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Floating offshore wind turbine aerodynamics: Trends and future challenges

Daniel Micallef [a,*], Abdolrahim Rezaeiha [b,c]

[a] University of Malta, Malta
[b] KU Leuven, Belgium
[c] Eindhoven University of Technology, The Netherlands

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ABSTRACT

Offshore wind turbines present novel challenges to the field of rotor aerodynamics because of complex behaviours associated with six degrees of freedom motions of the platform. The number of scientific articles on these specific issues has been steadily increasing during the past ten years, reflecting the criticality of aerodynamics to overcome the specific barriers in this area. In this work, we aim to comprehensively review the present literature in order to identify the existing knowledge gaps in this field of research and provide an outlook for future directions. This paper is not purely about aerodynamics as an isolated element of floating offshore wind turbine science. Rather, due to the multi-physics nature of the system, we emphasise the current trends in aerodynamics in relation to other fields such as platform hydrodynamics and control. Critical analysis of the literature reveals that the most common approaches are to study the problem in a coupled or uncoupled manner. The latter is generally done by prescribing platform motions. The existing literature has been so far mainly focused on an isolated solo floating turbine and the studies on the interactions between the floating turbines are scarce. These trends are critically assessed in order to provide the reader with a holistic overview of the current direction. We also present six major challenges in order to provide a future perspective of the existing research opportunities in floating offshore wind turbine aerodynamics.

1. Introduction

1.1. Background

The growth of offshore wind has been gradually increasing with a cumulative capacity of 22GW by 2019 [1]. With the substantial exploitation of wind energy harvesting in shallow waters, deep water offshore wind will be the next energy source to be unlocked. However, to exploit the potential of wind energy in deep waters, floating wind turbines could provide a solution. The shift towards floating offshore wind energy in deep water is reflected in the increased number of projects and developments given in Table 1. As a result of the growth in investments, levelised Cost of Energy (LCOE) for floating wind is expected to decrease at a very fast rate and is expected to reach 40–60 €/MWh by 2030 [2–4]. These price values are highly dependent on the scale of the undertaking but the LCOE trajectory is expected to decline with the commercialisation of Floating Offshore Wind Turbines (FOWTs) [5,6]. More recently LCOE analysis has been carried out on a FOWT with a particular floater type by [7].

The influence of rotor aerodynamics and its uncertainty is still less clear since most of these studies are based on the use of simplistic approaches for the evaluation of the power generation from the wind farm and for the calculation of LCOE. Nevertheless, the importance of aerodynamics to the development of FOWTs goes beyond the concept of LCOE. In terms of rotor blade design, in view of the floating motion of the platform, the velocities experienced by the blades undergo large variations. More complex aerodynamic phenomena occur which are not present in fixed rotors. For example, the blade of a rotor could interact with its own (highly unsteady) wake and this could result in dramatic large-amplitude fluctuations in the aerodynamic loading and thus the power output. Consequently, given the flexibility of longer slender blades, abrupt blade deflections could occur due to fluid–solid interaction. In addition, the periodic motion of the platform would also result in periodic variations in loading. All of these factors influence other turbine design considerations including, for instance, blade materials and manufacture and blade control. Fatigue damage could also be amplified which limits the turbine lifetime.

FOWTs also present new challenges in the design and analysis of the rotor and its platform. Such challenges were not experienced with the fixed rotors for both onshore and offshore. There exists several traditional floater types such as semi-submersible, spar, barge, tension-leg platform (TLP) floating platforms. These are mainly adapted from the oil and gas industry (see Fig. 1). Furthermore, research on FOWTs

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* Corresponding author.
E-mail address: daniel.micallef@um.edu.mt (D. Micallef).

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Nomenclature

a	Axial induction factor [-]
a'	Tangential induction factor [-]
A_x	Rotor surge amplitude [m]
ω_x	Rotor surge frequency [Hz]
α	Angle of attack [°]
B	Number of blades [-]
c	Chord length [m]
C_d	Drag coefficient [-]
C_l	Lift coefficient [-]
C_n	Normal force coefficient [-]
C_t	Tangential force coefficient [-]
C_T	Thrust coefficient [-]
C_P	Power coefficient [-]
H	Hub height measured from the centre of rotation to the pitching axis [m]
Ω	Rotor rotational speed [rad/s]
ϕ_x	Surge phase shift [rad]
P	Blade power [W]
P_{rotor}	Rotor power [W]
ϕ	Relative inflow angle [°]
Φ	Blade azimuth angle [°]
r	Rotor radius at section [m]
R	Rotor radius [m]
R_r	Rotor root radius [m]
ρ	Air density $[kg/m^3]$
t	Time [s]
T	Blade thrust force [N]
T_{rotor}	Rotor thrust force [N]
θ	Sum of blade twist and pitch angles [°]
θ_x	Rotor yaw angle [°]
θ_y	Rotor pitching angle [°]
θ_z	Rotor roll angle [°]
$\dot{\theta}_x$	Rotor yaw angular velocity [rad/s]
$\dot{\theta}_y$	Rotor pitching angular velocity [rad/s]
$\dot{\theta}_y$	Rotor roll angular velocity [rad/s]
U_∞	Freestream wind velocity [m/s]
$\mathbf{V}$	Velocity vector at a blade section [m/s]
v	Tangential velocity [m/s]
V_{blade}	Blade relative velocity [m/s]
V_{rel}	Flow relative velocity [m/s]
V_x	Rotor velocities in the heave direction due to platform motions [m/s]
V_y	Rotor velocities in the sway direction due to platform motions [m/s]
V_z	Rotor velocities in the surge direction due to platform motions [m/s]
w	Axial velocity [m/s]
x	Distance along the heave direction [m]
y	Distance along the sway direction [m]
z	Distance along the surge direction [m]
$\dot{x}$	Rotor heave velocity [m/s]
$\dot{y}$	Rotor sway velocity [m/s]
$\dot{z}$	Rotor surge velocity [m/s]

has been targeting novel floater types as well, where a few are discussed by [8] and [9]. In addition, a floating platform poses new challenges with respect to the estimation of the unsteady hydrodynamic loading mainly due to the fluid–solid interaction of the floater with the regular and irregular waves. Whereas this paper focuses on aerodynamics, these important aspects will still be touched upon in this work.

Table 1
Announced pre-commercial floating offshore projects.
Source: Adapted from [2].

Wind farm	Country	Capacity [MW]	Commissioning date
Hywind	Scotland	30	2018
WindFloat	Portugal	25	2019
Flocan 5 Canary	Spain	25	2020
Nautilus	Spain	5	2020
SeaTwirl S2	Sweden	1	2022
Kincardine	UK	49	2020
Forthwind Project	UK	12	2020
TetraSpar	Norway	3.6	2020
EFGL	France	24	2021
Groix-Belle-Ile	France	24	2021
PGL Wind Farm	France	24	2021
EolMed	France	25	2021
Katanes Floating Energy Park -Array	UK	32	2022
Hywind Tampen	Norway	88	2022

1.2. *Objectives, general approach and target audience*

The main aim of this article is to establish the current knowledge gaps and challenges of FOWT rotor aerodynamics using the now well established research work on fixed rotor aerodynamics The general approach adopted is to critically assess the current literature and establish the key conclusions supported by the work of various authors. To this end, a clear map of the various specialised topics in FOWT rotor aerodynamics is presented. On the one hand, some of the areas, which shall be identified, build upon the already existing knowledge of the fixed rotor case and simply extend that knowledge to include dynamic effects induced by the turbine's complex motions. Other areas of research are novel and highly specific and therefore require a more in-depth discussion to project future directions in such fields. Key challenges are then highlighted with a view of addressing the gaps in the current state of the art.

This work should be of particular interest to researchers working on FOWTs including topics such as control engineering, foundations, structural integrity, wind farm optimisation and rotor aerodynamics. The key challenges identified are intended to stimulate further research in the field by the wind energy community. The paper should also serve as a reference point to industry players in order to become familiar with the latest trends in the wind energy science of FOWTs.

1.3. *Paper structure*

The paper starts in Section 2.2 with an introduction of the background theory of FOWT aerodynamics, highlighting the main differences compared to the fixed rotor case. The aim of this section is to introduce the unfamiliar reader to the new complexities that arise when rotor motions, as found in FOWT operations, are introduced. The section paves the way to Section 3.1 which gives a complete road-map of the mainstream FOWT research available in literature, further highlighting the pivotal role of aerodynamics to the research community.

The paper continues in Section 3 to critically analyse the current literature of FOWT aerodynamics, particularly during the past ten years during which this niche field of study emerged. This section also provides a historical picture of the research developments moving in parallel with those found in the industry. Developments in studies related to platform motions, loads, power performance, wakes and modelling approaches are assessed.

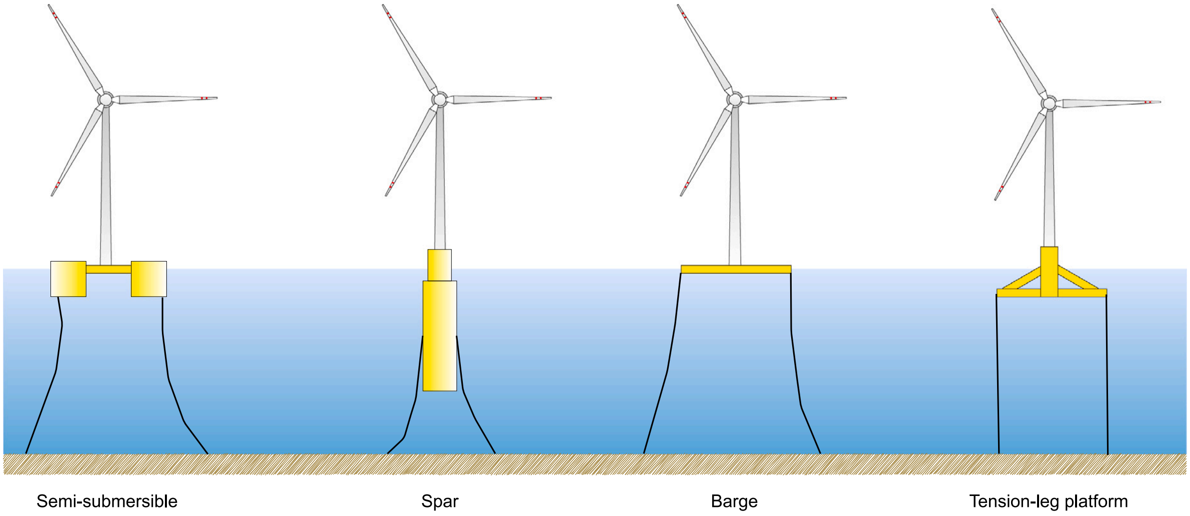


Fig. 1. Different floater types: (from left to right) Semi-submersible, spar, barge, tension-leg platform (TLP).

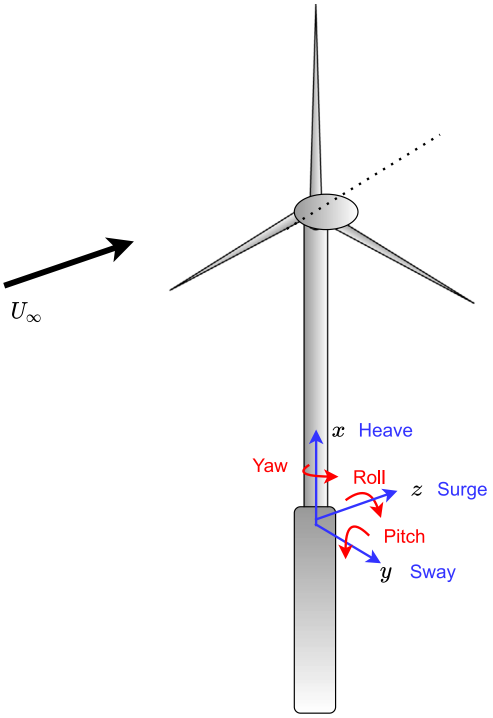


Fig. 2. FOWT motions including all six degrees of freedom.

The subsequent section, Section 4, uses the analysis of the literature to provide insight into current trends and future directions of FOWT aerodynamics research. The research map identified earlier in the paper is now populated with the established gaps and a discussion on the challenges and future outlook is made for the benefit of guiding researchers to research questions worthy of investigation.

2. Theory and state of the art methods

This section introduces the basic aerodynamic theory specific to FOWT rotors. In addition, the established state of the art in rotor aerodynamics and the current limitations will be briefly described. This precedes a more detailed discussion of the literature related to FOWT aerodynamics.

2.1. Platform motions

The 6-Degrees of Freedom (DOF) motions of a FOWT are depicted in Fig. 2. The resulting rotor velocities due to platform motions consist of a combination of translations and rotations which can be described by the following equations (adapted from [10]):

$$V_x = \dot{x} + \dot{\theta}_y z - \dot{\theta}_z y \tag{1}$$

$$V_y = \dot{y} + \dot{\theta}_z x - \dot{\theta}_x z \tag{2}$$

$$V_z = \dot{z} + \dot{\theta}_x y - \dot{\theta}_y x \tag{3}$$

where V_x, V_y, V_z are the rotor velocities due to the platform motions. $\dot{x}$, $\dot{y}$, $\dot{z}$ are the heave, sway and surge velocities. x, y and z are the distances from the centre of rotation. $\dot{\theta}_x$, $\dot{\theta}_y$ and $\dot{\theta}_z$ are the angular velocities around the yaw, pitch and roll axis.

These velocities have to be included when establishing the relative flow conditions found at the rotor blades. These will in turn affect the loads and the power production. One of the most important approaches found in rotor aerodynamics is known as the Blade Element Theory (BET). This has also been used in combination with the momentum theory which is described in well established texts such as [11]. This combination is more commonly known as the Blade Element Momentum (BEM) approach. In Section 2.2, BET will be described in more detail since this is also the foundation for more advanced modelling techniques.

2.2. Blade element theory for a FOWT rotor

Two major platform motions (surging and pitching) are considered in this section and a concise aerodynamic analysis of a blade section is performed. This will provide the reader with an appreciation of the fundamental physics. Fig. 3 provides a representation of the notation used for the various kinematics of the blade and turbine motions. The freestream velocity is denoted by U_∞, the turbine surge displacement is denoted by z and the rotor pitch is denoted by θ_y. The blade azimuth angle is given the symbol Φ while the blade rotational speed is denoted by Ω. The hub height from the centre of rotation of the pitching axis is denoted by H. Fig. 4 shows the velocity vectors of the blade and the airflow acting relative to a section at radius r from the centre of rotation of the rotor. The coordinate system denoted by the z and x directions is used to define the axis from which pitching angle is measured around the y axis. The z_0 and x_0 axis represent the rotor plane normal and tangential axis respectively. Note that the presented velocity vectors assume zero rotor precone angle, blade prebend, shaft tilt angle and hub overhang. The sum of the twist and pitch of the blade have a symbol θ. The relative blade velocity is V_{blade} and the relative flow velocity is V_{rel}. The relative inflow velocity angle to the vertical plane is given by ϕ. The axial induction (relative to the rotor plane) is denoted by a and the tangential induction (relative to the rotor plane) is denoted by a'. The effects of surge and pitching motions are reflected in $\dot{z}$ and $(H + r\cos\Phi)\dot{\theta}_y$, respectively, where the former corresponds to the rotor surge velocity and the latter corresponds to the rotational pitching velocity around the pitching axis.

Referring to the flow velocity, the vectors describing the velocity in the axial direction w and the tangential direction v relative to the rotor plane axis $z_0 - x_0$ are given by:

$$\boldsymbol{V} = \begin{Bmatrix} v \\ w \end{Bmatrix} = \begin{Bmatrix} U_\infty(\cos\theta_y - a) + \dot{z}\cos\theta_y + (H + r\cos\Phi)\dot{\theta}_y \\ r\Omega(1 + a') - (\dot{z} + U_\infty)\sin\theta_y \end{Bmatrix} \tag{4}$$

Where a and a' are the axial and tangential inductions. These inductions are inherently time dependent because of the dynamic effects caused by the surge and pitching motions. The instantaneous quantities at time t would be $a(r,t)$ and $a'(r,t)$. The time varying inflow angle $\phi(r,t)$ is given by

$$\tan\phi(r,t) = \frac{v}{w} \tag{5}$$

The angle of attack α can be found by adding the twist and fixed pitch angle (the sum of which is denoted by θ) of the blade with the inflow angle. Note that θ is negative when measured clock-wise with reference to the rotational axis definition of Fig. 4.

$$\alpha(r,t) = \phi(r,t) + \theta \tag{6}$$

Due to the unsteadiness of the problem [12], the lift C_l and drag C_d coefficients will now be unsteady to an extent determined by the reduced frequency k (see [13]). Relative to the rotor plane, the normal C_n and tangential coefficients C_t as functions of radius and time:

$$C_n(r,t) = C_l(r,t)\cos\phi(r,t) + C_d(r,t)\sin\phi(r,t) \tag{7}$$

$$C_t(r,t) = C_l(r,t)\sin\phi(r,t) - C_d(r,t)\cos\phi(r,t) \tag{8}$$

The blade elemental thrust $dT(r,t)$ is given by:

$$dT(r,t) = C_n(r,t)\frac{1}{2}\rho V_{rel}^2(r,t)c(r)dr \tag{9}$$

Where $c(r)$ is the chord as a function of radius and $V_{rel}(r,t)$ is the blade relative velocity as a function of radius and time.

The overall thrust $T(t)$ on a rotor blade is found by integration of Eq. (9) over the radius:

$$T(t) = \frac{1}{2}\rho\int_{R_r}^{R} C_n(r,t)V_{rel}^2(r,t)c(r)dr \tag{10}$$

Where R_r is the root radius. The total rotor thrust is given by the addition of Eq. (10) over all blades, where B is the number of blades.

$$T_{rotor}(t) = \sum_{i=1}^{B} T_i(t) \tag{11}$$

The thrust coefficient is given by:

$$C_T(t) = \frac{T_{rotor}}{\frac{1}{2}\rho U_\infty^2 \pi R^2} \tag{12}$$

The elemental power $dP(r,t)$ is found by

$$dP(r,t) = C_t(r,t)\frac{1}{2}\rho V_{rel}^2(r,t)c(r)rdr\Omega \tag{13}$$

and the power extracted from a single blade is given by

$$P(t) = \frac{1}{2}\rho\Omega\int_{R_r}^{R} C_t(r,t)V_{rel}^2(r,t)rc(r)dr \tag{14}$$

The total power is given by adding Eq. (14) over all blades.

$$P_{rotor}(t) = \sum_{i=1}^{B} P_i(t) \tag{15}$$

The power coefficient is

$$C_P(t) = \frac{P_{rotor}}{\frac{1}{2}\rho U_\infty^3 \pi R^2} \tag{16}$$

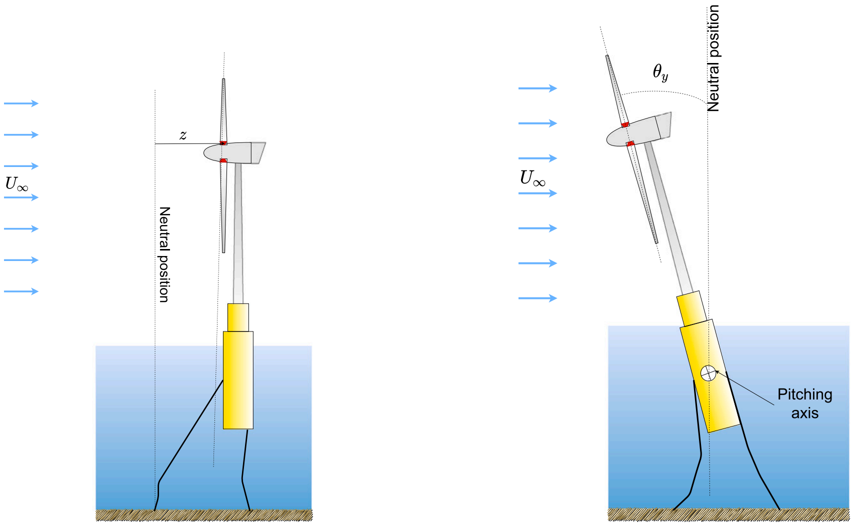
2.3. State of the art methods

The methods that have been used throughout the past 20 years or so for wind turbine research have been adopted for the analysis of FOWTs. The BEM model is still very commonly used today. For the sake of brevity, the reader is referred to [11] for a full description of BEM theory. Unfortunately such a theory has a major limitation which does not allow for 3D flow across various rotor radial elements. For FOWTs, the flow three-dimensionality can be extensive, making such a limitation even more important. If applied to FOWTs, an additional requirement of BEM is to use dynamic wake models (see [14] and [15]) to account for the transient nature of the flow. The suitability of such models will be discussed on the basis of the latest literature in Section 3. BEM does not model the flow physics of the wake and for such studies, more advanced approaches are necessary.

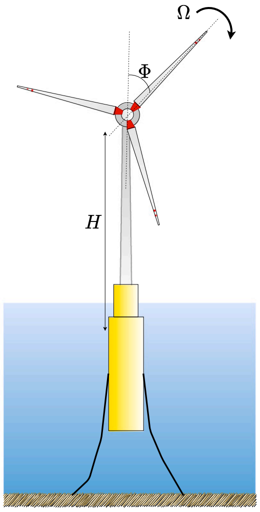
In contrast, Free Vortex Methods (FVM) are able to model the wake using vortex filaments which are released from the blade and are therefore able to account for the wake physics (see [16] for the full theory). The inherently unsteady nature of FOWT wake are modelled by means of shed vorticity. The method is based on potential flow theory. The blades can be modelled by means of lifting lines or source/doublet panels. If airfoil data is employed to prescribe loads on the lifting line, the airfoil data will affect the accuracy of the model since in many cases, only static airfoil data is available. Corrections for dynamic effects and stall can however be employed. The BET, described earlier, can be used to establish the blade loading. On the other hand, if the blade is modelled physically using panels, the onset of stall cannot be captured without the use of additional models that are able to account for this separation.

Another approach which is commonly used is the Actuator Line (AL) or Actuator Disc (AD) Computational Fluid Dynamics (CFD) approach. Using BET, the loads on the flow can be applied by means of a source term in the momentum equation. In the AL case, the loads are applied at the blade locations. With the AD, the loads are distributed over all the cells in the disc representing the rotor area. As with the lifting line FVM, these methods depend on the prescription of airfoil data. In addition, the application of the loads on a line or a disc has to be smeared out for numerical purposes. The Navier–Stokes equations [17] are then solved numerically in order to obtain relevant flow quantities such as wake inductions.

The above modelling approaches are usually validated by experimental model tests carried out in wave flumes with wave makers, circulating water channels with wave makers, ocean basins and shallow water wave tanks [18]. To study the aerodynamics, wind generators usually complement these types of facilities. The scale of the model is dependent on a number of conditions including the facilities available and the requirement of Froude similarity. When studying aerodynamics, uncoupled tests can also be carried out exclusively in wind tunnels where the platform motions are prescribed by means of a controller [19]. Coupled aero-hydrodynamic experiments can be carried out using a simplified representation of the rotor such as solid rotating discs but these fail to capture the aerodynamic details. On the other hand, direct modelling of the rotor can be used but correct calibration of the mean thrust and ensuring the right gyroscopic effect is important. More details related to model testing of FOWTs can be found in [18].



(a) Surging motion (b) Pitching motion



(c) Front view

Fig. 3. Notation used for the surging and pitching platform motions.

3. Critical assessment of the existing literature

3.1. Research areas surrounding FOWT aerodynamics

FOWTs entail a strong coupling between aerodynamics and other surrounding disciplines such as hydrodynamics, aeroelasticity, control, material science, structures and soil mechanics. Fig. 5 gives an overview of how FOWT aerodynamics fits in with surrounding disciplines. These may for instance include system level components such as mooring lines [20–24], hydrodynamic aspects on floaters [25–27] and system control [28].

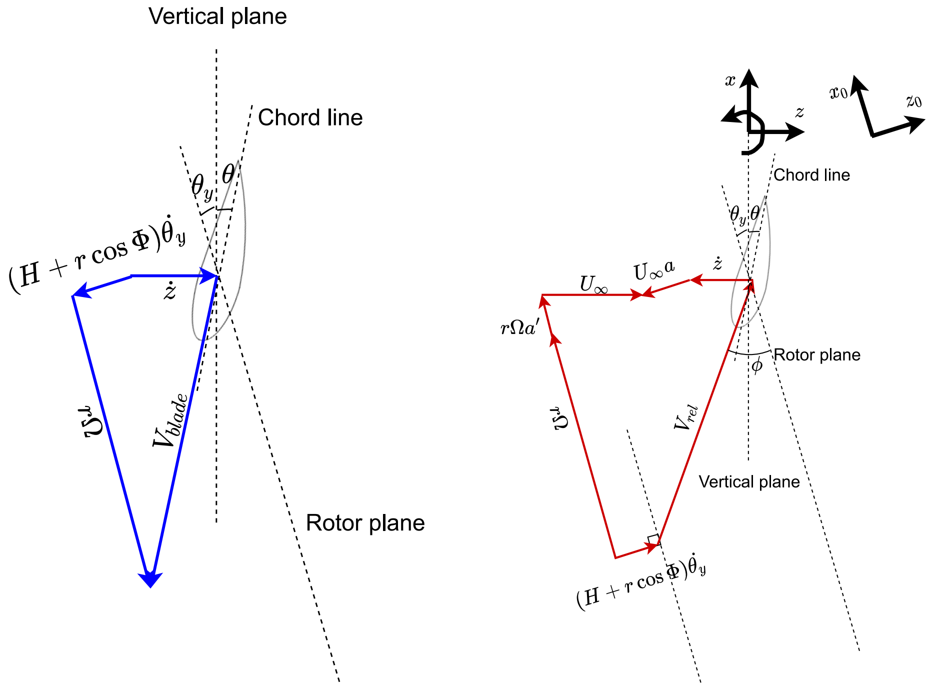
It is clear that many sub-fields in the various disciplines are not specific to wind energy science. However, it is clear that FOWTs have challenges that are new to the community. The trends in wind energy science, are in general continuously pushing the boundaries of our understanding of a wide variety of flow scales ranging from atmospheric meso-scale science down to system and sub-system level and down to the micro-metre scale for instance in the study of blade boundary layer flows. This paper will proceed towards identifying the associated challenges in aerodynamics but will also touch upon briefly on neighbouring disciplines.

3.2. Overview of research efforts during the past 10 years

The past ten years have drawn particular interest in the area of unsteady aerodynamics and, more specifically, FOWT aerodynamics. Much of the literature on fixed wind turbine flows addressed various topics involving unsteady effects such as dynamic inflow [81], sheared inflows ([82–86] and yawed inflow [87–91]. As will be shown in this article, investigations on complex rotor motions and the resulting local aerodynamics have become common but are still not fully mature as with fixed rotor aerodynamics.

Table 2 gives a list of the major publications in FOWT aerodynamics found in peer-reviewed articles and selected articles from conference proceedings. Note that the purpose of this is to give the reader a consolidated overview of the research efforts, along with relevant details performed in the past ten years. The table categorises the literature based on the publication type and year, the foundation type, the rotor rating, the studied turbine motions and the employed methodology. The aim, objectives and the focus of the study is also shortly mentioned. A summary of the table is given below:

- Foundation type: The literature deals with different types of platforms including the TLP and the spar platforms. In addition, a large bulk of the literature considers the simplified case of a decoupled analysis using a prescribed platform motion.



(a) Blade velocity vectors (b) Airflow velocity vectors

Fig. 4. Diagrams of flow and blade velocity for a blade section at a radius r for a turbine having hub height H. Only surging and pitching platform motions are considered.

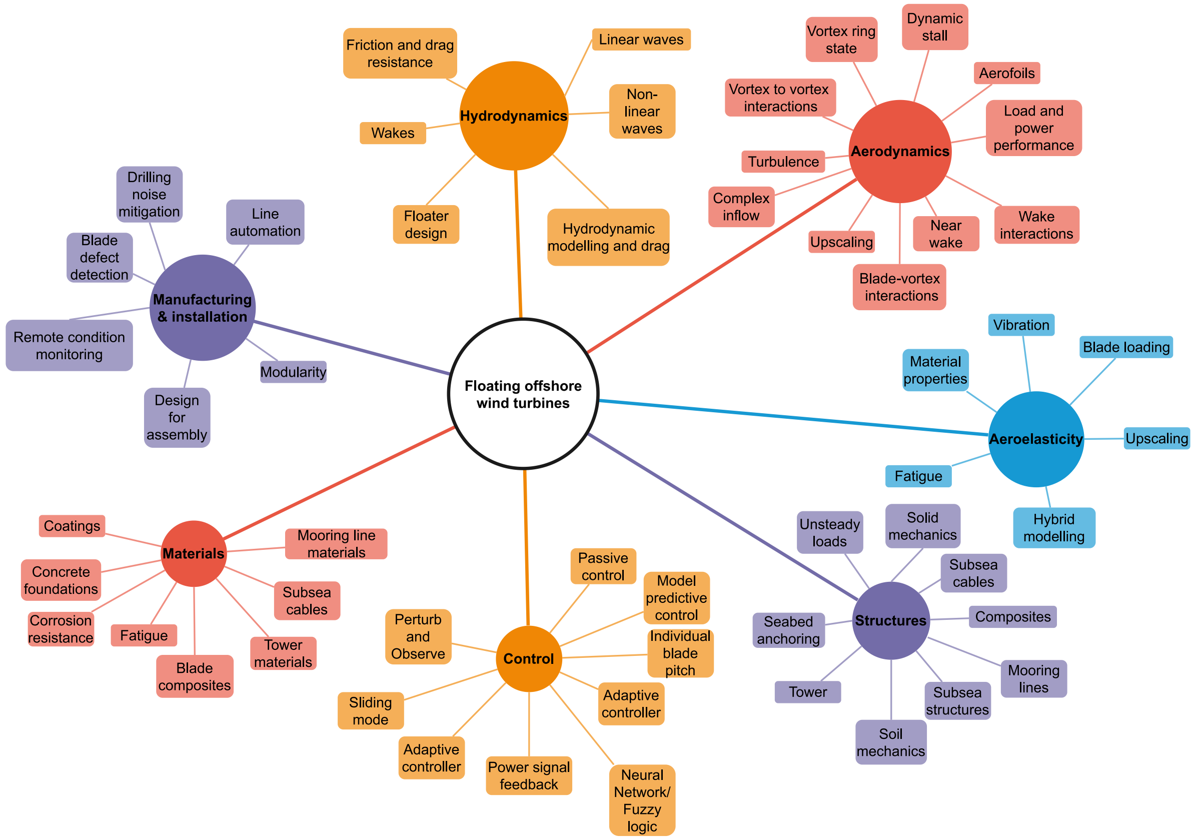


Fig. 5. Research areas surrounding FOWT aerodynamics. Note: research areas related to *Control* have been established with the help of [29].

Table 2

Latest publications in FOWT aerodynamics. Details of each paper are summarised in the columns for easy referencing. *Abbreviations:* Num — Numerical; Exp — Experimental; CFD — Computational Fluid Dynamics; CFD-AD — CFD using an Actuator Disc; NVLM — Non-linear Vortex Lattice Method; CFD-AL — CFD using an Actuator Line; FAST — Fatigue, Aerodynamics, Structures and Turbulence code (now known as OpenFAST); FAST-GDW — FAST using the Generalised Dynamic Wake; FVM — Free Vortex Method; VPM — Vortex Particle Method; BEM — Blade Element Momentum; FE — Finite Element method; CRAFT — Coupled Response Analysis of Floating wind Turbine.

Publication	Year	Publication type	Foundation type	Rotor rating	Turbine motion	Methodology	Aim/Objective/Focus of study
Wise and Bachynski [30]	2020	Journal	semi-submersible, spar buoy, tension-leg	10 MW (DTU)	All	Num (FAST, CFD)	Effects of wake interactions between two FOWTs. The effects of wake meandering are also investigated by means of the use of different environmental conditions
Balty et al. [31]	2020	Journal	semi-submersible	VAWT, diameter 60 m, height 96 m	All	Num (VPM)	Wake flow study with 6DOF motion characterisation
Rezaeiha and Micallef [32]	2020	Journal	N/A	5 MW (NREL)	surging	Num (CFD-AD)	Study of the impact of a surging rotor on the power performance of a downstream rotor due to their wake interactions
Corniglion et al. [33]	2020	Journal	N/A	5 MW (NREL)	Surging	Num (FVM CFD-AL)	Near wake flow study
Dong and Viré [34]	2020	Journal	spar buoy, tension-leg, barge	5 MW (NREL)	All	Num (FAST)	Identification of the vortex ring state for different platform types with 6-DOF motions
Schliffke et al. [35]	2020	Journal	N/A	Porous disc	Surging	Exp	Measurements of wake velocity and turbulence at a fixed downstream distance
Ortolani et al. [36]	2020	Journal	semi-submersible	5 MW (NREL)	Pitching	Num (FAST, CFD)	Cross-code comparisons
Mancini et al. [19]	2020	Journal	Prescribed motions	10 MW (DTU) - 1:75 scaled down	Surging	Exp & Num (various)	Investigation of the unsteady surging loads. Frequency domain analysis is also carried out.
Rodriguez and Jaworski [37]	2020	Journal	spar buoy, tension-leg, barge	5 MW (NREL)	Pitching	Num (FVM)	Coupling a free vortex wake method with an aeroelastic solver for FOWTs
Li et al. [38]	2020	Journal	Submersible (DeepCWind)	5 MW (OC4)	All	Num (FAST)	Study on the effects of yaw error on platform motions and performance
Kyle et al. [39]	2020	Journal	barge	5 MW (NREL)	surging	Num (CFD)	Propeller and vortex ring states during surging motions
Kopperstad et al. [40]	2020	Journal	spar buoy, barge	Model porous disc	Surging	Num (CFD-AD)	Wake dynamics of spar and barge concepts under surge motion
Kim and Shin [41]	2020	Journal	semi-submersible	750 kW	Pitching, surging and heaving	Exp & Num (FAST)	Model validation
Ahn and Shin [42]	2020	Journal	semi-submersible	10 MW	Pitching, surging and heaving	Exp & Num (FAST)	Validation of model motion response
Fang et al. [43]	2020	Journal	tension-leg	5 MW (NREL) - 1:50 scaled down	Pitching	Num (CFD)	Thrust and torque under pitching motion for different pitch amplitudes and frequencies
Johlas et al. [44]	2020	Journal	spar buoy, semi-submersible	5 MW (NREL)	All	Num (SOWFA-FAST)	To investigate wake effects of FOWTs for different wind and wave conditions. Also wind turbine yaw is considered in this study
Jessen et al. [45]	2019	Journal	tension-leg	5 MW (NREL) - 1:35 scaled down	All	Experimental	Experimental validation of an inhouse numerical code and FAST
Lienard et al. [46]	2019	Conference proceedings	N/A	5 MW (NREL)	Pitching, surging	Num (CFD)	Cross-code comparisons
Fu et al. [47]	2019	Journal	N/A	Model turbine	Pitching and rolling	Exp	PIV and hotwire measurements of wake velocities and turbulence and effects on power fluctuations under pitching and rolling
Wang et al. [48]	2019	Conference proceedings	tension-leg	N/A	All	Num (CFD)	Coupled analysis of wind turbine kinematics
Bezzina et al. [49]	2019	Conference proceedings	tension-leg	Model scale rotor, 10W	Surging	Num (CFD-AD)	Validation of model and analysis of performance including induction factors, thrust coefficient and power coefficient

(*continued on next page*)

Table 2 (*continued*).

Publication	Year	Publication type	Foundation type	Rotor rating	Turbine motion	Methodology	Aim/Objective/Focus of study
Lee and Lee [50]	2019	Journal	Prescribed motions	5 MW (NREL)	All	Num (NVLM and VPM)	Wake evolution of 6DOF platform motions
Sant and Micallef [51]	2019	Conference proceedings	Submersible (DeepCWind)	5 MW (NREL)	Surging	Num (CFD-AD, FAST, GDW)	Cross-code comparisons
Shen et al. [52]	2018	Conference proceedings	Prescribed motions	5 MW (NREL)	Pitching	Num (FVM)	Study of loads and wake unsteadiness
Shen et al. [53]	2018	Journal	Prescribed motions	5 MW (NREL)	Surging	Num (FVM)	Wake unsteadiness and turbine power performance under surging motion
Wen et al. [54]	2018	Journal	Prescribed motions	5 MW (NREL)	Pitching	Num (FVM)	Power performance with varying tip speed ratio and reduced frequency
Lin et al. [55]	2018	Journal	Prescribed motions	5 MW (NREL)	Pitching, surging	Num (CFD)	Wake and flow structures under 2DOF motions
Leble and Barakos [56]	2017	Journal	Prescribed motions	10 MW	Pitching and yawing	Num (CFD)	Vortex ring state and wake flow analysis under pitching motions
Lei et al. [57]	2017	Journal	Prescribed motions	VAWT, diameter 2 m, height 1.2 m	Surging	Num (CFD)	Power performance of a VAWT with various surge amplitudes and frequencies
Liu et al. [58]	2017	Journal	Submersible (DeepCWind)	5 MW (NREL)	All	Num (CFD)	Development and validation of a coupled analysis tool
Tran and Kim [59]	2016	Journal	Prescribed motions	5 MW (NREL)	Surging	Num (CFD)	Effects of surge amplitude and frequency on the thrust and power generation
Shen et al. [60]	2016	Journal	tension-leg	5 MW (NREL)	All	Num (CRAFT)	Coupled dynamic motion response analysis of a floating wind turbine
Farrugia et al. [61]	2016	Journal	tension-leg	5 MW (NREL)	Surging	Num (FVM)	Identification of reasons behind the increase in the aerodynamic torque and thrust variations with tip speed ratio
Toan Tran et al. [62]	2015	Journal	Prescribed motions	5 MW (NREL)	Surging	Num (CFD)	Analysis of load and performance variations with surge amplitudes and frequencies
Xu et al. [10]	2015	Journal	tension-leg	5 MW (NREL)	Surging	Num (FVM)	Development and validation of FVM
Sant et al. [63]	2015	Journal	tension-leg	Model scale rotor, 10 W	All	Exp	Model FOWT testing for induction, thrust and power measurements
Micallef and Sant [64]	2015	Journal	tension-leg	5 MW (NREL)	surging	Num (CFD-AD)	To numerically investigate whether the experimental observation of the increase in the amplitude of thrust and power for higher tip speed ratios can be confirmed using a CFD-AD model
Tran and Kim [65]	2015	Journal	spar buoy	5 MW (NREL)	Pitching	Num (CFD)	Pitching motion of the rotating turbine blades due to the floating platform motion is considered to investigate the effects of vortex–wake–blade interaction
Sivalingam and Narasimalu [66]	2015	Journal	spar buoy	5 MW (NREL)	Pitching	Numerical - CFD	Comparison of CFD model with other codes including analysis of wake states.
Rockel et al. [67]	2014	Journal	N/A	Model scale rotor, 1.2 W	Pitching	Exp	Wake measurements for pitching motions and comparisons with existing wake models.
de Vaal et al. [68]	2014	Journal	Prescribed motions	5 MW (NREL)	Surging	Num (CFD-AD)	Analysis of thrust and induction factors in surge motion
Jeon et al. [69]	2014	Journal	monopile	5 MW (NREL)	Pitching	Num (FVM)	Effects of turbulent wake state during pitching motion
Farrugia et al. [70]	2014	Conference proceedings	tension-leg	Model scale rotor, 10 W	All	Num (FVM)	Validation of a FVM with experimental data on a small scale rotor experiment
Tran et al. [71]	2014	Journal	spar buoy	5 MW (NREL)	Pitching	Num (CFD)	To investigate the unsteady aerodynamic effects of rotor pitching motion

(*continued on next page*)

Table 2 (*continued*).

Publication	Year	Publication type	Foundation type	Rotor rating	Turbine motion	Methodology	Aim/Objective/Focus of study
Sebastian and Lackner [72]	2013	Journal	monopile, barge, spar-buoy and tension-leg	5 MW (NREL)	All	Num (FAST)	To study the unsteady wake behaviour of a FOWT
Duarte et al. [73]	2013	Conference proceedings	spar buoy	5 MW (NREL)	All	Num (FAST, CFD, FE)	Code cross-comparison
Sebastian and Lackner [74]	2012	Journal	N/A	N/A	All	Num (FVM)	Development and validation of a FVM code intended for FOWTs. Validation carried out on fixed rotor.
Karimirad and Moan [75]	2012	Journal	spar buoy	5 MW (NREL)	All	Num (FVM, BEM)	The creation of a simplified aero-hydro coupled solver and compared with FVM methods
Sebastian and Lackner [76]	2012	Journal	monopile, barge, spar buoy, and tension-leg	5 MW (NREL)	All	Num (FVM)	Analysis of inductions and loads under different tip speed ratios and for different platform motions
Jonkman and Matha [77]	2011	Journal	tension-leg, spar buoy, barge	5 MW (NREL)	All	Num (FAST)	Study of the dynamics of FOWTs using different foundations
Robertson et al. [78]	2011	Conference proceedings	Spar buoy (OC3)	5 MW (NREL)	All	Num (FAST)	Investigation of loads using the FAST algorithm
Matha [79]	2010	Technical report	tension-leg	5 MW (NREL)	All	Num (FAST)	Loads and stability analysis for ultimate and fatigue loads according to the procedures of the IEC 61400-3 offshore wind turbine design standard
Sebastian and Lackner [80]	2011	Conference proceedings	N/A	N/A	N/A	Num (FVM)	Review of the aerodynamic challenges including unsteady behaviour. Includes also a presentation of the FVM WInDS

- Rotor rating: The NREL 5MW is by far the most studied rotor in the FOWT aerodynamics literature. Very few studies considered the DTU 10MW (full-scale or down-scaled), smaller rotors or even VAWTs.
- Turbine motion: Among the various motions, the majority of studies have focused on the surge and the pitch motion, as the most predominant platform motions for FOWTs [76].
- Methodology: FVM and CFD and FAST (Fatigue, Aerodynamics, Structures, and Turbulence) (later named OpenFAST) are the most widely employed methods for research on FOWTs.

3.3. Developments in FOWT modelling

The type of modelling approaches used to study FOWTs can be categorised under coupled or uncoupled approaches. This emphasis arises from the highly coupled physical behaviour exhibited by the actual system. While in general, coupled approaches intrinsically include multi-physics modelling of the aero-servo-hydro-elastic system, the increased computational expense generally limits the adoption of advanced numerical tools. This is particularly true in industrial applications. Some examples of these coupled approaches, where the aerodynamic load is simplified include [92–97] and [98]. Such models still provide advantages such as for instance the inclusion of second order hydrodynamic effects even though the frequency response of the turbine has been shown by [99] to be several orders of magnitude less than those caused by aerodynamic excitation.

The most documented coupled model for FOWT research found in the literature is the OpenFAST code developed by NREL. OpenFAST(refer to [100]) is composed of a number of modules operating in a coupled manner. There are numerous examples in the literature concerned with the use or validation of the OpenFAST code. Some examples include Coulling et al. [101], Robertson et al. [78], Coulling et al. [102], Chan et al. [103], Kim and Shin [41], Han and Nagamune [104]. The aerodynamics module in OpenFAST is called AeroDyn which is a BEM based solver [105,106]. Engineering models are also employed to account for tip losses [107,108], hub losses, skewed wakes such as in [15] and [109] and also dynamic stall based on the semi-empirical Beddoes–Leishman model [110]. A Generalised Dynamic Wake (GDW) model (see Peters et al. [111] and [112]) is also included, which inherently models the dynamic wake effect.

Lately, some examples of advanced coupled codes involving full CFD analysis of both the aerodynamic and hydrodynamic components have also been published [113] and [58]. Still the latter paper lacks the inclusion of an aero-servo-elastic solver. The general features of a coupled model, including the various multi-physical aspects that are involved in FOWT modelling, are shown in Fig. 6.

The rest of this section will be devoted to uncoupled approaches used in aerodynamic studies of FOWTS. In regards to model scale turbine experimental testing with prescribed motions, [114] described a wind tunnel testing setup at the Politecnico di Milano, where platform motions are simulated rather than produced by means of a more traditional wave tank setup. More commonly, such testing is carried out numerically using uncoupled solvers. Fig. 7 shows the general features of uncoupled models, where generally speaking platform motions are input into the model on the basis of either a simplified coupled approach, parametric data or experimental data.

Many efforts have been made to cross-compare the different FOWTs modelling approaches. An example is found in [68] where the authors use an AD CFD model to show that, for a typical TLP FOWT in surge motion, dynamic inflow effects were small. The authors further compared their results with a quasi-steady BEM as well as with a BEM model employing the Øye model [14]. [64] have also compared AD CFD models with the OpenFAST and GDW models and found discrepancies in the thrust forces and power. This is especially true for the rated to high tip speed ratios, The FVM method developed by [76] and [115] (WInDS) also showed how these methods can be useful in providing a mid-way inviscid alternative between the more simplified approaches such as BEM and the more computationally expensive full CFD models. WInDS has also been used in other instances to study both loads and wake evolution in [61]. Other FVM such as QBlade [116] have been used in the literature and compared to other methods including BEM with unsteady corrections and CFD. From this reviewed literature, the different classes of models used by the various authors can all be adequately adopted to the analysis of FOWTs with clear limitations on

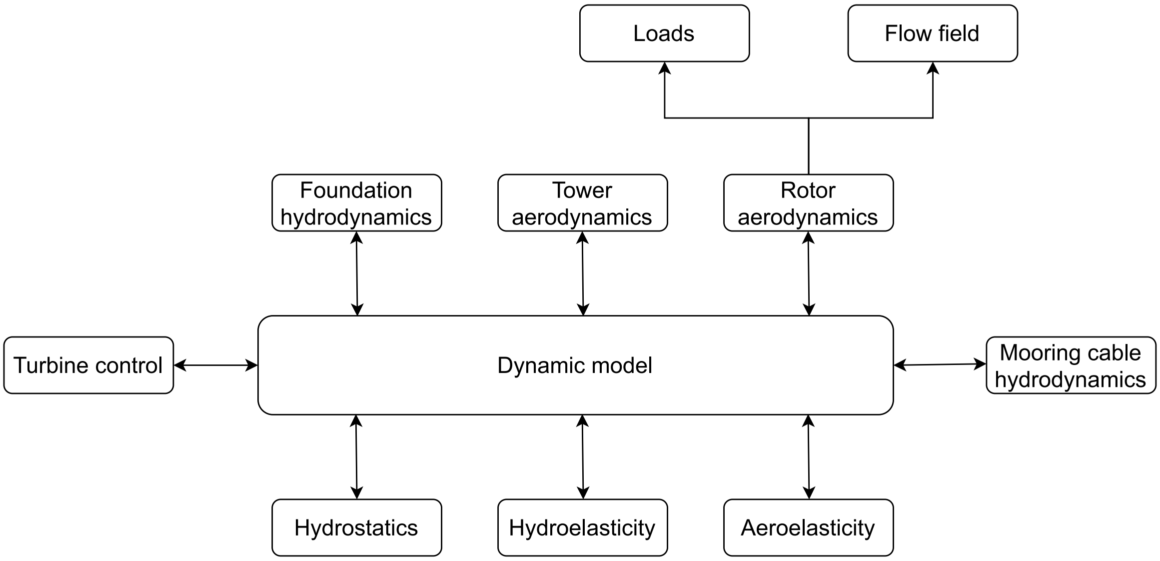


Fig. 6. Coupled method of analysis. The rotor aerodynamics part is generally used to establish loads or characterise flow fields in relation to wakes. The latter is however not always the case such as for instance when BEM models are adopted.

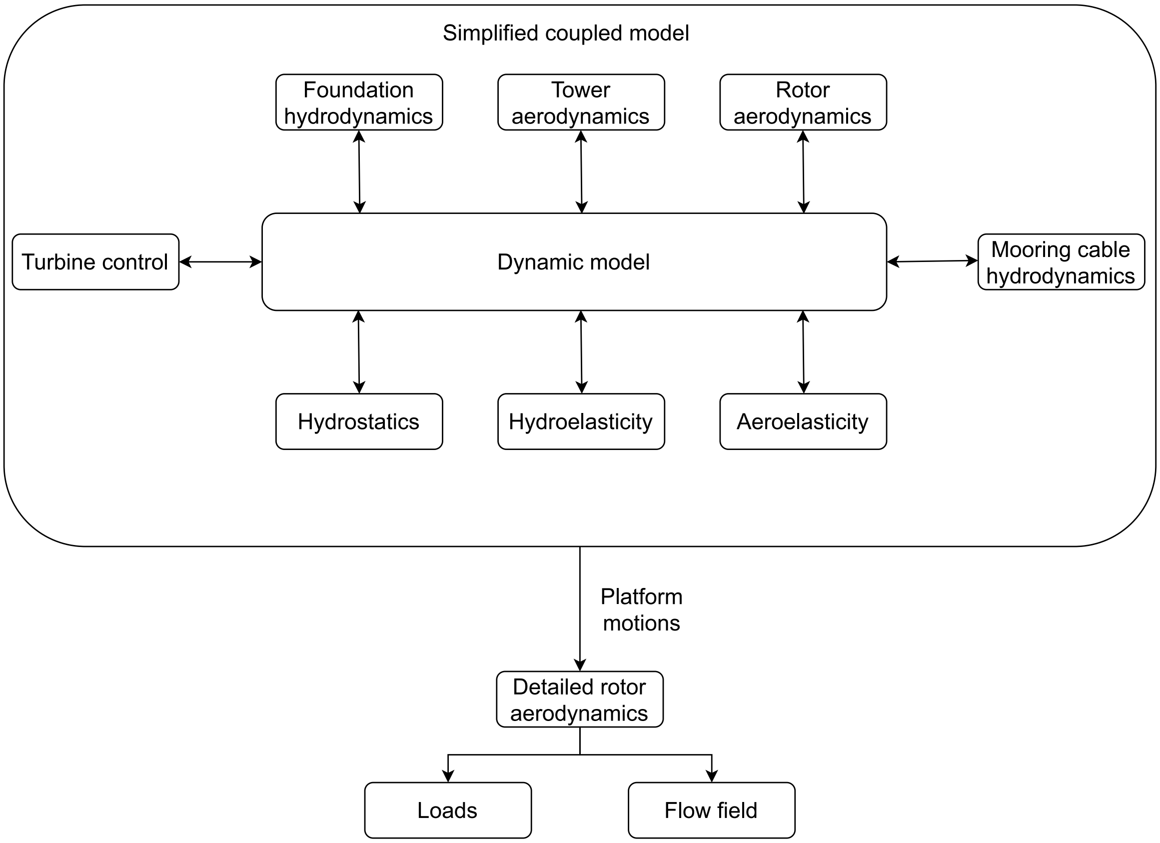


Fig. 7. Uncoupled method of analysis. The rotor aerodynamics part is usually of a more computationally expensive nature compared to when coupled methods are adopted. Platform motions are, however, required either as assumed motions or as inputs from a simpler coupled approach.

either computational expense or accuracy. In contrast to the discrepancies found by [64] in the use of AD CFD, OpenFAST and GDW, [117] found excellent agreement between a FVM model and an actuator line CFD model at the rotor position. Recently, [19] also made such cross-code comparisons including quasi-steady BEM, FVM, actuator line CFD and full CFD. Excellent performance of the quasi-steady BEM was noted under various surge conditions. This corroborates with the findings by [68]. Another study confirming these observations is that by [36] comparing OpenFAST with blade resolved CFD.

3.4. Platform dynamics

Platform motions provide a key parameter for studying FOWT aerodynamics. A fully coupled dynamic analysis of a FOWT has been proposed by [118] making use of an early version of the code OpenFAST [100,119], where AeroDyn [105], as an aerodynamic sub-routine, and ADAMS [120], as a multi-body dynamics simulation tool, are used. Validation of the physical model was mentioned as an important step.

Experimental model scale measurements have been carried out from the DeepCwind Consortium by carrying out 1:50 scale model tests at the Maritime Research Institute Netherlands (MARIN). Various FOWT platform types were used and the resulting data of the dynamic motions of the FOWTs were obtained [121]. Other major research initiatives from the International Energy Agency (IEA) Wind tasks have been undertaken under OC3 project. This was then followed by OC4 [122], OC5 [122] and lately by OC6 [123]. The purpose of the OC3 project was principally to validate and cross-compare FOWT dynamic modelling tools. OC4 furthered this work including the analysis of a 5 MW semi-submersible FOWT. In OC5, this exercise was continued with a wider variety of simulation test cases and modelling tools. One example is found in [124], where validation with the DeepCwind 1:50 scale model was extensively performed using unsteady engineering models for the aerodynamics. The authors highlight the need for a more sophisticated modelling approach using CFD. The Offshore Code Comparison Collaboration, Continued, with Correlation, and uncertainty (OC6) project focused on assessing the sources of uncertainty between the various codes.

These benchmarking experiments are important in the validation of numerical codes which by now form the bulk of the current literature in this area. Lack of good experimental data has been a general challenge in wind turbine aerodynamics in the past 20 years or so. With FOWTs the challenges are greater since these generally require wind tunnel - water/wave tank testing facilities which are not so common. Apart from infrastructural difficulties there are also issues related to physical testing because of the impossibility in achieving similarity in Reynolds and Froude numbers simultaneously. A study on FOWT model scale testing uncertainties has been reported recently in [125].

Even before the OC3 project and its subsequent continuations, platform motions have been investigated by [126] and consequentially, two floating concepts developed. The aerodynamic treatment was relatively simplistic and did not consider dynamic effects. Most of the past efforts involving coupled analysis to calculate platform motions were based on OpenFAST (see for example [127]). Authors such as [73] performed a cross-comparison and verification of various engineering based models including OpenFAST. Consistency between these models was found despite the differences in hydrodynamic models used between the codes. [77] and [79] studied numerically the dynamics of various platform concepts including the TLP and spar-buoy types. FOWT loads have been studied in [78] again using the OpenFAST algorithm. The authors found that there is not much difference in the loads between the TLP, semi-submersible, and the spar buoy cases with the exception of loads on the tower.

[60] also make use of a coupled methodology called Coupled Response Analysis of Floating wind Turbine (CRAFT) which is compared with both experiment and OpenFAST simulations. The authors conclude that for random sea-states, the platform motion turns out to be non-Gaussian for TLPs. It is clear from these works that the platform motions are strongly dependent on the FOWT type. In addition, [73] reports that the mean platform surge displacement is a function of the thrust loading of the rotor. Nonetheless, the authors clearly highlight that second-order hydrodynamic loads, if considered, could also modify the mean platform displacement. Using a BEM-based aerodynamic tool linked to ANSYS Aqwa®, the authors in [48] confirm the fact that wind loads mostly influence mean displacements. Some effect on the low-frequency response is also mentioned. On the other hand, the wave loads mostly influence the fluctuation amplitude of the TLP FOWT.

Following these substantial efforts in studying platform motions, aerodynamic modelling of FOWTs became a focused topic of investigation in its own right through a decoupled analysis. This will be described in Section 3.3. This inevitably led to investigations of more theoretically idealised scenarios such as sinusoidal surge displacements and velocities of the platform, given in Eqs. (17) and (18),

$$x(t) = A_x \sin(\omega_x t + \phi_x) \tag{17}$$

$$\dot{x}(t) = A_x \omega_x \cos(\omega_x t + \phi_x) \tag{18}$$

where A_x is the surge amplitude, ω_x is the surge frequency and ϕ_x is the surge phase shift. [76] showed that the most predominant platform motions are associated with pitch and surge motions and much of the efforts in aerodynamic investigations became mostly focused on these two major types of motions.

In many cases, the surge and pitch frequency are considered to be equal to the sea wave frequency. Nonetheless this might not be the case depending on the design of the platform. Fig. 8 shows recent work by [128] concerning novel platform designs where different spar platforms give dominant platform pitch frequencies which are lower than the wave frequency.

The platform oscillation amplitude is also some function of the sea wave height thus requiring more informed inputs such as the use of coupled models to be able to accurately input this information into an uncoupled aerodynamic solver. To clarify, results of the wave height and frequency obtained using low- to moderate-fidelity coupled analysis tools such as OpenFAST, can be employed to define prescribed platform motion into uncoupled high-fidelity analysis tools, such as CFD.

3.5. Rotor loading and power performance

Uncoupled aerodynamic analysis studies in the literature use a prescribed sinusoidal variation in platform motions with the amplitude either calculated from a coupled approach or imposed as a parametrisation criterion. As is clear in Table 2, most of the studies concern either surging or pitching motions or in rare cases, both.

Full blade resolved CFD simulations were carried out by [71] for pitching motions. The work focused on creating a benchmark validation of the loads with other codes without investigating the effects of various platform motion parameters on these loads. Later, [59] performed a similar analysis on a surging rotor for various surge amplitudes and frequencies. The authors confirmed observations in other experimental work by [63] and numerical work using a FWV method by [70] performed earlier. Essentially, load and power amplitudes are strongly dependent on the surge amplitudes. The authors also mention a dependence on surge frequency owing to secondary effects such as influences of tower shed vortices. [53] also report an increase in mean power while [33] report an increase in the mean thrust with the surging condition compared to the fixed condition.

[43] investigate the aerodynamics of a pitching TLP FOWT using blade resolved CFD. The thrust and torque amplitudes vary sinusoidally, with amplitude decreasing as the pitching period is increased. This is attributed to the decreased relative velocity. On the other hand, the thrust and torque amplitudes increase with the increase in pitching amplitude. Occurrence of dynamic stall was also observed from the CFD simulation during upward pitching. The authors, consistent with what was found by [53] for surge, also confirm an increase in the mean power with different pitch periods and amplitudes.

In the work of [129] and [56], combined yawing and pitching platform motions were considered. The peak power produced by the turbine in the dynamic yawing case was higher than the fixed yaw case. This is once again consistent with observations by other authors in the case of surging and pitching motions. For pitching motions, the authors also confirm the fact that the mean power is higher than the fixed case with a pitching amplitude of 5°. The power and thrust variations with pitch angle are reproduced in Fig. 9 from [129]. Later studies by [50] showed that the major influences on power variation are associated with pitching and surging motions.

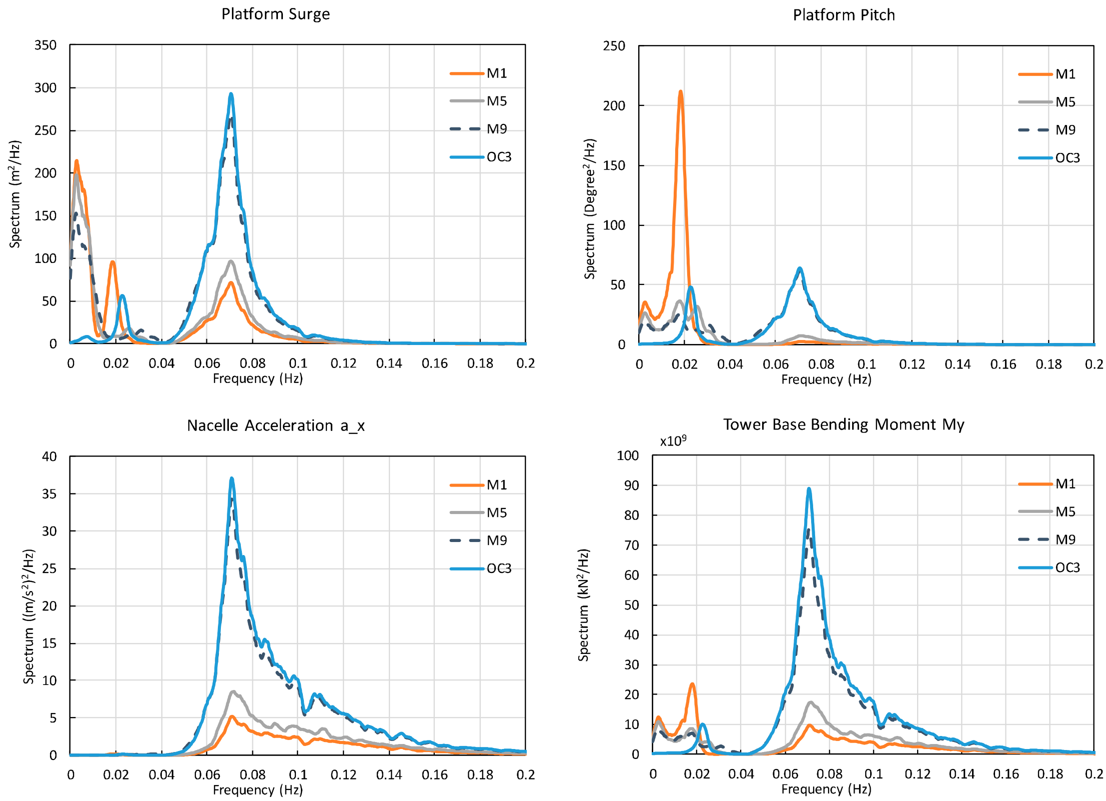


Fig. 8. Frequency domain analysis of FOWT (spar type) platform motions. *M1*, *M5* and *M9* refer to different vertical column diameters inside a moonpool located in the spar type platform while *OC3* refers to the OC3-Hywind spar design. Tests carried out at 12 m/s turbulent wind speed with irregular wave with wave height $H_s = 12.12m$, wave period $T_p = 14.17s$ ($f = 0.071$ Hz), and 0.37 m/s current speed.
Source: [128] (Open access).

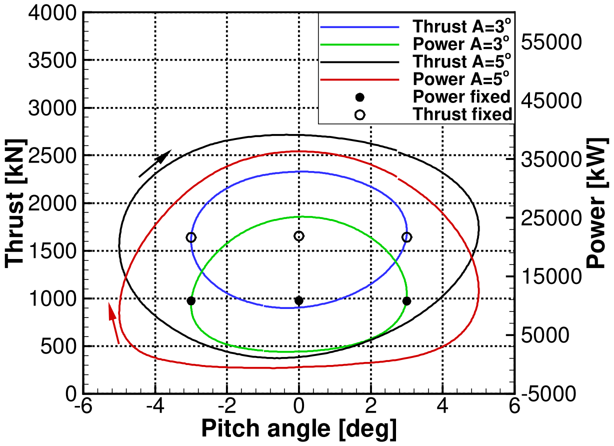


Fig. 9. Thrust and power variations for pitching amplitudes of 3° and 5° and compared to the fixed case.
Source: [129] (Open access).

Model scale testing on surging rotors at different tip speed ratios have also been carried out by [63]. It was found that the increase in the mean power of the turbine compared to its fixed rotor case increases with increasing tip speed ratio for given surge amplitudes and frequencies. This was then numerically confirmed also by [64] using an AD-CFD model. The authors also reported increasing peak-to-peak and dynamic variations of the loading as a result of the high tip speed ratio. Such phenomena have been also linked by [19] to the steady state characteristic curve of the wind turbine, which can conveniently be controlled by the turbine controller. Therefore, while operation at high tip speed ratio may be of a severe detriment to fatigue performance, the findings proposed here could be somehow mitigated by more optimal controls. Recently another interesting observation was made by [40] associated with barge type FOWT platform motions which cause a low frequency power variation.

3.6. FOWT wakes

In [67], authors performed Stereo Particle Image Velocimetry (SPIV) wake flow measurements of the near wake of a model FOWT with a diameter of 0.2 m in pitching motion. Fig. 10 shows the flow measurements for the mean streamwise velocity component. A vertical shift in the wake boundary and turbulent kinetic energy is observed which has important implications on wind farm planning.

Recently [35] performed wake velocity and turbulence measurements for a reduced scale surging porous disc model with an imposed sheared inflow. The authors showed that the wake recovery is enhanced due to the surging motion. This observation is consistent with the earlier work on the pitching and rolling motions by [47]. They also noted that the frequency of the power fluctuations was smaller than the pitching frequency.

Various authors such as [64,70] and [61] have noted wake expansions and contractions during surging motion associated with varying thrust loading with time. While not substantial, these types of wake instabilities can have important implications to the mid to far wake development. [50] performed Non-linear Vortex Lattice Method (NVLM) and Vortex Particle Method (VPM) simulations of a FOWT exhibiting all motions individually. The wake development clearly shows the resulting instabilities and wake dynamics which are so important to the study of wake development. On this topic, [40] focussed on the wake dynamics of spar buoy and floating barge platforms under pitching and surging motions. These were calculated by means of a dynamic

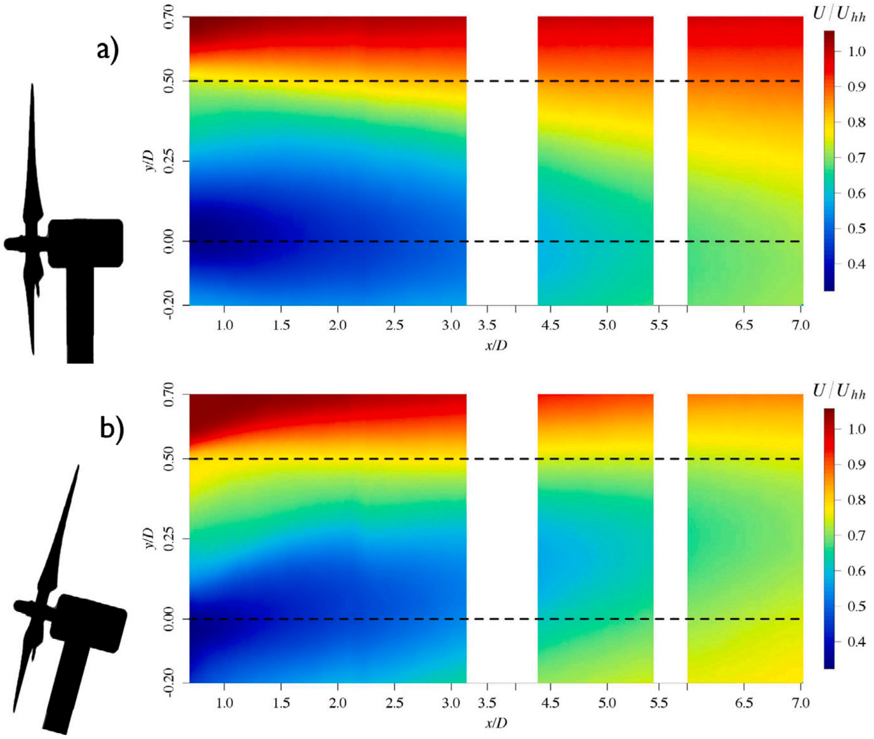


Fig. 10. Normalised axial velocity $\frac{U}{U_{hh}}$ during pitching motion of the turbine. Subfigure (a) and (b) show the turbine in neutral (0°) and maximum pitching position of ≈ 18.5°. *Source:* [67] (Open access).

model and then prescribed to a CFD, Large Eddy Simulation (LES) based turbulence modelling. An AD approach was used to prescribe the rotor loading. Laminar and turbulent inflows were considered. The former showed that the barge concept has a faster wake recovery than the spar buoy and also causes a *low-frequency modulation* of the wake. On the other hand, a faster wake recovery was observed (for both platform types) in the case of turbulent inflow. The authors report that the barge FOWT motions cause unsteady wake features that can be beneficial, in terms of energy extraction of other turbines in the wind farm context. Wind farm wake interactions are mentioned as possible future work. In [130], the authors performed simulations using the Simulator fOr Wind Farm Applications (SOWFA) coupled with OpenFAST to compare and contrast the wakes of fixed bottom turbines and floating turbines for different metocean conditions. The authors note that for high wind speeds and low wave heights, the wake differences are small. Consistent with the earlier work of [67] on pitching motions, it is clear that future directions will focus more on issue of wake interactions. A testament to this is the more recent work by [30] also assessed the influence of wake meandering in the context of a wind farm using the code OpenFAST.Farm which employs a coupled calculation tool employing CFD and OpenFAST. Yaw motions were noted to be excited by wake meandering. These findings further hint towards the need for more studies on FOWT wake interactions.

Another important finding made by [129] and [56] is the occurrence of partial vortex ring state during the pitching motion of a $10MW$ turbine. This was also recently confirmed by [39] for the NREL $5MW$ exhibiting surge motion leading to blade-vortex interactions and also propeller mode operation. Another recent confirmation also came from [34]. These types of complex interactions have been extensively studied in helicopter rotor aerodynamics (such as in [131,132] and [133]) but have only found limited attention (see [134] in the case of wind turbine aerodynamics. A summary of the possible modes of operation of the AD are shown in Fig. 11 including the vortex ring state being described here.

3.7. Control

Up to this stage of the development of FOWTs, the rotor controller is mainly decoupled from motion of the platform, meaning that no real-time information is exchanged between the platform and the controller [135]. As a result, the blade aerodynamic loads and the power performance of FOWTs would undergo substantial variations influenced by the platform motion. This, on the one hand, can result in significant fatigue loads, limiting the turbine lifetime. On the other hand, it would negatively affect the Annual Energy Production (AEP) of the turbine and consequently the farm. A strategy to mitigate this is to facilitate a real-time information transfer from the platform to a feedback (FB), a feedforward (FF), or a feedback-feedforward (FBFF) rotor controller. While the use of a FB controller is arguably the current trend in industry [135], future activities for FOWTs should steer towards FF or FBFF controllers because of their advantages in reducing load and power variations and improving the fatigue lifetime and AEP [136]. Such controllers can be realised using data-driven models trained with existing measurements or simulations. Another step which is still required in the same direction is to include smart dynamic wind turbine control for FOWTs. This means that, during the floating motion, the controller would provide real-time command to mechanisms that can dynamically counteract the platform motion (to some extent). Such mechanisms include, but not limited to, the collective blade pitch, trailing-edge flap, morphing blade shape or active mooring lines can be controlled independently. For such smart dynamic control systems, characteristics such as the actuation frequency and the control magnitude would be critical. In addition, the importance of windfarm control becomes more critical for FOWTs.

4. Discussion of current trends and future challenges

4.1. Current trends

From the reviewed literature, it transpires that there are various areas in rotor aerodynamics that are currently finding common attention

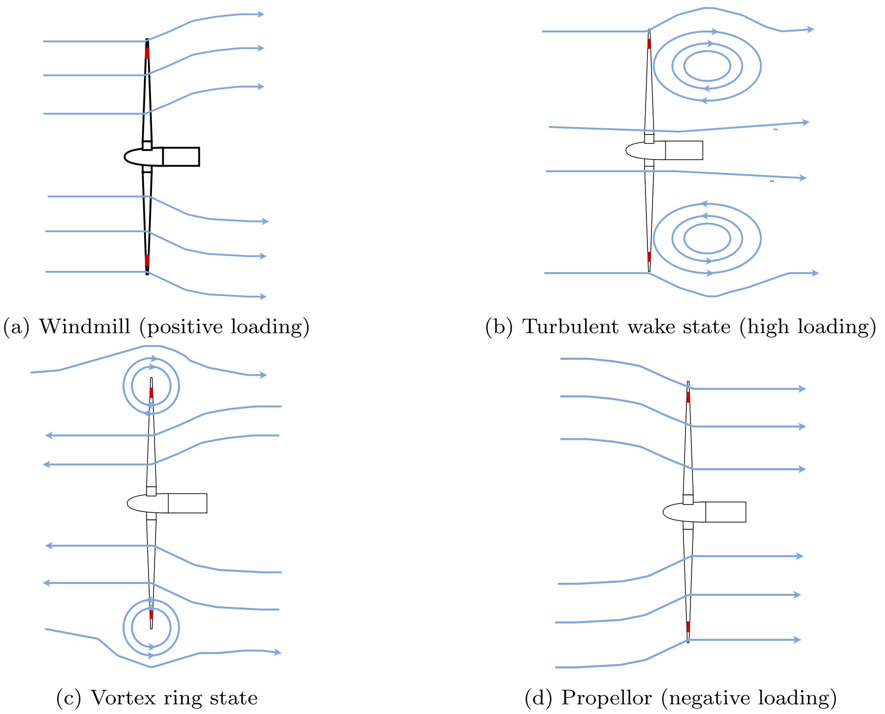

(a) Windmill (positive loading) (b) Turbulent wake state (high loading)
(c) Vortex ring state (d) Propellor (negative loading)

Fig. 11. Modes of operation of an actuator at various loading conditions.

from various research groups. The scope of this section is to shed more light on these current trends and identify existing gaps in the literature. This will then support the future challenges that will be proposed in the next sections. A consolidated list of major findings from the literature is provided in Table 3 with articles highlighting consensus or the need for further evidence. This table provides information about the topics that are finding attention from the community and also hints towards future work.

From this table, it is amply clear that there is consensus in most of the findings. There is the need for further evidence in relation to specific topics such as thrust and torque variations in pitching. This is also the case for the observed low frequency power responses in surge and pitching. Wake behaviour, particularly the turbulent kinetic energy and wake recovery, also needs further work. One area where the literature seems to be somewhat divergent is the reliability of various codes. This is currently being addressed also in the OC6 project. No particular divergences or disagreements on particular findings were noted.

The authors in [137] highlight a number of key aspects in relation to various main scientific challenges that have to be addressed by the wind energy research community in relation to FOWTs. These include; (i) upscaling of rotors for FOWT applications and associated challenges such as aeroelasticity, (ii) the need to devise new models including 3D actuator surfaces, (iii) the need of better and faster aerodynamic load prediction for the purpose of improving FOWT blade controls, (iv) better hydrodynamic load prediction once again to improve control strategies such as blade pitch control, (v) to further develop coupled methods of calculation. It is clear that from Table 3, the current trends in the literature are for the most part addressing these challenges. In order to identify research gaps in a structured manner, a mapping of these gaps is shown in Fig. 12 in order to understand better the specific areas where more research effort is needed. This chart provides, to the authors' opinion, an overview of the areas that ought to be tackled. In colour are those topic areas which are by now well covered in the literature. In grey, are those topics which are either in their early stages, with few publications, or which could be addressed in future work.

4.2. Challenge 1: New aerofoils for FOWTs

For fixed wind turbines there have been various studies aimed at designing aerofoils that are tailor-made for wind turbine operation (see early examples such as [138,139]). As mentioned earlier, unsteady aerofoil effects such as dynamic stall have been observed on FOWTs by [53]. Combined floater motions, especially when considering 6-DOF motions, lead to highly complex angle of attack variations. Knowledge of these variations is important for both the passive design of airfoils as well as for the identification of active control strategies which are specifically tailored for FOWT blade sections. Since the governing principles of aerofoil dynamics remains the same as the dynamic effects observed on fixed wind turbines the existing literature, modelling tools and experimental evidence can be used to guide future studies. The major challenge that must be emphasised here is the need to design aerofoils that are tailored for the complicated 6-DOF motions found in FOWTs. Studies on localised aerofoil effects such as separation zones, dynamic loads and dynamic vortex shedding as a result of 6-DOF rotor motions should be used to identify better aerofoil geometries for future floating rotors. As an example, new aerofoils with low sensitivity to 3D flows and a soft stall behaviour could be designed to minimise the variations of aerodynamic loads due to 6-DOF motions and possible frequent excursions of the angle of attack above the stall angle. In addition, as for the case of FOWTs, a range of design angles of attack is more relevant than a single value. This is in contrast with the case of fixed turbines, the design procedure for the aerofoils might also need to be revisited to accommodate an optimal operation within the relevant range.

The above needs also to be considered in light of the need for rotor upscaling which imply higher Reynolds number operation. Once again, the physical insight on high Reynolds number operation of aerofoils is well established and should be used to provide insight on the resulting physics of complex aerofoil motions which apart from the gross motions of the platform and rotor, is also subject to aeroelastic deflections and induced vibrations. Existing studies on devices such as vortex generators which are by now very common for fixed rotor conditions should be revised to include the additional complexities of FOWT aerodynamics.

Table 3
Consolidation of the consensus on the latest research outcomes and the needs for further research.

Topic	Consensus	More evidence needed
Thrust and power amplitudes are influenced by surge amplitudes	Tran et al. [71], Tran and Kim [59], Sant et al. [63], Farrugia et al. [70]	
For pitching, the thrust and power amplitudes increase with decreasing pitching frequency and increasing pitch amplitudes		Fang et al. [43]
Increase in mean power and loads compared to fixed rotor for both surging and pitching	Shen et al. [53], Corniglion et al. [33], Shen et al. [53], Leble and Barakos [129], Leble and Barakos [56], Lee and Lee [50]	
Power coefficient increases (compared to a fixed rotor) with increasing tip speed ratio	Sant et al. [63], Micallef and Sant [64]	
Low frequency power variation observed during surge and pitching motion		Sant et al. [63], Micallef and Sant [64]
Vortex ring state and propellor mode for pitching and surging	Leble and Barakos [129], Leble and Barakos [56], Kyle et al. [39], Dong and Viré [34] Gandhi and Tauszig [132]	
Turbulent kinetic energy for pitching rotor shifted vertically upward		Rockel et al. [67]
Laminar inflow causes the barge concept has a faster wake recovery than the spar buoy		Kopperstad et al. [40]
Turbulent inflow causes a faster wake recovery	Schliffke et al. [35], Fu et al. [47]	
Low frequency wake modulation		Kopperstad et al. [40]
Expansions and contractions observed due to varying thrust loading.	Micallef and Sant [64], Farrugia et al. [70], Farrugia et al. [61]	
Some appreciable discrepancies were found between the various codes was observed	Micallef and Sant [64], Sebastian and Lackner [76], Sebastian [115], Farrugia et al. [61], Marten [116], Bartl et al. [117], Mancini et al. [19], Ortolani et al. [36], Bartl et al. [117]	
Quasi-steady BEM still shown to give reasonable accuracy	Bartl et al. [117], Mancini et al. [19], Ortolani et al. [36]	

4.3. Challenge 2: Aerodynamic modelling of FOWTs

The future of FOWT modelling is directed towards high-fidelity coupled analysis using for instance hybrid CFD and FE methods. Of particular importance will be the accurate unification of aerodynamic, hydrodynamic and aeroelastic physics which will provide more reliable simulations of the FOWT system. The primary challenge envisaged here is related to the reliability of the models used and the extent to which simplifications are made. This can be ensured by means of experimental benchmark datasets which can be used to validate these high-fidelity models (see also Section 4.5). As shown in this review, most of the existing experimental results are available for global quantities of thrust and power measurements. More flow and localised blade load measurements are needed in the future.

Full body CFD methods can be used to account for aero- and hydro-dynamics, along with FE modelling to model aero-elasticity or hydro-elasticity. On the other hand, this goes in parallel to the development of large scale rotors (15 MW+), which in their own right lead to novel challenges such as tip flow compressibility effects [140,141]. As explained earlier, simplified coupled approaches such as those found in OpenFAST have been used for years. New coupled approaches are still not mature enough for adoption in the industry due particularly to the complexity and computational resources that are required. Nonetheless, from a research point of view, much insight can be gained from these high fidelity approaches. As was noted (see Table 2), much of the modelling efforts have been focused on pitch and surge since these are the most influential in terms of loading and power output. The need for creating engineering models especially associated with aero-elastic effects from more advanced models for wakes of FOWTs would be an interesting focus given the latest work surrounding wind farm wake interactions (see [32]).

4.4. Challenge 3: FOWT wake interactions

From the work of [40], it was clearly shown that the wake dynamics of different FOWT types present new challenges for wind farm simulation. Work on turbine to turbine interactions is still very rare and should be the subject of further studies given the different wake dynamics confirmed on fixed turbines. The two geometrical parameters of interest in this case are the horizontal distance between turbines (X) and the lateral distance (Y). The relative difference in the 6-DOF motions of the turbines could also be influential on their wake interactions. Such scenarios have been studied extensively for fixed turbines but with FOWTs, the platform motions may have an important role to play in determining the optimal spacing dimensions (X, Y). A diagram is presented in Fig. 13.

Simulation of wind farm wake interactions would be the next extension following two-turbine interactions and would enable more insight on the design and development of offshore wind farms of the future. In this regard there is an ample volume of literature on wake interactions of fixed bottom wind turbines (see some examples in [117,142–145] and [146]) and also dealing with concepts such as active wake management [147] for wind farm optimal operation.

For FOWTs, floater motions will affect the wake evolution including turbulent kinetic energy dissipation. As mentioned in this review, this has been found to enhance wake recovery. For this reason, the guidelines on turbine locations in wind farm contexts needs to be revisited. The effects on loading and in turn on the platform motions of downstream turbines due to the dynamic wakes of upstream turbines is as yet unexplored. This understanding becomes crucial to optimise better floating wind farm configurations. Current analysis methods on wake recovery have been tried and tested for fixed rotors usually using CFD with an LES turbulence model with rotor loads prescribed on actuator discs or lines. Further validation with experiment is however necessary to ensure that the downstream effects of turbulence dissipation are well captured as a result of the FOWT motion. A possible reason why the reliability of such models could be hampered is the simplification of the application of rotor loads, common in such methods.

4.5. Challenge 4: FOWT near wakes

Models of near wakes with a wide range of complexity have by now been used extensively in the literature. However, near wake flow

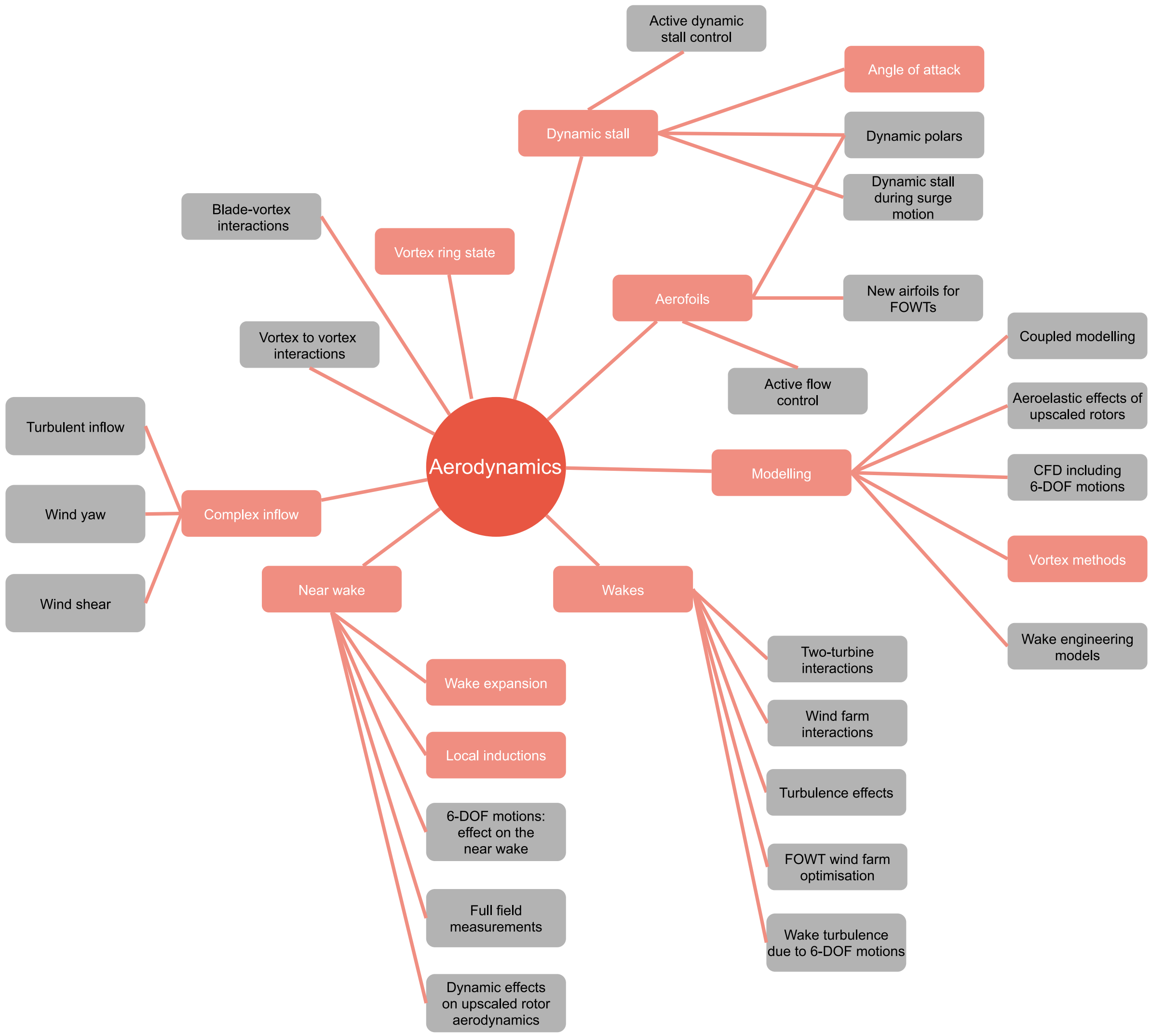


Fig. 12. FOWT aerodynamics research gaps. *Coloured areas*: widely investigated *Greyed areas*: possible research gaps.

measurements are not common apart from a few exceptions involving SPIV such as by [67] and hot-wire measurements by [63]. These could provide very useful insight on the wake's dynamic behaviour upon release and also its effects on loads. Blade-vortex interactions such as those recently found by [39] would also be a subject of great interest particularly its direct measurement using advanced measurement techniques such as SPIV. Vortex-to-vortex interactions are also very poorly documented in the literature and relevant here. The driving motivation for these studies is the unique conditions resulting due to the FOWT motions. Aeroelastic effects on the wake dynamics become very important for unravelling the near wake physics. For the most part, these aeroelastic phenomena are carried out using numerical techniques and already some recent examples have emerged in the literature such as [148] and [37]. Experimental validation on full scale rotors is a possible way to provide validation data for model benchmarking.

4.6. *Challenge 5: Turbulence and complex inflow*

The effects of wind heterogeneity and shear on FOWTs is still a subject that needs further investigation. Fixed rotor studies in relation to non-uniform inflow are quite common and this provides a suitable background for future investigations. This is particularly important in relation to the development of larger rotors. Atmospheric stability will influence the rotor inflow and therefore loading. As specified this challenge is also found in the fixed turbine case. The understanding of this effect coupled with rotor motions is important for characterising better the loads and fatigue performance of FOWTs. These coupled effects of wind shear and rotor motions also require further research in the control requirements of FOWTs to account for these complexities.

Moreover, turbulent inflow conditions coupled with the different wake dissipation mechanisms shown for FOWTs is something that requires further investigation. Another challenging aspect to consider is the wave effects on local inflow. What is required is to transition from more idealistic conditions such as limited platform motions, fully laminar, unyawed and unsheared inflow to more realistic scenarios which have substantial bearing on issues such as fatigue. With fast developing parallel fields such as control, monitoring, operation and maintenance these aspects of complex inflow and more realistic response of the FOWT are necessary for future offshore wind farms.

Spectral analysis of the platform loading under unstable atmospheric condition for the OC4-DeepCwind semi-submersible FOWT showed peaks in the energy spectra at low frequencies corresponding to the pitch and yaw motion natural frequency of the floater [149]. This observation was only considering the impact of the atmospheric turbulence effects and in the absence of any wake effects. Wake interactions of two tandem floating NREL 5MW, oscillating in surge motion, also revealed the presence of a low-frequency period mode in the transient

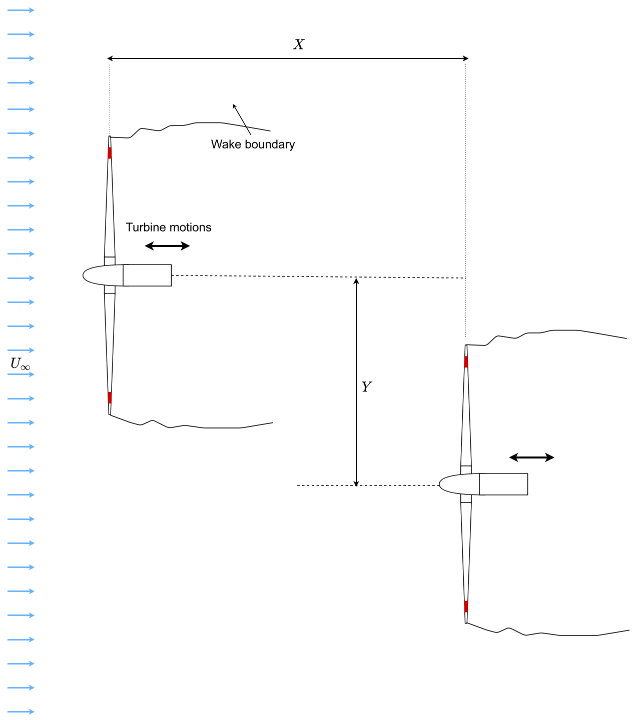


Fig. 13. Wake interactions between two floating turbines with staggered positioning.

loads and power data of the downstream turbine with a frequency almost a tenth of the surge frequency [32,150]. Although clarification of the underlying mechanisms corresponding to this low frequency oscillation requires further research, special attention needs to be made in consideration of the natural frequency of the floater [151].

5. Conclusions

With the ever increasing interest in making FOWT technology feasible for mass deployment, the research literature has been populated with various works related to FOWTs. Aerodynamics is one of the major topics in this multi-disciplinary field and the latest literature has been reviewed with the main objective of underlining the major developments, challenges and opportunities.

An effort has been made in placing aerodynamics within the context of other sub-fields rather than addressing the state of the art as an isolated field in its own right. In doing so, the knowledge requirements of other sub-fields from aerodynamics and vice verse have been identified and a more holistic future outlook has been sketched.

It was found that the current trend in the literature is to focus on the aerodynamics with specific platform motions imposed as an operating condition. Surging and pitching platform motions are the most commonly investigated situations. With the ever increasing rotor scale operating at Reynolds numbers in the multi-million range, wind tunnel testing has become a challenge also for FOWT applications. The literature in fact focuses heavily on simulation and numerical work with validation using more uncommon measurements and downscaled models. In the first years of the new century, coupled FOWT models were common but had to be limited to simple models such as quasi-steady BEM or BEM corrected using engineering models for the dynamic wake. Later, these simplified coupled models were also used to define platform motions for more dedicated aerodynamic simulations using for instance the FVM or full body CFD approaches amongst others. A number of principal outcomes, in many cases supported by various works, have been drawn.

Loads and power performance have been extensively studied in the literature with both experimental measurements and simulation. In surge motion, the amplitudes of both thrust and power coefficients are found to be influenced by surge amplitudes. During pitching, the thrust and torque amplitudes increase with decreasing pitching frequency and increasing pitch amplitudes. Secondary effects may also influence the variations of these parameters in the time domain. Multiple sources in the literature have confirmed an increase in mean power compared to the fixed foundation case for both surging and pitching. A low frequency power variation was observed during surge and pitching motions. The authors also noted a partial vortex ring state and propeller mode operation during pitching and surging. This gives more pertinence to blade vortex interactions and the growing importance of unsteady aerodynamics in FOWT research.

Wake expansions and contractions observed due to varying thrust loading were observed by various authors who confirmed a low frequency power response. A low frequency wake modulation was also confirmed. Studies on the near wake are important not only for characterising the turbine loading with more accuracy, but also to understand the mid to far wake development. Experimental observations on the latter suggest that turbulent kinetic energy for a pitching rotor is shifted upward. Laminar inflow causes the barge concept to have a faster wake recovery than the spar-buoy concept. Also, turbulent inflow causes a faster wake recovery. Dynamic effects of surging rotors were shown to be very small and quasi-steady BEM was shown to have reasonable accuracy. On the other hand, some appreciable discrepancies were found between codes such as AD CFD, OpenFAST and GDW.

On the interface of aerodynamics and control for FOWTs, smart dynamic wind turbine control, on the rotor scale, and wind farm control, on the larger scale, would become promising next steps to minimise the power and load fluctuations and to maximise the turbine lifetime.

Future challenges have also been outlined with an emphasis on the need for multi-disciplinarity. Studies on unsteady aerofoil aerodynamics with focus on FOWT rotors are needed by taking into account the complex 6-DOF motions of the rotor. Aerodynamic modelling of FOWTs should steer towards multi-physics particularly including aeroelasticity and compressibility effects in view of the 15 MW+ rotors of the future. Work on FOWT wake interactions is also identified as a major key challenge starting from a consideration of tandem rotors and the wind farm scale. Measurements of near wake flows remain essential for the correct prediction of loading conditions on the rotor as well as more specific issues, already identified by the current literature, related to blade-vortex interactions. Complex inflow conditions are also another challenge, which need to be considered in depth including wind turbulence effects, yaw and shear.

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.

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