

## Review Article

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# A State-of-the-Art Review on the Numerical Simulation of Dynamics of Floating Offshore Wind Turbines: Coupling, Fidelity, Validation, and Model Selection

Bin Peng<sup>1</sup>, Sunwei Li<sup>1\*</sup>, Huaxiao Wu<sup>1</sup>, Yang Ni<sup>2</sup>, Wei Li<sup>3</sup>

<sup>1</sup> *Shenzhen International Graduate School, Tsinghua University, Shenzhen 518055, Guangdong, China*

<sup>2</sup> *China Power Engineering Consulting Group Corporation Limited, Beijing 100120, China*

<sup>3</sup> *ZHEJIANG Ocean Wind Power Technology Development Corporation Limited, Hangzhou 310012, China*

**Address correspondence to Sunwei Li, [li.sunwei@sz.tsinghua.edu.cn](mailto:li.sunwei@sz.tsinghua.edu.cn)**

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## Abstract

Numerical analysis of floating offshore wind turbines (FOWTs) combines aerodynamic, hydrodynamic, structural, mooring, and control models. Coupling topology is often used as a proxy for model fidelity, although topology describes information exchange whereas fidelity describes the physical processes represented within each subsystem. This state-of-the-art review treats these attributes separately. Coupling is classified as uncoupled, partially coupled, or fully coupled, while

subsystem fidelity is assessed through governing assumptions, target responses, validation evidence, and computational cost. Quantitative comparisons from code-comparison projects, laboratory experiments, and high-fidelity studies relate model classes to loading conditions and design tasks. Engineering-level fully coupled tools remain suitable for broad design-load calculations when their component models are validated for the responses of interest. Higher-fidelity methods are most useful for targeted analyses in which nonlinear wave loading, viscous effects, large platform motion, structural flexibility, wake interaction, or local flow and stress govern the response. The review proposes a task-oriented workflow that identifies required feedback pathways and physical mechanisms, checks validation coverage, and increases complexity only when lower-cost models omit a controlling process. The resulting guidance covers conceptual design, integrated load assessment, extreme conditions, and floating-wind-farm wake analysis.

**Keywords:** Aero-hydro-elastic-servo dynamics; Floating offshore wind turbines; Integrated design; Numerical modeling

## 1 Introduction

The growing urgency of addressing climate change has led to a consensus on the transition to a net-zero future globally, with renewable energy sources like wind energy at the forefront of this transition. Global installed wind capacity reached 1,299 GW at the end of 2025, including 165 GW added during that year [1]. Offshore wind accounted for 92.5 GW of the cumulative total, with 9.3 GW newly connected in 2025 [2]. As offshore wind energy continues to expand, there is a clear trend toward moving into deeper waters, where higher wind speeds and steadier conditions offer greater energy production potentials. However, the use of fixed-bottom turbines becomes

technically or economically restrictive in waters deeper than 70 meters [3]. This has driven the need for innovative solutions such as Floating Offshore Wind Turbine (FOWT), which can be deployed in deeper waters, tapping into these previously inaccessible resources. Despite the potentials of FOWTs, their commercial viability remains limited due to high installation and operation costs. Floating systems experience six-degree-of-freedom platform motions under combined wind, wave, and current loading, and these motions feed back into rotor inflow, structural response, control action, and mooring loads [4]. Reliable numerical simulation is therefore central to integrated design, load assessment, and risk reduction [5].

The numerical simulation of FOWT is characterized by the integration of multiple physical processes and therefore requires interdisciplinary technologies regarding aerodynamic, hydrodynamic, structural, mooring, and control [5, 6]. FOWT numerical models differ in two independent respects. Coupling topology describes whether and how those modules exchange information, whereas model fidelity describes the simplification made or physical detail retained within each module. Coupling level should not be interpreted as a fidelity scale. For instance, a fully coupled model such as OpenFAST [7] or Bladed [8] uses low-fidelity modules like blade-element momentum (BEM) for aerodynamics and potential-flow for hydrodynamics to achieve computational efficiency, while an isolated rotor or platform calculation may use a high-fidelity module like Computational Fluid Dynamics (CFD), which is valuable in disclosing key information concerning the blade, the turbine tower, or the floating platform. Uncoupled models remain useful when the design question is confined to a component and feedback from the rest of the system is secondary [9]. Rotor-only calculations can resolve load distribution, fatigue, and structural deformation of blades in detail [10, 11], enabling precise optimization of turbine blades for efficiency and durability under varying wind conditions [3, 12], while platform-only analyses

can assess hydrodynamic response and station-keeping concepts. Their value depends on whether the omitted interactions are weak for the target quantity of interest, rather than on the design stage alone. Partially coupled analyses occupy an intermediate position in the information-flow hierarchy. Prescribed motion like surge and pitch or platform motions obtained from experiments can be imposed on a rotor model to isolate and quantify their effects on unsteady rotor loads, wake dynamics, blade-wake interactions, and fatigue-relevant load fluctuations [13]. It provides critical insights into turbine and platform optimization by revealing how specific factors influence aerodynamic unsteadiness, wake instability, and overall FOWT stability. Conversely, mean, spectral, or time-varying rotor loads can be transferred to a platform model as prescribed external load, allowing the aerodynamic contribution to platform motions and response sensitivity to be assessed without solving the complete feedback loop [12, 14]. These workflows support mechanism identification and sensitivity analysis but do not reproduce the complete aero-hydro-servo-elastic response. Fully coupled simulations exchange loads and motions among the active modules during the solution and are required when system-level feedback governs stability, fatigue, ultimate loads, or controller response. Their fidelity nevertheless depends on the aerodynamic, hydrodynamic, structural, mooring, and control submodels used. Fully coupled frameworks support system-level assessment of dynamic stability, structural integrity, and operational reliability, and can inform the optimization of FOWT configurations and subsystems [12, 15]. Engineering tools are suited to extensive design-load-case calculations, whereas CFD–Finite-element-Analysis (CFD–FEA) and other high-fidelity frameworks are generally deployed selectively to investigate nonlinear interactions, local responses, or discrepancies identified in lower-cost models [12, 15]. This article is positioned as a state-of-the-art technical review of numerical simulation technologies for horizontal-axis FOWTs. The review covers aerodynamic, hydrodynamic, structural, and mooring representations and their integration in coupled simulation.

Controller-design algorithms are not reviewed comprehensively; however, servo dynamics are retained as a cross-cutting modeling requirement because pitch and generator-torque control affect aerodynamic damping, platform motion, structural loading, fatigue, and the reliability of coupled predictions. The review addresses the following questions:

- What governing assumptions and resolved physical processes distinguish the main aerodynamic, hydrodynamic, structural, and mooring models used for FOWTs?
- How can coupling topology and submodel fidelity be classified independently, and how do they jointly determine the capability of an integrated FOWT model?
- What verification and validation evidence is available for each model class, quantity of interest, and loading condition?
- How should numerical models be selected and combined for conceptual design, design-load assessment, extreme-condition analysis, farm-scale simulation, and targeted operational applications?

This article presents a critical narrative review covering studies available through August 2026. The literature was selected to represent established engineering tools, international code-comparison and validation campaigns, dedicated experiments, and recent high-fidelity and data-driven studies. Priority was given to studies reporting governing assumptions, quantities of interest, validation evidence, or computational cost. Studies focused exclusively on fixed-bottom turbines, vertical-axis turbines, or controller synthesis were included only where they informed modeling issues transferable to horizontal-axis FOWTs.

Section 2 introduces a 2-dimensional coupling-fidelity framework and model selection recommendation. Section 3 and section 4 review the uncoupled and partially coupled simulation,

respectively, with emphasis on their information pathways and applicable physical questions. Section 5 reviews fully coupled engineering and high-fidelity frameworks. Section 6 synthesizes benchmark evidence, provides model-selection guidance, and identifies research priorities. Section 7 summarizes the principal conclusions and boundaries of the review.

## **2 Coupling-fidelity frameworks for numerical model selection**

### **2.1 Coupling topology**

Coupling topology specifies the direction, frequency and scope of information exchange among model components. Three coupling categories are distinguished here. In an uncoupled analysis, a component is solved without response information from the other subsystems. Partially coupled analyses retain only selected interaction pathways through prescribed motions, external loads, boundary conditions, or simplified response-dependent loads, but do not concurrently update the complete set of system-level feedback pathways [16-18]. In a fully coupled analysis, all feedback pathways included in the selected system model are updated during the solution [19, 20]. These definitions concern information flow and do not prescribe the fidelity of the individual solvers.

Information may also be transferred sequentially between separate analyses without forming a closed feedback loop. For example, platform-motion histories from a wave-basin experiment or an engineering model can be imposed on a rotor calculation. The resulting rotor-load histories or coefficients may then be supplied to a platform model [17, 18, 21]. Because the updated platform response is not returned to the rotor calculation, this remains an open-loop sequential workflow rather than a fully coupled simulation. Within this review, such an open-loop workflow is

classified as a partially coupled analysis. The prescribed inputs, transfer sequence, and use of any offline iteration should therefore be reported explicitly.

Table 1 Classification matrix of coupling topology and submodel fidelity

| Coupling topology | Engineering fidelity                                      | Intermediate fidelity                                       | High fidelity                                                   |
|-------------------|-----------------------------------------------------------|-------------------------------------------------------------|-----------------------------------------------------------------|
| Uncoupled         | BEM; linear potential flow; rigid-body or beam models     | Free-vortex wake; second-order potential-flow; flexible MBD | Blade-resolved CFD; fully nonlinear hydrodynamics; detailed FEA |
| Partially coupled | Prescribed motions, loads, or boundary-condition transfer | Vortex method, RANS, nonlinear hydrodynamics                | CFD based framework with selected feedback                      |
| Fully coupled     | OpenFAST- or Bladed-type aero-hydro-servo-elastic tools   | Engineering frameworks with targeted nonlinear modules      | Resolved aero-hydro-elastic CFD-FSI frameworks                  |

## 2.2 Submodel fidelity

Model fidelity describes the physical processes resolved and the approximations introduced within each subsystem. It should be assessed component-wise because a coupled framework may combine BEM aerodynamics, second-order potential-flow hydrodynamics, flexible multibody structural dynamics, dynamic mooring, and a detailed controller [20, 22]. Reducing this heterogeneous fidelity profile to a single label can conceal the source of model error [23].

For practical comparison, this review uses three broad fidelity bands. Engineering-fidelity models rely mainly on reduced-order or semi-empirical formulations suitable for extensive load cases. Intermediate-fidelity models retain additional unsteady, nonlinear, or flexible-body physics at moderate cost. High-fidelity models resolve local flow or structural fields through CFD, fully nonlinear hydrodynamics, finite-element analysis, or fluid-structure interaction[4, 23, 24]. These

bands are descriptive rather than absolute, and higher fidelity does not guarantee higher accuracy without appropriate inputs, numerical convergence, and validation.

### **2.3 Model selection principle**

Model accuracy is considered here for a specified quantity of interest and loading condition and refers to the agreement between a prediction and reference data, accounting for uncertainty in both [25]. Agreement in mean rotor power does not establish accuracy for wake turbulence, blade-root fatigue, platform slow drift, local pressure, or mooring-line tension[26]. Verification evaluates whether the mathematical model is implemented and solved correctly, including numerical convergence. Validation evaluates its agreement with physical observations for the intended application. Code-to-code comparisons help identify implementation differences and model sensitivity, while model-scale tests, and full-scale measurements provide physical validation evidence [4, 25].

Model selection should therefore begin with the design question, target output, dominant physical processes, and required feedback pathways [27]. The minimum sufficient fidelity is then chosen and checked against relevant validation evidence and computational constraints[28]. Fidelity should be escalated only when the lower-cost model omits a dominant process or fails for the required response. This decision logic is used throughout the following sections.

### **3 Uncoupled analysis**

Uncoupled FOWT analysis isolates the blade, the rotor, tower, or floating platform from feedback from the remaining subsystems. Computational efficiency denotes the computational cost required to achieve acceptable accuracy of the target quantity of interest, and therefore

determines whether a method is practical for large-scale simulations and design optimization [29, 30]. While FOWTs include both horizontal- and vertical-axis wind turbine, this review focuses on horizontal-axis FOWTs, which dominate current industrial development.

### 3.1 Aerodynamics

Aerodynamic modeling determines rotor power, thrust, sectional loads, and wake development, and is therefore central to FOWT simulation. The calculation starts from the inflow velocity relative to each moving blade section, which combines the ambient and induced flow with rotor rotation, platform motion, and blade deformation. This relative velocity and the local blade orientation determine the angle of attack. Sectional lift and drag can then be evaluated from airfoil coefficients, or surface pressure and viscous stresses can be integrated in a blade-resolved flow calculation. Integrating the resulting forces along the blades gives rotor thrust and torque; the product of torque and rotor angular velocity gives aerodynamic power [31, 32].

The main modeling choices follow from this calculation. Wind shear, turbulence, yaw, and platform motion change the incident velocity; wake induction changes the velocity seen by the rotor; rotation, separation, and dynamic stall change the sectional aerodynamic response. Blade deformation further changes the local velocity and orientation. BEM models represent these effects through sectional data and correction models, vortex methods calculate the evolving induced flow, and CFD resolves the flow field at a level set by the rotor representation and turbulence treatment [31-33].

BEM is the established engineering method for assessing wind turbine aerodynamics. It combines momentum theory with blade element theory by dividing the rotor into annular streamtubes and the blades into spanwise elements. Each element uses two-dimensional airfoil lift

and drag data, while momentum balances determine axial and tangential induction. Chord, twist, and airfoil properties may vary along the span; interaction between neighboring annuli is simplified in the basic formulation. An iterative solution matches the sectional aerodynamic forces to the momentum balances. The converged forces are integrated over the rotor to obtain thrust and torque. This reduced description makes BEM suitable for repeated load calculations and design-space exploration [34, 35].

BEM is computationally efficient, but its fundamental assumptions may be violated under some FOWT operating conditions [34]. The OC6 Phase III project evaluated aerodynamic models against experiments for rotors undergoing prescribed surge and pitch motions. For the forced-motion cases tested, most approaches reproduced the mean and cyclic rotor loads reasonably well, whereas larger differences emerged when variations in rotor speed or blade pitch introduced dynamic inflow effects [26]. Two-dimensional sectional data require corrections to represent rotor-specific three-dimensional effects [31, 35, 36]. Many correction models have been developed to address these limitations, such as corrections for tip loss [37, 38], three-dimensional rotation effects [39-41], and dynamic stall corrections [42], in an effort to enhance its fidelity and expand its applicability, as detailed in the review by Bai et al. [32]. Although BEM has been continuously improved, its applicability still depends on the operating condition, correction models, and target response [43]. Papi et al. showed how the dynamic inflow formulation and platform motions influence BEM predictions for floating wind turbines [33]. BEM supports conceptual design and large design-load-case sets when its correction models represent the relevant operating conditions. BEM nevertheless remains the most widely accepted approach for aerodynamic load calculations, and the mainstream simulation tools, such as OpenFAST, GH-Bladed, SWT, AeroDyn, and others, employ the BEM theory for aerodynamic load calculations.

At intermediate fidelity, lifting-line[44] and lifting-surface [45] representations can be coupled to free-vortex wakes [46] to estimate aerodynamic thrust and torque [47, 48]. A prescribed wake assumes its geometry, whereas a free-vortex wake evolves with the local induced velocity and ambient flow. The latter represents wake deformation and rotor-wake interaction explicitly [46, 49]. Sectional aerodynamic data and, where needed, dynamic stall models still supply the viscous and unsteady airfoil response. Coupling these methods to structural solvers enables aeroelastic calculations [50]. They are useful for motion-induced induction and near-wake studies at lower cost than blade-resolved CFD [6, 31].

The OC6 project Phase III benchmark used a 1:75-scale DTU 10 MW rotor in wind-tunnel tests with prescribed surge and pitch motion and added numerical cases with rotor speed and blade pitch variations [26]. For the latter cases, BEM without a dynamic inflow correction predicted rotor thrust peak-to-peak amplitudes that were 9% lower during rotor speed variation and 18% higher during blade pitch actuation than the mean predictions of models accounting for dynamic inflow [26]. These are differences between numerical predictions, whereas the prescribed-motion experiments provide the physical validation data. The comparison identifies rotor actuation and dynamic inflow as important model-selection factors.

In contrast to the aforementioned methods, the CFD simulation offers a significantly higher level of fidelity in assessing the aerodynamics of a FOWT. CFD can resolve flow features and blade load distributions unavailable to other lower fidelity models, but its accuracy still depends on governing assumptions, turbulence closure, boundary conditions, numerical convergence, and validation. More specifically, the CFD simulation can account for the molecular and turbulent viscous effect of the wind flow, whereas BEM and related engineering models do not explicitly resolve viscous flow, although they can incorporate its effects on aerodynamic loads through

airfoil data and supplementary empirical corrections. With the increasing computational resources, and the growing size of blades used in modern offshore wind turbines, CFD simulations have become an important tool for FOWT research, design, and optimization.

Within the CFD framework, three main approaches exist to model turbulence, which significantly affects computational demands: Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), and Reynolds-Averaged Navier-Stokes (RANS) modeling. Due to computational resource constraints, DNS is generally impractical for routine full-scale rotor simulations, while blade-resolved LES remains computationally demanding. RANS is widely used for blade-load and mean-flow calculations [51], whereas actuator-line LES is used for wake-resolving studies. The accuracy of a RANS simulation, however, is highly sensitive to the choice of the turbulence model [52]. Among various turbulence models practically available, the Shear-Stress Transport (SST)  $k-\omega$  model is commonly used for blade boundary layers and aerodynamic loads [53], with separated-flow predictions depending on the operating condition and numerical resolution [54]. Combining the advantages of the RANS with the LES, the Detached Eddy Simulation (DES) and Improved Delayed DES (IDDES) have been suggested for simulating the aerodynamic performance of wind turbines [55, 56]. Lei et al., for example, compared the IDDES with the RANS simulation and identified significant advantages for the IDDES to estimate wind turbine aerodynamic loads and to discern flow separations [57], which are important in the simulation of the FOWT [58]. The additional grid and time resolution increases computational cost. Section 4.1 and Table 3 compare the capabilities and reported costs of wake resolving approaches for selected floating wind cases.

### 3.2 Hydrodynamics

Hydrodynamic analysis balances platform inertia against wave excitation, radiation, viscous loads, hydrostatic restoring, and mooring forces. For an incident wave, fluid velocity and acceleration generate drag and inertia loads; the presence of the platform diffracts the wave, and platform motion radiates additional waves. The resulting forces and moments drive the six degree-of-freedom rigid body motions. Their relative importance depends on member dimensions, wavelength, wave amplitude, flow velocity, and motion amplitude [59].

For typical semisubmersibles, member size relative to wavelength helps determine whether diffraction must be represented, while flow separation around columns, braces, and heave plates can make viscous loading important [60] [61]. Wave steepness and the ratio of oscillatory fluid excursion to member size further influence nonlinear excitation and drag. For tension-leg platform (TLP), high tendon stiffness restrains heave, roll, and pitch and shifts the associated natural frequencies; tendon dynamics and platform coupling remain relevant to load assessment. Simplified hydrodynamic and mooring models can reproduce selected global responses, with dynamic mooring and nonlinear wave effects added when they control the response [62].

Morison's equation remains a widely employed semi-empirical model for predicting viscous drag and inertia forces on slender structures [3]. The drag term depends on the squared relative fluid-member velocity, and the inertia terms depend on fluid and structure accelerations through prescribed coefficients. This model assumes a long wavelength relative to the structure's characteristic dimensions, implying a negligible influence of the structure on the surrounding wave field. Slender-member guidance commonly uses diameter-to-wave length ratios of approximately 1/10 [63] to 1/5 [64] ; coefficient selection and the importance of diffraction must also be assessed for the actual geometry and flow. For larger structures, where wave diffraction and radiation become dominant, potential flow theory is more appropriate. This approach accounts for the

modification of the wave field due to the structure and the generation of radiated waves from the platform's motion [65].

In practice, Morison drag terms and potential-flow hydrodynamics are often combined to represent viscous loading together with wave excitation and radiation [60, 66] [67] [68]. This is useful for semisubmersibles containing members of different sizes, provided that inertia and added-mass contributions are assembled without double counting. The approach is implemented in engineering tools such as AQWA, OpenFAST, and Bladed. In OC5 Phase II, comparisons with the DeepCwind basin measurements showed underprediction of low-frequency response in several engineering models [69]. Second-order difference-frequency excitation and viscous damping are consequently important when wave loading excites the low-frequency surge and pitch modes. Sum-frequency excitation can instead affect higher-frequency responses [70]. Model uncertainty should be evaluated for the resulting platform motions and mooring line tensions [61].

CFD resolves additional viscous and nonlinear flow physics compared to either Morison's equation, the potential flow theory, or their combination, but this added fidelity does not guarantee higher accuracy without convergence assessment and validation [4]. Further investigation in OC6 Phase Ib demonstrated that CFD simulations could effectively capture nonlinear wave interactions that were not well represented by mid-fidelity models. For the fixed, simplified three-column DeepCwind geometry in bichromatic waves, second-order potential-flow quadratic transfer functions (QTFs) underpredicted difference-frequency pitch moments by approximately 20%-40% relative to measurements [71]. This comparison concerns wave-excitation moments on a fixed body and motivates improved representation of nonlinear loading. Tran et al. conducted a series of numerical tests targeting the free decay of the DeepCwind semi-submersible platform [67], and demonstrated that while CFD simulations, potential flow theory, and the hybrid method all yielded

good agreement with experimental measurements, the CFD results gave the closest agreement for the reported comparison. Dunbar et al. have revealed limitations in traditional engineering models, particularly in capturing vortex shedding-induced oscillatory loads and nonlinear interactions between platform components [72]. Given the growing trend for numerically simulating the FOWT, scholars have engaged in the development of hydrodynamic CFD solvers based on open-source platforms, such as OpenFOAM. For instance, Wan et al. developed the naoe-FOAM-SJTU hydrodynamic solver within the framework of OpenFOAM [73]. Bruinsma and Dunbar, in addition, either used an existing solver or developed a custom solver based on the OpenFOAM package to estimate the hydrodynamic loads acting on the floating foundations both adopted in the OC5 project [74] and in line with the OC4 DeepCWind design [72].

Hydrodynamic model selection should be driven by the load and response mechanisms that control the quantity of interest. Linear potential-flow models efficiently represent radiation, diffraction, and wave-frequency response when the assumptions of inviscid, irrotational flow and sufficiently small motions are appropriate. For semisubmersibles, second-order difference-frequency excitation can become important near low-frequency platform resonances; Difference-frequency loading has been identified as a source of low-frequency response underprediction in engineering-level models [65, 70, 71]. When viscous separation, vortex shedding, slamming, or wave run-up controls the design response, the selected model should explicitly represent, or be calibrated for, the relevant mechanism. The choice among augmented potential-flow, hybrid potential-flow/viscous, fully nonlinear potential-flow, CFD, and particle methods should consequently be based on the controlling physics, the response quantity of interest, and validation evidence.

Structural flexibility introduces an additional model-selection question. A coupled aero-hydro-elastic representation is warranted when deformation of the floater, tower, or blades materially changes load transfer, modal properties, or the response quantity of interest; a rigid-body representation may be sufficient for preliminary screening of global platform motions. Following appropriate linearization, frequency-domain coupled models can provide efficient response and sensitivity estimates [75-77]. Their applicability is nevertheless limited by the underlying linearization, and time-domain simulations are generally required when transient, nonlinear, or control-dependent processes govern the design load case.

### 3.3 Structural dynamics

A FOWT is a complex system consisting of both flexible and rigid bodies. Its structural analysis encompasses the blades, hub, nacelle, drive chain, tower, and floating platform. Structural dynamics balances inertial, damping, and internal forces against external aerodynamic, hydrodynamic, gravitational, and transmitted mooring loads. The required outputs range from displacements and natural frequencies to sectional forces and local stresses. Mass and stiffness distributions, damping, rotational stiffening, joint constraints, and deformation amplitude determine the necessary structural representation [11] [4, 78] [79] [6]. Modal reduction, multibody assembly, and Finite-Element Methods (FEM) discretization address different parts of this calculation and may be used together.

In simulating the dynamics of a complex system, modal analysis typically involves selecting a few modes that significantly contribute to the overall system dynamics. Therefore, the accuracy of modal analysis relies on the proper mode identification and selection [4]. In the numerical simulation of wind turbine blades, mode identification could be inaccurate due to the insufficient consideration of two key factors: the complex stiffness distribution of the three-dimensional blades

and the dynamic stiffening effect of the blades. The former arises from the anisotropic mechanical properties of composite materials, complex geometric shapes, and thin-walled closed-chamber structures used in modern large-scale blades [80, 81]. The latter is due to the rotation of the blades, which causes the modal shapes to vary with rotational speeds [82]. Rotation changes the effective stiffness and modal properties, so the relevant operating speed should be included when establishing the structural model [82, 83]. Once the modes are identified, the overall dynamics of the wind turbine can be determined via combining all modes linearly, or by selecting a subset of representative modes for analysis [84]. The common simulation codes, such as Bladed and OpenFAST, utilize modal analysis for wind turbine structural dynamics. Modal truncation is efficient when the retained modes span the response of interest; large deformation and strong modal coupling may require an updated modal basis or a nonlinear beam formulation [85, 86].

Similar to the modal analysis, Multi-Body Dynamic (MBD) models the overall dynamics of the FOWT system via explicitly simulating the interactions between its components, which are typically modeled as rigid bodies individually [4, 87]. Given its relatively high computational efficiency, MBD has been widely adopted to simulate the dynamics of large-scale wind turbines and is implemented in various numerical tools, such as HAWC2, OpenFAST, Adams, Darwind, etc. [11]. Linear beam models are efficient for small elastic deflections, and suitable sectional stiffness matrices can include bending-torsion coupling. Geometrically nonlinear beam models additionally account for large rotations and deflections, which become important for long, flexible blades [88, 89]. Flexible multibody formulations combine these beams with rigid components and joint constraints [90] [91, 92]. They provide an efficient route to integrated aeroelastic load calculations, while shell or solid elements are used where local sectional deformation and stresses are required.

Shell and solid FEM models resolve additional sectional or through thickness deformation and are used for analysis including blade stress-strain analysis, buckling analysis, stability analysis, and local stress concentration analysis [93, 94]. Liu et al., for example, performed a buckling analysis of a rotating wind turbine blade, with the composite blade modeled by shell elements [95]. In addition, Ullah et al. revealed that local skin buckling was induced by pressure stress concentration on the blade suction side via the FEM simulation [96]. Celso Jaco et al. demonstrated the shell finite element models are particularly advantageous for modeling the local buckling phenomena, compared to the beam elements [97]. These studies show why local buckling and stress assessment require structural detail beyond a beam representation.

A quantitative structural comparison by Camarena and Anderson used beam, shell, and solid models of a 100 m blade under large static deflection [98]. Relative to the solid model, tip deflection was approximately 4.3% lower with the beam model and 2% lower with the shell model. The corresponding twist was 5.6% higher and 24% lower, respectively, with shell predictions improving under mesh refinement. This component-level numerical benchmark illustrates why displacement, twist, and local stress require separate assessment.

### **3.4 Mooring dynamics**

Mooring models determine the restoring forces transmitted to the platform and the tensions along each line. Quasi-static models solve the instantaneous equilibrium for a specified fairlead position, including line weight, buoyancy, and, where implemented, axial elasticity and seabed contact. Dynamic formulations additionally resolve line inertia, hydrodynamic loading, and time-dependent deformation, commonly using lumped-mass or FEM discretization [99, 100]. Water depth, line geometry, pretension, axial stiffness, fairlead motion, and seabed contact determine the importance of these effects. Quasi-static models are useful for equilibrium and initial restoring

characteristics; dynamic models are appropriate for tension fluctuations and fatigue when line dynamics contribute appreciably [99] [101].

Hall et al. compared quasi-static and dynamic mooring representations for the OC3-Hywind spar, ITI Energy barge, and MIT/NREL TLP [99]. For the spar in their load case, quasi-static predictions for the selected upwind fairlead damage-equivalent load (DEL) were, on average, 32% below the dynamic-model predictions, whereas extreme fairlead tensions agreed within 1%. This distinction shows that agreement in peak tension can coexist with substantial differences in fatigue relevant loading.

#### **4 Partially coupled analysis**

In this review, partially coupled model retains selected information pathways among FOWT subsystems while omitting the complete simultaneous feedback of the integrated system. Most studies considered here use prescribed motions or externally specified loads. When rotor aerodynamics is the primary concern, platform motions are imposed on the rotor model. Conversely, when platform hydrodynamics is examined, aerodynamic effects are represented by prescribed or response-dependent external loads. These simplifications support mechanism identification and sensitivity analysis, but they do not reproduce the complete aero-hydro-servo-elastic response.

Partially coupled model can isolate specific dynamic behaviors that may otherwise be obscured in fully coupled simulations. For example, Li et al. demonstrated that platform sway motion could be one source of wake meandering. Although wake meandering can be observed in fully coupled simulations, isolating the contribution of certain platform motions is challenging. Partially coupled model, hence, enables an investigation on how certain motion influences wake

dynamics [102]. Similarly, Lee H and Lee D-J found that surge and pitch motion in FOWTs is prone to inducing dynamic stall [103]. Prescribed-motion analyses therefore allow the effects of individual platform motions on wake dynamics and dynamic stall to be quantified independently.

#### **4.1 Rotor aerodynamics**

In a partially coupled numerical simulation concerning aerodynamics, the prescribed motions acting on the rotating blades to represent the impact from the floating platform are typically modeled as harmonic motion. This approximation reflects the cyclical nature of wave-induced motions, and therefore provides a reasonable estimate for the influence from the floating platform hydrodynamics. Such simplification understandably does not deliver the full spectrum of aerodynamics under experimental conditions or actual sea states. Instead, its primary purpose is to isolate and study specific aerodynamic characteristics of the rotor in a FOWT under certain periodic motions induced by the waves.

Regarding the amplitude and frequency of the imposed harmonic motions, the values are primarily referenced from experimental studies [104-106]. For the translations and rotations amplitudes, the ranges of 1m–16m and 1 degree–8 degree are typically used. As for the periods of the induced motions, the range from 5s to 100s is commonly used [107-109] (see Table 2). Such values reflect typical platform motions observed in controlled experimental environments.

Among these motions in different directions, the streamwise motions (surge and pitch) are of particular interest [6], as they are the aerodynamically most relevant [110], and hence have more prominent impacts on aerodynamic loads [103, 111-113]. From reviewing the existing literature, the impact of surge and pitch motions on rotor aerodynamics comprises three aspects:

**Amplify the unsteadiness of aerodynamic loads.** The streamwise motion adds an additional time-varying streamwise velocity on the effective velocity and thus alters the angle of attack of each blade. Consequently, unsteady aerodynamics of blades and induced-velocity are amplified [109]. While this slightly changes the mean aerodynamic loads, it leads to severe periodic fluctuations in aerodynamic load acting on the blade, with peak values exceeding 150% of those observed without surge or pitch motion [114]. Similar phenomena have been observed in the studies on surge motions by De Vaal et al. [109], Micallef et al. [115], Tran et al. [116], Wen et al. [117], and Lin et al. [118], as well as pitch motions by Tran et al. [119, 120], Lennie et al. [121], Shen et al. [45], Chen et al. [114], and Fang et al. [122]. Pitch and surge produce similar trends in the aerodynamic loads [123]. The severe fluctuation in aerodynamic loads is primarily attributed to the fluctuation in the angle of attack, rather than the motion-induced relative velocities [117]. To explore the factors that might influence aerodynamic loads of a rotor subjected to the surge or the pitch, Micallef et al. [115] examined the impact of tip speed ratios on a surging rotor. They concluded that the impact of surge motion on the fluctuation and mean aerodynamic loads depends on the operating conditions. More specifically, the loads fluctuation range increases as tip speed ratio increases in all cases, and mean loads increase as tip speed ratio increases in the above-rated cases (tip speed ratio  $\geq 7$ ). While in the below-rated case (tip speed ratio = 4), a decrease in the mean power coefficients of a surging rotor was observed. This conclusion substantiates previous studies including the numerical study by Farrugia et al. [124] and the model turbine experiment investigation by Sant et al. [125]. As regards the influences of the amplitudes and frequencies of the imposed motions, Chen et al. found that the power output of a FOWT is more sensitive to amplitude than the frequency of the motion added to the rotor [114]. Wen et al. took a systematic investigation on the impact of both surge amplitude, and surge frequency on the mean and fluctuation of aerodynamic loads. They concluded that as surge amplitude or frequency

increases, the fluctuation range of aerodynamic loads expands [117]. A similar trend in transient load variations was also observed when the added motion is in the pitch direction [122].

**Induce complex inflow states and in turn complex blade-wake interaction.** Such complexity indicates that some widely-used aerodynamic models, developed for the bottom-fixed wind turbine, are no longer valid for FOWTs. Besides, the surge/pitch-induced time-varying angle of attack that may lead to dynamic stall [111], the streamwise back-and-forth surge/pitch motion cycle also introduces a complex inflow that interacts with the blades. During a surge/pitch motion cycle, the inflow state continuously switches among various conditions, including the normal working state, turbulent wake state, vortex ring state, and windmill braking state [126], as illustrated in Fig. 1 and Fig. 2. Such blade-wake interaction is particularly prominent in the operating condition with higher tip speed ratio [6]. In extreme cases, the turbine may even enter a propeller-like state where the turbine releases energy into the ambient flow [112, 127]. Such complexity is more pronounced in the pitch motion, as the pitch motion incorporates a velocity component within the rotating plane, in addition to the perpendicular component, thereby inducing a linear wind shear [120].

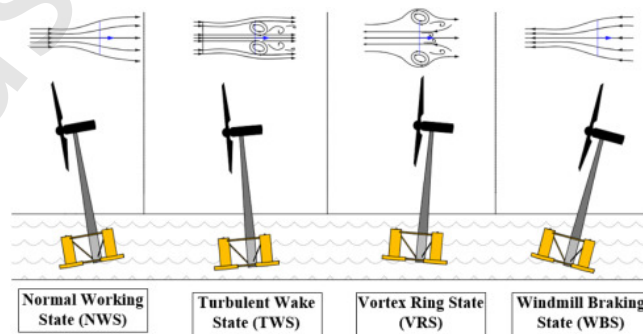


Fig. 1 Dynamic inflow states during one pitch cycle [6].

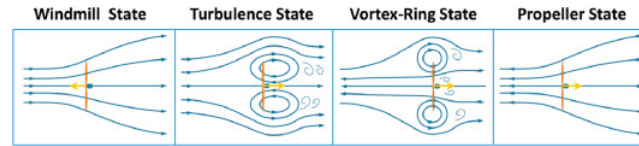


Fig. 2 Dynamic inflow states during one surge cycle [128].

In addition, the blade-wake interactions of a moving rotor cannot be accurately captured by the widely-used BEM theory, necessitating the adoption of higher-fidelity aerodynamic models for FOWT simulation [118]. Even though the Generalized Dynamic Wake (GDW) model can be integrated with the BEM theory to account for dynamic inflow effects, it remains inadequate for modeling the unsteady wake and complex blade-wake interaction, particularly for FOWT simulation where those phenomena are obvious [103, 126]. Therefore, previous investigations, including code-to-code comparisons conducted by Micallef et al. [115], and Tran et al. [17, 120], have demonstrated that the BEM underestimates the variations in peak aerodynamic loads for rotors experiencing surging and pitching motions. Experimental validations by Sant et al. [125] have corroborated these observations, revealing that even the lifting-line method also significantly overestimated the fluctuation in aerodynamic loads of a surging rotor.

Although free vortex wake method [46, 128] and vortex lattice method [129] remain useful for prescribed-motion studies, CFD becomes appropriate when the target response depends on separated flow or detailed blade-wake interactions that these reduced-order approaches do not resolve. Lei et al. showed, for a two-bladed vertical-axis wind turbine, that IDDES resolved separation driven flow structures and unsteady aerodynamic loads more fully than RANS [57]. Their subsequent study also demonstrated that prescribed platform pitch and surge altered the wake development of a floating vertical-axis wind turbine [58]. These studies provide transferable evidence of the importance of turbulence model selection, but they do not constitute direct validation for horizontal-axis FOWTs. For horizontal-axis FOWTs, recent RANS-to-LES

comparisons coupled with Actuator Line Method (ALM) indicate that RANS can remain useful for selected mean-load and mean-wake quantities, whereas LES is better suited to resolving turbulence statistics, wake meandering, and downstream load variability [130]. The required turbulence treatment should therefore be determined by the quantity of interest, platform-motion regime, and available validation evidence, rather than by assuming that LES is universally necessary.

**Increase the wake complexity.** Platform motion can increase wake unsteadiness by modifying axial advection, tip-vortex spacing, vortex interaction, and blade–wake interaction. For pitch motions, Lienard et al. observed distorted and meandering tip vortices, increased wake instability [123]. Similar tip vortex distortion phenomenon was also observed by Shen et al. [45] and Tran et al. [17, 120]. Pitch motion can also intensify blade–wake interaction and promote the fragmentation of coherent tip vortices. Rockel et al. observed higher turbulence levels in the near wake but slower wake recovery under the investigated conditions [113]. This result illustrates that increased wake unsteadiness or turbulence does not necessarily produce uniformly faster recovery, because the response also depends on motion characteristics, inflow conditions, and downstream position.

The reported effects of surge motion on wake recovery are likewise not uniform. Hu et al. observed relatively low Reynolds shear stress and slower wake recovery for a surging rotor under their proposed conditions [131]. Using DES, Yuan et al. similarly reported slower recovery and less turbulent in the far field [132]. In contrast, Chen et al. found that the surge motion can increase the wake recovery rate, with both the surge amplitude and frequency having a positive effect on the wake recovery [133], whereas Duan et al. found that the wake recovery rate could be either increased or decreased, depending on the surge frequency. [134]. In the study by Chen et al., the

wake vortex structures become much more discrete, and the wake becomes obviously more turbulent with surge motion, with an increase in motion amplitude further strengthens this effect [133]. At relatively low surge frequencies, Duan et al. also identified vortex ring structures associated with the axial compression and pairing of tip vortices during backward rotor motion [134]. Such structures may retain coherence and transport energy farther downstream than conventional tip vortices; related behavior has also been reported for a surging tidal-current turbine [135]. Collectively, these results show that platform motion does not produce a universal change in wake recovery. Its influence depends on motion type, amplitude and frequency, operating condition, inflow turbulence, and downstream distance.

Although the impact of motions in other degrees of freedom on the aerodynamic loads is quite limited compared to the surge and pitch, these motions are nonetheless considered in discussions about the interaction of multiple turbines in a floating wind farm. Lee et al., for example, indicated that unsteady and asymmetric wake structures are observed behind the rotor moved in all six degrees of freedom [103]. In their study, the wake vortex structures were investigated by the vortex lattice method. The tip vortex distortion and breakdown were found to occur with the added motions in all degrees of freedom, and the influence of different added motions seems equally obvious. However, the wake topology behind the rotor moved in directions other than surge and pitch is far from being well characterized, and the relevant studies are limited. More recently, Li et al. investigated the impact of sway motion on the wake distribution and found the specific amplitude of sway can trigger large-scale far wake meandering [102].

Compared to the fully coupled analysis, the partially coupled analysis lacks consideration of blade deformation, the studies mentioned above treat the blades as rigid bodies. Given the significance of flexibility in modern large-scale blades, ignoring blade deformations is a critical

oversight. Zhang et al., for example, investigated the deformation and stress distribution of the 15MW full-scale turbine blades under surge and pitch motion by a one-way CFD-FEM coupling approach, they found that blade tip deformations and stress on blade shell are significantly amplified by platform motions. Specifically, the maximum deformations of blade tips in surge and pitch cases are 1.41 times and 1.73 times higher than the counterparts without any floating platform motions, and the maximum stress on blade shell in surge and pitch cases are 1.52 and 2.16 times higher [14].

In summary, the partially coupled numerical simulation offers a substantial reduction in computational complexity compared to fully coupled approaches, making it practical to employ high-fidelity fluid simulation techniques. However, these simulations remain sparsely validated against dedicated experiments, which raises questions about their reliability. Overall, the partially coupled simulation can rapidly provide high-fidelity aerodynamic loads and detailed wake information for wind turbine blades under the specific motion of a floating platform, and hence is useful in localized optimization concerning the key component of FOWT.

Table 2. Partially coupled simulations regarding rotor dynamics

| Researcher     | Year | Degree of freedom | Amplitude | Frequency        | Turbine model and modeling method         | Aerodynamic model                                         | Main conclusion                                                                                                                                                                                                                                                                                                                                           |
|----------------|------|-------------------|-----------|------------------|-------------------------------------------|-----------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| De Vaal [109]  | 2014 | surge             | 2-16m     | 0.02-0.159Hz     | Full-scale NREL-5MW;<br>Diameter of 126m; | BEM+Dynamic inflow model                                  | BEM is still valid in calculating the mean aerodynamic loads;<br>For TLP, the typical surge amplitude and frequency are insufficient to have an obvious influence on the wake structure;                                                                                                                                                                  |
| Jeon [126]     | 2014 | pitch             | 3m        | 12s<br>(0.083Hz) | Full-scale NREL-5MW;<br>Diameter of 126m; | Vortex Lattice Method (VLM)                               | The inflow states will switch to a turbulent wake state when a rotor is pitching upwind;<br>Pitch motion significantly increases the wake unsteadiness;                                                                                                                                                                                                   |
| Micallef [115] | 2015 | surge             | 1.02m     | 9s (0.111Hz)     | Full-scale NREL-5MW;<br>Diameter of 126m; | BEM+Generalized dynamic wake (GDW);<br>RANS+Actuator Line | BEM is only valid for predicting the mean aerodynamic loads of a surging rotor under a low tip speed ratio, while the GDW method is also capable of predicting the load fluctuations of a surging rotor under a low tip speed ratio;<br>The wake vorticity magnitudes are increased at surge cases;<br>The mean power output is increased in surge cases; |

|            |      |                                      |                                                 |                                                  |                                                                | Method (ALM)                                |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
|------------|------|--------------------------------------|-------------------------------------------------|--------------------------------------------------|----------------------------------------------------------------|---------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Tran [119] | 2014 | pitch                                | 1-4degree                                       | 0.1Hz                                            | Full-scale NREL-5MW;<br>Diameter of 126m;                      | RANS (SST $k-\omega$ )                      | The fluctuation range increases as pitch amplitude increases;<br>Blade-wake interaction phenomenon was observed in the pitch case;<br>BEM is not valid for the predicting of aerodynamic loads under surge motion with high amplitude/frequency;                                                                                                                                                                                                                                                                                                                                             |
| Tran [120] | 2015 | surge, yaw                           | 1-4degree                                       | 0.1Hz                                            | Full-scale NREL-5MW;<br>Diameter of 126m;                      | BEM+GDW<br>RANS (SST $k-\omega$ )           | Both BEM and GDW methods overestimate the aerodynamic loads of wind turbines under surge/yaw motion;<br>The wind turbine blades repeatedly move in and out its wake during surge motion, which leads to a significant aerodynamics unsteadiness;<br>The fluctuation of aerodynamic loads is 12-16 times more sensitive with surge motion than yaw motion;                                                                                                                                                                                                                                    |
| Tran [136] | 2016 | surge                                | 4-16m                                           | 0.127-0.77rad/s (0.020-0.123Hz)                  | Full-scale NREL-5MW;<br>Diameter of 126m;                      | RANS (SST $k-\omega$ )                      | Surge motion leads to severe aerodynamic unsteadiness;<br>The pressure on the blade surface fluctuates periodically, which may result in fatigue damage;<br>In some surge cases, the turbine blades move into its wake region and interact with tip-vortex;<br>Surge motion has a significant impact on its wake distribution;<br>The gap of tip-vortex changes intermittently at surge case;                                                                                                                                                                                                |
| Wen [117]  | 2017 | surge                                | 0.5-2.5m                                        | 0-0.3Hz                                          | Full-scale NREL-5MW;<br>Diameter of 126m;                      | Free vortex wake method+lifting line method | The fluctuation of aerodynamic loads at surge case is primarily owing to the time-varying angle of attack during surge case, rather than the surge-induced velocity;<br>The variations in surge amplitude and frequency have an equivalent impact on the aerodynamic loads;                                                                                                                                                                                                                                                                                                                  |
| Lee [103]  | 2019 | surge, heave, sway, yaw, roll, pitch | Surge/heave/sway: 4degree<br>yaw/roll/pitch: 4m | Surge/heave/sway: 0.5Hz<br>yaw/roll/pitch: 0.1Hz | Full-scale NREL-5MW;<br>Diameter of 126m;                      | VLM                                         | All 6 degrees of freedom have a significant impact on the wake dynamics;<br>The additional platform motions promote the breakdown of the tip vortex;                                                                                                                                                                                                                                                                                                                                                                                                                                         |
| Yuan [122] | 2020 | pitch                                | 1.5-3deg                                        | 0.375-3s (0.667-2.667Hz)                         | 1:50 scaled NREL-5MW model;<br>Diameter of 2.52m;              | IDDES                                       | The dynamic stall was observed when the rotor was pitching upwind;<br>The increase in surge amplitude/frequency will lead to an increase in mean power output and fluctuation range of both power output and thrust;<br>The blade-wake interaction occurs at certain pitch cases;                                                                                                                                                                                                                                                                                                            |
| Yuan [132] | 2021 | surge                                | 0.04-0.12m                                      | 0.375-3s (0.667-2.667Hz)                         | In-house designed 1:50 scaled model;<br>Diameter of 2.52m;     | IDDES                                       | Even under pitch case with small amplitude/frequency, the aerodynamic loads still fluctuate drastically;<br>Surge motion could lead to dynamic stall;<br>Similar to the pitch case [122], the increase in pitch amplitude/frequency will lead to an increase in mean power output and fluctuation range of both power output and thrust;<br>Blade-wake interactions result in aerodynamics unsteadiness and wake distortion;<br>At surge cases, the level of turbulent is strengthened in the near wake and decreased in the far wake;<br>The wake recovery rate is decreased at surge case; |
| Duan [134] | 2022 | surge                                | 0.025-0.75m                                     | 0.75-3s (0.667-1.333Hz)                          | 1:50 scaled NREL-5MW model;<br>Diameter of 2.52m;              | IDDES                                       | Pitch frequency is the dominant parameter in affecting wake dynamics;<br>Vortex rings are developed in surge cases with long surge periods;<br>Depending on the surge amplitude/frequency, the wake recovery rate can be increased or decreased;                                                                                                                                                                                                                                                                                                                                             |
| Chen [133] | 2022 | surge                                | 0-0.09m                                         | 0.25-1s (1-4Hz)                                  | In-house designed 1:100 scaled model;<br>Diameter of 0.944m;   | IDDES                                       | The increase in surge amplitude/frequency leads to higher mean power output, severer load fluctuation, faster wake recovery, and greater wake unsteadiness;<br>Dynamic stall is observed at surge cases.                                                                                                                                                                                                                                                                                                                                                                                     |
| Li [102]   | 2022 | sway                                 | 1.26-5.04m                                      | 11.1-110.5s (0.009-0.09Hz)                       | Full-scale NREL-5MW;<br>Diameter of 126m;<br>Actuator surface; | LES                                         | Sway motion with a specific frequency can trigger wake meandering;<br>Inflow turbulence and shear also have an obvious impact on the wake meandering;                                                                                                                                                                                                                                                                                                                                                                                                                                        |

|               |      |                 |                               |                               |                                               |                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|---------------|------|-----------------|-------------------------------|-------------------------------|-----------------------------------------------|-------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Zhang<br>[14] | 2023 | surge,<br>pitch | surge<br>4m;<br>pitch<br>2deg | surge 0.25Hz;<br>pitch 0.25Hz | Full-scale IEA-<br>15MW;<br>Diameter of 240m; | RANS<br>(Realizable<br><i>k-ε</i> ) | <p>The surge and pitch motion significantly amplified the maximum thrust, torque, and pressure on the blades, and bald tip deformations;</p> <p>The maximum blade tip deformations in surge and pitch cases are 1.41 and 1.73 times that of the fixed cases;</p> <p>The minimum power output is nearly zero, indicating that the turbine gearbox may suffer a sudden halt in surge and pitch cases;</p> <p>The maximum von Mises stress on the blade shell in surge and pitch cases is 1.52 and 2.16 times that of the fixed cases.</p> |
|---------------|------|-----------------|-------------------------------|-------------------------------|-----------------------------------------------|-------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Platform motion can alter the mean wake deficit, coherent-vortex evolution, wake recovery, and the unsteady inflow experienced by downstream turbines. The required model fidelity depends on whether the quantity of interest is array-scale energy production and global loading, mean near-wake velocity, turbulence statistics and wake meandering, or downstream load fluctuations. Engineering wake models, including FAST.Farm, support computationally efficient farm-scale aero-servo-elastic calculations, whereas free vortex wake and actuator-line CFD approaches provide additional wake-flow resolution, subject to their inflow representation, calibration, and computational cost [130, 137-139].

For the prescribed-motion wind-tunnel configurations examined to date, RANS can reproduce useful mean near-wake characteristics, whereas LES with turbulent inflow is better suited to resolving local turbulence distributions, wake meandering, and downstream load variability when these fluctuations are of interest [130]. Prescribed platform motions remain valuable for isolating mechanisms; however, they do not replace coupled farm-scale assessment under representative atmospheric inflow and environmental conditions [138]. Their role is therefore to establish and validate mechanism-level behaviour, rather than to provide a complete prediction of farm-scale wake interactions.

Recent multi-fidelity studies illustrate this trade-off. In the benchmark of Cioni et al., a tuned free vortex wake model reproduced rotor loads and the motion-affected wake response up to

approximately three rotor diameters for the tested conditions, whereas higher-fidelity models were needed farther downstream [140]. The same study reported approximately  $1.2 \times 10^3$  CPU hours per ALM-RANS condition, approximately  $4 \times 10^5$  CPU hours for the referenced ALM-LES data, and approximately  $2.5 \times 10^5$  CPU hours for 9 s of blade-resolved RANS[140]. These figures are illustrative only and do not constitute a direct ranking because the solvers, hardware, meshes, inflow conditions, and simulated durations differed. Separately, a non-floating wind-farm comparison found that a DWM/FAST.Farm workflow required approximately 7 times more wake-and-load computation and 14 times more inflow-generation time than an effective-turbulence approach, while remaining executable on one compute node [141].

Table 3 Cost-accuracy comparison of wake model classes for FOWT applications.

| Model class         | capability                                                                         | Main limitation                                                              | computational cost                                                                                                   | Recommended use                                                 |
|---------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|
| BEM-DWM / FAST.Farm | Array-scale power, global loads, wake deficit, and meandering when calibrated      | Limited local turbulence and vortex detail; formulation-specific calibration | DWM: 7x wake/load and 14x inflow cost versus an effective-turbulence method in one study; feasible on one node [141] | Broad design-load cases and farm optimization [139, 141]        |
| Free-vortex wake    | Rotor loads and motion-affected near wake to about 3D when tuned                   | Accuracy degrades farther downstream and for turbulence-driven meandering    | A fraction of ALM-RANS cost in the reported comparison [140]                                                         | Rotor and near-wake studies; intermediate escalation step       |
| ALM-RANS            | Mean near-wake profiles and deterministic platform-motion response                 | Under-resolves turbulence-driven meandering and downstream load variability  | About $1.2 \times 10^3$ CPU h per condition [140]                                                                    | Mean-wake and selected interaction studies [130, 140]           |
| ALM-LES             | Local turbulence, wake oscillation and meandering, and downstream load variability | High grid, time-step, and sampling sensitivity; very high cost               | About $4 \times 10^5$ CPU h in the reported benchmark [140]                                                          | Targeted farm physics and downstream-load validation [130, 140] |
| Blade-resolved CFD  | Blade pressure, sectional loading, and resolved rotor flow                         | Very high cost and typically short simulated durations                       | About $2.5 \times 10^5$ CPU h for 9 s of blade-resolved RANS [140]                                                   | Local aerodynamics and high-fidelity benchmark generation       |

## 4.2 Platform hydrodynamics

In a partially coupled analysis focusing on the hydrodynamics of the floating platform, aerodynamic forcing is commonly represented either as constant thrust or as a function of the

aerodynamic coefficients and the relative wind velocity [142]. And the mass and inertia of the tower and turbine are modeled as external mass, transferred to the mass point of the platform.

When the aerodynamic loads are represented by constant thrust, platform's motion induced variations in relative wind speed are ignored. This leads to a misrepresentation of aerodynamic damping effects, which are critical for suppressing low-frequency platform oscillations. Zheng et al. used a thrust value obtained from a thrust–wind-speed curve to investigate an OC4 DeepCwind semi-submersible with a flooded-column damage [143]. Nematbakhsh et al. adopted a similar representation for a tension-leg-platform FOWT. [144]. Huang et al. compared constant thrust with an ALM representation for a spar-type FOWT and reported appreciable differences in platform response. Their findings indicate that modeling aerodynamic effects as constant thrust significantly compromises the accuracy of results, highlighting the inescapable coupling between aerodynamic loads and platform motion [145].

Alternatively, aerodynamic loads can be expressed as functions of relative wind speed, allowing platform velocity to modify the prescribed forcing without resolving the complete rotor–platform feedback. Zambrano et al. combined this aerodynamic representation with potential-flow and Morison's equation based hydrodynamics [146]. Karimirad et al. compared this partially coupled workflow with a BEM-based fully coupled analysis and reported good agreement for the selected responses, together with substantially lower computational cost [16]. Phuc et al. used quasi-steady aerodynamic with Morison's equation based hydrodynamics and obtained platform responses that agreed with the available experimental data [142]. These results support response-dependent aerodynamic forcing as an efficient intermediate representation, provided that validation covers the target response and operating condition[147].

## 5 Fully coupled analysis

As discussed in Section 2, numerical modeling of a FOWT consists of several key components, including aerodynamic models, hydrodynamic models, structural dynamics models, and mooring system models. A fully coupled model integrates these submodels into a unified computational framework, enabling the simultaneous simulation of aero-hydro-servo-elastic interactions. Such an approach is required when load transfer, dynamic response, controller action, and operational performance depend on simultaneous feedback. Veers et al., identified the fully coupled analysis of complex FOWT systems as a major unsolved challenge [5]. Current fully coupled approaches can generally be divided into low-to-mid fidelity models and high-fidelity models.

Low-to-mid fidelity frameworks commonly combine BEM, potential flow theory, Morison's equation, modal or multibody structural dynamics, and reduced-order mooring models. Presently, mainstream numerical tools predominantly adopt this model class. Examples of these engineering-applicable tools include OpenFAST, Bladed, and HAWC2, which have been widely adopted as demonstrated by code-to-code comparison and experimental validation efforts within the OC3/4/5 projects under the International Energy Agency's Task 30 initiative [4]. OC4 compared predictions for a common floating semisubmersible configuration and identified differences associated with model formulations and their implementation [148, 149]. These frameworks reduce computational cost by simplifying selected processes; their accuracy must therefore be assessed for the stated quantity of interest and loading condition. High-fidelity frameworks use CFD, detailed structural models, or fluid-structure interaction to resolve local fields and nonlinear processes. Their role in targeted FOWT design assessment has expanded with advances in high-performance computing. This has attracted the attention of both industry and academia. For example, OC6 combines

numerical comparisons with focused experiments to assess aerodynamic, hydrodynamic, and coupled-system predictions [26, 71, 150, 151].

## **5.1 Low-to-mid fidelity models**

Table 4 summarizes the commonly used programs developed based on low-to-mid fidelity models, which can be broadly categorized into two types. The first integrates hydrodynamic load and mooring load modules into existing programs targeting the onshore fixed wind turbine (e.g., FAST). The second is built upon existing hydrodynamic analysis programs by adding aerodynamic load modules (e.g., F2A, Simo-Riflex-AeroDyn, Simo-Riflex-HAWC2, Simo-Riflex-TDHMILL, etc. [16, 20, 152]).

### **5.1.1 Programs targeting onshore wind turbine with floating system modification**

National Renewable Energy Laboratory (NREL) developed FAST for the dynamic simulation of onshore bottom-fixed wind turbines. Initially, in 1998, Halfpenny et al. highlighted two significant challenges with existing simulation methods for FOWTs [153]: 1) Linear frequency domain analysis methods fail to capture the nonlinear and transient characteristics due to the rotating blades of FOWTs. 2) The conventional time-domain hydrodynamic analysis methods require rigorous validation before they can be effectively applied to the dynamic simulation of FOWTs.

To address these problems, Jonkman et al. developed a time-domain hydrodynamic simulation module named HydroDyn [100], based on potential flow theory and the Morison's equation. HydroDyn calculates linear hydrostatic restoring, nonlinear viscous drag, added mass, linear damping, and incident wave excitation acting on the floater with various sizes. In the OC3 project, FAST and HydroDyn predictions for the NREL 5 MW turbine on the OC3-Hywind spar

were compared with those from other numerical tools. Separately, Coulling et al. validated a FAST model of the DeepCwind semisubmersible against 1:50-scale basin measurements [154].

Subsequently, NREL integrated HydroDyn into FAST (named OpenFAST in its later version), which is now one of the most widely used software packages for fully coupled simulations of FOWTs. Tian et al., for example, adopted OpenFAST to investigate the impact of turbulence intensity, wind speed, and wave height on the motion response of a FOWT [155]. Similarly, Dong et al. used FAST to quantitatively identify the occurrence of the vortex ring state for the wind turbine during operational states [156]. Li et al. numerically investigated the effects of turbulent inflow, considering turbulence intensity, coherence structure, and wind shear, on the overall performance of FOWTs using FAST [157]. Sebastian et al. used FAST to analyze the overall dynamics of the baseline 5MW turbines on different floating foundations [110].

### **5.1.2 Offshore engineering programs extended with aerodynamic modules**

Norwegian University of Science and Technology extended offshore engineering software with aerodynamic modules. Kvittem et al. integrated the aerodynamic simulation module AeroDyn into Simo-Riflex and combined it with the wind field modeling tool TurbSim to present the fully coupled simulation of FOWT [158]. Following this trend, Solberg et al. combined TDHMILL3D, a code library targeting the aerodynamic simulation, with HydroDyn and DeepC to deliver fully coupled numerical simulations of FOWT [159]. Similarly, Karimirad et al. used the library of TDHMILL to input aerodynamic loads into Simo-Reflex, and then conducted fully coupled simulations of spar-type FOWTs [16].

Massachusetts Institute of Technology, supported by the NREL, has also been active in this area since 2004, integrating the aerodynamic module into the existing hydrodynamic analysis code.

Kim developed the SML (SWIM-MOTION-LINES) [160, 161], which consists of three modules: the SWIM module, solving linear or second-order frequency domain wave problems; the MOTION module, addressing large-amplitude, low-frequency motion of floaters with simple geometries; and the LINES module, dealing with the nonlinear effects of mooring loads on platform motion. Lee used the SML package to analyze the nonlinear hydrodynamics of 1.5 MW FOWTs with different mooring systems [162]. Withee extended these capabilities by adding the AeroDyn module to ADAMS for coupled analysis of the FOWT with a tensioned-leg platform under various environmental conditions [163].

Frequency-domain approaches have been developed to support response screening, parameter studies, and early-stage design. Chen et al. developed a matrix-based frequency-domain framework for aero-hydro-servo-elastic modeling of floating wind turbines [76], while Wang et al. introduced an AQWA-based frequency-domain approach that examined the impact of wind, current, and mooring damping [75]. Lamei et al. further formulated coupled aeroelastic and hydroelastic responses in the frequency domain for floating wind turbines subjected to combined wind and wave loading [77]. When a time-domain response is required, the frequency-domain response may be reconstructed using an inverse fast Fourier transform; however, the reconstructed time series remains subject to the linearization and spectral assumptions of the underlying frequency-domain model [164]. These approaches achieve computational efficiency by representing the coupled system in a linearized frequency-domain form, which makes them well suited to preliminary design, response screening, and sensitivity analysis. Their applicability is nevertheless bounded by the assumptions used to represent transient behavior, nonlinear hydrodynamic loads, aerodynamic unsteadiness, and nonlinear mooring or damping effects. Frequency-domain analysis is therefore best viewed as a complementary screening and sensitivity

tool within a multi-fidelity workflow, rather than as a universal replacement for time-domain coupled simulations.

These models are valuable for preliminary design and broad load screening, but their applicability to detailed design depends on whether the governing submodels are validated for the target response and loading condition. Reported limitations are concentrated in two areas:

In terms of aerodynamics: Matha et al. and Sebastian et al. have indicated that the applicability of the BEM theory or potential flow theory is limited when it comes to predicting aerodynamic loads of FOWTs [110, 165]. Specifically, the momentum-balance-based BEM theory cannot capture complex physical phenomena such as blade and wake interactions, flow separations, and vortex shedding. Although the potential-flow-based method, like the free vortex wake model, can approximate the blade-wake interaction, they do not inherently resolve viscous diffusion or turbulence. Their accuracy therefore depends on the wake discretization and convection scheme, circulation-shedding model, vortex-core regularization, inflow specification, and validation range. Comparisons of the numerical results from the low-to-mid fidelity models with experimental results performed at the Maritime Research Institute Netherlands [69, 154] have shown deviations in measured and modeled aerodynamic and hydrodynamic loads. As Tran et al. revealed, even minor errors in predicted aerodynamic loads can induce a large deviation in the platform motion [166]. Therefore, accurate aerodynamic load calculations that are capable of correctly estimating unsteady, skewed, and sheared transitional flows in cases with high tip speed ratios are necessary for the integrated design of the FOWT, albeit the underlying expensive computational cost.

In terms of hydrodynamics: Morison's equation relies on empirically or experimentally obtained hydrodynamic coefficients to calculate viscous drag, and does not explicitly resolve the complete time-dependent force history [166]. In addition, simple empirical hydrodynamic models

cannot represent complex unsteady physical phenomena such as wave run-up against semi-submersible columns [167], wave slamming, and viscous flow separation on the floaters, etc. Empirical and CFD models can therefore produce different loads for geometrically complex floater like OC4 semi-submersible platform [168].

In addition, fidelity and accuracy of individual submodels directly affect the overall performance of coupled simulations. For example, the coupling between aerodynamic and hydrodynamic models can affect the accuracy of load predictions on the turbine structure. He et al. reviewed advancements in coupled aero–hydrodynamic simulations for FOWTs and noted that the interplay between different modules could lead to nonlinear responses, which are essential to capture for accurate performance assessment [13]. Furthermore, the fidelity of the mooring line model has been shown to significantly impact the overall simulation results. A study by Hall and Buckham evaluated the importance of mooring line model fidelity in FOWT simulations and found that dynamic mooring models improved platform motion and load predictions when line inertia, hydrodynamic loading, and dynamic tension were important [99].

Accordingly, low-to-mid fidelity models remain the practical basis for preliminary design, broad design-load-case screening, and integrated response analysis, provided that their component models have been validated for the target quantity and loading condition [4, 9, 23]. Their limitations should be identified at the subsystem and response levels rather than interpreted as a uniform deficiency of the complete coupled framework. The task oriented procedure for selecting the minimum sufficient model fidelity and, where necessary, escalating model complexity is presented in Section 6.2.

Table 4 based programs low-to-mid fidelity models

| Programs | Developer | Hydrodynamic | Aerodynamic | Structural dynamics | Mooring line dynamics | Accessibility |
|----------|-----------|--------------|-------------|---------------------|-----------------------|---------------|
|----------|-----------|--------------|-------------|---------------------|-----------------------|---------------|

| OpenFAST               | NREL            | Potential flow theory/Morison | BEM/GDW               | Modal/MBD | Quasi-steady model (QS)/Lump Mass model (LM)/FEM | OA         |
|------------------------|-----------------|-------------------------------|-----------------------|-----------|--------------------------------------------------|------------|
| HAWC2                  | DTU             | Morison                       | BEM/GDW               | MBD/FEM   | FEM                                              | Commercial |
| Bladed                 | DNV             | Morison                       | BEM/GDW               | MBD       | FEM                                              | Commercial |
| 3DFloat                | IFE-UMB         | Morison                       | BEM                   | FEM       | FEM                                              | Commercial |
| DARWIND                | UNew+SJTU       | Potential flow theory/Morison | BEM                   | MBD/FEM   | QS                                               | Commercial |
| ADAMS                  | MSC corporation | Potential flow theory/Morison | BEM                   | MBD       | QS                                               | Commercial |
| SESAM                  | DNV             | Potential flow theory/Morison | BEM                   | FEM       | QS/FEM                                           | Commercial |
| F2A                    | Yang Yang       | Potential flow theory/Morison | BEM/GDW               | Modal/MBD | FEM                                              | In-house   |
| CHARM3D+FAST           | Texas A&M       | Potential flow theory/Morison | BEM/GDW               | MBD/FEM   | FEM                                              | In-house   |
| A2AD (ADAM TO AeroDyn) | NREL            | Potential flow theory/Morison | BEM/GDW               | Modal/MBD | QS                                               | OA         |
| Simo/Reflex/AeroDyn    | NTNU            | Potential flow theory/Morison | BEM/GDW/Dynamic stall | FEM       | FEM                                              | In-house   |
| SIMPACK+HydroDyn       | Simula          | Potential flow theory         | BEM/GDW               | Modal/MBD | QS                                               | In-house   |

## 5.2 High-fidelity models

High-fidelity coupled solvers can resolve local flow and pressure fields and, when coupled to detailed structural models, local deformation and nonlinear interactions that many engineering-level models represent only in reduced form. Their use is most justified for targeted model assessment, model calibration, local response analysis, and extreme-condition investigations in which a lower-cost model omits a physical process that materially affects the quantity of interest. Substantial differences have been reported between CFD-based and engineering-level predictions; however, these differences are configuration-, model-, and output-specific. Without independent experimental validation, code-to-code disagreement alone does not establish that one fidelity level is universally more accurate[166, 168-170].

In terms of structural dynamic simulation, the main components of FOWTs are either modeled as rigid or flexible structures. Most of the above-mentioned CFD-based fully coupled simulations focus on hydrodynamics and aerodynamics, and the structural dynamics are typically modeled by the MBD approach. Here, the main components are modeled as rigid bodies, and their interactions are explicitly calculated. Although this rigid body representation is computationally efficient,

neglecting blade deformation can bias structural response, aerodynamic loads, and ultimately the overall dynamics of FOWTs, especially for modern large-scale wind turbine blades.

Several applications account for the elasticity of the major FOWT components using models such as geometrically exact beam or nonlinear beam. These approaches, despite their high computational cost, can resolve flexible component dynamics and large deformation behavior in modern blade. For instance, Liu et al. used a three-node beam element to model the flexible bodies, capturing local characteristics such as tower interference and rapid oscillations in blade tip deflection and root bending moment due to platform motions [170]. Yu et al. proposed a fully coupled analysis framework that adopts a solver that models aerodynamics and elasticity with beam element [171]. Yan et al. proposed a fluid-structure-interaction framework that incorporates FEM and isogeometric analysis to conduct a fully coupled simulation of the OC3-HyWind FOWT [172]. Hu et al. carried out a fully coupled analysis of a semi-submersible FOWT by their in-house code RIAM-CMEN which is a free-surface flow solver based on the Constrained Interpolation Profile [173]. Overall, the CFD-based fully coupled simulation that models the elasticity of the main component of a FOWT provides detailed coupled flow and structural fields, but it is not automatically the most accurate approach and remains a targeted method because of its computational cost and validation requirements.

Among CFD codes, OpenFOAM is recognized as a common tool for developing fully coupled numerical tools for FOWT dynamics. Dunbar et al. [72], Zhang et al. [174], and Liu et al. [175] developed fully coupled solvers based on OpenFOAM and subsequently conducted a series of detailed code-to-code comparisons against the benchmark results obtained from FAST. These simulations have explored detailed aerodynamic load distribution on the blades and vortex wake structure.

A team at Shanghai Jiao Tong University developed the in-house code of FOWT-UALM-SJTU framework in OpenFOAM by integrating an in-house hydrodynamic code of naoe-FOAM-SJTU and a mooring line module [176]. This framework was adopted to analyze wind turbine performance on both the OC4 semi-submersible platform [19] and a spar-type platform [177], showing great advantages in wake investigation, especially for wake interference in an array of FOWTs [178] and wake interaction with turbine/tower [177].

Another way to reduce the computational cost is to combine the potential theory with the CFD simulation. The in-house codes qaleFOAM [179, 180] and its latest version named qaleFOAM-BM [181] fall in this category. The qaleFOAM decomposes the computational region into a local region that encompasses FOWT and the outer region, with the former treated by the CFD simulation and the latter modeled by a fully nonlinear potential theory model. Reported validation cases indicate that qaleFOAM model is several times faster than the full-set of CFD while retaining comparable accuracy for the tested responses [179]. In its latest version, the qaleFOAM-BM, by taking the elasticity of the turbine blades into consideration, is an aero-elastic-hydro-mooring-wake analysis code, and is validated against experimental data and compared with numerical predictions from FAST.

STAR-CCM+ is a commercial CFD platform used for coupled FOWT simulation with overset mesh, rigid body motion solvers, and mooring capabilities. Heilskov et al., for example, performed a code-to-code comparison targeting a dynamic simulation of a FOWT and reported greater robustness for STAR-CCM+ than for their OpenFOAM configuration[182].

High-fidelity models play a crucial role in the later stages of integrated FOWT design, particularly in local optimization, load assessment, and extreme condition analysis. Their ability to resolve nonlinear fluid-structure interactions and local aerodynamic or hydrodynamic fields

enables assessments that are unavailable from many lower-fidelity models. Several applications exemplify their significance in this context. For instance, Zhang et al. reviewed the role of CFD-based solvers in FOWT analysis and highlighted their advantages in capturing wake flow interactions, complex inflow conditions, and blade-tower interactions [183]. Liu et al. developed a fully coupled CFD-FEM framework to analyze the aero-hydro-elastic-mooring behavior of a floating vertical-axis wind turbine [184]. Their results showed that high-fidelity modeling is essential for capturing dynamic responses such as blade tip deformation and mooring line interactions, which significantly influence design robustness. Furthermore, Mathis Miroux employed OpenFOAM-based CFD simulations to evaluate the hydrodynamic and aerodynamic responses of the IEA 15MW wind turbine on a semi-submersible platform, comparing results against OpenFAST [185]. The study found that OpenFAST underestimated damping effects, showing how high-fidelity CFD can refine performance predictions in large-scale FOWT systems.

Extreme condition analysis is another critical application. Tagliafierro et al. applied a Smoothed Particle hydrodynamic solver to the DeepCwind semi-submersible FOWT [186], whereas Leble and Barakos used high-fidelity hydrodynamic and aerodynamic solvers to investigate a 10MW floating wind turbine [187]. These studies illustrate the use of particle- and CFD-based approaches to examine nonlinear wave-structure interactions, mooring dynamics, and aerodynamic responses under severe sea states. However, such predictions should be regarded as validated only to the extent that they are supported by independent experimental or benchmark comparisons. Yang et al. compared coupled models of different fidelity and reported that the predicted platform responses were sensitive to the representation of viscous hydrodynamic effects [188]. Taken together, these studies support the targeted use of high-fidelity methods when nonlinear wave loading, viscous effects, slamming-induced impact loads, large platform

excursions, mooring dynamics, or elastic structural responses materially affect the quantity of interest. Engineering level models nevertheless remain essential for screening the large number of environmental conditions required in practice, whereas high-fidelity models are more appropriately applied to selected critical cases for model calibration, mechanism identification, and design verification [13, 189, 190].

Table 5 Programs based on high fidelity model

| Programs                       | Hydrodynamic                            | Aerodynamic                             | Actuator line model            | Structural dynamics | Mooring line dynamics          | Accessibility |
|--------------------------------|-----------------------------------------|-----------------------------------------|--------------------------------|---------------------|--------------------------------|---------------|
| OpenFOAM [191]                 | CFD                                     | CFD                                     | Included (third-party library) | /                   | QS/ LM/FEM                     | OA            |
| STAR-CCM+ [192]                | CFD                                     | CFD                                     | Not included                   | MBD/FEM             | QS/ LM                         | Commercial    |
| qaleFOAM-BM [181]              | CFD combined with Potential flow theory | CFD combined with Potential flow theory | included                       | FEM                 | LM                             | In-house      |
| CFDSHIP-Iowa [193]             | CFD                                     | CFD                                     | Not included                   | /                   | QS/ LM                         | Commercial    |
| FOWT-UALM-SJTU [137, 138, 194] | CFD                                     | CFD                                     | included                       | /                   | Piecewise extrapolating method | In-house      |

## 6 Validation evidence, model-selection guidance, and research priorities

### 6.1 Benchmark evidence and model limitations

The usefulness of a numerical model depends on the evidence supporting the intended quantity of interest, rather than on its nominal fidelity alone. OC3 and OC4 primarily provide code-to-code comparisons for representative fixed-bottom and floating offshore wind systems [195, 196], whereas OC5 compares coupled engineering predictions with measurements from the DeepCwind wave-basin campaign [69]. OC6 extends this evidence through focused studies of

free-decay damping, nonlinear low- and difference-frequency hydrodynamics, large-motion rotor aerodynamics, and the coupled response of a novel floating support structure [26, 71, 150, 151, 197]. Its Phase IV considers the 1:43-scale TetraSpar system with a 3.6 MW reference turbine and includes platform motions, tower response, and line tensions [151]. These campaigns connect particular physical mechanisms and response quantities to repeatable benchmark cases.

Table 6 brings together component and integrated-system benchmarks, identifying the reference configuration, loading condition, compared models, response metric, and reference used to calculate each difference. The aerodynamic and structural examples show sensitivity to model formulation, the mooring example separates peak and fatigue loading, and the wave-basin example quantifies discrepancies against measurements. In the fully coupled FLOATECH comparison, lifetime DEL predictions differed by up to +14% for OpenFAST and -13.5% for DeepLines relative to QBlade across the studied configurations [23]. These numerical differences identify outputs that are sensitive to modeling choices; comparisons with measurements provide the corresponding physical validation evidence [4, 198].

Table 6. Representative component and integrated-system benchmarks and reported model differences.

| Domain and benchmark                          | Configuration and loading                                                                           | Models and reference                                                                                                                                    | Reported comparison                                                                                                             | Implication for selection                                                                                               |
|-----------------------------------------------|-----------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|
| Aerodynamics: OC6 Phase III [26]              | 1:75 DTU 10 MW rotor; prescribed motion plus numerical rotor-speed/pitch-actuation cases            | BEM with and without dynamic inflow, vortex methods and CFD; mean predictions accounting for dynamic inflow as the reference for the quoted differences | Without dynamic inflow: thrust peak-to-peak amplitude 9% lower for speed variation and 18% higher for pitch actuation           | Rotor actuation makes dynamic inflow relevant; these two percentages are numerical differences, not experimental errors |
| Hydrodynamics: OC6 Phase Ib [71]              | Fixed simplified three-column DeepCwind geometry; bichromatic waves                                 | Second-order potential flow QTFs and CFD; basin measurements as reference                                                                               | Potential-flow difference-frequency pitch moment approximately 20%-40% lower than measured                                      | Resolve nonlinear excitation for slow drift assessment; the metric is fixed-body loading, not platform motion           |
| Structural mechanics [98]                     | 100 m blade; large static deflection                                                                | Beam and shell models compared with a detailed solid model                                                                                              | Tip deflection: beam 4.3% and shell 2% lower; twist: beam 5.6% higher and shell 24% lower                                       | Assess deflection and twist separately; component-level numerical comparison                                            |
| Mooring dynamics [99]                         | OC3-Hywind spar; LC 5.3: 18 m/s wind, 15% turbulence; 6 m significant wave height, 10 s peak period | FAST quasi-static lines and dynamic ProteusDS; dynamic prediction as reference                                                                          | Selected upwind fairlead DEL 32% lower on average with quasi-static lines; extremes within 1%                                   | Peak-tension agreement does not establish fatigue-load agreement                                                        |
| Fully coupled loads: FLOATECH [23]            | OC4 semisubmersible, Softwind spar and Hexafloat; realistic environmental load cases                | OpenFAST, DeepLines and QBlade; QBlade as numerical reference                                                                                           | Lifetime DEL differences up to +14% (OpenFAST) and -13.5% (DeepLines) across the compared cases                                 | Quantify coupled-model sensitivity for the selected configuration and output                                            |
| Integrated-load validation: OC5 Phase II [10] | 1:50 DeepCwind/NREL 5 MW model; quoted results for wave-only cases excluding white noise            | Coupled engineering tools compared with wave-basin measurements                                                                                         | Average underprediction: ultimate tower-base load 14%, upwind mooring tension 20%; fatigue loads 21% at tower base and moorings | Low-frequency load discrepancies motivate improved nonlinear excitation and damping                                     |

## 6.2 Model selection across design stages

A practical model-selection workflow begins by defining the design task and target quantity of interest. The dominant physical processes and feedback pathways are then identified, after which the minimum sufficient coupling topology and subsystem fidelity supported by relevant validation evidence are selected. This staged approach avoids assigning either one low-cost model or one high-fidelity solver to every application. Escalation is justified when the available validation evidence does not cover the intended operating regime, when a target response is sensitive to a mechanism omitted by the current model, or when prediction uncertainty is too large for the design

decision [4, 23]. For fatigue and extreme-load assessment, this workflow assumes that the chosen tool represents the relevant pitch and generator-torque control laws and the operating, shutdown, parked, or fault state being evaluated. Controller action affects aerodynamic damping, platform motion, and the resulting load spectrum and must be included in the selected feedback pathways [23, 151]. Table 7 translates this workflow into task-oriented guidance.

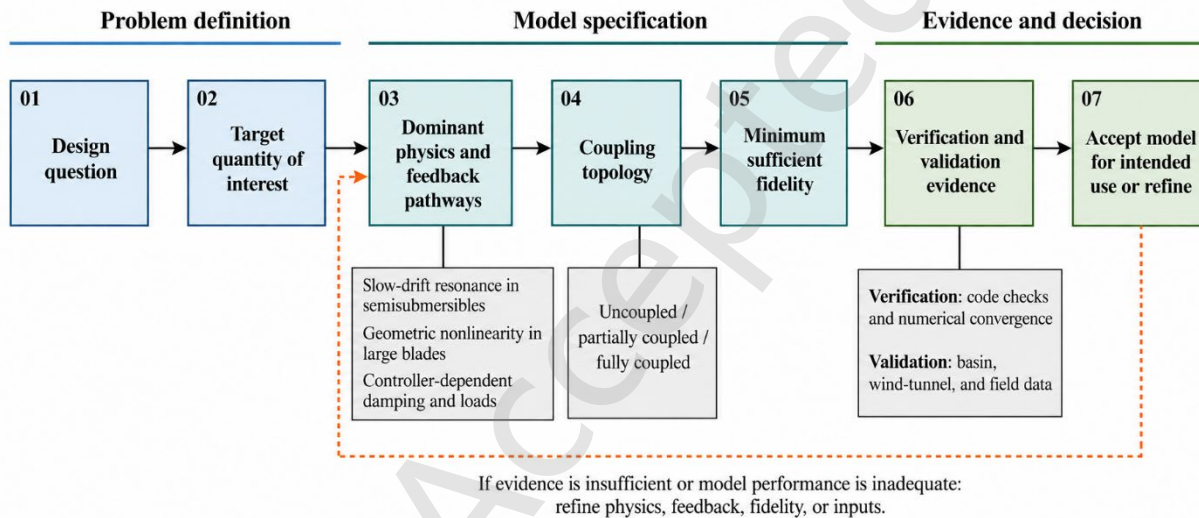


Fig. 3. Task-oriented workflow for selecting and escalating FOWT numerical models.

The workflow proceeds from the design task and quantity of interest to the dominant physics and feedback pathways, coupling topology, subsystem fidelity, and verification and validation evidence. The model is accepted for the intended use when the available evidence supports the target response and loading conditions; otherwise, its physics, feedback pathways, fidelity, or inputs are refined. Examples include slow-drift resonance in semisubmersibles, geometric nonlinearity in large blades, and controller-dependent damping and loads.

Table 7. Task-oriented guidance for selecting FOWT numerical models.

| Design task                                | Target quantity of interest                                                          | Recommended coupling topology                                        | Minimum sufficient fidelity                                                                                                                 | Validation evidence needed                                                                                                                                   |
|--------------------------------------------|--------------------------------------------------------------------------------------|----------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Blade or rotor concept design              | Power, thrust, section loads                                                         | Uncoupled or partially coupled with prescribed motion                | Engineering to intermediate aerodynamics                                                                                                    | Airfoil, rotor, or prescribed-motion data covering the relevant reduced frequency and control action[26, 31]                                                 |
| Platform and mooring concept design        | Response Amplitude Operators, global motions, line tension                           | Uncoupled hydrodynamics, partially coupled analysis                  | Engineering to intermediate hydrodynamics and mooring                                                                                       | Wave-basin or focused hydrodynamic data; dynamic-mooring evidence when line inertia and damping influence the response[69, 99, 151]                          |
| System fatigue and design-load cases       | Integrated loads, fatigue, and controller-coupled response                           | Fully coupled                                                        | Aero-hydro-servo-elastic model with the relevant controller and operating states; dynamic mooring where line dynamics affect fatigue        | OC benchmark evidence or project-specific validation across representative environmental and operating conditions [23, 199]                                  |
| Extreme or nonlinear conditions            | Local pressure, impact load, large excursion, nonlinear motion, and mooring extremes | Partially coupled analysis or fully coupled analysis                 | Nonlinear hydrodynamics, dynamic mooring, and structural flexibility as needed; controller and operating state appropriate to the load case | Focused experiments or experimentally validated high-fidelity calculations with numerical convergence assessed for the relevant response [71, 197, 200, 201] |
| Wake and array assessment                  | Wake deficit, meandering, turbulence, power, and downstream loading                  | Fully coupled or partially coupled (with prescribed motion)          | Engineering wake model to LES/ALM                                                                                                           | Wind-tunnel, field, LES, or targeted multi-fidelity evidence matched to the required wake and load quantities [130, 140, 202, 203]                           |
| Operational monitoring and load estimation | System states, damage-equivalent loads, and remaining-life indicators                | Reduced-order coupled model or measurement-assimilating digital twin | Calibrated engineering, state-space, or                                                                                                     | Full-scale sensor data, independent validation periods, and predictive-                                                                                      |

|  |  |  |                                  |                                      |
|--|--|--|----------------------------------|--------------------------------------|
|  |  |  | probabilistic surrogate<br>model | uncertainty assessment<br>[204, 205] |
|--|--|--|----------------------------------|--------------------------------------|

## 6.3 Emerging directions and unresolved gaps

### 6.3.1 Nonlinear hydrodynamics and structural flexibility

Nonlinear hydrodynamics, higher-order wave loading, viscous effects, and structural flexibility require more targeted validation across different platform classes and extreme sea states. The central research question is which omitted mechanism controls a specified response, rather than whether one solver is globally more faithful than another. Future studies should distinguish errors associated with wave excitation, viscous damping, mooring dynamics, and hydroelastic response and should determine when these mechanisms materially change global motions, local loads, or structural stresses [65, 70, 71, 77, 150, 151, 197].

### 6.3.2 Floating-wind-farm wakes and FAST.Farm

Floating-wind arrays require models that connect platform motion, realistic turbulent inflow, wake dynamics, controller action, and downstream fatigue loading. FAST.Farm-type engineering tools, free-vortex methods, and high-fidelity wake simulations provide complementary routes: engineering tools enable broad array studies, whereas LES and focused experiments resolve turbulence-driven wake behavior and provide calibration evidence. Section 4.1 compares the underlying wake-model capabilities and computational costs [130, 139, 140, 202, 203, 206]. Recent two-turbine wind-tunnel experiments with prescribed upstream motion and a fixed downstream turbine provide direct evidence of motion-induced changes in downstream power and loading [207]. Extending such datasets to interacting floating turbines under realistic turbulent inflow and combined wind-wave conditions would strengthen farm-scale model validation.

### **6.3.3 Artificial intelligence, surrogate models, and digital twins**

Artificial intelligence, surrogate models, and digital twins should be developed as uncertainty-aware extensions of physics-based models. Probabilistic surrogates can accelerate lifetime-load assessment and propagate statistical uncertainty from site conditions, whereas digital twins can assimilate operational measurements to estimate unmeasured states and structural loads [204, 205]. Their use in design or operation should report the training and validation domains, performance under interpolation and extrapolation, predictive uncertainty, and the validation status of the simulations or measurements used to construct the model.

### **6.3.4 Reduced-order and frequency-domain methods**

Reduced-order and frequency-domain methods remain promising for design-space exploration, sensitivity analysis, and multi-fidelity optimization. Their use should explicitly document the linearization point and the treatment of transient aerodynamics, nonlinear hydrodynamic excitation, viscous damping, nonlinear mooring behavior, and control-system interactions. These methods should therefore complement, rather than universally replace, nonlinear time-domain simulations [75-77].

Future benchmark studies should report coupling topology and subsystem fidelity separately; define the loading condition and target quantity of interest; document grid, time-step, iterative, and statistical convergence where applicable; quantify experimental and numerical uncertainty; and compare predictions with response-relevant physical evidence [198, 200, 208]. Computational cost should be reported together with hardware, parallelization, simulated physical duration, mesh or particle count, and convergence criteria. Shared benchmark cases should progressively include irregular waves, realistic turbulent inflow, controller action, structural flexibility, dynamic

mooring, and downstream-turbine loads so that multi-fidelity methods can be compared using common outputs rather than nominal fidelity labels.

## 7 Conclusion

This review reframes FOWT numerical simulation as a model-selection problem rather than a linear progression from uncoupled to fully coupled analysis. Coupling topology and component level fidelity are independent descriptors, and their combination should be chosen according to the target quantity of interest, dominant physical processes, computational constraints, and available validation evidence.

- Engineering-level coupled tools remain indispensable for broad design-load calculations and iterative design studies, but they should be calibrated and bounded by the physics represented in their aerodynamic, hydrodynamic, structural, mooring, and control modules. High-fidelity simulations are most valuable when deployed selectively to investigate nonlinear waves, large platform motion, wake interaction, local flow or stress, and discrepancies identified by lower-cost models.
- Validation should be organized by response quantity and loading condition. Code-comparison studies, basin experiments, focused component tests, and full-scale measurements provide complementary evidence; none alone establishes universal model accuracy. The benchmark matrix and model-selection guidance presented here are intended to make these boundaries explicit.
- The principal research priorities are targeted validation of nonlinear hydrodynamics and hydroelasticity, coupled investigation of platform-motion-induced wake dynamics in floating arrays, and robust treatment of flexible structures and controller effects. These priorities require

shared benchmark cases that expose model uncertainty rather than only reporting agreement in selected global responses.

- Physics-informed surrogate models and digital twins may extend multi-fidelity workflows from design into operation, but their predictions should remain traceable to training coverage, uncertainty estimates, and physical validation. Frequency-domain and reduced-order methods can further accelerate screening and optimization when their nonlinear limitations are stated clearly.

- The scope of this review is horizontal-axis FOWT numerical simulation at the component, turbine, and emerging farm levels. Controller design is acknowledged as a cross-cutting influence on coupled dynamics but is not reviewed as an independent discipline. This boundary keeps the proposed framework focused on how numerical models should be classified, evaluated, and selected for FOWT dynamics.

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## **Author contribution statement**

Bin Peng is responsible for conceptualization, data curation, and writing-original draft. Sunwei Li is responsible for supervision, funding acquisition, and writing-review & editing. Huaxiao Wu is responsible for Investigation. Yang Ni is responsible for Investigation. Wei Li is responsible for Investigation. All the authors have approved the final manuscript.

## **Data availability**

Not applicable.

## **Declaration of competing interest**

Yang Ni is the employee of China Power Engineering Consulting Group Corporation Limited; Wei Li is the employee of ZHEJIANG Ocean Wind Power Technology Development Corporation Limited. The other authors declare no competing interests.

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## **Use of AI statement**

No AI was used in writing of the submitted manuscript. During the revision of this manuscript, the authors used ChatGPT to assist with language editing and formatting. All scientific claims, citations, numerical values, and figure content were independently checked and revised by the authors, who take full responsibility for the final manuscript.

No generative AI was used to generate or alter research data.

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