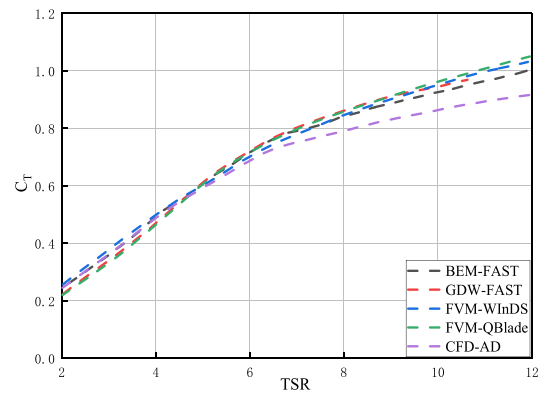
Due to ocean the atmosphere effect and the interference between wind turbines, FOWT in the operational environment must withstand the vertical shear and turbulence of inflow and platform motions under hydrodynamics. The power, thrust and other loads fluctuate strongly. The airflow generates vortices and falls off in the blade tip after passing through the rotor, and quickly splits and decays into heat dissipation. Downstream wind turbines will be seriously disturbed by the wake [84, 85]. All of these aerodynamic and wake characteristics will be reviewed next.

4.3. Process and results

Unsteady aerodynamics and wake under six degrees of freedom



(a). Power coefficients.



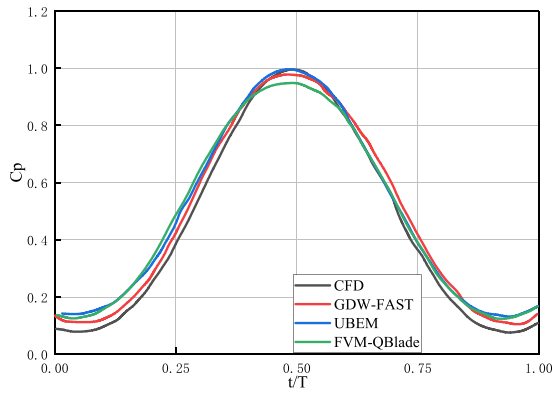
(b). Thrust coefficients.

Fig. 14. C_p and C_T against TSR for NREL 5 MW wind turbine under different models [92,93,96]. (WInDS: Wake Induced Dynamic Simulator.)

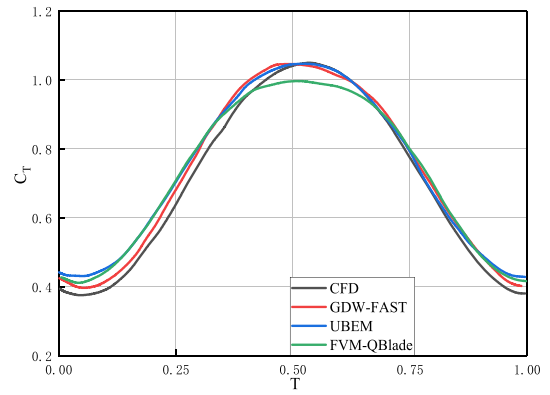
motions can be obtained by methods and algorithms mentioned above. Among all, pitch and surge are more important factors affecting the FOWT. The numerical simulation results of the power, thrust and wake under these motions will be comprehensively summarized below.

Before the main contents, static aerodynamics is the basis of dynamic analysis. Fig. 14 shows the curves of the power coefficient (C_p) and thrust coefficient (C_T) with the tip speed ratio (TSR) of the widely used NREL 5-MW wind turbine under different numerical methods, and they are drawn according to relevant articles. Under the rated or below rated operating conditions, the tip speed ratio is high, the flow is attached, and the aerodynamic output increases compared with the fixed wind turbine. In case of stall flows, the tip speed ratio is low, and the flow separation on the blade surface and the instability of pitch angle control will be caused [87]. Aerodynamic coefficients show similar shapes in different methods, but differ greatly in regions with high tip speed ratios.

In the aerodynamic studies under surge motions, De et al. [88] used the Dynamic Wake Model of BEM and moving Actuator Disc (AD) theory to calculate the influence of periodic motion on aerodynamic loads respectively. The results showed that surge motion was slow enough not to cause influence. With the increase in surge frequency, the aerodynamic damping increased, but it would not exceed 4% of the theoretical value in the AD theory. BEM combined with appropriate engineering models is still used to accurately predict aerodynamics until now. Meanwhile, The $k-\omega$ shear stress transport turbulence model of the open-source software OpenFOAM was used for computing the power and thrust under the coupling of platform motion and rotor rotation in 2016 [89]. Compared with the FAST calculation results, it showed that the method could better predict the transient flow effects of the rotor. This year, considerable research was carried out on the exploration of the thrust and power under different amplitudes and frequencies of surge motions. Typically, Fig. 15 showed the fluctuation of the power coefficient and thrust coefficient of the NREL 5-MW with the time of surge motions under different numerical methods, in which the tip speed ratio was 7, the amplitude was 4 m and the period was 10 s. It could be seen that the frequency and phase of fluctuations were the same with various methods, but the amplitudes showed a slight difference. Under surge motions with and the optimal tip speed ratio, the average power increased and the thrust decreased, and the time-varying thrust would increase the fatigue load of blades, shaft and other components. The increase in power coefficients was caused by the hysteresis of the aerodynamic model to flow changes, which was mainly caused by the increase of surge frequency [90]. Besides, the influence of platform motion on aerodynamics might be amplified due to the existence in the tower [91]. Important conclusions under other tip speed ratios and surging parameters were drawn: when the surge amplitude and



(a). Power coefficients.



(b). Thrust coefficients.

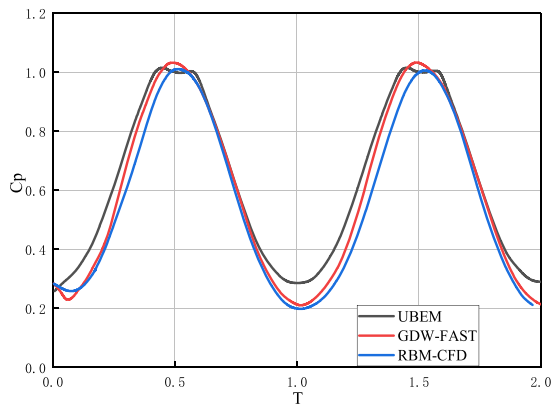
Fig. 15. C_p and C_T against surging time for NREL 5 MW wind turbine under different models [75,88,92,104].

frequency increased, the average power decreased at the low tip speed ratio and increased at high tip speed ratio. The average thrust would decrease at all tip speed ratios, but the variation range of thrust and power would increase [92,93]. The frequency and amplitude of the surge could be integrated into a reduced frequency, which was another factor affecting aerodynamics. As a result, the future design of FOWT should avoid operating under high tip speed ratio for a long time, and make the platform more stable under motions to significantly reduce fatigue loads.

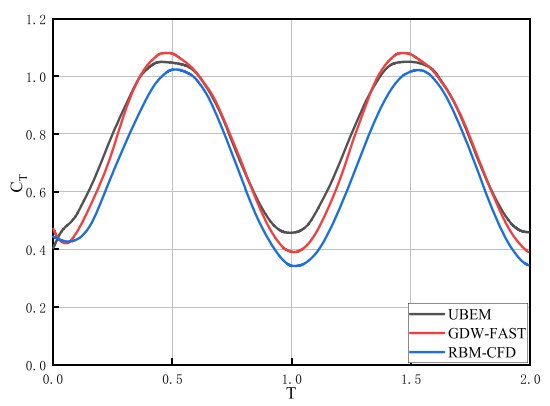
For the surge motion, some believed that the fluctuation of the aerodynamics was caused by the dynamic change of angle of attack [94], while others believed that it was mainly related to factors such as the wake expansion, tip vortex fluctuation and shedding vorticity [95]. Results of aerodynamic performances under the vortex-wake-blade interaction were interpreted in 2015, and different numerical methods were compared. The vorticity caused by surge motion increased with the change of tip speed ratio, and surge motion would increase the amplitude of the fluctuating thrust and power. Here, the simulation of the AD model, BEM model and GDW model are compared [96]. Moreover, the aeroelastic method based on FVM was used to study the interaction between the rotor and wake firstly [97]. The surge motion affected the evolution of the wake, resulting in the periodic deformation of the wake and the rupture of the spiral wake vortex [98,99]. Due to the disturbance of platform motion and wake vortex, the flow spacing of tip vortices changed, and when the wind turbine moved backward, the interaction effect decreased. When the wind turbine moved forward, the high-speed

wake area became larger [77]. The interaction wakes between wind turbines were more sufficient with the increase of motion amplitude and frequency. The influence of amplitude on wake velocity was greater than that of frequency. It is necessary to consider the disturbance of wake to the wind turbine itself and downstream ones in the aerodynamic design and wind farm layout.

In unsteady analyses under pitch motions, Tran et al. [100] compared three numerical methods: unsteady BEM, FAST using BEM and GDW. No significant difference was found until the pitch amplitude increased to 4° . As the amplitude and frequency continued to increase, the aerodynamic performance fluctuated greatly. Fig. 16 showed the fluctuation of power coefficients and thrust coefficients of the NREL 5-MW wind turbine with the pitching time under different numerical methods, in which the tip speed ratio was 7, the amplitude was 4° and the period was 10 s. The curves were reproduced from existing simulations, and the conclusions were similar to those in the surge motion. Under this condition, the pitch motion showed large fluctuations of aerodynamic coefficients, which could reach 32.8%. Performances under other pitching parameters were also described in detail. Under the high frequency and large amplitude, when the platform moved backward, it could promote the combination and recovery of wake, and increase the power. When the platform moved forward, it would cause a stall, lead to blade flutter and increase the thrust and torque of the rotor [74]. On the contrary, loads caused by wind would increase the overturning moment of the wind turbine, thus increasing the average value of pitch motions [101]. Conclusions in other research were consistent



(a). Power coefficients.



(b). Thrust coefficients.

Fig. 16. C_p and C_T against pitching time for NREL 5 MW wind turbine under different models [104]. (RBM: Rigid Body Motion).

with the above [102], but a new explanation was that the power fluctuation was mainly caused by the change of the fluid field and it depended on the relationship between tip speed ratio and angle of attack with time. Compared with surge motions, the aerodynamic fluctuation was five times larger in equivalent conditions, and the power fluctuation was two times that of thrust [103]. Compared with yaw at the same frequency and amplitude, the influence of aerodynamic power and thrust of pitch motion was 12–16 times that of the yawing motion, which was calculated under advanced CFD [104]. In general, it is necessary for FOWT to ignore the small power increase caused by pitch motions and design a more stable platform with a smaller frequency and amplitude.

As for pitch motions, Sebastian et al. [105] calculated wake characteristics of the NREL 5-MW wind turbine using FVW method in 2012. It was concluded that the interaction between the rotor and wake caused by pitch motions was very complex to explain, but the impact of platform motions on aerodynamics was insignificant, which was only a rough qualitative judgment and needed to be accurately proved. Then a partial vortex ring state in some pitch motion (amplitude 5° and period 8.8 s) was found [106]. What's more, the pitch motion would cause obvious wake deflection in the near wake region and insufficient wake velocity. The periodic change of pitching angle would increase the wake width and turbulence intensity. Some specific conclusions are drawn: when the turbine was in the state of tilting forward, it would be in a turbulent wake, and the blade tip vortex was the main factor controlling the rotor performance [107]. When it was in the backward tilting state, the interaction between the blade and wake was stronger, and the wake intensity after the rotor was stronger, which was similar to the previous conclusion [104]. There are few wake models applicable to FOWT, so wind tunnel measurements and the above numerical simulation results can better guide its correction and development.

A prominent problem in simulations is that the fluctuating power coefficients under platform motions will exceed the limit of Betz theory, as shown in Figs. 15 and 16. This is because the velocity used for aerodynamic coefficient calculation is selected as the wind at infinity. This velocity should be the relative speed of the platform motion and incoming flow. Although the load analysis will not be affected, the dimensionless coefficient will be completely opposite to the real situation, which requires high attention in future calculations.

Large scale and inertia are beneficial to analyze the dynamic aerodynamics of FOWT, and software development of high-fidelity calculations for dynamic characteristics is of great significance. So far, simulations can only provide effective qualitative inference, and the specific quantitative results need to be compared with the model test, but this does not mean that the numerical method is not persuasive, it is still the fastest and most economical research method.

4.4. Other aspects

In addition to the above platform motions, the aerodynamics is affected by many other aspects, such as control means, modeling methods, operating conditions and so on.

Aerodynamics will be different under yaw conditions, which is mainly caused by advancing & retreating and skewed wake effect [108]. The superimposed wake shows that the impact of wake on downstream turbines may be underestimated, and the upstream yawing turbine reduces the maximum turbulence intensity and insufficient wake velocity [109]. More experimental and simulation data are needed in the future to quantify the reasonable influence area when the wake is tilted by yaw. Moreover, the angle of attack will change periodically under yaw conditions, resulting in aerodynamic load fluctuations and dynamic stalls. The change of angle of attack is simultaneously affected by the blade advancing & retreating effect, the non-uniform induction effect and the upwind & downwind yawing effect [76].

Sebastian et al. [110] proposed a method to identify platform modes related to aerodynamics in 2012, and gave the reason why the flow field is more complex than offshore fixed wind turbines. He also used Wake

Induced Dynamics Simulator to calculate the aerodynamic load and wake evolution [111], and the calculation accuracy was much higher than that of BEM method. Pustina et al. [112] Proposed a fully coupled aero-hydro-servo-mechanic model, and verified the effectiveness of the control scheme to suppress the fluctuation of power and structural fatigue load under the interaction of the wave and wind. In addition, a model with 17° of freedom of FOWT was established to analyze the gyroscopic effect [113]. It was concluded that the gyroscopic effect could not be ignored in both idle and running states, otherwise, it would lead to excessive overestimation in the tower torque design. Meanwhile, an active shutdown strategy was proposed to cope with the extreme thrust and torque response in typhoon weather, which was based on the aerodynamic numerical calculation, and the safety and reliability of the wind turbine were greatly guaranteed [114]. Although some attempts have been made in the numerical simulation of control methods, experimental tests are still the most powerful evidence to verify the effectiveness.

Sudden or large movements of the platform may occur in some extreme cases, such as gusts, typhoons, freak waves, tsunamis, earthquakes and other survival scenarios. These violent motions will have a great impact on the aerodynamics and wake of the wind turbine, resulting in serious consequences such as mooring line or tendon failures, pitching errors, etc. However, there are few aerodynamic simulations under the coupling of aero-hydro-servo-structure. BEM method in FAST can obtain macro aerodynamics relatively simply and economically, and is suitable for qualitative analysis. Ma et al. [114] found that under the typhoon of high velocity and strong turbulence, the thrust and power would rise sharply, which was considered to be caused by pitching fault. The rated-power control kept the power at a lower level than the generator-torque control, which was more conducive to coping with typhoon impact. Li et al. [115] used OpenFAST and obtained that when one blade was stuck, the unbalanced aerodynamic force would amplify fatigue loads under rotation, and the maximum acceleration of the nacelle increased by 27.9%. In the study of mooring line or tendon failure [116–118], the mooring system could be modeled by FEM method, and the transient motion such as pitch or yaw would reach 6 times of the normal state, and even higher than the extreme value under the 50 years' operation. However, thrust and power were insensitive to the strong platform motion, and this was caused by variable speed and pitch control strategy. For the reflection of internal flows and wakes, CFD method coupled with FEM is more intuitive for aerodynamic research in extreme environments, but it will generate more computational overhead [119]. Under the influence of typhoon, the flow field would show high velocity and turbulence. The huge motion would lead to a deep stall before shutdown, aerodynamic loads rose sharply, and interactions between blade and wake were enhanced [120]. At the same time, the tower shadow effect would also aggravate this effect [121]. In addition, BE method combined with potential theory is also applicable to the aerodynamic analysis of sudden changes of the flow field, including abrupt wind velocity, pitching and platform motion [82,83,122]. Aerodynamics will display as hysteresis with respect to time, and the dynamic stall and dynamic inflow effects can be accurately captured. The application of this method on FOWT is very meaningful but rarely seen. Compared with the existing numerical methods, the integrated simulation with multi-model coupled needs to be developed to calculate the aerodynamics under the aero-hydro-servo-elastic coupling mechanism.

5. Conclusions

This review summarizes the aerodynamic and wake characteristics of wind turbines installed on floating platforms under specific motions. The continuous emergence and development of floating platforms and projects reveal that FOWT will become the main promoter of net-zero carbon emissions. The similarity criterion and model scaling of the wave basin or wind tunnel experiments, and numerical simulations

including the algorithm and modeling are discussed in detail. A cyclic pitch control technology is introduced, and it's expected to realize the effective adjustment of reducing aerodynamic load fluctuations.

The completely geometric scaled model cannot satisfy the same aerodynamics as the prototype because of the huge difference in Reynolds number, and the thrust will be seriously reduced in experiments. On this basis, a simplified approach of numerically and physically substituted rotor need to meet the requirements of real-time and high fidelity, and it is difficult to achieve. The full approach of the rotor with blade reconstruction is more reasonable to research aerodynamics and wakes. The determination of platform motion parameters and the guarantee of similar dynamic thrust and power are important in similarity criterion and scaling of the model respectively. The influence of the amplitude and frequency of pitch or surge motions on the average power and thrust is not particularly obvious, but the fluctuation is serious. Under pitch motion, the reduced velocity of the mainstream and vertical velocity behind the rotor will lead to greater loads and less available kinetic energy of the downstream wind turbine. The cyclic pitch control technology based on the mechanical transmission can be applied to FOWT, which effectively reduces fatigue loads and guarantees output by adjusting the phase and amplitude.

CFD method intuitively calculates the flow field, especially caused by the inclined platform which cannot be achieved by the traditional BEM theory, but it needs the full balance in cost and accuracy, and FVW is a more effective solution. Under high frequency and large amplitude pitching motion, the fluctuation of the aerodynamic coefficient is as high as 32.8%. When the platform moves backward, the combination and recovery of wake are promoted, and the average power increases. When the platform moves forward, the stall and strong vibration may occur, the average thrust and moment increase. In the near wake, the flow deflection is obvious, the velocity is insufficient, and the periodic change of pitch angle will increase the wake width and turbulence intensity. Under surge motion, the average power increases and the thrust decreases, but the time-varying thrust will increase fatigue loads of blades, shafts and other components. The influence of amplitude on wake velocity is greater than that of frequency, which can be integrated into the reduced frequency for analysis. As a result, it is necessary to ignore the small power increase caused by pitch or surge motion in the design, so as to make the platform have more stable dynamic performances.

In the future, designs of the scaled model should mainly focus on the similarity of dynamic behaviors. MIL experiments in wind tunnels should be carried out more in the high-fidelity and real-time numerical and physical environment for its flexibility and controllability of motions, so as to make it possible to accurately reproduce dynamic aerodynamics of the prototype. At the same time, the integrated simulation with turbine-floater-mooring coupled model needs to be established and standardized to calculate the aerodynamic characteristics under the aero-hydro-servo-elastic coupling mechanism. All these efforts can better promote the design and performance evaluation of large FOWT.

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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