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REVIEW ARTICLE

# A review of numerical modelling and optimisation of the floating support structure for offshore wind turbines

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**Abstract**

Compared to onshore wind power, floating offshore wind power is a promising renewable energy source due to higher wind speeds and larger suitable available areas. However, costs are still too high compared to onshore wind power. In general, the economic viability of offshore wind technology decreases with greater water depth and distance from shore. Floating wind platforms are more competitive compared to fixed offshore structures above a certain water depth, but there is still great variety and no clear design convergence. Therefore, optimisation of the floating support structure in the preliminary phase of the design process is still of great importance, often up to personal experience and sensibility. It is fundamental that a suitable optimisation approach is chosen to obtain meaningful results at early development stages. This review provides a comparative overview of the methods, numerical tools and optimisation approaches that can be used with respect to the conceptual design of the support structure for Floating offshore wind turbines (FOWT) attempting to detail the limitations preventing the convergence to an optimal floating support structure. This work is intended to be as a reference for any researcher and developer that would like to optimise the support platform for FOWT.

**Keywords** Renewable energy · Wind turbine · Offshore · Floating platform · Optimisation

## 1 Introduction

Wind energy is expected to play an important role in the European Green Deal aimed at decarbonizing the European economy (Hainsch et al. 2020). Offshore wind technology is less mature than onshore technology due to its more challenging operating conditions and higher costs. In addition, offshore wind turbines are expected to have higher loads on their structural components compared to a land-based system (Robertson and Jonkman 2011). However, the offshore wind potential is larger than onshore because higher wind speeds are normally achieved at sea, thanks to lower dissipation and disturbance (Esteban et al. 2011). Offshore wind turbines are primarily deployed next to the coast with a water depth of less than 60 m, where fixed-bottom foundations are still economically feasible (Breton and Moe 2009; Musial and Ram 2010; James and Ros 2015). Deeper water depths require a floating support structure, the design of which is still a major challenge for the industrialization of this technology (James and Ros 2015). In the Carbon Trust report (James and Ros 2015), it is shown that the greatest potential for reducing overall costs (about 16%) from prototype to commercial scale is achieved by reducing the size and weight of the platform. Similar cost reduction opportunities are also described in the ORE Catapult report (ORE Catapult 2022), where other areas of cost reduction are also associated with mooring, anchors, installation and maintenance. Other key cost drivers of a FOWT are also identified in ORE Cata-

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pult (2022). These are related to turbine rating, learning rate, transmission charges and project visibility.

Currently, there are three major types of platforms used in the industry, based on three different design drivers to reach the stability of the platform (Castro-Santos and Diaz-Casas 2016): the *buoyancy*-stabilized platform (or barge/semi-submersible platform), the *mooring*-stabilized platform (or tension-leg platform (TLP)), and the *ballast*-stabilized platform (or spar platform). The restoring moment of the semi-submersible platform is achieved by a large waterplane area that raises the metacenter well above the center of gravity. The TLP platform is stabilized by vertical taut moorings, whereas the spar stability is achieved by a heavy ballast that is as low as possible to increase the metacentric height. The semi-submersible platform is likely the concept that can benefit the most from optimisation procedure, since it has the highest platform cost compared to the other concepts (James and Ros 2015). However, the three above-mentioned substructure principles are often combined in hybrid solutions, so that a classification diagram, like the one shown in Fig. 1, could help to understand and discriminate between different concepts. The semi-submerged type has probably been the most explored compared to the others, as can be seen from the larger number of devices developed (see Fig. 1). It is usually referred to as a barge when the restoring torque comes mainly from the waterplane area. A good example is the Damping Pool device developed by IDEOL (Beyer et al. 2015). Most semi-submersibles combine the buoyancy and the ballast stabilized effect introducing some ballast to the lower part of each column. Some semi-submersibles might have three columns such as Windfloat (Roddier et al. 2010), VolturnUS (Viselli et al. 2016), and Tri-Floater (Huijs et al. 2014) or four columns such as Nautilus (Galván et al. 2018). Hywind (Ahn and Shin 2019) is the most successful of the spar concepts, having commissioned a commercial floating wind farm in Scotland in 2017 (Equinor 2022). Other types of spars include the Windcrete (Borrell and Hortigüela 2016), Sway (Koh et al. 2013), and Advanced Spar (Matsuoka and Yoshimoto 2015). Their design is similar to Hywind with an elongated single body shape, except Advanced Spar, which has a shorted body with multiple disks instead. Blue H TLP (Blue H Engineering 2022), GICON SOF (GICON-SOF 2022b), and ECO TLP (DBD Systems 2022) are examples of TLP devices in which taut tendons provide the required stability of the platform. Their design generally consists of a lightweight platform combined with a highly buoyant structure. Finally, the Hexafloat device (Delahaye et al. 2019) is an example of a floating wind platform where the restoring moment comes mainly from the counterweight under the float and can be described as a *Pendulum* type concept. However, this type could also have some similarities with the semi-submersible platform, as the restoring torque could come from the waterplane area as well for example during towing.

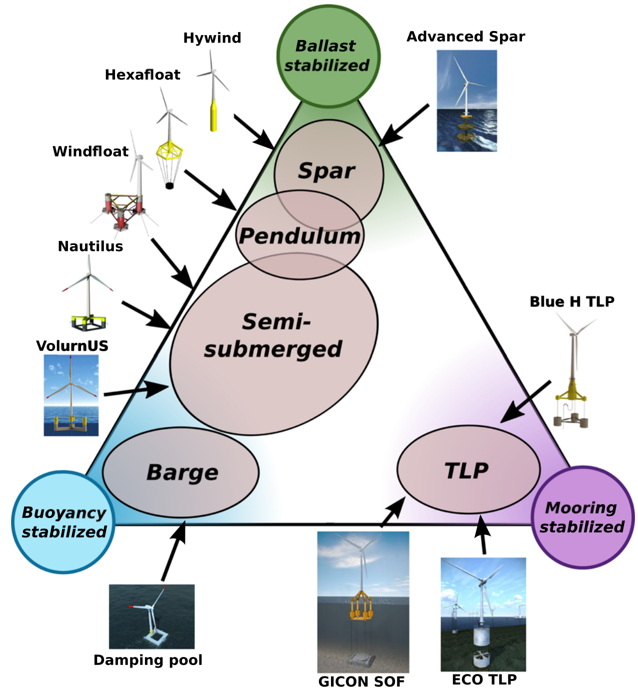


**Fig. 1** Classification diagram of the floating wind platform concepts (Cermelli et al. 2009; Cottura et al. 2021; Beyer et al. 2015; Blue H Engineering 2022; GICON-SOF 2022a; ECO-TLP 2022; Galván et al. 2018; RECHARGE 2022; Fukushima Offshore Wind Consortium 2022)

The design and the optimisation of such devices requires the development of a numerical model that is obtained as a trade-off between accuracy and computational time. Generally, a more advanced design stage will require a more detailed and accurate model. There are several challenges to be tackled, such as the coupling of the aerodynamic and the hydrodynamic loads acting on the floating structure (Atcheson et al. 2016), the modelling of the aerodynamic loads and of the control. A better understanding of the numerical choices, accuracy and computational time of the coupled model is required to have an appropriate modelling choice. The modelling of aerodynamics could require a modelling method that ranges from potential flow methods to high fidelity computational fluid dynamics (CFD) methods (Matha et al. 2011). The calculation of aerodynamic loads is more complex than for a fixed wind turbine, where a blade element momentum theory (BEMT) would be more accurate, due to the interaction of the platform motion with the rotor and the wake model. Modelling the controller is also challenging as the objective function could be extended to include the reduction of structural loads rather than just optimising the power generated as a function of wind speed (Salic et al. 2019). For a fixed wind turbine, a single input and single output (SISO) model is generally sufficient, whereas for a

FOWT, multiple input multiple output (MIMO), an AI based method or predictive control are more suitable (Lemmer et al. 2015; Christiansen 2013).

The optimisation of the floating support structure for offshore wind turbines has been recently of great interest, both for industry and academy perspectives because of the huge potential of this technology that could harvest wind energy in deeper sea. Recent projects such as the LIFES50+ (LIFES50+ 2022) have tried to develop a methodology for the evaluation and qualification of floating substructures. However, a developer still has to decide between a wide range of numerical tools and options that could delay the development and the assessment of the device. Furthermore, design optimisation requires state-of-the-art numerical tools that have the best compromise between accuracy and computational time obtained, for example, by cascading high fidelity tools (Michael 2015). However, literature is very limited in suggesting the most appropriate tools and optimisation approaches during the concept design stage. Previous reviews on floating wind energy are limited to the current status and future prospects of the technology (Henderson and Witcher 2010), experimental methods and tests (Stewart and Muskulus 2016; Chen et al. 2020), numerical methods and tools (Chen et al. 2020; Cordle and Jonkman 2011; Atcheson et al. 2016; Otter et al. 2021) and structural optimisation of the support structure for offshore wind turbines (Muskulus and Schafhirt 2014). However, to date, a review of the optimisation of the support structure for floating offshore wind turbines is missing. The aim of this paper is to overview the design, modelling and optimisation of a floating offshore wind turbine to assist a sensible decision of the numerical tool and of the optimisation method at the concept design stage. Here are some open questions that have been addressed in this review: “Are there conceptual design schemes for floating wind turbines?”; “Are there optimisation tools for floating offshore wind at the concept design stage?”; “How the accuracy of each numerical tool is identified?”; “How an optimisation study can be classified?”; “Which is the best trade-off between fidelity and efficiency of an optimisation tool?”. This paper will attempt to provide an answer to all these questions.

The paper is organized as follows: Sect. 2 investigates the design schemes associated with the the floating support structure of a FOWT. Section 3 describes the main numerical modelling, tools, validation and verification studies related with a preliminary design and optimisation of FOWT indicating the modelling capabilities for each numerical tool identified. Section 4 classifies the work made dealing with the optimisation of a FOWT according to different criteria such as the concept of a floating wind turbine and the type of analysis. These three sections are summarized in Fig. 2. Finally, Sect. 5 provides a critical comparative study of the numerical approaches while Sect. 6 draws some conclusions about the choice of the optimisation approach and numerical model.

## 2 Floating support structure design

In Lemmer et al. (2020b), Crozier (2011), Liu et al. (2018), Huijs et al. (2013), Collu et al. (2014), Borisade et al. (2015), Azcona et al. (2013), Fernandez et al. (2013) several design schemes of FOWTs are elaborated, describing an iterative model development process. A state-of-the-art design process for the floating support structure of a FOWT up to a Technology Readiness Level (TRL) 4 is described in the report of the Horizon Europe project LIFES50+ (Borisade et al. 2015). According to Borisade et al. (2015), the design process is divided into conceptual, basic, and detailed design (see Fig. 3). In the *conceptual design*, dimensioning is used in combination with a frequency domain model to evaluate the performance of the design. At this stage, the wind turbine is represented as a rigid body with wind loads acting on the rotor. A fully coupled time-domain simulation is used for the *basic design* where further details of the system are defined. Numerical modelling is the focus of these first two phases, but then experimental validation of the model during *detailed design* becomes crucial to validate the simulation model at component level.

Similarly, Collu et al. (2014) and Lefebvre and Collu (2012) present different steps to analyse the concept of a floating support structure: preliminary sizing, static analysis, and dynamic analysis of the structure. In preliminary sizing, both buoyancy and restoring pitch requirement must be satisfied. In Lefebvre and Collu (2012) the criteria used to evaluate the support structure concepts were only the estimated cost, restoring capacity, natural frequencies, and manufacturing. However, it is concluded in Collu et al. (2014) that the requirement driving the design of the floating platform is a good response to waves. Preliminary sizing and static analysis only would lead to an underestimation of the size of the structure. So, the conceptual design should include also the dynamic performance of the platform such as the response amplitude operators (RAOs).

According to the design standard for offshore wind turbines IEC 61400-3 Quarton et al. (2005); Turbines-Part (2009), an integrated load analysis should be performed for a cost-effective floating wind turbine. Therefore, it is important to perform a dynamic analysis at the concept design stage. A dynamic model in the frequency-domain model is preferred in an optimisation approach for platform design. A frequency-domain is faster compared to a time-domain and therefore, more suitable for optimisation. An optimisation scheme similar to the one presented in Fig. 3 aimed at obtaining a pre-design output can be found in Michael (2015). The iterative optimisation process includes a parametric tool

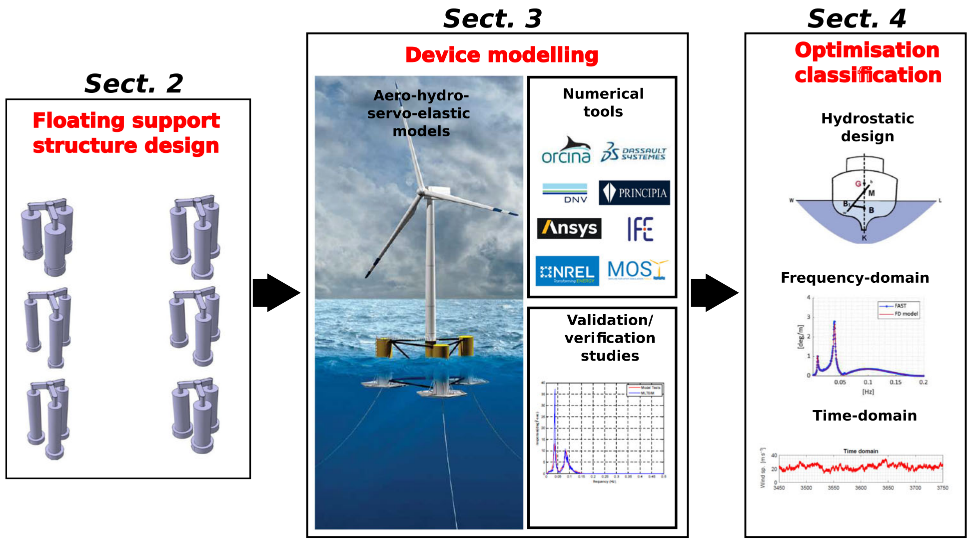


**Fig. 2** Main sections described in the paper. (Müller et al. 2016; IRENA 2016; Koo et al. 2014; Ferri et al. 2021; Pegalajar-Jurado et al. 2018)

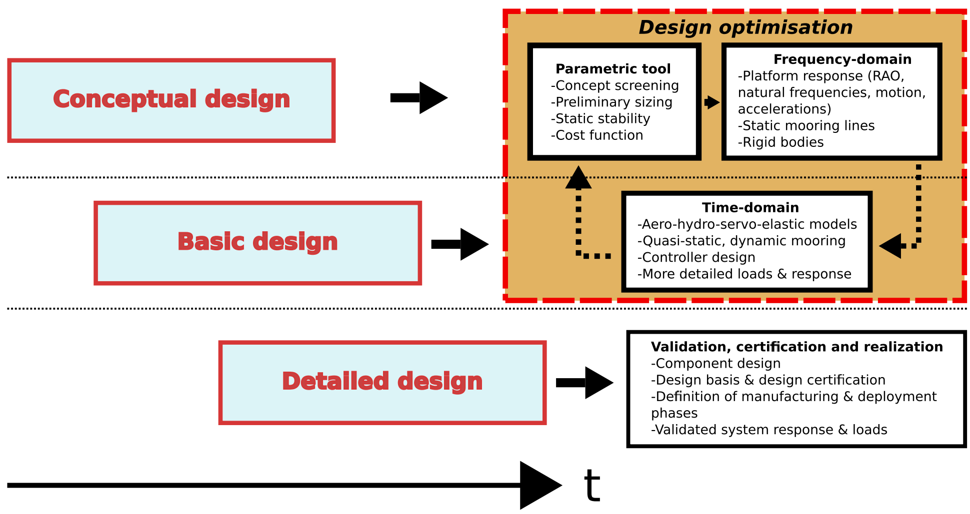


**Fig. 3** Design process of a FOWT

for preliminary sizing and the frequency-domain model that computes the dynamic checks. A fully coupled time-domain simulation is then used for a set of design load cases and, if necessary, the process is iterated until the desired requirements are met. A conceptual design of the platform shape of a FOWT is described in detail in Müller et al. (2016). The conceptual design involves the optimisation of a parameterized hull shape where the key geometric parameters are identified. The simulation software used was a simplified low-order wind turbine (SLOW) (Lemmer et al. 2020a), in which a frequency-domain was obtained from the linearization of the time-domain model. In the numerical procedure, an optimised control design was considered since it had a significant influence on the behaviour of the whole system. DoE (Design of Experiments) were used for the initial exploration phase of the selected design variables, followed by a single-objective optimisation algorithm to achieve minimisation of material cost and tower-top displacement.

## 3 Device modelling

The design of the floating platform requires modelling of the entire device system, as it is largely influenced by its various components. The numerical modelling is more complex for a FOWT compared to a bottom-fixed or on-shore wind turbine (Atcheson et al. 2016). The dynamic model also requires the inclusion of the hydrodynamics and the mooring model. Moreover, the additional degrees of freedom of the FOWT affect the aerodynamics of the turbine, which may require a higher complexity of the aerodynamic model. In Robertson et al. (2014); Jonkman (2013), both a diagram for modelling a FOWT that identifies the applied loads and the system response can be found. Figure 4 shows a similar modelling diagram but with a focus on the different components of the wind turbine for each modelling section. The external loads are caused by the wind, waves and currents. The aerodynamic loads act mainly on the rotor and the tower, while the hydrodynamic loads act on the platform and

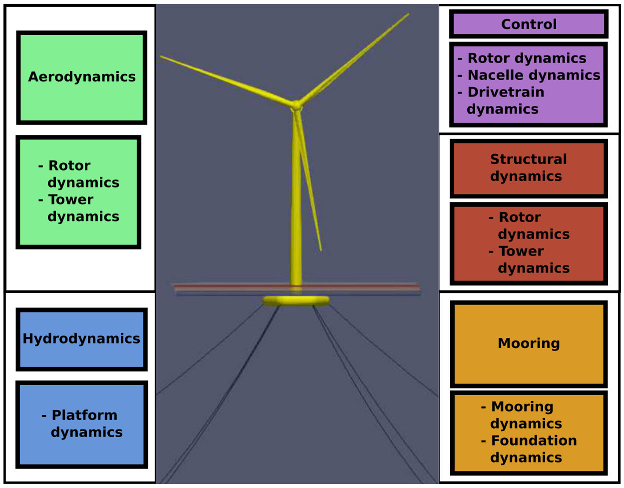


**Fig. 4** The main modelling sections and their influence on the device components of an FOWT

the mooring. However, the platform and mooring dynamics are generally associated with a different modelling module because of their different dynamic behaviour. It is also very important to include in the numerical model the control algorithm that provides power generation using a drivetrain. The control system will exert some loads on the rotor and affect its dynamics. A more accurate model will also consider the structural response of some selected components, such as the rotor and the tower, as they have a flexible behaviour. This response could be quite important, especially if the excitation frequencies are not too far from the lowest structural natural frequency. The main modelling techniques related to each modelling module are shown in Fig. 5.

The optimisation of the support structure of a floating wind turbine would preferably require a frequency-domain for an iterative optimisation process, as described in Sect. 2. However, these are usually not able to capture non-linear dynamic loads that are important for the dynamic response of the device. Therefore, a wide range of numerical time-domain tools have been developed to model a floating wind turbine. An overview of the modelling tools used for verification and validation studies can be found in Robertson et al. (2014, 2017) with the aim of supporting the development of these tools. These studies have been supported by the International Energy Agency Wind Research Task 23 and 30 respectively and they are the result of Offshore Code Comparison Collaboration between different participants. Task 23 aimed to compare the time-domain results of the coupled dynamic codes while task 30 aimed to validate the ultimate and fatigue loads of the system. The results of the comparison have shown a better understanding of the different approximations used for each model choice, while the ultimate and fatigue loads have been generally under-predicted. An overview of different numerical models for offshore wind turbines can also be found in Michael (2015). Most of the tools compared in this work have been qualified for preliminary design and optimisation of floating wind turbines. A summary of the main tools that have been used to simulate and/or optimise a FOWT is given in Table 1. Each tool is described based on its modelling capabilities to calculate the main loads acting on the floating system. Most of them simulate in the time-domain, but some are in the frequency-domain and have been successfully used to optimise a FOWT, such as QuLAF (Dou et al. 2020), SLOW (Lemmer et al. 2020a) and WINDOPT (Fylling and Berthelsen 2011). These codes have been developed by industry and research institutes or groups. Most of them are private and commercial, while only a few of them are open-source and available to the public, such as FAST (Jonkman 2013) and the nonlinear multibody dynamics package for wind turbine Mbwind (Lupton 2015b). The choice of the most appropriate tool for an optimisation study depends mainly on the accuracy and computational effort and will be discussed in Sects. 4 and 5.

### 3.1 Aerodynamics

Aerodynamic loads are generally calculated using the blade element momentum theory (BEMT). The BEMT theory combines momentum and blade element theories. The local forces on each blade section are determined for a given angle of attack and airfoil. A typical standard reference for this theory can be found in Hansen (2007). This type of modelling makes several assumptions, such as discretizing the rotor as annuli, not considering root and tip losses, and steady flow (Burton et al. 2011). However, the computation time of BEMT has been shown to be very efficient and some corrections can be added to increase the accuracy. A variety of corrections to the BEMT have been developed to increase the accuracy of the BEMT and overcome the assumptions explained earlier, such as the model to correct for hub and root losses (Burton et al. 2011). Another important correction is addressing the limitations of the BEMT theory for large axial induction factors (fractional decrease in wind speed between the freestream and the turbine rotor) where re-circulation effects become significant, and the rotor is described by a turbulent wake state where the basic theory is no longer valid Chapman et al. (2013). This last limitation is generally solved with the Glauert correction. A good review of correction models applied to a BEMT model can be found in Snel (1998); Sant (2007). A second important theory for modelling wind turbine aerodynamics is the generalised dynamic wake (GDW) model, also known as the acceleration potential method, which is an extended version of the dynamic inflow model already developed in Peters and He (1991), since higher-order terms are also included (Suzuki and Hansen 1999). The main advantages are that the dynamic wake effect and the root and tip losses are inher-

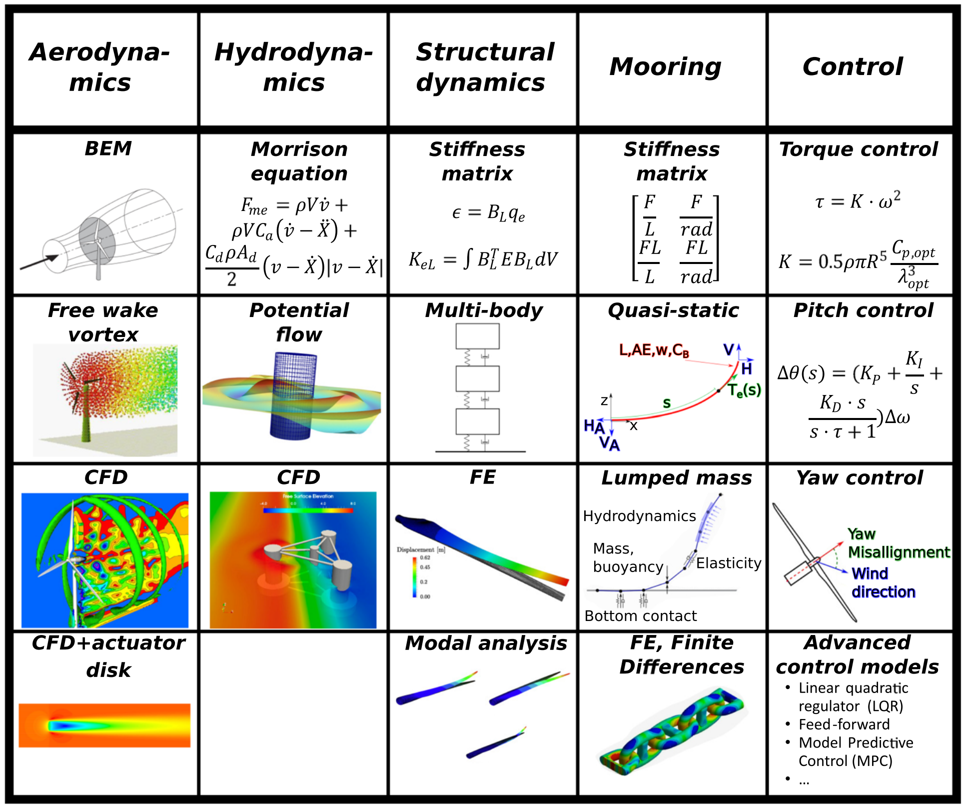


**Fig. 5** Modelling techniques of an FOWT (Zhou et al. 2019; Lemmer et al. 2020a; Hall 2015; Masciola 2018; Xue and Chen 2017; National Technical University of Athens 2022; Innosea 2022; Albanesi et al. 2017; Boudounit et al. 2020; Sturge et al. 2015)

ently included in the model compared to the BEMT model. However, there are some instabilities in this type of modelling at low wind speeds where the choice of BEMT method would be better. These two theories have been implemented in FAST (National Renewable Energy Laboratory 2022a), while a further description of the aerodynamic model can be found in the AeroDyn user manual (Moriarty and Hansen 2005). Dynamic effects of the airfoil such as dynamic stall could also be included in the wind turbine modelling. Such events have been measured in Butterfield et al. (1991) for a 10 m horizontal axis wind turbine (HAWT). The dynamic stall increases the dynamic and structural loading and therefore it is essential to take it into account when estimating the fatigue life. A higher order model is the free-wake vortex method, which models both wake flow and fluid–structure interaction. This modelling is particularly suitable for a non-standard modelling of a wind turbine blade, such as a blade with a winglet (Maniaci 2013). This method has been implemented in a fully coupled hydro-servo-aero-elastic model of an offshore wind turbine in the simulation tool hGAST in the PhD thesis of Manolas (2016). Finally, computational fluid dynamics (CFD) models have been applied to FOWT, but their computational complexity makes these models very challenging and less suitable for a design optimisation study (Liu et al. 2017; Lin et al. 2015; Rodrigues and Lengsfeld 2019). The most used approximation for wind turbine rotor aerodynamics is based on the Reynolds average Navier–Stokes equations (RANS) (Atcheson et al. 2016). These equations can be discretised by either finite elements, finite volumes or finite differences methods. They are usually used for isolated single load case simulation, e.g., for a detailed rotor blade design (Amano and Malloy 2009). Hybrid models that combines the actuator disk models with CFD have been used also to increase the computational efficiency required especially when computing a large domain such as the one of a wind farm (Sturge et al. 2015). The far wake region can be reasonably approximated using the actuator disk model while the near wake region requires a high fidelity CFD model.

## 3.2 Hydrodynamics

Hydrodynamic loading is very important in the design of a floating platform. Hydrodynamics modelling ranges from linear modelling, generally used for small to moderate wave conditions, to non-linear modelling, particularly suitable for extreme events. Non-linear methods are generally more accurate, but also more computationally expensive than linear methods. Potential flow models are the most common choice for solving the wave-structure interaction problem. Laplace's equation is solved under the assumptions of incompressible fluid, inviscid and irrotational flow. A review of these models, also known as panel methods or Boundary element methods (BEM), can be found in Hess (1990) and Newman (1992) while some classical books are Newman (2018); Le Méhauté

**Table 1** Summary of main tools capabilities used to model a FOWT

| | Aerodynamics | Hydrodynamics | Struct. dynamics | Mooring | Control | Simulation | Development/License |
|---|---|---|---|---|---|---|---|
| 3DFloat (Nygaard et al. 2016) | BEMT+DS DI | ME, CE+QD | FE | SM, FE | BPC, VSTC, UD | TD | RIG, CO |
| ANSYS AQWA (ANSYS 2012) | N/A | PT+CE+(MD+NA), FDE | RB, FE | SM, QS, FE | N/A | FD, TD | IN, CO |
| aNySIM-PHATAS (Gueydon et al. 2013) | BEMT+DS+DS+DI | ME, CE+QD+MD | MOD | DYN | BPC, VSTC | TD | RIG, PR |
| BLADED (DNV-GL 2022) | BEMT+DS+DI | ME, CE+QD | MOD, MB | SM, QS, FE | BPC, VSTC, YC | TD | IN, CO |
| CHARM3D+ FAST (Bae et al. 2011) | (BEMT, GDW)+DS | ME, CE+QD+(MD+NA) | MOD, MB | FE | BPC, VSTC, YC, UD | TD | RIG, PR |
| Deeplines Wind (Principia 2022) | BEMT+DS | ME, CE+(MD+QTF+NA) | FE | FE | BPC, VSTC, YC, UD | TD | IN, CO |
| Dymola+ MoWiT (Leimeister et al. 2020a) | (BEMT, GDW)+DS | ME, CE | FE, MOD | DYN | BPC, VSTC | TD | RIG, PR |
| FAST v8 (Jonkman 2013) | (BEMT,GDW)+DS+DI | ME, CE+QD | MOD, MB, FE | QS, FE, LM | BPC, VSTC, YC, UD | TD | RIG, OS |
| Flex5 (Jørgensen 2013) | BEMT+DS+DI | ME, CE+QD | FE, MOD | QS | UD | TD | RIG, CO |
| FloaWDyn (Campos et al. 2017) | (BEMT, GDW)+DS+DI | ME, CE | FE | FE | BPC, VSTC | TD | RIG, PR |
| HAWC2 (Larsen et al. 2005) | BEMT+DS+ DI | ME, CE+ QD | MB, FE | SM, QS, FE | BPC, VSTC, UD | TD | RIG, CO |
| hydro-GAST (Manolas 2016) | BEMT, FWV | ME, CE+QD+(MD+NA) | MB, FE | FE | BPC, VSTC | TD | RIG, PR |
| Mbwind+Lupton PhD thesis (Lupton 2015b) | Lin. BEMT | FDE | SM (Lin. MB) | SM | Lin. (BPC, VSTC) | FD | RIG, OS |
| MLTSIM-FAST (Koo et al. 2013) | (BEMT, GDW)+DS+DI | CE+QD+(MD+NA) | MOD, MB, FE | QS, FE | BPC, VSTC, YC, UD | TD | IN, PR |
| MOST (Cottura et al. 2021, 2022; Sirigu et al. 2022) | BEMT | CE+QD | N/A | QS | BPC, VSTC | TD | RIG, PR |
| OPASS+ FAST (Armendáriz et al. 2011) | (BEMT, GDW)+DS | ME, CE+QD | MOD, MB | LM | BPC, VSTC, YC, UD | TD | RIG, PR |
| OpenFAST (National Renewable Energy Laboratory 2022b) | (BEMT, GDW)+DS+DI | ME, CE+QD | MOD, MB, FE | QS, FE, LM | BPC, VSTC, YC, UD | TD | RIG, OS |
| OrcaFlex (Orcina 2022) | (BEMT, GDW)+DS+DI | ME, CE+QD | FE | SM, QS, FE, LM | BPC, VSTC, YC, UD | TD | IN, CO |
| QuLAF (Pegalajar-Jurado et al. 2018) | DM | FDE | SM (Lin. MB) | SM | Lin. (BPC, VSTC) | FD | RIG, PR |

**Table 1** continued

| | Aerodynamics | Hydrodynamics | Struct. dynamics | Mooring | Control | Simulation | Development/License |
|---|---|---|---|---|---|---|---|
| SIMA (SIMO/RIFLEX) (MARINTEK 2022) | BEMT+DS+DI | ME, CE+QD+(MD+NA) | MB, FE | SM,QS, FE | BPC,VSTC, UD | TD | IN, CO |
| Simo+Riflex+ Aerodyn (Ormberg and Bachynski 2012) | (BEMT, GDW)+DS | ME, CE | FE | FE | BPC, VSTC | TD | RIG, PR |
| Simpack (Matha et al. 2011) | (BEMT, GDW)+DS+DI, FWV, CFD | ME, CE+QD | MOD, MB | SM, QS, MB | BPC, VSTC, YC | TD | IN, CO |
| SLOW (Lemmer et al. 2020a) | APM | ME, CE, FDE | MOD, MB, SM(Lin. MB) | QS, SM | BPC, VSTC | FD, TD | RIG, PR |
| UOU+FAST v8 (Ahn and Shin 2019) | (BEMT, GDW)+DS+DI | ME, PT+ CE+QD | MOD, MB, FE | QS, FE, LM | BPC, VSTC, YC, UD | TD | RIG, PR |
| WAMIT (Newman and Lee 1992) | N/A | PT+(MD+ NA), FDE | RB, MOD | SM | N/A | FD | IN, CO |
| WINDOPT (Fylling and Berthelsen 2011) | N/A | FDE | RB | QS, FE | N/A | FD | RIG, PR |
| Aerodynamics | BEMT = blade element momentum theory; GDW = generalized dynamic wake; DS = dynamic stall; FWV = free-wake vortex; DI = dynamic inflow; CFD = computational fluid dynamics; APM = actuator point model; FDT = filtered dynamic thrust; DM = damping matrix | | | | | | |
| Hydrodynamics | PT = potential theory; ME = Morrison equation; QD = quadratic drag; MD = mean drift; QTF = quadratic transfer function; CE = Cummins equation; FDE = frequency domain equation; NA=Newman's approximation | | | | | | |
| Struct. dyn. | RB = rigid body; SM = stiffness matrix; MB = multi-body; FE = finite element; MOD = modal | | | | | | |
| Mooring dynamics | QS = quasi-static; FE = finite element; LM = lumped mass; SM = stiffness matrix; DYN = dynamic | | | | | | |
| Control | BPC = blade pitch control; VSTC = variable speed torque control; YC = yaw control; UD = user defined | | | | | | |
| Simulation | FD = frequency-domain; TD = time-domain | | | | | | |
| Development/License | IN = industry; RIG = research institute or group; OS = open-source; CO = commercial; PR = private | | | | | | |

(2013); Mei et al. (2005); Faltinsen (1993). WAMIT is a good example of a well-known software developed by the authors of Newman and Lee (1992, 2002) at Massachusetts Institute of Technology (MIT). For higher accuracy of the model, nonlinear hydrodynamic effects are considered. These could be caused by the incoming wave and the hydrodynamic body (Penalba et al. 2017). The incoming wave can be approximated using linear wave theory, but in general, nonlinear wave theories can also be selected based on wave height, wave period, and water depth (Wilson 2003). The Froude–Krylov force is one of the most important nonlinear loads acting on the hydrodynamic body. It requires the calculation of the incident wave pressure and the hydrostatic pressure over the instantaneous wetted surface at each timestep of the simulation (Giorgi et al. 2021a; Giorgi 2019; Giorgi et al. 2021b). The mean wave drift force could also be used to represent the mean nonlinear loads due to the diffraction and incident hydrodynamic pressure acting on the body. There are several approximations to obtain this loading, such as the quadratic transfer function (QTF) and the Newman's approximation (Faltinsen 1993). The viscous forces become significant when the size of the hydrodynamic body is small compared to the wave amplitude. They are generally modelled as a quadratic drag term (Todalshaug et al. 2011). An empirical expression for the hydrodynamic loads acting on offshore structures has been formulated by Morison (Morison et al. 1950). This equation accounts for both viscous and inertia effects estimating a drag and an inertia coefficient. The dynamics generated by the hydrodynamic loads acting on a given body can be solved in the frequency-domain or in the time-domain (Folley 2016). The frequency-domain model considers only the linear hydrodynamic loads, while a time-domain model can more accurately represent the nonlinear loads as well, despite an increase in computational time. A time-domain model is generally described by the Cummins equation, where the fluid memory effect is captured by a convolution integral formulation (Cummins et al. 1962).

### 3.3 Structural dynamics

Structural dynamics is usually included in the numerical model when fatigue analysis is required. Three types of limit states are considered in structural design: the ultimate limit state, the fatigue limit state and the accidental limit state. DNVGL-ST-0119 contains some relevant design practises for the structural design of floating wind turbines (DNV-GL 2018). The dynamic response of the floating structure is very important to determine its excitation wave frequencies. More precisely, these should be sufficiently low compared to the structural natural frequencies. There are different types of numerical methods to simulate a flexible structure. The best known is probably the finite element method (FEM), which consists in discretising the structure into finite elements. The application of FEM to a floating structure is generally limited to slender bodies such as beam theory (Campos et al. 2017). This theory is implemented using the Legendre finite element method (LFSE) in Fast's BeamDyn module to simulate flexible wind turbine blades (Wang et al. 2017). A multibody approach can also be used to model the structure. This method has been successfully applied in SLOW, developed by Lemmer (Lemmer et al. 2020b; Lemmer 2018). The wind turbine blades and tower are decomposed into rigid and flexible multibody systems. A rigid multibody formulation is considered sufficient for the platform, nacelle and rotor, while the blades and the tower generally require a more complete flexible multibody formulation. Finally, a modal method can be used to obtain a more computationally efficient simulation. Indeed, modal methods use a reduced number of degrees of freedom that identify the main structural deformation patterns. Good agreement is generally found for the dominant deformation directions, but less so for the non-dominant ones (Larsen et al. 2002).

### 3.4 Mooring dynamics

Mooring modelling can be approached in two main ways: quasi-static and dynamic. Quasi-static is usually used in a preliminary design phase and assumes that the mooring line is in static equilibrium at each timestep, and the position of the body depends only on the static restoring force. A quasi-static mooring model ranges from a simple linear stiffness matrix to the catenary equations that solve Newton's force equation at each connection node (Masciola et al. 2013). A dynamic mooring model is used to obtain more accurate mooring loads, especially for large displacements of the float where inertial effects play a greater role. A dynamic model is classified into three main types: a lumped mass model, finite element method (FEM), and finite difference (FD) models (Davidson and Ringwood 2017; Masciola et al. 2014). The mooring line is discretized in small elements in which the hydrodynamic drag and added mass are taken into account (Walton and Polachek 1960). The lumped mass is the easier numerical method to implement if it is assumed that the mooring line consists of concentrated masses connected by massless springs. The mooring dynamics is obtained by solving a system of equations of motion for each individual mass. A high fidelity solution is obtained with FEM and FD, where the mooring line is considered to consist of infinitesimally small differential elements. The main difference between these two methods is the formulation of the governing equation in a differential and integral form, respectively (Davidson and Ringwood 2017). In general, the lumped mass method converges to the same solution as FEM and FD, given sufficient resolution (Leonard and Nath 1981). There are also a number of other methods that have been used to discretise the mooring line. For example, the finite segment scheme, which consists of a series of ball-and-socket connected rigid rods (Winget and Huston 1976; Kamman and Huston 1985; Nichol et al. 2014; Garrett 2003).

### 3.5 Control

A control system is essential for a wind turbine system as it manages the different operating conditions affecting the rotor speed, the aerodynamic load on the blades and the energy capture (Burton et al. 2011). Two main types of control are distinguished in a wind turbine control system: variable speed control and variable pitch control (Lupton 2015a; Bianchi et al. 2007). Variable speed control operates at low wind speed with the aim of optimising the power produced. The optimal tip-speed ratio is maintained, resulting in a quadratic relationship between rotor speed and generator torque (Johnson et al. 2006; Pao and Johnson 2009). Apart the optimal torque control which is the most common control technique applied to commercial wind turbines there are also the power signal feedback, the hill climb search and the sliding mode control (Menezes et al. 2018). Variable pitch control is instead used at higher speeds when the rated power is reached. The blade pitch angle is actuated to maintain the rated power using a proportional-integral-derivative (PID) controller that computes the error between generator speed and nominal generator speed (Apata and Oyedokun 2020; Stol and Balas 2002; Hand and Balas 2000). A feedback control that adjusts the wind turbines operational states is mostly used for these two regions to account for the rotor speed disturbance (Laks et al. 2009). Advanced strategies might be required due to the interaction between pitch control and platform stability (van der Veen et al. 2012; Fischer 2013; Namik and Stol 2009; Namik et al. 2008). A pitch controller that considers multiple inputs and multiple outputs (MIMO) can be developed for higher performance (Lescher et al. 2006; Geyler and Caselitz 2008; Lemmer et al. 2015; Christiansen 2013; Luo et al. 2011; Lackner and Rotea 2011). A linear quadratic Gaussian (LQG), the model predictive control (MPC) and the feed-forward control have demonstrated improved results compared to PID for example in Bossanyi (2003); Christiansen et al. (2011); Raach et al. (2014); Schlipf et al. (2013). MPC and feed-forward control need to forecast the disturbance from wind and waves and so are more complex to model compared to a PID (Shah et al. 2021). A linear quadratic regulator (LQR) was designed in Lemmer et al. (2016) and it showed an improvement at the platform pitch and tower eigenfrequencies. However, at the wave frequency there was no visible improvement with the LQR. Fatigue loading of tower and blades using a multivariable control design could be reduced significantly (Lescher et al. 2006; Geyler and Caselitz 2008; Christiansen 2013; Lackner and Rotea 2011). In particular, this will determine a reduction of the cost of the mechanical structure of the plant or an increased lifetime. In addition, yaw control can also be implemented to maximise the energy yield by aligning the swept area of the rotor with the wind direction (Astolfi et al. 2019).

Individual blade pitch control has also been proposed to reduce the motion of the platform as on each blade is characterised by different local velocities (Bossanyi 2003; Namik and Stol 2010, 2011). Power optimisation control algorithm such as the neural network (NN) and fuzzy logic (FL) have been combined with individual blade pitch control in Han et al. (2016); Kang and Kim (2015). Structure control has also received some interest in the academia as the structural loads can be reduced. A passive and active hybrid mass-damper system placed on the nacelle was investigated by Lackner in Lackner and Rotea (2011) showing a reduction of the dynamic loads. Other examples of structure control based on mass-spring-damper systems in different parts of the floating wind turbine structure can be found in Si et al. (2014); Dinh et al. (2016); Li and Gao (2015). A tuned liquid column damper system was investigated in Coudurier et al. (2015). Finally, a more detailed modelling of the control will need to integrate also a full model of the generator, power converter, and grid response (Menezes et al. 2018).

### 3.6 Numerical model validation and verification

The accuracy of the numerical model is critical during the floating platform design process. However, there is generally a compromise between computational time and accuracy of the model, which depends on the purpose of the model. The optimisation of the floating structure requires many simulations and therefore, the computational time must be sufficiently low. A good overview describing the trade-off between computational time and model fidelity of linear and nonlinear hydrodynamic approaches can be found in Penalba et al. (2017). Another overview of experimental and numerical methods for offshore wind turbines is given in Chen et al. (2020). For validation of experimental results, a time-domain model is usually preferred as it has higher accuracy. The open-source software FAST has shown to capture very well most of the physics involved for all classes of floating wind systems (Oguz et al. 2018; Coulling et al. 2013; Driscoll et al. 2016; Philippe et al. 2013). FAST accurately reproduced the wind loads of a DeepCwind semi-submersible floating device while it did not captured the second-order hydrodynamic effects (Coulling et al. 2013). The mooring loads were also underpredicted, most likely because FAST was not able to account for dynamic mooring effects. However, most recent versions of Fast such as Fast v8 and OpenFast are able to model dynamic mooring as well. The numerical model of the Dutch Tri-floater floating wind platform was compared with experimental results using FAST in Philippe et al. (2013). Good agreement was found for regular waves for surge and heave, but less for pitch, which was more influenced by wind loading. FAST controller response and structural loads of Statoil's Hywind Demo spar have matched well with measured data (Driscoll et al. 2016) and it has also shown good capability to simulate a TLP system in Oguz et al. (2018). In this case, the influence of wind was found to be a significant contributor to the platform response compared to the variation in wave conditions. Most recent updates of FAST are included in OpenFast (National Renewable Energy Laboratory 2022b) which better supports the open-source developer community. One of the last improvements of OpenFast includes for example the nonlinear low frequency wave loads and responses of a floating wind turbine platform (Wang et al. 2022). In this study, it was obtained a better agreement of the surge and pitch wave loads on the DeepCwind floating wind semisubmersible platform with experimental data compared to the previous version of OpenFast. FAST has also been coupled with in-house codes (Ahn and Shin 2019; Koo et al. 2013; Kim and Kim 2016; Koo et al. 2014). In Ahn and Shin (2019), the computation of hydrodynamic coefficients is combined with the in-house code of Ulsan University and FAST. Good agreement was found between experiment and model for the OC3 spar, except for a single sea state where there was a larger difference in the significant motions due to strong nonlinearities of waves and mooring loads. FAST has also been coupled with CHARM3D, which calculates first- and second-order hydrodynamic loads and instantaneous tensions for mooring lines (Kim and Kim 2016). The results of the DeepCWind model test have shown a good correlation. In the same way, the DeepCWind numerical model was used in Koo et al. (2013, 2014) to compare experimental data with a very good agreement. In this work, FAST was combined with MLTSIM, which computes the hydrodynamic loads and the mooring dynamics. The in-house numerical tool aNySIM, developed by MARIN (MARIN 2021), has been implemented to compare the experimental results of the semi-submerged floater from the DeepCWind project in Gueydon and Weller (2013). This model failed to predict the pitch motion of the floater as it only considered a simplified version of the wind loading and did not simulate the dynamics of the rotor. The in-house code SIMO-RIFLEX (MARINTEK 2022) was combined with HAWC2 (DTU Wind Energy 2022) to compare a model-scale experiment of the Hywind system (Skaare et al. 2007). Accurate results have been obtained for a wide range of environmental conditions. The simulation code developed by a Japanese research group based on Morison's equation was compared with a tank-scale spar model in Utsunomiya and Matsukuma (2013). Good agreement has been obtained with the experimental results, except for the yaw motion. Commercial software such as ANSYS AQWA (ANSYS 2012), OrcaFlex (Orcina 2022) and SIMPACK (Matha et al. 2011) were used to compare experimental results in Sethuraman and Venugopal (2013); Ren et al. (2020); Borisade et al. (2018). AQWA has been used to model a hybrid system of a TLP wind turbine and a heave point absorber wave energy converter (WEC) (Ren et al. 2020). The model mostly overestimated the response of the dynamic system because viscous damping was neglected. In Sethuraman and Venugopal (2013), OrcaFlex was used to model a floating spar wind turbine. The results show a very good agreement in terms of RAO between experiment and model, considering the hydrodynamic responses of the spar under regular and irregular waves. The OC4 DeeCWind semi-submersible model has been validated in Borisade et al. (2018) with a SIMPACK model coupled with the module Hydrodyn (NREL 2022) for the hydrodynamic loads, MAP++ (Masciola 2018) for the mooring loads and Aerodyn for the aerodynamic loads (NREL 2022).

Verification studies are often preferred to validation studies because public measurement data are still very limited. (Buhl et al. 2001) and (Jonkman 2009) are some early examples in which the aero-elastic features of FAST were verified against ADAMS (Adams 2022) and the frequency-to-time conversion of FAST was compared with WAMIT respectively. MoWiT was verified with an overall good agreement with OC3 results in (Leimeister et al. 2020a). Established codes such as FAST are often chosen as reference for newly developed codes (Ferri et al. 2020, 2021; Lemmer et al. 2020a; Karimi et al. 2017). The coupled model ANSYS AQWA/PHATAS was verified against an uncoupled frequency-domain model in Huijs et al. (2014). The Simo/Riflex code was verified against some software of the Offshore Code Comparison project such as FAST, Adams and HAWC2 in Luxcey et al. (2011); Ormberg et al. (2011) while five numerical models that included some variations of a Simo/Riflex/Aerodyn were compared in Luan et al. (2017). Motion and loads of the TetraSpar floating platform were compared between OpenFast and OrcaFlex, with a generally good agreement, including the flexibility of the structure (Thomsen et al. 2021). The various studies discussed here have generally shown reasonable agreement bewteen numerical models and experimental studies. Fast is the numerical code that has been most commonly used for validation studies and has also been combined with in-house and commercial software such as CHARM3D, MLTSIM and Ulsan University's in-house code. Most of the preferred floating platforms compared with experimental results are the DeelCwind platform and the OC3 spar with a scaling factor generally between 1:50 and 1:100. Froude scaling is mostly adopted for the FOWT prototype in the experimental tests. The aerodynamic loads are mainly influenced by the Reynolds number and cannot be correctly reproduced with a Froude scaling. Only the rotor thrust, which has the greatest influence on the pitch motion, was simulated correctly with the inclusion of a new wind turbine rotor profile. OpenFast is

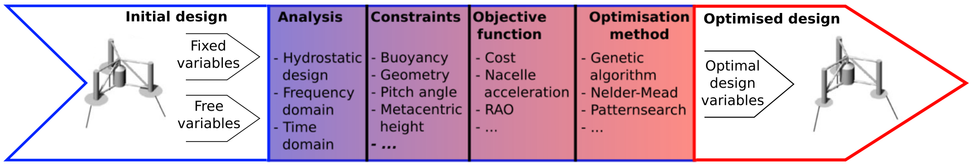


**Fig. 6** Floating support structure optimisation framework

probably one of the most advanced and accurate numerical models for FOWT as they have also improved recently the response of the FOWT for low-frequency wave loads (Wang et al. 2022). An extended comparison between the numerical models is given in the Offshore Code Comparison Collaboration (OC3, OC5, OC4 and OC6) (Robertson et al. 2014, 2015, 2017, 2020), as described earlier in Sect. 3. Projects OC3 and OC4 were very useful in determining the differences between the various codes in simulated response, but they lacked to estimate the most accurate solution. To this end, project OC5 and OC6 compared the simulated solutions with experimental measurements. Modelling techniques that improved agreement with the measurements were a dynamic mooring model, higher-order wave models and unsteady aerodynamic models. OC6 investigated the underprediction of low frequency hydrodynamic loads of a FOWT and concluded that the inclusion of QTF for second-order potential flow solutions and measured waves from the basin would generally improve the results significantly.

## 4 Optimisation classification

To be competitive in the energy market, a FOWT must reduce its costs. Therefore, optimising the design of this technology is fundamental to its success. Compared to experimental modelling, numerical modelling is an efficient method to optimise a floating wind turbine due to its lower cost. However, the accuracy of the model is very important, as explained in the previous section. When optimising a floating wind turbine, a simplified model that captures the most important physical relationships is generally used, but at the expense of the accuracy of the model. The optimisation framework of the floating support structure for an offshore wind turbine is represented in Fig. 6. First, the optimisation identifies the design variables of the initial design, which can be distinguished in fixed and free variables. The latter are then optimised after the type of analysis, constraints, objective function and optimisation algorithm have been defined.

Hydrostatic and frequency-domain models, which have lower accuracy than a time-domain model, are often used to optimise the floating support structure of a wind turbine, as shown in Table 2. The genetic algorithm is often used in these models because it offers the possibility to perform multi-objective optimisations, as for example in Karimi et al. (2017); Hall et al. (2013). A multiple objective function is necessary because the cost calculation associated with platform movement is subject to uncertainties. While some cost components, such as structural cost, are easier to determine, others, such as those related to nacelle acceleration, are less predictable. Greater nacelle acceleration is responsible for greater stress on the blades and drivetrain of the wind turbine, which reduces the turbine's lifetime (Sclavounos et al. 2008). Instead, a time-domain model is usually restricted to parametric design studies where a limited number of configurations are investigated (Robertson and Jonkman 2011; Jonkman and Matha 2011; Bachynski and Moan 2012). This type of optimisation is rather limited due to the larger computational time compared to hydrostatic and frequency-domain based optimisations. However, the calculation of fatigue and ultimate loads is limited to time-domain models. There are some similarities between the design constraints of the different types of optimisation. For instance, they all must fulfil the restoring requirement and some geometrical conditions. Typical constraints for hydrostatic design are also the metacentric height and the static pitch angle, while in the frequency and time-domain, constraints related to the dynamics of the system such as mooring loads, natural frequencies, nacelle acceleration and tower inclination can also be considered.

### 4.1 Hydrostatic design

In Ghigo et al. (2020), a platform optimisation of five different concepts, including a semi-submersible and a spar, was considered. Each concept was optimised in terms of material cost, with design parameters relating to geometry and the use of ballast. The study concluded that the Hexafloat was the most promising floating platform among the concepts considered for the Pantelleria site. Wayman (2006) performed a steady-state design and optimisation for several configurations, including spar, barge, TLP and the Tri-floater. The optimisation minimized the material cost of the structure and satisfied the desired value of the restoring coefficient in pitch. In Lefebvre and Collu (2012), a tri-floater concept was selected from seven support concepts based on various criteria such as cost, restoring performance, natural frequencies and manufacturing. A score was given for each criterion and multiplied by a weighted factor where the cost was the most important. The geometry parameters of the Minifloat III have been optimised using a genetic algorithm in Aubault et al. (2007). The aim of this work was to minimise the CAPEX considering various static constraints such as the

**Table 2** Overview of publications featuring the optimisation of a floating support structure of an offshore wind turbine

| Device classification | Design variables | Analysis | Design constraints | Objective function | Optimisation method |
|---|---|---|---|---|---|
| Semi-sub. | Platform geometry, ballast mass | Hydrostatic (Karimirad and Michailides 2015; Wayman 2006; Lefebvre and Collu 2012; Aubault et al. 2007; Ghigo et al. 2020) | Geometry, buoyancy, restoring stiffness, metacentric height, natural frequencies, static pitch angle | Cost, restoring capacity, natural frequencies, manufacturing, GZ curve | Parametric design, genetic algorithm |
| | Platform geometry, mooring configuration, ballast mass | Frequency-domain (Lemmer et al. 2020b; Karimi et al. 2017; Hall et al. 2013; Sclavounos et al. 2008; Brommundt et al. 2012; Benassai et al. 2014; Clauss and Birk 1996; Tracy 2007; Hall et al. 2014; Ferri et al. 2020, 2021) | Geometry, buoyancy, restoring stiffness, cost, static and dynamic pitch angles, mooring loads, slamming | Cost, nacelle acceleration, mooring configuration, RAO, displacement, mooring loads | Parametric design, genetic algorithm, Nelder-Mead simplex algorithm, tangent search method, fminsearch |
| | Platform geometry | Time-domain (Robertson and Jonkman 2011; Jonkman and Matha 2011; Lemmer et al. 2017) | geometry, buoyancy, static pitch angle | Fatigue and ultimate loads | Parametric design, Pattern Search |
| TLP | Platform geometry, platform submersion depth, tether tension | Hydrostatic (Wayman 2006) | Geometry, buoyancy, restoring stiffness, mooring loads | Cost | Parametric design |
| | Platform geometry, mooring configuration, tether tension, ballast mass | Frequency-domain (Karimi et al. 2017; Hall et al. 2013; Sclavounos et al. 2008; Tracy 2007; Hall et al. 2014; Parker 2007) | Geometry, buoyancy, cost, static and dynamic pitch angles, slamming, mooring loads | Cost, nacelle acceleration, displacement, mooring line tension | Parametric design, genetic algorithm, fminsearch |
| | Platform geometry, ballast mass | Time-domain (Jonkman and Matha 2011; Bachynski and Moan 2012; Myhr and Nygaard 2012; Lee et al. 2015) | Geometry, buoyancy, natural frequencies, mooring loads, tendon area | Fatigue and ultimate loads, cost, mooring loads, mass, displacement, nacelle acceleration | Parametric design, BOBYQA method, neuro response surface method |

**Table 2** continued

| Device classification | Design variables | Analysis | Design constraints | Objective function | Optimisation method |
|---|---|---|---|---|---|
| Spar | Platform geometry, ballast mass | Hydrostatic (Wayman 2006; Ghigo et al. 2020) | Geometry, buoyancy, restoring stiffness, metacentric height, static pitch angle | Cost | Parametric design, genetic algorithm |
| | Platform geometry, mooring configuration, ballast mass | Frequency-domain (Fylling and Berthelsen 2011; Karimi et al. 2017; Hall et al. 2013; Sclavounos et al. 2008; Clauss and Birk 1996; Tracy 2007; Hall et al. 2014; Dou et al. 2020; Hegseth et al. 2020) | Geometry, buoyancy, natural frequencies, static and dynamic pitch angle, cost, nacelle acceleration, tower inclination, fatigue life of mooring lines, slamming, mooring loads, mooring parameters, tower parameters, control | Cost, nacelle acceleration, RAO, displacement, mooring loads, power quality | Parametric design, genetic algorithm, NLPQL, tangent search method, fminsearch, fmincon, gradient method |
| | Platform geometry | Time-domain (Robertson and Jonkman 2011; Jonkman and Matha 2011; Leimeister et al. 2020b) | Geometry, buoyancy, nacelle acceleration, translational motions, rotational stability | Fatigue and ultimate loads, nacelle acceleration, translational motions, rotational stability | Parametric design, Non-dominated Sorting Genetic Algorithm |

buoyancy requirement, the minimum metacentric height and the heave period. In Karimirad and Michailides (2015), a selected design was selected from different shape variants of the V-shape semi-submersible wind turbine. The selected design was chosen considering the best performing righting arm and the generated moment as a function of the heeling angle using the hydroD software (DNV 2022).

## 4.2 Frequency-domain

Hall et al. (2014) performed a hydrodynamics-based optimisation to allow a more complete exploration of the design space of the platform geometry without any assumptions. Selected designs were optimised in the frequency-domain to minimise the nacelle acceleration. In Clauss and Birk (1996), hydrodynamic shape optimisation was used to optimise semi-submersible offshore wind turbines using a tangent search method. The optimised configuration resulted from minimising the response amplitude operator (RAO) of the most significant responses selected for evaluation. Constraints such as hydrostatic stability, cross-sectional areas to ensure strength and fatigue resistance, and fabrication, installation and maintenance costs were also considered in the optimisation. The hull of a semi-submersible wind turbine was optimised in Lemmer et al. (2020b). The aim was to obtain a design that does not respond to wind and wave excitations, resulting in low structural fatigue. A simplified low-order wind turbine model (SLOW) developed in the PhD thesis of Lemmer (2018) was used in this work. The proposed model aimed to represent only the most relevant physical effects for the system dynamics and consisted in its core of a flexible multibody system (Lemmer et al. 2020a). The numerical model has shown a good prediction of the response magnitude to wind and wave forces even for the linearized model compared to a high-fidelity code such as FAST (National Renewable Energy Laboratory 2022a). Two key design parameters of the DTU 10 MW platform were optimised to minimise the peaks and the areas of the heave and pitch RAOs in Ferri et al. (2020, 2021). The optimal configuration resulted smaller and with a better performance in surge, heave and pitch compared to the OC4 5MW upscaled platform. In Brommundt et al. (2012), a preliminary optimisation of the mooring system of a semi-submersible structure in the frequency-domain was performed. The optimal mooring configuration was obtained using MATLAB Nelder-Mead algorithm to minimise the cost of the mooring system. The design conditions considered were the ultimate load conditions, platform motion and seabed conditions. In Benassai et al. (2014), the most suitable mooring configuration for a tri-floater support structure was investigated. A parametric study was made depending on the water depth and the type of mooring line. It was found that a wire rope system was lighter than a chain rope system only up to a length of about 50 m. An extended study of a large number of configurations of platform geometries, including semi-submersible, spar and TLP, was addressed in Hall et al. (2013). In this work, a frequency-domain model was used in which hydrodynamic forces, mooring and wind turbine effects were considered. The Pareto front generated by a cumulative multi-nitching genetic algorithm (GA) has shown the optimal solutions that minimize both the structure cost and the nacelle acceleration. The Pareto front showed that lower costs were generally associated with greater nacelle acceleration. So, the optimal configuration was a trade-off between these two factors. The six-column semi-submersible configuration was the best configuration for the lowest nacelle accelerations, while the three-column semi-submersible configuration and TLP were the best choices for the lowest costs. However, the results of this study were limited to the uncertainties of the cost model, which could be significant due to the lack of experience in the sector. In Karimi et al. (2017), a similar approach was used to obtain an optimal platform. Three platform classes were optimised using the multi-objective GA of the MATLAB toolbox. It has been shown that TLPs and semi-submersibles with three outer columns were the optimal choice for platform design, but just like in the previous study, they were very sensitive to the cost model. Simultaneous optimisation of spar buoy geometry, mooring and power cable was studied using the WINDOPT optimisation tool in Fylling and Berthelsen (2011), but without considering wind turbine dynamics and control. Five or six spar shape variables, including vertical fairlead position, diameter and height for each spar section, were optimised with a view to minimising material costs, considering design constraints such as maximum tower inclination, natural periods and nacelle acceleration. The mooring and the spar buoy geometry for the DTU 10MW wind turbine was optimised in Dou et al. (2020). In this study, QuLAF (Pegalajar-Jurado et al. 2018) was used to model the dynamics of the floating wind turbine and MATLAB function *fmincon* was used for the optimisation algorithm. An integrated optimisation of a 10MW spar buoy which include the design of the platform, tower, mooring system and blade-pitch controller was investigated in Hegseth et al. (2020). The goal of the optimisation was a weighted function between system costs and power quality. In Tracy (2007), a parametric design optimisation of floating wind turbines was performed considering both the geometry and the mooring system in the design space using a frequency-domain model. Wind turbine effects have been accounted in the model through aerodynamic stiffness and damping matrices calculated from FAST (National Renewable Energy Laboratory 2022a). Optimal results were shown for different sea states in terms of nacelle acceleration and cost drivers such as displacement volume and mooring line tension. The TLP design has been demonstrated to be superior compared to the slack catenary design due to the low root mean square (rms) nacelle acceleration and negligible pitch and heave motion. A parametric optimisation of the TLP design has investigated the influence of water depth and wind as well as the effects of TLP geometry, ballast weights and initial mooring tension in Parker (2007). A similar numerical model to Tracy (2007) was also used in this work. In Sclavounos et al. (2008), a surface piercing vertical cylinder floater supporting a 5 MW wind turbine was optimised, considering both tethers in TLP designs and catenaries. Optimal structures were found that minimised various cost factors such as nacelle acceleration, mooring line tension and displacement volume of the platform. A narrow deep drafted spar and a shallow drafted barge ballasted with concrete were found to be equally optimal.

### 4.3 Time-domain

A 10 MW three column semi-submersible wind turbine was optimised in SLOW including the effect of the controller (Lemmer et al. 2017). The optimal hull is obtained minimizing the amplification of the wind and wave loads on the tower-top displacement. However, structural costs are increased because of the more voluminous heave plates and column spacing of the optimal solution. In Bachynski and Moan (2012), Bachynski (2014), a parametric TLP geometry study was performed for five different design structures using a coupled nonlinear code combining Simo (MARINTEK 2011b), Riflex (MARINTEK 2011a) and Aerodyn (Moriarty and Hansen 2005). Simo was used for the hydrodynamics of the hull, Riflex for finite element modelling of the tendons, tower, shaft and blades and AeroDyn for the aerodynamic forces and moments on the blades. In addition, the generator torque and blade pitch control were also included in the model. As a result of the investigation, some design recommendations, such as a larger pontoon radius, were made. In Lee et al. (2015), Ansys was used to optimise the substructure of a TLP using a neuro-response surface method. In this study, the nacelle acceleration, displacement and line tension were minimised. An optimisation of the geometry of a Tension-Leg-Buoy (TLB) and the preload of the mooring lines in the time-domain was addressed in Myhr and Nygaard (2012). For the calculations of the aero-hydro-servo-elastic loads, 3DFloat was used as a computational tool. It was concluded that a space-frame design of the buoy improved the performance due to the reduced wave loads. In Leimeister et al. (2020b), the height, diameter and ballast density of the OC3 spar buoy were optimised in Dimola using the MoWiT library (Leimeister et al. 2020a) considering global limit states such as rotational stability, translational motion and nacelle acceleration and a specific design load case according to IEC 61400-3 (Quarton et al. 2005; Turbines-Part 2009). Initially, a pre-screening of a large number of load cases was made, but then only the most critical one was considered in the optimisation. In Robertson and Jonkman (2011), a comparison of loads between six different concepts was carried out using FAST (National Renewable Energy Laboratory 2022a). They demonstrated higher loads compared to land-based systems, while showing similar ultimate and fatigue loads between them. The exception was the loads in the tower, which were lower for the TLP system. In Jonkman and Matha (2011), three different concepts were compared using FAST based on the fatigue and ultimate loads in a similar way as in Robertson and Jonkman (2011). The TLP and spar concepts have resulted in similar loads, but the load in the tower is larger for the spar system.

## 5 Discussion

FOWT technology is still in a nascent stage and the design process is not yet fully defined. Some large projects such as the LIFES50+ (LIFES50+ 2022) have developed a methodology for the assessment and qualification of floating platforms. Frequency-domain analysis is preferred over time-domain analysis in a concept design stage. It is more suitable for an optimisation process due to its higher computational efficiency. Literature shows that this type of analysis is also the most chosen, as shown in Fig. 7. The time-domain is mostly limited to parametric design studies, where the number of simulations is lower. The semi-submersible platform is also the most commonly chosen configuration for optimisation studies because, as explained earlier, it offers the greatest opportunities for cost reduction.

Figure 8 describes the computational efficiency for the different modelling options mostly used for a FOWT. Their classification is purely indicative and is done separately for each modelling section. A low-fidelity model is associated with the use of a damping matrix describing the aerodynamic loads, with the use of Morison's equation for the hydrodynamics and with a linear stiffness matrix for the mooring and the structure. However, Morison's equation is limited to slender structures and a typical FOWT support structure can not be classified as a slender structure. However there are a few examples where Morison's equation has been used to model the hydrodynamic loads of a FOWT. The spar buoy is probably the most suitable floating structure to be approximated by the Morison equation, as it can be considered as a slender cylinder. Good agreement between the numerical model of the spar buoy based on Morison's equation and the experimental results is shown in Utsunomiya and Matsukuma (2013). Sufficient agreement between the RAOs of the Eolink semi-submerged support structure from the Morison equation and the potential flow theory was obtained in Connolly et al. (2018). The structure could also be represented as a rigid body but neglecting the flexible behaviour of the structure. For higher accuracy, BEMT or GDW are mainly used to simulate the aerodynamics, the potential theory to simulate the hydrodynamic loads, the quasi-static and lumped mass models to simulate the mooring and the modal and multi-body approaches to simulate the structural dynamics. Numerical options with higher fidelity are usually chosen in a time-domain model while models with lower fidelity are generally associated with a frequency-domain model. An optimisation study usually requires as low computation as possible. FWV, FE and CFD can reach the highest fidelity to the real model but they are computationally intensive solutions that are not the best choice for an optimisation study. State-of-the-art numerical tools are introduced to achieve reasonable agreement for normal operating conditions and higher computational efficiency compared to high-fidelity tools. They may introduce some model modifications to better capture the physics associated with extreme events, unsteady aerodynamics, substructure flexibility and viscous hydrodynamic damping. These are coupled models that take into account all relevant physics and can be used during preliminary design. However, their use for an optimisation study is limited because they are generally time-domain and still too computationally expensive. The conceptual design of a floating platform could have several design parameters and a frequency-domain is probably the most appropriate. Optimisation tools for conceptual design could be obtained by cascading State-of-the-art tools such as QuLAF (Pegalajar-Jurado et al. 2018), in which an efficient frequency-domain model was successfully compared with FAST (National Renewable Energy Laboratory 2022a). However, a few exceptions have shown that an optimisation tool in the time domain is also feasible if an efficient computation is performed, e.g., in Leimeister et al. (2020b), Lemmer et al. (2017). This makes it possible to take into account the non-linearities of the coupled model and the effects of the controller on the dynamics of the wind turbine (Lemmer et al. 2017).

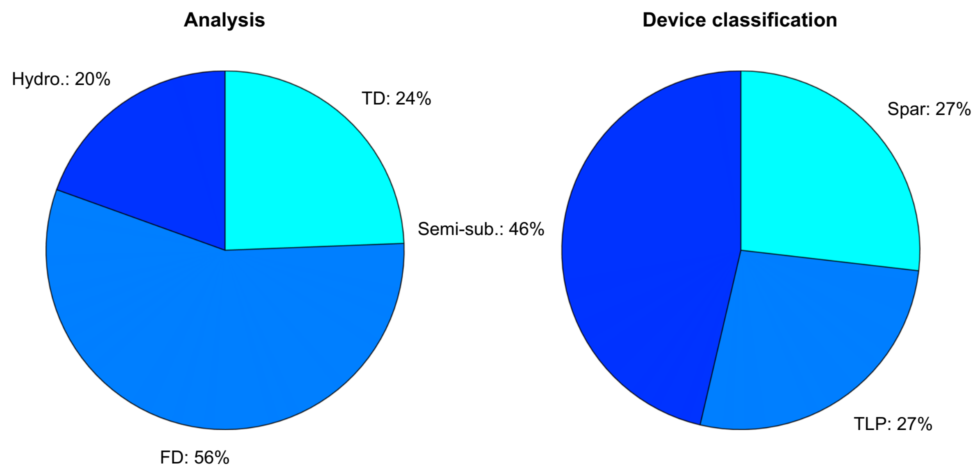


**Fig. 7** Type of device and simulation analysis chosen in the reviewed literature

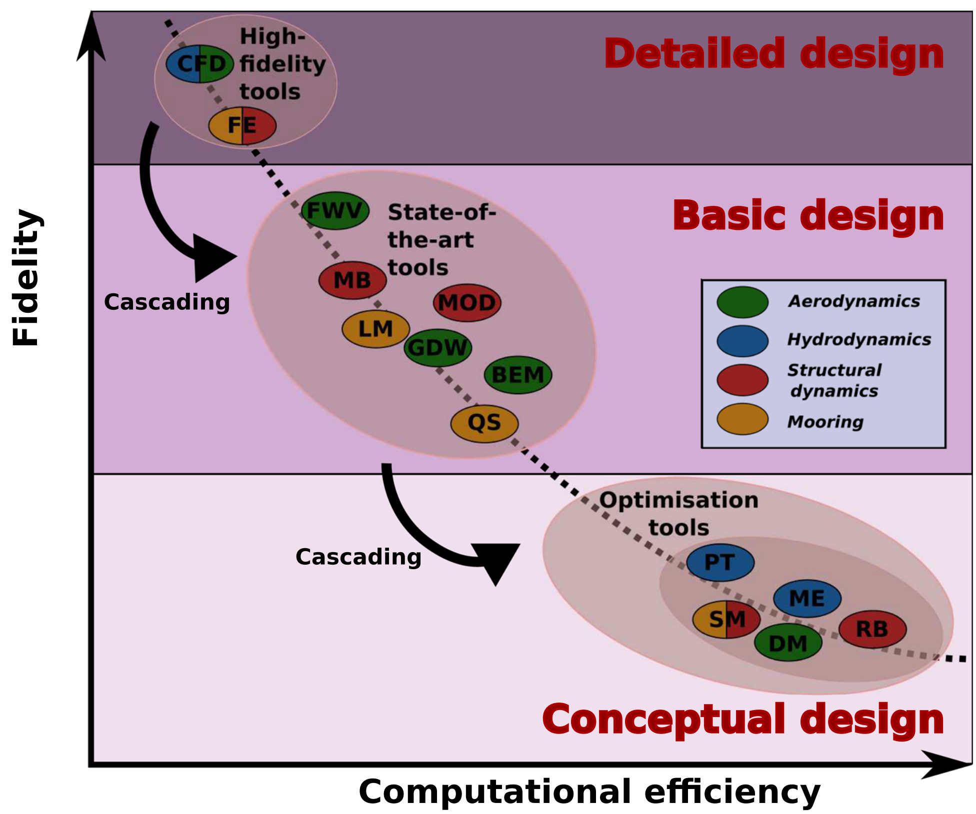


**Fig. 8** Trade-off between computational efficiency and fidelity for the most common numerical modelling applied to a FOWT. Nomenclature is the same of Table 1

Table 2 shows that costs are generally included in the objective function. The total cost depends mainly on the structure cost and thus on the platform geometry. Indeed, the structure cost is computed considering the material cost of the geometry. The material cost is minimized but at the same time several constraints must be respected. Restoring properties such as the metacentric height and the static pitch angle are typical constraints of a hydrostatic analysis. However, due to the limited development of this technology, constraint values are still not clear. For example, the static pitch angle was limited to 10 degrees in Karimi et al. (2017); Hall et al. (2013); Wayman (2006) but also to 5 degrees in Ghigo et al. (2020). A clear definition in the standards related to FOWT is probably needed for the development of a similar optimisation design process in different research projects. Few works have used hydrostatic analysis to optimise the design, but this analysis has been considered insufficient to fully evaluate the design (Collu et al. 2014). The design driver of a floating structure is not only about a stable platform but also about a good dynamic response to the waves of the platform. If the dynamic response is neglected, much smaller and lighter structures would be selected, but they would have a less efficient dynamic response. Calculating the natural frequencies of the structure due to wave excitation could give a first indication of the dynamic response. They are sometimes added to a hydrostatic analysis to obtain a preliminary structure with natural frequencies far from those of the wave excitation. However, the natural frequencies are usually only approximations and only a fully coupled dynamic model can give a more accurate answer. The dynamic performance is usually evaluated considering the RAO and the nacelle acceleration. The dynamic parameters can be considered both as constraints and as objective functions. They have some influence on the cost (Sclavounos et al. 2008) and therefore also need to be minimised. For example, the nacelle acceleration was optimised together with the costs in a multi-objective optimisation in Karimi et al. (2017), Hall et al. (2013). They could also be used as constraints, but there is no clear definition of their values in the standards yet. A standard could guarantee a certain lifetime of the system if the dynamic constraints are met. We assume that a future development of the FOWT will help to clarify the design constraints.

## 6 Conclusions

The optimal concept of a floating support structure for offshore wind turbines has not yet been defined. Many concepts have been patented without a clear convergence to a specific type. They differ mainly in the way stability is achieved, and three main classes can be distinguished: the semi-submersible, the spar and the TLP. This paper is intended to provide a guidance for optimising the design concept of a floating offshore wind platform. First, an overview of the design process is given to obtain an optimal floating support structure. Then, three important steps to optimise the concept are identified:

- The development or identification of the numerical tool is of primary importance in order to have a cost-effective way to design the device. The numerical tool must face new challenges due to the combination of hydrodynamic and aerodynamic loads. The offshore research community has largely solved this problem by linking codes from the onshore wind industry and offshore structures. However, the coupling is still very complex, e.g., related to the influence of the platform's motion on the aerodynamic loads. The natural frequencies of the structure might not be too far from the wave excitation frequencies, so, accurate modelling of the structural dynamics is also important. Inertial effects on the mooring lines require dynamic models, as FOWT are usually designed for deep waters where these effects are large. The control algorithms are also more complex compared to onshore wind turbines. The control of a FOWT faces the challenge of not only maximising the power generated by the turbine, but also minimising the movement of the platform. To overcome all these challenges, a suitable numerical tool must be selected or developed. This review provides a comparison of the numerical capabilities of the major software for modelling a FOWT to assist in selecting the most appropriate software during conceptual design. Several commercial codes have proven to be reliable and effective for modelling a floating wind turbine, such as OrcaFlex, which has also been compared in experimental studies. However, in general, commercial software for use in an optimisation study is more rigid than software developed by research groups, as it is directly accessible and can be inserted into an optimisation process. Design optimisation also requires computationally efficient models, which is why frequency domain models should be preferred in a preliminary phase. However, these are mostly private in-house codes, so they are not as widely used as time-domain models which are commercial and open-source as well. MbWind is an example of a frequency-domain model that is also open source, but is limited to the multi-body dynamics of the wind turbine. QuLAF is a good example of computationally efficient frequency-domain model which has been successfully used to optimise several parameters of the spar buoy. WINDOPT is also a frequency-domain model, but it lacks some important physical effects, such as aerodynamic loads. Time-domain models have been compared in the Offshore Code Comparison Collaboration studies and would be more reliable as they take into account the non-linearities of the dynamics. MoWiT is a good example of time-domain software that was used for an optimisation study of the OC3 spar buoy. MoWiT is non-commercial and can be combined with Python code, which makes it very powerful for automated simulations. MOST is an aero-hydro servo model based on Simulink, which also makes this software particularly suitable for design optimisation studies. In addition, look-up tables for the aerodynamic and mooring loads have been added to MOST, making it more computationally efficient compared to other time-domain codes. For optimisation purposes, we particularly recommend SLOW and FAST. SLOW was successfully used in the LIFES50+ project and takes into account an optimised control design to optimise the hull shape, as this significantly influences the response of the system. FAST is also recommended as it has been validated and verified in several papers and is probably one of the most accurate state-of-the-art codes available. It is an open-source code from NREL, used by a large research community and continuously improved. However, optimisations using FAST will be probably limited to a few design parameters as time-domain simulations are generally computationally expensive.

- Validation of the numerical model is an important step to assess the accuracy of the model. Usually, a fully coupled code is used to achieve an acceptable accuracy of the model compared to experimental results. Several validation studies have been carried out where good agreement between model and experimental results has been achieved. So far, the most validated software and used software in the research community is FAST. This numerical tool is open-source and is used by many users for their numerical studies. The main benchmarking cases between experiment and numerical model for a FOWT were identified in the literature to get a better understanding of the accuracy of the numerical tools developed.
- Numerical optimisation of the platform is used to reduce the cost of the platform. It has been shown that an optimal floating platform is not only related to the cost of the material and the structure, but also, for example, to a lower nacelle acceleration, which affects the lifetime of the device. The optimisation also considers various constraints related to the static and dynamic parameters of the system. Research conducted on this topic was reviewed and classified into three main classes based on the type of simulation chosen, namely hydrostatic design, frequency domain and time domain. Frequency-domain has been preferred from most of the studies as summarized in Fig. 5. We therefore, recommend this type of analysis as the first choice because of its computational efficiency. However, the accuracy of the frequency domain model should be carefully checked and it is recommended to check the results with a time domain model to increase the reliability of the final results.

An essential requirement of the numerical model is the accuracy of the model. However, a numerical optimisation must deal with another important aspect, namely the limited computational resources due to the large number of simulations required. In the concept design phase, a lower accuracy is generally accepted than in the following phases and the numerical tool is selected considering a trade-off between fidelity and computational time. In this sense, hydrostatic models and models in the frequency-domain are usually chosen for the optimisation of the platform of a FOWT, as they are faster than models in the time-domain. The latter, on the other hand, can be used in the final phase for a limited number of load cases to evaluate ultimate and fatigue limit states. However, a time-domain model was also used in parametric design studies where the number of simulations is limited and in a few exceptions an optimisation algorithm was also combined with the simulation of the model.

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