



## Project UpWind

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"Integrated Wind Turbine Design"

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# State-of-the-art in design tools for floating offshore wind turbines

## Deliverable D4.3.5 (WP4: Offshore Foundations and Support Structures)

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## **Abstract**

The continued growth of the offshore wind industry and the corresponding decrease in availability of shallow water sites mean there is an increasing need to deploy offshore wind turbines in deeper water. This has led to more detailed investigation of alternative support structure concepts suitable for deep water, such as floating platforms. In order to design and analyse floating support structures, sophisticated design tools are required that can simulate floating offshore wind turbines in an integrated way. Currently a number of simulation codes exist that are capable of modelling floating wind turbine support structures.

This report presents an overview of the simulation and modelling requirements for floating offshore wind turbine design tools. The various techniques for modelling floating wind turbines are presented and the strengths and weaknesses of these methods are analysed. The current status of a number of simulation codes capable of modelling floating offshore wind turbines is presented. An overview of the testing and validation of these tools is presented and conclusions are drawn about the development needs and future verification activities of such tools.

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# 1. Introduction

## 1.1 Background

The offshore wind industry has experienced significant growth in recent years, and continues to expand across the world. The global offshore wind resource is abundant and has the potential to contribute significantly to meeting world energy demands; however nearly all of the offshore wind turbines installed to date are in North European Seas and are mounted on fixed-bottom support structures in water depths of 45m or less. As the demand for offshore wind farms continues to grow, so the number of suitable shallow water sites will become more limited.

A large part of the global offshore wind resource is in locations where the water is much deeper and fixed-bottom support structures are not feasible, for instance off the coasts of the United States, China, Japan and Norway. The possibility of mounting wind turbines on floating support structures opens up the potential to use this deepwater resource. The economic potential of floating wind turbines is demonstrated in [1]. However in order to realise this potential cost-effective floating wind turbine designs are needed which can compete with other energy sources.

The IEC 61400-3 international design standard for offshore wind turbines [6] requires that an integrated loads and response analysis be performed in order for a wind turbine to be certified. This type of analysis is also important from the point of view of the designer as it enables the wind turbine performance to be optimised as well as the structural integrity verified. A full design optimisation is not possible without taking into account the fully coupled response of the system. Therefore, in order to efficiently design optimised floating wind turbines reliable tools are needed which can model the dynamics and response of floating wind turbine platforms in a comprehensive and fully integrated manner.

## 1.2 Previous research

Frequency-domain methods are commonly used in the offshore oil and gas industries to analyse and design floating structures. These methods have also been employed in a number of instances for the preliminary design of floating wind turbines. Bulder et al. [2] used linear frequency-domain hydrodynamic techniques to find response amplitude operators (RAOs) to investigate a tri-floater concept. Lee [3] used a similar process to analyse a tension-leg platform (TLP) design. Vijfhuizen [4] used frequency domain analysis to design a barge for a 5MW turbine including a wave energy device. Wayman [5] also performed calculations in the frequency domain to model various TLP and barge designs.

There are a number of advantages to design calculations in the frequency domain: the above studies were useful in order to demonstrate the initial technical feasibility of floating wind turbines by showing that they could be designed so that the natural frequencies are placed away from the wave energy spectrum to minimise dynamic response. However, frequency domain calculations also have important limitations: they cannot capture non-linear dynamic characteristics or model transient loading events, both of which are important for wind turbines since the non-linear dynamics introduced through transient events and control system actions are a big factor in the loads analysis. Matha [7] performed a typical frequency domain analysis for a floating wind turbine and showed that some couplings between the platform motion and the flexible tower and blades were not accounted for, which could lead to natural frequencies being wrongly predicted and critical system resonances not being identified. This result underlines the importance of performing calculations for floating wind turbines in the time domain.

For the purposes of this report, therefore, frequency domain calculations are not considered and the design tools presented are all based on a time domain analysis.

### 1.3 Floating support structure concepts

There are a number of different floating platform configurations used in the offshore oil and gas industries. A helpful classification system is developed in [8], which divides floating platforms into three general categories according to the means by which the concepts achieve stability.

The first approach for achieving stability is by means of ballast. In this configuration the centre of gravity of the structure is below the centre of buoyancy, which creates a righting moment and provides resistance to pitch and roll. The spar-buoy design uses this means of stability and is typically moored by catenary or taut mooring lines. The second approach uses the mooring lines to achieve stability, for instance the tension leg platform concept which relies on tension in the mooring lines combined with excess buoyancy in the tank. Finally stability can be achieved through buoyancy, relying on the waterplane area for restoring moments. An example of this is the barge concept, which is generally moored using catenary lines. These three methods for achieving stability are illustrated in Figure 1 below.

In practice floating wind turbine platforms will use a combination of all three methods to gain stability, although generally relying on one method for primary stability. Each approach has pros and cons: these are discussed in more detail in [8].

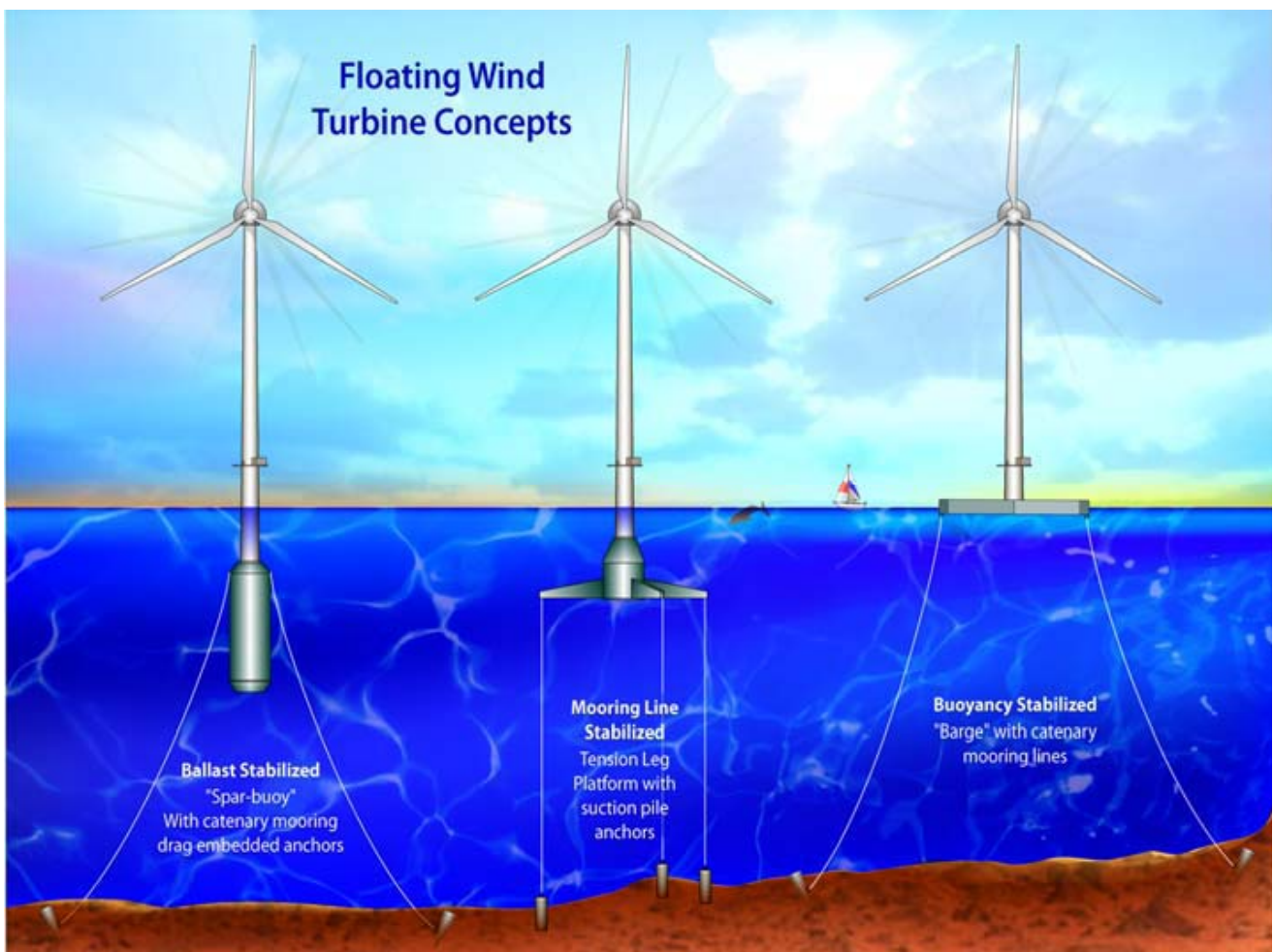


Figure 1: Floating wind turbine stability concepts Source: Ref. [8]

## 2. Modelling of floating offshore wind turbines

In this section an overview is presented of the methods used for the numerical modelling of floating offshore wind turbines. Different methods for the modelling of structural dynamics, aerodynamics, hydrodynamics and mooring lines are compared and comparative strengths and weaknesses presented. The detailed equations describing the various theories are not presented here for the sake of clarity and brevity.

### 2.1 Structural dynamics

#### 2.1.1 Modal representation

The majority of the wind turbine simulation codes available for the onshore market utilise a modal approach for the calculation of structural dynamics. This approach can also be used for the modelling of floating offshore wind turbines. In this approach the fundamental mode shapes and frequencies of the structure are calculated, usually using a finite element pre-processor. These eigenmodes are then superimposed and coupled together to enable the calculation of the overall dynamic response of the total structure using the system equations of motion.

This method of structural analysis benefits from a low number of degrees of freedom: the exact number will depend on the structural properties of the turbine but is typically less than 30. Modal representation is therefore computationally very efficient and results in rapid simulation times. For this reason it remains the method of choice for many of the onshore wind turbine simulation codes currently used.

However the flexibility of this method is limited somewhat by the restrictions on the number and type of degrees of freedom allowed in the structure. This is not so much of a problem when modelling conventional fixed-bottom wind turbines as it is possible to generate a reliable representation of the wind turbine dynamics using relatively few degrees of freedom. However when modelling floating wind turbines additional degrees of freedom are required which often are not available using simple modal representation. In addition to this the modal method does not allow the modelling of more complex floating wind turbine configurations e.g. multiple rotor concepts.

Another limitation of modal representation is that the method is inherently limited to linear responses, i.e. the deflected shape of the blades or tower at any instant must be a linear combination of the available mode shapes. This means that large deflections of flexible components may not be accurately predicted e.g. in the case of lightweight rotor blades. This is of particular importance when it comes to modelling floating offshore wind turbines as they can experience significant translational and rotational displacements during normal operation, which may not be accurately predicted using modal representation.

#### 2.1.2 Multibody systems

An alternative method for the calculation of wind turbine structural dynamics is the multibody system approach. In this method the structure is split up into a number of elements, which can be either rigid or flexible. These elements are interconnected by joints, each with the required constraints applied, and may undergo large translational and rotational displacements. The dynamics of the resulting system can then be analysed using equations of motion, usually derived from the Newton-Euler equations or Lagrange's equations.

The multibody method benefits from increased modelling flexibility due to the ability to create and couple together any number of separate bodies in any number of configurations. This enables an increased number of degrees of freedom to be modelled compared to modal representation, but still with a relatively small number of equations of motion compared to a full finite element analysis.

In addition to this, because the bodies are treated separately and without the assumption of linearity the multibody method also enables accurate modelling of systems with large displacements and rotations. This is an important feature for the modelling of floating offshore wind turbines, and as a result the multibody system method is more common for floating wind turbine simulation codes.



### 2.1.3 Finite Element Modelling

Finite element modelling is the most detailed and also the most computationally expensive of the three methods described here. In this method the wind turbine structure is discretized into a mesh of finite elements interconnected at nodes, each of which has a number of degrees of freedom. The elements can be modelled as one-dimensional beams, two-dimensional plates or three-dimensional solids, and are given physical properties including mass and stiffness. In most cases the theory of linear elasticity but large deflection is applied. The dynamic behaviour of the system can then be analysed by finding numerical solutions to the ordinary and partial differential equations of motion for each element.

The main advantage of finite element modelling is that it allows complex structures to be modelled with a high level of detail and a very large number of degrees of freedom. This is useful for the modelling of more complicated floating platform geometries. Another important advantage of the finite element approach is that it allows for modelling of material non-linearities. This is important for fixed-bottom wind turbines when modelling pile-soil interaction, but also for the modelling of additional components found in floating wind turbines such as mooring lines.

However the level of detail in finite element analysis means that the computational effort required is very high, which results in slow simulations compared to the alternative methods described above. This is a major disadvantage for a commercial wind turbine modelling code where thousands of fully integrated time-domain simulations may be required in order to fulfil the design criteria specified by the international standards. Finite element modelling can also be less efficient than the multibody systems approach for modelling wind turbines, particularly in the way that large rotations, relative kinematics of system components and deformations of structural members are handled. The efficiency of the method depends on the numerical methods and algorithms employed. Standard finite element packages are generally used to model structures for which the motion occurs about a mean undisplaced position, and for this reason finite element codes used to model wind turbines must be specially developed to model large movements of one structural component with respect to another.

It is worth mentioning at this point that a number of wind turbine modelling codes use combinations of the above approaches; for instance some use a multibody representation with modal elements included, and others use a combined multibody and linear finite element approach. These are dealt with in more detail as they arise in Section 3.

## 2.2 Aerodynamics

### 2.2.1 Blade Element Momentum theory

The vast majority of commercial aeroelastic wind turbine simulation codes use combined blade element and momentum (BEM) theory to model the aerodynamic forces acting on a wind turbine rotor. This method was developed from helicopter aerodynamics and due to its convenience and reliability has remained the most widely-used method for calculating the aerodynamic forces on wind turbines. Floating wind turbine design codes are no exception and BEM theory is used in all the floating codes currently available.

In this method the rotor is modelled as an actuator disc assuming axi-symmetric, incompressible, steady flow in a stream tube. The power extracted by the rotor and the thrust force acting on the rotor can be derived using Bernoulli's theorem, which assumes that the balances between changes in momentum and energy flow rates are conserved. Momentum theory can then be applied on an annular level to match the results of momentum analysis with the blade element properties and geometry. Simple BEM theory is very rarely used in isolation, as it does not deal with the unsteady nature of the aerodynamics experienced by a wind turbine rotor. There are a number of corrections commonly applied in conjunction with the BEM model to account for this.

The first of these corrections is the inclusion of tip and hub loss factors in the BEM equations. The tip and hub loss factors account for the fact that the axial flow induction factor  $a$  is not uniform over the rotor area but fluctuates between the passing of each blade, with the overall effect of reducing the net power extracted. This fluctuation is due to the vorticity distribution in the wake arising from the finite number of blades. At the blade

root and blade tip the bound circulation around the aerofoil must reduce to zero resulting in a vortex being trailed into the rotor wake, which is what causes the losses. The most common implementation of the tip and hub loss factors is based on an analysis by Prandtl from propeller theory.

Another important correction is dynamic inflow theory. BEM theory in its most simple form assumes that the induced velocities along the blade can be calculated instantaneously for given flow conditions, i.e. that the wake reacts instantaneously to changes in blade forces. In practice, the vorticity distribution in the rotor wake is influenced by changes in blade loading, and the full effect of this change in the induced velocity flow field takes a finite time. Dynamic inflow theory enables this dependence of induced velocities on rotor loading to be modelled. This is done by rewriting the BEM equations for the calculation of axial inflow as dynamic differential equations, which can then be integrated to give time dependent values for inflow including a time delay. One advantage of this method is that it allows induced velocities to be determined non-iteratively, rather than going through loops to convergence as in the BEM equations. However the theory was developed for lightly loaded rotors which is questionable for wind turbines especially in situations with high thrust coefficients.

The occurrence of stall on a wind turbine blade in unsteady flow is a complex process, as the angle of incidence can change rapidly and with significant amplitude. As a result the onset of stall may be delayed beyond the static stall angle, and the corresponding aerodynamic forces can undergo large hysteresis. In order to represent this process dynamic stall models to calculate the unsteady lift coefficient have been implemented as an extension to BEM theory. These models also include a time lag in the calculation of trailing edge separation. The inclusion of these models is important as the quasi-steady approach, in which the flow field adjusts instantaneously to each change in the angle of incidence, can result in an under-prediction of the aeroelastic damping associated with stalled flow and hence an over-prediction of structural vibrations.

There are a number of advantages to the use of BEM theory for calculating aerodynamic forces on a wind turbine rotor. The main advantage of this method is its simplicity and consequently its speed. It has also been extensively validated against measured data and shown to be accurate and reliable. However BEM theory also has a number of limitations. It is really intended only for steady flow with wind directly approaching the rotor, and although the extensions described above can be applied to improve the accuracy of prediction in turbulent flow these extensions do not fully capture all the unsteady effects. In addition to this the theory is still not validated for rotors operating in large yaw angles or with significant upflow.

There are also research codes which use free wake lifting line methods, such as the free-vortex based AWSM code developed by ECN in the Netherlands [9]. This is based on Prandtl's lifting line theory taking into account non-linear contributions, and is able to more accurately describe the shape and strength of the time-dependent wake generated by the turbine blades. The use of this method leads to better predictions in situations where the aerodynamic characteristics vary significantly with time and where the dynamic wake effects are important, for instance in yawed flow. It also captures the effects of mutual blade interference which BEM theory does not do, and models the dynamics of tip vortices more accurately. However it is significantly slower than the BEM method, and also numerically more unstable meaning that the iteration scheme may require relaxation of the tolerances in order to prevent divergence. The assumption of irrotational flow also means that effects such as wind shear cannot strictly be included.

The alternative to BEM theory and vortex-based methods is to use computational fluid dynamics codes, which use the Navier-Stokes equations. This approach is much more complex and has high computer processing requirements, which makes industry-scale analysis impractical.

## **2.3 Hydrodynamics**

### **2.3.1 Wave particle kinematics**

In order to calculate the hydrodynamic loading on a submerged structure in the time domain the wave particle kinematics must be determined. For linear sea states the wave particle velocity and acceleration vectors and dynamic pressure can be calculated using linear Airy wave theory. This theory represents the wave elevation as a sinusoid propagating with a constant amplitude and period. For fatigue load calculations in which irregular

sea states are required, Airy wave theory can be combined with an appropriate wave energy spectrum in order to create an irregular sea state.

One limitation of Airy theory is that wave particle kinematics can only be defined up to the mean water surface (i.e. at  $z = 0$ ). The theory can be extended up to the instantaneous free surface by using positive values of  $z$ ; however this approach tends to over-estimate particle kinematics at the wave crest and under-estimate particle kinematics in the trough. In order to take proper account of the forces acting between the mean water level and the instantaneous free surface, Wheeler stretching may be used. This is described in more detail in [10].

Airy wave theory is widely used due to the relative simplicity and speed with which it calculates wave particle velocities and accelerations. The main disadvantage of Airy wave theory is that it relies on the assumption of linearity, which means that the non-linear characteristics of real sea states, such as steep-sided waves and breaking waves, cannot be modelled. This rules out the possibility of calculating slap and slam loading which can result from non-linear waves.

The assumption of linearity is taken to be reasonable in deep water, where wave heights are much smaller than wavelengths. However for large waves or for waves in shallow water it may be required to account for non-linearities in the wave structure. In this case stream function wave theory may be used. This theory gives more accurate wave kinematics than linear Airy theory in shallow waters or when the wave height is large compared to the water depth. However the limitation of stream function theory is that it cannot be used to compute irregular sea states, which are required for fatigue load calculations according to [6].

### 2.3.2 Morison's equation

Once the wave particle kinematics have been derived, the hydrodynamic loads acting on the support structure may be calculated using Morison's equation. Morison's equation is valid for slender, vertical cylinders and is a function of the diameter of the cylinder, fluid particle velocity and acceleration, and the hydrodynamic drag and inertia coefficients  $C_D$  and  $C_M$ . The drag and inertia coefficients are functions of Reynold's number, Keulegan-Carpenter number and surface roughness as well as a number of other factors. In order to calculate the applied hydrodynamic loads acting over the length of the structure the cylinder can be divided into a number of elements, in a similar way to BEM theory, and the total applied load found by integrating the loads acting on each element. Morison's equation accounts for the relative motion between the platform and the fluid and includes added mass effects from the movement of the water.

One major advantage of Morison's equation is that the hydrodynamic loads are calculated in terms of wave particle velocities and accelerations rather than velocity potential. This enables Morison's equation to be used not only with linear Airy wave theory but also with non-linear wave kinematic models. This is the reason that Morison's equation is used in the majority of codes used to model fixed-bottom offshore wind turbines in relatively shallow water.

However when it comes to modelling floating support structures Morison's equation also has a number of disadvantages. For support structures with a small diameter relative to the wavelength of the incident waves, i.e. when the member diameter is less than  $0.2 \times$  wavelength, diffraction effects may be neglected [11]. This comes from G.I.Taylor's long-wavelength approximation, which states that for surface-piercing bodies with a small diameter relative to the wavelength, the wave potential can be assumed to be constant across the body and therefore calculations can be performed at the centre of the body. Morison's equation uses this approximation to simplify the diffraction problem. However when the submerged body has a diameter large enough for the waves to be disturbed by the presence of the structure, wave diffraction effects must be accounted for in order to correctly determine the local pressure force and global wave loads. This is often the case for floating platforms, in particular for those stabilised by buoyancy, which means that Morison's equation cannot be used.

Morison's equation also assumes that viscous drag dominates the drag loading, and that wave radiation damping can therefore be ignored. This assumption is only valid if the motions of the support structure are very small, which is usually the case for fixed-bottom support structures with soft-stiff characteristics. However for floating platforms with low-frequency rigid modes the support structure may experience significant movement, which means that wave radiation forces should be accounted for.

Because Morison's equation is only used for axi-symmetric cylindrical structures it does not take account of any added mass-induced coupling between hydrodynamic force and support structure acceleration in different degrees of freedom. This is a reasonable assumption for cylindrical structures; however for an accurate modelling of non-cylindrical floating platforms these coupling terms should be taken into account. Morison's equation also neglects hydrostatic restoring forces; however additional terms can be added to account for this.

### 2.3.3 Linear hydrodynamic equations

When dealing with slender structures it is considered to be a reasonable assumption that the submerged body does not exert any influence on the surrounding fluid either in terms of diffraction or radiation. However we have seen above that when the structures in question are larger in diameter and experience significant movement, as is often the case for floating platforms, then wave diffraction and radiation forces must be included in the analysis. In order to calculate these effects the additional boundary condition of zero flow velocity perpendicular to the surface of the structure must be followed. For most practical cases the resulting problem cannot be solved analytically, so numerical methods based on the assumptions of linear wave theory must be used. Assuming that the hydrodynamics of the sea state are linear, the sources of loading can be sub-divided into three separate problems: radiation, diffraction and hydrostatic restoring. These problems can then be solved individually and the resulting loads summed together. This approach is described in more detail in [15].

Wave radiation loading describes the loads which arise from the influence of a moving body on the surrounding fluid when no incident waves are present. In this case it can be assumed that loads due to wave radiation are independent of incident waves since the radiation problem is being treated separately from the diffraction problem. The loading on the body arises as the body radiates waves away from itself, and includes contributions from both added mass and damping. The added mass contribution comes from the hydrodynamic forces resulting from the outgoing wave pressure field induced by the acceleration of the support structure. The damping contribution comes from free surface memory effects; because the pressure field induced by outgoing waves continues for as long as the waves radiate away, radiation loading depends on the history of motion of the submerged body. The free surface memory effect can be accounted for using a radiation kernel to represent the hydrodynamic forces at any given moment in time due to a change in support structure velocity. Both the added mass matrix  $A_{ij}$  and the radiation kernel  $K_{ij}$  depend on the geometry of the floating platform and must be computed in the frequency domain using potential flow theory.

Wave diffraction loading describes the loads which arise from the influence of the surrounding fluid on a stationary body when incident waves are present. In this case it can be assumed that loads due to wave diffraction are independent of the motion of the body, i.e. the loads are calculated for the body fixed at its mean position, since the diffraction problem is being treated separately from the radiation problem. As the waves pass the stationary body the wave pattern is modified due to the presence of the body and loading on the body arises as a result of the modified pressure field. The wave excitation force is closely related to the wave elevation, which can be computed using linear Airy wave theory, and also depends on the geometry of the floating platform, the frequency and the direction of the waves. A normalised complex transfer function to represent this force can be computed in the frequency domain using potential flow theory.

Hydrostatic loading describes the static loads on the body arising from the pressure in the surrounding fluid. It is normally calculated by computing the surface pressure applied by the fluid on the submerged part of the structure, including the restoring forces due to water plane area arising from the displacement of the support platform. The magnitude of the net upward force is equal to the weight of the fluid displaced by the body, in accordance with Archimede's Principle. The hydrostatic load contribution is relatively simple to compute.

The advantage of this method for calculating hydrodynamic loads is that it takes proper account of the influence of the body on the fluid. This is particularly important for floating bodies which often have large diameters and experience significant motion. It is also possible that there may be additional dynamic effects which are only accounted for when diffraction and radiation are included in the analysis: for instance it has been shown that the presence of wave radiation damping can in some cases reduce instabilities in platform surge motion arising from controller actions [30]. This illustrates the importance of including these effects in the hydrodynamic loading calculations for floating wind turbines.

The main limitation of this method is that it requires the assumption of linearity, which restricts its use to deep water sites where wave heights are much smaller than wavelengths; however it should be said that this is not as much of a limitation for floating wind turbines as it is for most of the fixed-bottom offshore wind turbines installed to date, since floating wind turbine sites will normally be in deep water. The use of linear hydrodynamic equations clearly also means that non-linear wave kinematics cannot be used in calculating hydrodynamic loads. The linearisation assumptions are also invalidated if the translational displacement of the floating platform is large relative to the wavelengths or characteristic length of the platform or if the rotational displacements of the platform are large relative to the wave steepness, which can be the case for some floating wind turbine configurations.

## **2.4 Mooring lines**

Mooring systems are necessary for floating bodies in order to restrain the global movement of the platform against the effects of wind, waves and currents. It is important to accurately model the effect of mooring lines on the response and dynamics of a floating system, particularly in the case of floating wind turbine configurations which use mooring lines to achieve stability. However mooring system dynamics are non-linear in nature, and often include hysteresis effects. An accurate modelling of mooring line dynamics is therefore a complex problem and is dealt with fully only by dedicated codes. However the interaction of the mooring lines with the floating platform can also be approximated in a number of ways as described below.

### **2.4.1 Force-displacement representation**

A common method for modelling foundations for fixed-bottom offshore wind turbines is to use P-Y springs in the translational and rotational degrees of freedom to represent the relationship between force and displacement in the soil. This method can be extended to the modelling of mooring lines for floating wind turbines by applying non-linear spring stiffnesses for all six degrees of freedom at the fairlead position. A damping matrix may also be included as appropriate. The relevant force-displacement characteristics of the mooring system must be calculated separately and added as inputs into the model. This method can also be extended to include a force-velocity relationship to account for mooring line drag.

The force-displacement method enables the non-linear geometric restoring properties of the mooring system to be described in a single stiffness matrix, which has the advantage of simplicity and ease of implementation. However in most cases this method is limited due to the fact that the loads are generally not specified as functions of displacement in all six degrees of freedom (surge, sway, heave, roll, pitch, yaw). Often restoring forces are specified as independent functions of each platform displacement, in which case important couplings can be missed; although modelling a spring at each mooring line attachment can minimise this loss of accuracy. Because the load-displacement data is given in discrete form it must also be interpolated, which can lead to small losses in accuracy.

### **2.4.2 Quasi-static representation**

An alternative method for representing the non-linear mooring line restoring forces is the quasi-static approach. In this method the tensions in the mooring lines are solved from the equations of static equilibrium for the suspended mooring line for a given platform displacement at any instant in time, not accounting for the drag and inertia of the lines. The elasticity of the mooring lines should be included in the analysis, otherwise the tensions in the lines can be significantly overestimated.

This approach enables the properties of the mooring lines (length, diameter, mass and extensional stiffness) to be provided as direct inputs to the system, thus cutting out the pre-processing requirement of the force-displacement method. The quasi-static approach also accounts for the non-linear geometric restoration of the complete mooring system, but with a full representation of restoring forces as a function of displacement in all degrees of freedom built in to the method. This is because the restoring forces on the support platform are calculated at each time step taking into account the contribution from the tension in each mooring line.

Both of the above approaches have the limitation that they do not account for the dynamics of mooring lines. The assumption that the mooring lines are in static equilibrium for each successive instant in time could be considered to be appropriate for slowly varying platform motion where frequencies are of the order of minutes rather than seconds. However the motion of the platform due to waves is typically at frequencies of the order of 0.1Hz, and at these frequencies the inertia and damping of the mooring lines means that they are unable to follow the platform motion instantaneously. Neglecting mooring line damping can lead to inaccuracies since the dynamics of mooring lines are significantly affected by the drag loading due to hydrodynamic damping [12]. Neglecting mooring line inertia is justified in [15] (for the system and water depth in question) since it represents such a small percentage of the overall inertia of the system (around 2%). The bending stiffness of the mooring lines is also neglected in both the force-displacement and quasi-static approaches: however this is rarely of any significance.

### **2.4.3 Full dynamic modelling**

The governing equations for mooring line dynamics are rather complex and cannot be solved analytically, so advanced numerical techniques must be used. One approach is to discretise the line into point masses connected by weightless inextensible elements, and solve the resulting ordinary differential equations using the finite difference method. A more general solution can be found using the finite element method. A number of discrete finite elements are used to approximate a continuum, each with physical properties, and the differential equations for each element solved numerically to find the dynamics of the line. Both these methods are extremely computer intensive. There are a number of codes, mainly developed for the offshore oil and gas industries, which provide full models of the dynamics of mooring lines for floating offshore systems.

The full dynamic modelling approach gives an accurate representation of the drag and inertia of mooring lines and their effect on the floating platform. These effects can be significant, especially in very deep water where the mooring line is much less likely to take up its catenary shape instantly and a quasi-static analysis is unable to accurately predict the line tensions. Therefore for floating wind turbines with catenary mooring systems in deep water a full dynamic analysis of the mooring lines should be undertaken.

One of the limitations of this method is that it requires much more processing time than the alternatives, due to its complexity. This is a problem for offshore wind turbine design calculations, for instance as specified in [6], in which a large number of simulations is required to fulfil the design criteria. It can also be difficult to find an appropriate way to interface the mooring line analysis codes with conventional aeroelastic offshore wind turbine design tools.

### 3. Description of existing floating design tools

There are a number of design tools available to the offshore wind industry that have the capability to model floating offshore wind turbines in a fully coupled time-domain dynamic analysis. In this section the content and structure of these design tools is presented, in particular the methods employed by each design tool for the modelling of structural dynamics, aerodynamics, hydrodynamics and mooring lines. The summaries presented here apply to the design tool capabilities available at the time of writing; future development is planned for most codes to expand their capabilities.

#### 3.1 FAST by NREL

FAST is a publicly-available simulation tool for horizontal-axis wind turbines developed by the National Renewable Energy Laboratory (NREL) in North America. It has been largely developed by Jonkman [13], based at NREL. The FAST code was developed for the dynamic analysis of conventional fixed-bottom wind turbines, but has been extended with additional modules and to enable fully coupled dynamic analysis of floating wind turbines.

##### *Structural dynamics*

The FAST code uses a combined modal and multibody dynamics representation. The wind turbine blades and tower are modelled using linear modal representation assuming small deflections, with two flapwise bending modes and one edgewise bending mode per blade and two fore-aft and two side-to-side bending modes in the tower. The drive train is modelled using an equivalent linear spring and damper. A finite element pre-processor (BModes) is used to calculate the mode shapes of the blades and tower.

##### *Aerodynamics*

The aerodynamic subroutine package AeroDyn is used to calculate aerodynamic forces in FAST. This model uses quasi-steady BEM theory or a generalized dynamic inflow model. Both of these models include the effects of axial and tangential induction. The aerodynamic calculations include tip and hub losses according to Prandtl, and dynamic stall corrections using the Beddoes-Leishman model. Further details can be found in [14].

##### *Hydrodynamics*

The hydrodynamic subroutine package HydroDyn is used to calculate applied hydrodynamic forces in FAST. Wave kinematics are calculated using Airy wave theory with free surface corrections. The hydrodynamic loading includes contributions from linear hydrostatic restoring, non-linear viscous drag contributions from Morison's equation, added mass and damping contributions from linear wave radiation (including free surface memory effects) and incident wave excitation from linear diffraction. Full details are given in [15]. The linearised radiation and diffraction problems are solved in the frequency domain for a platform of arbitrary shape using 3D panel-based program WAMIT (or an equivalent hydrodynamic pre-processor). The resulting hydrodynamic coefficients are used in HydroDyn.

##### *Mooring lines*

The FAST code uses a quasi-static mooring system module to represent the non-linear mooring line restoring forces. This module accounts for the apparent weight of the mooring line in fluid, the elastic stretching of the mooring line and the seabed friction of each line. For a given platform displacement the module solves for the tensions within each mooring line by assuming that each cable is in static equilibrium at that instant, and uses the resulting tensions to solve the dynamic equations of motion for rest of the system. Full details of the quasi-static mooring line module are given in [15].

FAST has been used in a number of research contexts to model coupled wind turbine and floating platform dynamics. The configuration described above is that used by Jonkman et al [15]. However the FAST code has also been coupled with a number of other dynamic analysis programs to model the dynamics and response of floating wind turbines. Two examples of this are presented below.

#### 3.1.1 FAST with Charm3D coupling

The FAST code is coupled with floater-mooring dynamic analysis program Charm3D by Shim [17]. Charm3D is a finite element program jointly developed by Texas A&M University and Offshore Dynamics Inc. with partial funding from Charm3D JIP (Joint Industry Program) for the dynamic analysis of moored floating offshore structures. The coupling of this program with FAST enables the mooring line and rigid body dynamics of a floating wind turbine system to be integrated with the wind turbine dynamics in a fully coupled time-domain simulation. In Charm3D the hydrodynamic coefficients of the floating platform are calculated in the frequency domain using a panel-based 3D diffraction and radiation program (in this case WAMIT). In the time domain analysis various non-linearities are taken into account including the drag force on the mooring lines, the large (translational) motion of the platform, the free surface effects, and the geometric non-linearity of the mooring system. The mooring line dynamics are solved simultaneously at each time step by a coordinate-based FEM program. The floating body motions and velocities computed by Charm3D are provided as inputs to FAST, and the resulting dynamic loads from the wind turbine computed by FAST are returned as external forces.

### 3.1.2 FAST with TimeFloat coupling

The TimeFloat software has also been coupled with FAST in order to model the dynamic response of the WindFloat floating foundation concept for large offshore wind turbines [16]. TimeFloat is a time-domain software tool developed by Marine Innovation and Technology for the analysis of floating structures. The coupling of TimeFloat with FAST enables the aerodynamic, hydrodynamic and mooring system forces acting on the structure to be simultaneously computed, including non-linear quasi-static mooring forces and the non-linear viscous forces generated by the water-entrapment plates.

As above, the wave interaction effects are processed in the frequency-domain software WAMIT and the resulting added-mass, damping and mean drift coefficients and wave-exciting forces passed to the TimeFloat code. The hydrodynamic forces are then calculated by TimeFloat. These include memory effects, wave-excitation forces (using force components computed by WAMIT), viscous forces resulting from drag effects, drift forces, mooring line forces and wind forces. The hydrodynamic forces are provided as an input to FAST, which then solves the turbine and tower equations of motion and passes the platform motion back to TimeFloat.

## 3.2 ADAMS by MSC

ADAMS (Automatic Dynamic Analysis of Mechanical Systems) is a commercially available general purpose multibody dynamics code developed by MSC Software Corporation. The code is not wind turbine-specific and is also used by the automotive, aerospace and robotics industries. ADAMS models of wind turbines can be generated by the FAST tool through its FAST-to-ADAMS pre-processor functionality.

### *Structural dynamics*

The ADAMS code uses a multibody representation to allow a large number of structural configurations and degrees of freedom. The wind turbine blades and tower are modelled as flexible members consisting of a series of rigid bodies with lumped mass and inertia connected by flexible joints with linear stiffness and damping. The drive train may either be modelled similarly as a series of lumped masses or through a simple hinge/spring/damper element. ADAMS can also model a number of additional features including torsional degrees of freedom in the blades and tower, flap/twist coupling in the blades, mass offsets in the blades and tower, and pitch actuator dynamics.

### *Aerodynamics*

The AeroDyn aerodynamic subroutine package is used to calculate aerodynamic forces in ADAMS, as described in Section 3.1.

### *Hydrodynamics*

The hydrodynamic forces may be calculated in ADAMS by interfacing with the hydrodynamic subroutine package HydroDyn, as described in Section 3.1. Alternatively an equivalent subroutine may be used for calculating loads on the floating platform (see for instance Withee [18]).

### *Mooring lines*



The ADAMS code can also be extended in a similar way to the FAST code to enable the modelling of mooring lines. This can be done either by solving the mooring line tensions quasi-statically in a separate module and interfacing with the main code at each time step, or using an equivalent force-displacement relationship defined at the mooring line interface point.

### 3.3 Bladed by Garrad Hassan

GH Bladed is an integrated software tool for calculating wind turbine performance and dynamic response [19], developed by Garrad Hassan in the UK. It was originally developed for the modelling of onshore fixed-bottom wind turbines, but has been extended to include hydrodynamic loading for the modelling of offshore wind turbines.

#### *Structural dynamics*

The Bladed code uses a modal representation to model the structural dynamics of a wind turbine. The modal properties of the rotating and non-rotating components of the system (i.e. the rotor and tower) are computed independently using a finite element representation of the structure. The component modes are then coupled together using the appropriate equations of motion in the dynamic response analysis. The mode shapes and frequencies of the rotor are dependent on the number of blades, the mass and stiffness properties of the blades, the blade twist and pitch angle and the presence or otherwise of a teeter hinge. For modelling the tower a multi-member model may be used, consisting of an arbitrary space-frame structure of interconnecting beam elements with given mass and stiffness properties. The resulting mode shapes will be three-dimensional with six degrees of freedom at each node.

#### *Aerodynamics*

The aerodynamic forces on the rotor are calculated in Bladed using combined Blade Element and Momentum theory, including tip and hub loss models based on Prandtl. A dynamic wake model is included to account for the effect of blade loading on wake vorticity. The model included in Bladed is based on Pitt and Peters and has received substantial validation in the helicopter field. Dynamic stall is also accounted for using the Beddoes-Leishman model.

#### *Hydrodynamics*

The applied hydrodynamic forces on the wind turbine support structure are calculated in Bladed using Morison's equation. For linear sea states the wave particle kinematics are calculated using Airy wave theory with free surface corrections using Wheeler stretching. If linear waves are used an irregular sea state may be defined using either a JONSWAP spectrum or a user-defined wave energy spectrum. For linear irregular sea states the effects of wave diffraction may be accounted for using a time-domain MacCamy-Fuchs approximation. In this approach the wave energy spectrum is altered to give the same resulting hydrodynamic load on the structure as the standard MacCamy-Fuchs method, in which the  $C_d$  and  $C_m$  coefficients are modified in the frequency domain. For non-linear waves the wave particle kinematics are calculated using stream function theory. The order of the solution is chosen based on the input values of wave height, wave period and water depth.

#### *Mooring lines*

The Bladed code uses a user-defined force-displacement relationship to model non-linear restoring forces from mooring lines. The relationship between the displacement of the platform and the applied force from the mooring line is calculated separately by the user and implemented via a stiffness matrix at the fairlead position.

#### 3.3.1 Recent development of GH Bladed

The representation of structural dynamics in the standard GH Bladed design code is performed using modal representation, as described above. For conventional wind turbine structures this approach is accurate, reliable and well validated. It is also highly efficient since the entire structure can be modelled with relatively few degrees of freedom. However for less conventional wind turbine structures, for instance those mounted on floating platforms, additional modelling issues arise. The large structural deflections experienced by the tower in many floating wind turbine configurations cannot be accurately modelled using the existing Bladed set-up.

The coupling between vertical tower modes and rotor modes is also not accounted for, which is required in order to properly account for the influence of the heave motion of a floating platform.

One approach is to continue developing the Bladed code in its existing form, making improvements to the code as required. Bladed has previously been modified in this way to cope with the large rigid body motions experienced by a floating structure (with the exception of heave motion). However the structure of the Bladed code means that there are inherent restrictions on modelling more complex wind turbine configurations. Because of these inherent limitations an alternative approach is currently being taken, which is to change the whole way in which Bladed represents structural dynamics and convert it from a pure modal code to a multi-body code. In the new multibody code, instead of modelling the whole turbine as a single dynamic structure consisting of one rotor and tower with coupling between rotor modes and tower modes hard-wired into the code, the structure can now be modelled with any number of separate bodies, each with individual modal properties, which are coupled together using the equations of motion. The use of multi-body dynamics enables floating structures to be properly modelled, including all six support structure degrees of freedom and large rotations and displacements.

### **3.4 SIMO/RIFLEX by MARINTEK**

SIMO (Simulation of Marine Operations) is a general-purpose time-domain program developed by MARINTEK for the modelling and simulation of offshore structures. It is used extensively to model motions and station keeping of floating structures in the offshore industry. The code has been extended to enable modelling of floating wind turbines by the addition of an external module for the simulation of rotor aerodynamic forces [20]. SIMO has also been coupled with non-linear finite element code RIFLEX [21], also developed by MARINTEK, a tailor-made code for the static and dynamic analysis of slender marine bodies such as risers and mooring lines.

#### *Structural dynamics*

The SIMO code uses interconnected multibody systems to model structural dynamics. In order to model a floating offshore wind turbine multiple bodies may be defined and coupled together. In [20] the turbine and support structure are defined using a small number of rigid bodies (2-body and 4-body configurations are investigated). In this case the rotor loads are transferred to the support structure using three flexible coupling elements consisting of two radial bearings and one axial bearing. In [21] the coupling with RIFLEX enables a finite element formulation of the structure, allowing for unlimited displacements and rotations in 3D space. The rotor is still modelled as a rigid body but the tower is made up of flexible beam elements, each with 12 degrees of freedom, which means that the elastic behaviour of the tower can be investigated.

#### *Aerodynamics*

The aerodynamic forces are calculated in a separate module and implemented in SIMO as a user-specified external force. Blade Element Momentum theory is used to calculate the forces on the rotor blades, with dynamic inflow effects included. Individual blade element forces are then summed together and applied in SIMO as a six-component external load on a rotating body. The drag force on the tower and nacelle is also accounted for in the aerodynamic loading.

#### *Hydrodynamics*

The hydrodynamic forces are modelled within the standard SIMO code. Linear Airy wave theory is assumed for calculating wave kinematics. The calculation of hydrodynamic loads takes into account linear and quadratic potential forces including frequency-dependent excitation, added mass and damping contributions (calculated in the frequency domain using WAMIT) and slow drift. Viscous drag forces from Morison's equation, mooring line forces and body-to-body hydrodynamic coupling force models are also included.

#### *Mooring lines*

The mooring lines are modelled using the RIFLEX code. This enables the representation of mooring lines as flexible finite elements, incorporating non-linear material properties and dynamic properties. A separate mooring system module is not required as it is an integrated part of the RIFLEX code.

### 3.4.1 SIMO/RIFLEX with HAWC2 coupling

The SIMO/RIFLEX code has also been coupled with the HAWC2 code in [22] and [23]. HAWC2 is an aero-elastic simulation tool developed by Risø National Laboratory for the dynamic analysis of fixed-bottom wind turbines [24]. The coupling of these two codes enables detailed modelling of both the aerodynamic and hydrodynamic forces acting on a floating offshore wind turbine. The HAWC2 code has also been used to directly model a floating wind turbine in [25], with the mooring line analysis performed separately in SIMO/RIFLEX.

#### *Structural dynamics*

The HAWC2 code uses a combined linear finite element and nonlinear multibody representation to calculate the structural dynamics of a wind turbine. A number of separate bodies can be defined, consisting of an assembly of linear Timoshenko beam finite elements. The bodies are connected by algebraic constraint equations, which can take the form of flexible joints, bearings or rigid connections. Internal forces are calculated from these algebraic constraints. In order to couple the two codes together the position, velocity and acceleration vectors and rotation matrix at the interface point are passed to HAWC2 by SIMO/RIFLEX and the reaction force at the interface point is returned to SIMO/RIFLEX by HAWC2 at each time step.

#### *Aerodynamics*

The aerodynamic forces on the rotor are calculated in HAWC2 using Blade Element Momentum theory. The classic approach has been modified to include the effects of dynamic inflow, dynamic stall, skewed inflow, shear effects on induction and effects from large deflections. The aerodynamic calculation points are positioned independently of the structural nodes to provide an optimal distribution of these points.

#### *Hydrodynamics and mooring lines*

In [22] and [23] the modelling of hydrodynamics and mooring lines is performed in SIMO/RIFLEX, as described in Section 3.4 above. In [25] the hydrodynamics are calculated using Morison's equation based on the instantaneous position of the platform. The mooring lines are modelled in SIMO/RIFLEX using a finite element model and the resulting force-displacement relationship applied as an external force at the fairlead position.

## 3.5 3Dfloat by UMB

3Dfloat is a code developed by the Norwegian University of Life Sciences (UMB) for the modelling of floating offshore wind turbines with full coupling between structural dynamics, aerodynamics, hydrodynamics and control system actions. The code has been used to analyse floating offshore wind turbine models and compare conceptual designs [26].

#### *Structural dynamics*

3Dfloat uses a finite element method for modelling the structural dynamics of a floating wind turbine. Euler-Bernoulli beams with 12 degrees of freedom are used, and geometric non-linearities in the elements are taken into account by casting the model in a co-rotational framework. The rotor and drive train are modelled as rigid, with no interaction between the rotor and the tower. Flexibility is included in the tower. The global motion of the structure is taken into account using structural modes.

#### *Aerodynamics*

The rotor aerodynamics are calculated in 3Dfloat using Blade Element Momentum theory. Extensions for dynamic inflow and large yaw errors are also included.

#### *Hydrodynamics*

The hydrodynamic forces are calculated in 3Dfloat using Morison's equation, with wave particle kinematics derived using linear Airy wave theory. The hydrodynamic loads include terms for added mass of water from the acceleration of the structure, linear hydrostatic restoring and non-linear viscous drag.

#### *Mooring lines*

The mooring lines are modelled using finite elements in 3Dfloat with bending stiffness neglected. The mooring lines can also be replaced by linear stiffnesses at the fairlead positions for the purposes of eigen-frequency analysis.



## 4. Testing and validation of design tools

The development of design tools capable of modelling floating platforms is an important step forward for the offshore wind turbine industry, but in order to give security to the industry the results obtained from these codes must be shown to be accurate and reliable. Comprehensive testing and validation is therefore crucial for giving sufficient confidence to developers and investors. The best way to achieve this kind of confidence is to take measurements from a real machine and compare the measured data with the results from numerical simulations. In the case of floating wind turbines there is limited measurement data available with which to validate the codes, so a second method is also employed, that of comparing the results of different codes with each other.

### 4.1 Code-to-measurement comparisons

A number of studies have been performed by Hydro Oil & Energy for the development of the Hywind floating wind turbine concept, [21]. The floating platform consists of a deep-water slender spar-buoy with three catenary mooring lines. The integrated SIMO/RIFLEX/HAWC2 design tool was used in [22] to model the structure, as described in Section 3.4.1. As part of the development of this concept model scale experiments were carried out at the Ocean Basin Laboratory at Marintek in Trondheim in order to validate the coupled wind and wave modelling of the Hywind concept. A variety of sea states, wind velocities and control algorithms were tested and a number of parameters measured for the purposes of comparison. The hub wind speed from the model scale experiments was measured and used as the basis for the turbulent wind field used in the simulations. The JONSWAP wave spectrum was applied for both simulations and model experiments. The results of these tests showed very good agreement between the responses of the scale model and the predictions from the simulation code. The results also showed a significant increase in the damping of the tower motion when active blade pitch damping was introduced.

Another floating wind turbine code which has been validated with the use of measurements is TimeFloat, a time-domain design tool for coupled analysis of floating structures described in Section 3.1.2. The hydrodynamic calculations within this code were validated using wave tank tests performed at the UC Berkeley ship model testing facility [16]. A scale model of the floating platform was fabricated at 1:105 scale, with a foam disk at the tower top to represent wind forces and an electrical motor to model the gyroscopic effect of the rotor. A 3-hour realization of the 100-year sea state was generated with and without steady wind, and the resulting platform motion measured using a digital video camera. The floating platform was also modelled in the TimeFloat software using a simplified model for aerodynamic forces acting on the rotor. The results from these numerical simulations were then compared with the measurements from the tank tests. The comparison between model test results and numerical simulations showed good agreement, with the TimeFloat software generally underpredicting platform motion slightly.

Because of the relative novelty of the floating wind turbine industry there is very little experimental data available for code-to-measurement comparisons. However future measurement campaigns are being planned: for instance the University of Maine DeepCwind Consortium in the U.S. were recently awarded an \$8m grant to develop floating offshore wind capacity [27], in a project which will include tank testing, deployment of prototypes and field validation.

### 4.2 Code-to-code comparisons

In addition to the validation of codes using measurements, an important way to verify the predictive accuracy of numerical simulation tools is through code-to-code comparisons. Most of the codes used for the analysis of floating wind turbines have been validated in this way. One example is the FAST code, the aero-elastic features of which have been verified through comparisons with ADAMS, described in [28]. Another example is the SIMO/RIFLEX code used to model the Hywind floating wind turbine concept, which was validated in part through comparisons with HywindSim, a relatively simple Matlab/Simulink code developed for the purposes of such comparison [21]. The methods used to validate the hydrodynamic calculation module HydroDyn used in the FAST code are described in [15]. These methods included comparisons between the output from WAMIT

and results from a different numerical solver, comparisons between the WAMIT frequency to time conversion and HydroDyn calculations, using a benchmark problem to test the accuracy of the quasi-static mooring line calculations, comparing the mooring line force-displacement relationship calculated by the quasi-static method with that calculated by another code, and comparisons of time-domain results with frequency-domain results.

However the most extensive code-to-code comparison work in the offshore wind industry has been performed as part of the Offshore Code Comparison Collaboration (OC3) project within IEA Wind Task 23 [29]. In this project a number of participants used different aero-elastic codes to model the coupled dynamic response of the same wind turbine and support structure, with the same environmental conditions. The results were then compared in order to verify the accuracy and correctness of the modelling capabilities of the participant codes, and to improve the predictions.

#### **4.2.1 Offshore Code Comparison Collaboration Phase IV**

In Phase IV of the OC3 project a floating offshore wind turbine was modelled [30]. The turbine model used was the publicly available 5MW baseline wind turbine developed by NREL, and the floating platform was a modification of the Hywind spar-buoy developed by Statoil of Norway. The turbulent wind fields and irregular wave kinematics were generated independently and provided to all participants in order to ensure tight control of all the inputs. A stepwise verification procedure was then used with the complexity of the model and the test cases being increased with each step.

A number of floating design tools were involved in Phase IV of the project, including FAST, ADAMS, Bladed, HAWC2, 3Dfloat, SIMO, Sesam and DeepC. A variety of different load cases were performed, including a full system eigenanalysis; a static equilibrium test; free-decay tests for each of the six rigid-body degrees of freedom of the platform; time series response tests with regular waves and irregular waves modelled with a rigid rotor and no wind; time series response tests with regular waves and irregular waves modelled with a flexible rotor and steady and turbulent wind; and “effective RAOs” calculated with regular waves at varying frequencies. Not all of the codes were able to contribute results to every test case performed, due to various limitations on their modelling capabilities. The test cases showed up a number of interesting results, some of which are outlined below.

##### *Structural dynamics*

The participating codes all employ different methods for modelling structural dynamics, which was illustrated in a number of differences in the results. The rotor-nacelle assembly was modelled rigidly in 3Dfloat and both the rotor-nacelle assembly and tower were modelled rigidly in SIMO, Sesam and DeepC. This meant that these codes could not model structural deflections in these components. The FAST code predicted a higher natural frequency for the second blade asymmetric flapwise yaw frequency than the other codes; this is because FAST does not account for a torsional mode in the tower whereas the other codes that include tower flexibility do account for this mode. The ADAMS code predicted less energy from the irregular wave simulations in the power spectra for tower top shear and rotor torque at the second tower and blade bending natural frequencies than FAST and Bladed. This may be because of an effect typical of ADAMS simulations in which numerical damping increases with frequency. The free-decay tests showed a few differences between codes in their prediction of the amount of damping present in the various modes. HAWC2 predicted too much heave and pitch damping; and ADAMS predicted too little pitch damping.

##### *Aerodynamics*

Most of the participating codes use BEM theory for the calculation of aerodynamic loads, with the exception of Sesam and DeepC which did not model aerodynamics for the purposes of this project. The 3Dfloat, SIMO, Sesam and DeepC codes modelled the rotor as rigid, which meant that the aero-elastic response was not correctly modelled. One example of this was in the calculation of effective RAOs, for which the 3Dfloat code showed lower excitation in yaw, higher excitation in fairlead tensions and higher excitation at the first tower bending frequency for all parameters. This was thought to be due to differences in aerodynamic damping due to rigid rotor, although it may also have been related to the modelling of the rigid spar with artificially high stiffness. The 3Dfloat code also gave a higher mean thrust in the simulations with regular wind and waves, which corresponded with higher platform surge and pitch displacements.

### *Hydrodynamics*

The main difference in terms of hydrodynamic analysis was between codes which used linear potential flow methods and those which used simple Morison's equation. The most interesting difference was found from the effective RAO calculations. The FAST code used by POSTECH was missing one hydrodynamic damping term, which led to the surge displacement and fairlead tension having a negative effective RAO: the physical meaning of this being that there was more system motion in still water than there was with waves. This occurred because there was a controller-induced instability of the platform surge mode at the surge natural frequency, where there was negligible hydrodynamic damping in the model. With waves included the wave radiation damping at the wave excitation frequency damped out this instability, thus reducing platform motion considerably. This result indicates the importance of using potential flow based solutions which include wave radiation damping for the analysis of floating support structures.

### *Mooring lines*

The methods used for modelling mooring lines varied quite a lot between the codes, from user-defined force-displacement relationships to full dynamic models. The Sesam and DeepC codes used finite element models for the mooring lines, and also predicted more energy content above 0.1Hz for fairlead tension in the power spectra from irregular wave simulations both with and without wind. This is probably due to undamped high-frequency motions in the finite element representations of the mooring lines. Other results confirmed that the mooring line tensions were interacting with the floating platform as expected: for instance, in the simulations with regular wind and waves the upstream fairlead tension was higher than the downstream fairlead tension, which is what you would expect given that the mooring line tensions are counteracting the thrust from the rotor. The fairlead tensions were also higher overall in 3Dfloat, which had a higher mean thrust. The results from the effective RAO calculations showed that the behaviour of the fairlead tension was similar to that of the surge displacement, which confirms that platform surge is what most influences fairlead tensions.

One of the most significant outcomes of the project is that it has helped to identify deficiencies and areas in need of improvement in the participating codes, which has led to significant improvements in the accuracy of modelling and response prediction. This is extremely beneficial both for the developers of the floating design tools and for the industry in general. More details and full results from the project can be found in [30].

## **4.3 Case study: testing and validation of GH Bladed**

The GH Bladed code is currently undergoing development from a modal representation of structural dynamics to a multibody representation, as described in Section 3.3.1. The testing and validation of the new code structure is obviously highly important since Bladed is used by a large number of wind turbine manufacturers worldwide for design calculations. One of the aims of the Bladed multibody code is to better enable the modelling of floating wind turbine platforms, so the testing and validation of this aspect of the code is directly relevant to this report. The validation work is currently being undertaken within Garrad Hassan, and is described briefly below.

The validation of the multibody code is being done on several levels. Firstly, each individual feature of the core multibody code has been checked against hand calculations for known cases to give an initial indication of its accuracy. Secondly, checks have been made against ADAMS for simple dynamic cases. Since ADAMS is a general-purpose multibody design tool which has been rigorously tested through extensive use in other industries this gives a good measure of confidence in the multibody Bladed results. Checks have also been made against ANSYS, a general-purpose finite element analysis software tool, of non-rotating mode shapes and frequencies for structurally complex cases such as blades. Thirdly, the results for a complete wind turbine structure have been compared with hand calculations for simple known cases to verify the accuracy of the code as a whole.

The current GH Bladed code is well documented and has been extensively validated against measured data from a large number of turbines of different sizes and configurations [19]. Therefore an important check in the validation of multibody Bladed was to perform internal comparisons with the existing Bladed code. These comparisons have been performed on a case by case basis, and also at the level of a complete set of fatigue and extreme calculations. The results from these comparisons showed good agreement, with natural frequencies from multibody Bladed matching well with existing Bladed. The main difference is in the edgewise fatigue

loads, which have reduced a little. This is due to the use of individual blade modes rather than rotor modes, which include a component of aerodynamic damping in the edgewise direction.

In addition to these internal tests the new multibody Bladed code has been compared with other aero-elastic codes in the context of the OC3 project [31]. The model definitions and load cases used in the OC3 project have been performed with multibody Bladed and the results compared to those obtained from other participants. The comparison with the OC3 results is especially useful since the new capabilities of multi-body Bladed include the ability to properly model the dynamics of floating structures, so a like-for-like comparison with the existing Bladed code is not possible. However a useful comparison is provided by the OC3-Hywind model from Phase IV of the OC3 project together with the OC3 Phase IV test cases. These simulations are being used to ensure that the prediction of dynamic response from multibody Bladed is in line with other floating wind turbine design tools. Again, the multibody Bladed code is showing good agreement with other industry codes. These tests are still ongoing, with results expected to be included in a future report.

There are also plans to compare the results from multibody Bladed against measurements for further validation and user confidence, but not all of these measurements will be public domain and therefore the results cannot be published.



## 5. Limitations and future work

It is clear that the floating wind turbine design codes currently available to the offshore market contain a number of limitations. It is important to be clear on exactly what these limitations are, so that these codes can be improved and areas in need of further research identified. This section outlines the limitations of the design codes currently available and proposes topics for future research and further work.

### 5.1 Aerodynamic theories

All of the design codes currently capable of performing integrated modelling of floating wind turbines use combined Blade Element Momentum theory to calculate aerodynamic forces on the wind turbine rotor. However the large low-frequency platform motions experienced by floating offshore wind turbines result in flow conditions which are considerably more complex than those experienced by conventional onshore or fixed-bottom offshore wind turbines. In particular there is a change in the interaction between the rotor and wake, with the rotor in some cases traversing back over its own wake.

Sebastian and Lackner [32] have performed an analysis of the motions and resulting aerodynamic loading of a floating wind turbine, and have shown that the BEM method is lacking in its prediction of aerodynamic loads in such conditions. However, beyond this study very little research has been performed in this area specifically for floating wind turbines. It is proposed that the effect of low-frequency floating platform motions on rotor-wake interaction should be the subject of further research and investigation.

### 5.2 Hydrodynamic theories

The fullest way of accounting for the different sources of hydrodynamic loading is to divide them into separate problems and solve them independently, as described in Section 2.3.3. In order to divide the hydrodynamics problem up in this way the assumption of hydrodynamic linearity is required. This assumption is also necessary in order to use linear Airy wave theory for the calculation of wave particle kinematics.

There are a number of important limitations introduced with the assumption of linearity, some of which are discussed in Section 2.3. The use of Airy wave theory means that steep-sided or breaking waves found in shallow water cannot be modelled, together with the resulting slap and slam loading. In addition to this the potential flow theories used in a number of floating wind turbine design tools to calculate hydrodynamic loads were developed for stationary bodies, and are only valid when the support structure motion is small relative to the length of the platform. However many floating configurations experience large translational displacements relative to the length of the platform, for instance catenary moored systems where there is low resistance to surge and sway, which means that these theories are no longer valid.

Linear wave theories also do not take into account second or higher order hydrodynamic effects, which more properly account for the hydrodynamic loading on the wetted surface of the body and are necessary for the analysis of platforms which are subject to steep-sided or very large waves. Second order hydrodynamic loads are proportional to the square of the wave amplitude, and have frequencies equal to both the sum and the difference of the multiple incident wave frequencies. This means that although the natural frequencies of the structure are designed to be outside the wave energy spectrum the second order forces will excite these frequencies, so despite the forces normally being small in magnitude the resonant effect can be important. Three examples of second order hydrodynamic forces are given below.

- Mean drift forces. These forces result in a mean offset of the body relative to its undisplaced position, and are typically an order of magnitude lower than first order wave excitation forces. The mean drift force is a combination of second order hydrodynamic pressure due to first order waves and the interaction between first order motion and the first order wave field. The viscous drag contribution to this force is significantly increased when there is a current present. Since the mooring line tension is often related non-linearly to platform displacement the mean drift forces can have an important effect.
- Slowly varying drift forces. These forces have much longer periods than the main wave energy spectrum but are still within the range of horizontal platform motion. They result from non-linear interactions

between multiple waves with different frequencies. Again the forces resulting from slowly varying drift are generally small compared to forces at the wave frequency, but they can cause large displacements in moored floating wind turbines which can in turn lead to high loads in the mooring lines. In addition these forces can excite the large amplitude resonant translational motion of the floating platform.

- High frequency forces. These forces have a frequency which is higher than the wave frequency and are also generally small in amplitude. They arise from the same source as low frequency drift forces, i.e. interactions between multiple waves of varying frequency. The contribution from these forces can be particularly important when analysing ‘ringing’ behaviour for floating wind turbine configurations such as TLP concepts, which typically have high natural frequencies in heave, roll and pitch.

Of the codes presented in Section 3, currently only the SIMO design code developed by MARINTEK takes account of second order hydrodynamic effects. However even with second order hydrodynamic terms included the hydrodynamic theory may not completely apply to floating wind turbine platforms, since it was derived for use in the offshore oil and gas industry in which floating platforms typically have much smaller displacements than what is conventional for floating wind turbines. Work is currently being done at MIT on developing a new nonlinear hydrodynamic theory that may be more appropriate for floating wind turbines, which would enable more detailed design of floating concepts which are particularly susceptible to second order effects. However there are no publications on this work as yet.

Another effect currently not accounted for in hydrodynamic analysis for floating wind turbines is vortex-induced vibrations. This effect is caused by steady currents or by velocities associated with long period waves, and refers to the dynamic loading which occurs as a result of fluctuations in pressure due to the motion of vortices in the wake of a body. If the frequency of excitation is near a natural frequency of the structure the interaction between the flow and the motion of the structure can cause the two frequencies to lock in to each other, which can result in large amplitudes of oscillation. The forces due to vortex shedding are complex and predictions of loading and response are not well understood; however the frequencies at which oscillations may occur can be predicted with more confidence. Vortex-induced vibrations are not generally seen in conventional fixed-bottom offshore support structures, but are more likely to be experienced in mooring lines and can be critical for the stability of some designs.

### 5.3 Mooring line dynamics

The restoring forces on a floating wind turbine platform due to mooring lines can be approximated using force-displacement or quasi-static methods, as described in Section 2.4. However these methods do not account for mooring line dynamic effects, for instance line inertia, the drag of the line through fluid and vortex shedding. For some configurations these effects can have a significant contribution to the overall response of the system. A number of programs exist which can model the dynamics of mooring lines. However these programs do not generally allow for the detailed modelling of an integrated wind turbine system, the aerodynamic forces from which also make a significant contribution to the response of the whole system. There is therefore a problem: how to simultaneously account for the dynamic response of the mooring lines and the wind turbine in a single fully-coupled analysis.

One approach is to use a dynamic line analysis code to derive a force-displacement relationship and apply this as a non-linear spring at the fairlead position: see [25] for an example of this. The limitations of this approach are discussed in Section 2.4.1. Another approach is to couple together dedicated mooring line and wind turbine analysis codes. An attempt has been made by Jonkman et al to couple the dynamic mooring line system LINES of SML with the aero-elastic wind turbine codes FAST and ADAMS. However this attempt was abandoned after it was found that LINES encountered numerical instabilities when modelling the slack catenary mooring lines of interest [15]. The most fruitful attempt to date is the coupling between offshore floating structures code SIMO/RIFLEX and the multi-body wind turbine code HAWC2, described in [22]. However this approach is still limited in that the floating wind turbine cannot be modelled as a single integrated dynamic structure, since the two problems must be solved in separate programs and information exchanged between the programs at a single interface point.

The central issue with regard to mooring line dynamics is whether or not it is acceptable to neglect the dynamic effects of mooring lines for floating wind turbines. For shallow mooring systems the total mass of the

lines is negligible and the motion is small, so even though the drag force of the lines through the fluid may still be significant it is generally accepted that dynamics may be neglected. However for deeper water configurations mooring line dynamics become increasingly important. The question is, what is the transition depth beyond which mooring line dynamic effects become non-negligible?

A number of studies have been performed to answer this question in the context of ships and semi-submersible vessels. Polderdijk [33] proposed approximate analytical solutions to the line dynamic problem which can be used to give preliminary checks as to whether line dynamic effects are likely to be significant. Kwan and Bruen [34] analysed line dynamic tensions due to platform wave frequency motion for a range of conditions using both dynamic and quasi-static methods, and showed that the ratio of maximum dynamic to quasi-static tension varied between 1.2 and 19.5 across the cases investigated. Their results can be used to help determine whether or not dynamic analysis is necessary for a given configuration. A Joint Industry Project managed by the Noble Denton Group on the dynamics of catenary mooring [35] studied a number of vessel types, mooring systems and water depths from both a theoretical and practical point of view. The conclusion from these studies was that line dynamic analysis should be conducted when the wave frequency response of the vessel is large, when the water depth exceeds 150m, or when the mooring line includes large drag elements such as chain moorings [12].

However, as yet no dedicated studies have been performed into the dynamics of mooring lines for floating wind turbines. It is proposed that a study should be performed investigating which aspects of mooring line behaviour are important specifically for floating wind turbines, the depth at which dynamic mooring line effects become non-negligible for floating wind turbines, and which types of mooring system have the most dynamic effect on floating wind turbine platforms and therefore need to be designed using a full dynamic analysis. This study could incorporate a comparison between the different methods for calculating mooring line tension forces for floating wind turbines presented in Section 2.4.

## 6. Conclusions

The development of floating wind turbine technology will open up the potential to utilise a vast amount of wind resource located in deep waters. In order to efficiently design and analyse floating support structures, sophisticated design tools are required that can simulate floating offshore wind turbines in an integrated way. These codes must perform calculations in the time domain to ensure that all non-linear dynamics are captured. The current status of a number of floating design tools is presented in this report, together with a description of the analysis methods used and the strengths and weaknesses of those methods.

In order to give confidence in the predictions from these simulation codes they must be comprehensively tested and validated. This is achieved through comparisons with measured data and also through code-to-code comparisons. There is very little measured data from floating wind turbines available with which to validate the codes. Further tank tests and measurements from full-scale installed prototypes are therefore needed in order to validate the simulation codes. Code-to-code comparisons have been carried out both in the development of individual codes and also as part of the OC3 project. Further industry-wide code comparisons are planned.

The limitations of the various analysis methods used in current simulation codes have been identified. The BEM method for calculating aerodynamic loading does not perform so well for floating wind turbines with large low-frequency motion. More research therefore needs to be performed into the modelling of rotor-wake interaction for floating wind turbines. Most floating wind turbine codes do not account for second order hydrodynamic effects, which may be more important for floating platforms than for fixed-bottom structures. In addition to this the second order hydrodynamic theory commonly used in general offshore codes may not completely apply to floating wind turbine platforms. More research is therefore needed into developing hydrodynamic theories which will be applicable to floating wind turbines, including second order hydrodynamic effects and the prediction of forces due to vortex shedding.

The effects of mooring line dynamics for floating wind turbines is an area of considerable uncertainty. There are no dedicated studies into the dynamics of mooring lines specifically for floating wind turbines. It is proposed that such a study should be performed, incorporating the following elements:

- Quantitative comparison between the different methods for calculating mooring line tension forces
- Analysis of which aspects of mooring line behaviour are important specifically for floating wind turbines
- Analysis of which mooring system types and configurations have the most dynamic effect on floating wind turbine platforms and therefore need to be designed using a full dynamic analysis
- Investigation into the transition depth at which dynamic mooring line effects become non-negligible for floating wind turbines.

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