Hydrodynamics of Offshore Structures with Specific Focus on Wind Energy Applications

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Abstract

This review covers the broad scope of ocean hydrodynamics on offshore marine structures, laying the framework for studying offshore wind energy with a variety of engineering methods. First, water wave theory is described beginning with the fundamental equations of fluid mechanics. A variety of wave theories are discussed, beginning with linearized wave theory, and continuing with Stokes, cnoidal and solitary wave theory. The regions of wave applicability for different theories is shown, summarizing the discussion of water wave theory. Following the introduction of water wave theory, ocean physics are introduced. This section includes ocean wave generation, random waves, spectral representation and commonly used wave spectra, including the Pierson-Moskowitz and JONSWAP spectra. Next, wave-body interaction is presented, first looking at static and then dynamic loads. The dynamic load discussion covers waves, added mass and impulse loads. The section on wave-body interaction concludes with a review of recent literature on wave-body interactions, with emphasis on offshore wind energy. Additionally, a sample of existing engineering tools for modeling hydrodynamics on offshore wind turbines is presented. Finally, finite volume methods are presented to lay the groundwork for reviewing recent computational fluid dynamics research relating to the wave-body interaction problem. The review culminates in a review of recent CFD research.

Key words: hydrodynamics, wind energy, fluid-structure interaction, computational fluid dynamics

1. Introduction

Large-scale offshore wind energy has become a reality in Europe over the past decade, with continued development on the horizon in Europe, as well as Asia and the United States. While the vast majority of offshore wind energy development utilizes fixed bottom support structures, in shallow waters that are close to shore, floating offshore wind

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turbines show great potential for harnessing the wind resource far from shore, in transitional to deep water where the wind resource is greater and concerns about visibility are reduced [1] [2]. However, in both near shore, shallow water applications, and especially in deeper waters farther from shore, technical and economic feasibility challenges must be overcome. Understanding the fundamental hydrodynamic forces in the offshore environment, and in particular the added challenges of operating floating platforms in the ocean environment, is crucial to the success of future projects. Not only are floating platforms subject to loading from ocean waves, but also increased motion due to the wave-body interactions.

Understanding the loading on offshore wind turbine platforms, including fixed bottom and floating, requires a strong grasp of basic wave theory, ocean physics, and wave-body interaction. Additionally, researchers must select from a variety of modeling approaches, including but not limited to Morison's equation, potential-flow theory and computational fluid dynamics. This review seeks to describe the individual components of the fundamental hydrodynamics experienced by offshore wind turbines, beginning with water wave theory, then adding ocean physics and finally wave-body interactions, before concluding with a more detailed treatment of computational fluid dynamics approaches.

This review focuses on the theory for studying the hydrodynamics of offshore wind turbine platforms, and does not cover measured data from experiments nor installed projects. Although a handful offshore floating wind turbines have been deployed [3, 4, 5, 6] measured data from these installed platforms is publicly unavailable. A small sample of model-scale experiments have been performed in wave tanks [7, 8, 9, 10, 11, 12]. While these scale tests provide data for validation and verification of numerical models, they do suffer from various complications related to scaling issues. The purpose of this review is to provide a guide for researchers now and in the future to better apply the theory when developing simulation tools that match real platforms.

To establish an understanding of ocean wave interaction with fixed and floating bodies, we begin with an overview of water wave theory which draws from works by Apel [13], Mei [14], Sarpkaya, [15], Phillips [16], Lamb [17], Stoker [18], Whitham [19] and Crapper [20]. First fundamental equations of fluid motion are presented, and the kinematic and dynamic boundary conditions are added, leading to linearized wave theory. Next, Stokes wave theory is discussed [21], followed by solutions to the Korteweg-deVries equation [22] which include cnoidal and solitary wave theory. Breaking waves are briefly mentioned, which includes work by Longuet-Higgins [23], Ochi and Tsai [24] and Michel [25]. The water wave theory section concludes with commentary on the applicability of different wave theories depending on wave height and water depths, which draws on work by LeMéhauté [26].

Building on the foundation of water wave theory, ocean physics are introduced next. Whereas basic water wave theory is treated as a deterministic process, the ocean environment is anything but, and must be treated stochastically. Ocean wave generation and growth mechanisms are briefly addressed, based on more extensive work by Phillips [16], Jeffreys [27] [28], Miles [29, 30, 31, 32], Sverdup and Munk [33], and Pierson [34]. Random waves and their spectral representation are described, followed by an explanation of the Pierson-Moskowitz and JONSWAP spectra [35, 36].

Following the review of wave theories and ocean physics, the wave-body interaction problem is introduced. The discussion of wave-body interaction covers static and dynamics loads, including topics such as radiation, diffraction, added mass, and Mori-

son's equation. Relevant research related to the hydrodynamics of wave-body interaction is presented. Computer aided engineering tools, such as FAST [37], WAMIT [38], SIMO/RIFLEX developed by MARINTEK, and HAWC2 developed at the Technical University of Denmark (DTU), which are currently being used for modeling offshore wind turbines are discussed.

Finally, finite volume methods are presented as a high-fidelity, yet more computationally expensive, approach to modeling the hydrodynamics on offshore wind turbines. First, the Navier-Stokes equations are discretized, leading to a system of algebraic equations. Next, a review of Eulerian methods for multiphase flow modeling is given, including discussion of Volume-of-Fluid, Moment-of-Fluid, Level Set and Marker Methods. Finally, recent CFD research on fluid-structure interactions is highlighted.

2. Water Wave Theory

A basic understanding of wave modeling is the first component necessary for simulating the interaction of rigid bodies in the ocean. Before delving into ocean wave theory, a more fundamental treatment of basic water wave theory is given in this section. Both linear and non-linear wave theories are discussed here. This section concludes with a brief discussion of the regions of applicability for various wave theories. The discussion here is synthesized from more detailed texts on water wave theory and ocean dynamics, including work by Apel [13], Mei [14], Sarpkaya [15], Phillips [16], Lamb [17], Stoker [18], Whitham [19] and Crapper [20].

Waves vary over a wide range of spatial and temporal domains. In describing ocean waves, there are variety of physical mechanisms which act as restoring forces. These are categorized in Table 1. This work largely focuses on wind waves and swell, which are the primary waves types that affect the motion and loading on floating platforms of offshore wind turbines. These waves are referred to as surface gravity waves, or sometimes just surface waves. As a starting point, the basic equations of fluid motion are reviewed, followed by simplifications for irrotational and inviscid flows. Boundary conditions for interfacial and rigid impermeable boundaries are covered. Linearized equations for infinitesimal waves are derived, followed by a discussion of non-linear wave theories.

2.1. Fundamental Equations

Water density varies little over time and space in gravity wave problems, such that we can describe the motion of the fluid with the incompressible Navier-Stokes equations. First, mass conservation for incompressible flow is given by,

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

The conservation of momentum is expressed as,

$$\left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla\right)\mathbf{u} = -\nabla\left(\frac{p}{\rho} + gz\right) + \nu \nabla^2 \mathbf{u} \quad (2)$$

where $\mathbf{u}$ is the velocity vector in the x, y and z directions, p is pressure, ρ is the density, g is gravity, z upwards in is the vertical direction and ν is the viscosity.

Vorticity is defined as the curl of velocity ($\Omega = \nabla \times \mathbf{u}$). Taking the curl of the momentum equation results in an expression describing the evolution of the vorticity, shown below.

$$\left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla\right)\Omega = \Omega \cdot \nabla \mathbf{u} + \nu \nabla^2 \Omega \quad (3)$$

The momentum conservation in Equation 2 can be non-dimensionalized using length scales and velocities, resulting in the final term taking the form

$$\frac{\nu}{L\mathbf{u}} \nabla^2 \mathbf{u}, \text{ which is equivalent to } \frac{1}{Re} \nabla^2 \mathbf{u} \quad (4)$$

In many flows, including structures in the ocean, the Reynolds number is large, such that the inertial terms dominate over the viscous terms. In these large Reynolds number cases, viscosity is negligible, so a good approximation of the evolution of vorticity is given by,

$$\left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla\right)\Omega = \Omega \cdot \nabla \mathbf{u} \quad (5)$$

When the vorticity is zero ($\Omega = 0$) the flow is irrotational. For an inviscid, irrotational flow the velocity can be expressed as the gradient of a scalar function. The scalar function represented by ϕ is called the velocity potential. Using the vector identity $\nabla \times \nabla \phi = 0$, and plugging in $\nabla \times \mathbf{u} = 0$ for the case of irrotational flow, results in the velocity represented as the gradient of a scalar, ϕ .

$$\mathbf{u} = \nabla \phi \quad (6)$$

The velocity must still satisfy mass conservation, and for the case of incompressible flow it can be shown that the velocity potential obeys Laplace's equation.

$$\nabla^2 \phi = 0 \quad (7)$$

Rewriting the momentum equation in terms of the velocity potential ϕ , for the inviscid, irrotational case gives,

$$\nabla \left[\frac{\partial \phi}{\partial t} + \frac{1}{2} |\nabla \phi|^2 \right] = \nabla \left(\frac{p}{\rho} + gz \right) \quad (8)$$

Integrating the above equation once with respect to the space variables results in the unsteady Bernoulli equation, given by,

$$-\frac{p}{\rho} = gz + \frac{\partial \phi}{\partial t} + \frac{1}{2} |\nabla \phi|^2 + c(t) \quad (9)$$

where $c(t)$ is some arbitrary function of time. The gz term gives the contribution from hydrostatics, while the remaining terms are the hydrodynamic contributions to the total pressure, p .

2.2. Boundary Conditions

To complete the set of governing equations, initial and boundary conditions are necessary. Initial conditions depend greatly on the specific problem under consideration, while boundary conditions depend on the physical domain of the problem. Two main classes of boundary conditions are considered here, which are rigid impermeable and interfacial boundaries. Rigid impermeable boundaries include the wetted surfaces of solid objects, and in this discussion are assumed to maintain their shape. Interfacial boundaries include the air-water interface, or other immiscible fluid interfaces, and can be thought more generally as deformable boundaries. In these cases it is assumed that there is no spray or mixing between the two fluids of consideration. Three main assumptions are made here: pressure is constant across the interface between two fluids, once a particle is on a free surface it remains there, and there is no flow through an impervious boundary.

For the case of rigid impermeable boundaries it is assumed that there is no fluid flow across the boundary. If the boundary is not only impermeable, but also fixed, then the normal component of the fluid velocity must vanish. A common example of this is at the sea floor. Mathematically, it is given by,

$$u_n = \mathbf{u} \cdot \hat{n} = 0 \quad (10)$$

where $\hat{n}$ is the unit normal to boundary, and u_n is the normal component of the fluid velocity.

This zero-flux boundary condition can also be expressed in terms of the velocity potential and is shown in the equation below.

$$\frac{\partial \phi}{\partial n} = \nabla \phi \cdot \hat{n} = 0 \quad (11)$$

There are many examples of impermeable boundaries that move, including floating objects such as wind turbine platforms. We let $\mathbf{V}$ be the velocity of the moving object. In the simplest treatment, the normal component of the fluid velocity must equal the velocity of the moving surface.

$$u_n = \vec{u} \cdot \hat{n} = \mathbf{V} \cdot \hat{n} \quad (12)$$

For potential flows, this boundary condition is given by,

$$\frac{\partial \phi}{\partial n} = \nabla \phi \cdot \hat{n} = \mathbf{V} \cdot \hat{n} \quad (13)$$

It is shown that the case of a fixed impermeable boundary is just a special case of the moving impermeable boundary case.

Interfacial boundaries are deformable, as in the case of the air-water interface. Here both the velocity potential, ϕ , and the location of the free surface, η , must be determined. Since there are two unknowns, two boundary conditions are needed to close the system. First, the kinematic free surface boundary condition is derived, followed by the dynamic free surface boundary condition.

The kinematic condition states that any particle sitting on the free surface will remain there always. This can be treated mathematically by letting η be the free surface elevation

above some equilibrium level z_0 , so that the vertical coordinate of the particle on the free surface is given by,

$$z = z_0 + \eta(x, y, t) \quad (14)$$

Using the assumption that a particle on the free surface will remain on the free surface always, leads to

$$\frac{D}{Dt} (z - z_0 - \eta) = 0 = \left(\frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z} \right) (z - \eta) \quad (15)$$

The z -coordinate is independent of x , y and t , so that leaves the differentiation of η . Following the rearrangement of terms, we arrive at the kinematic free surface boundary condition, shown below.

$$w = \frac{\partial \eta}{\partial t} + u \frac{\partial \eta}{\partial x} + v \frac{\partial \eta}{\partial y} \text{ at the free surface} \quad (16)$$

For small amplitude problems it may become useful to make approximations for small fluid velocities or slopes. These approximations result in a simplified expression for the kinematic free surface boundary condition, given by,

$$w \cong \frac{\partial \eta}{\partial t} \quad (17)$$

Now, we look at the dynamic free surface condition. A normal force is required to balance the pressure difference across the interface to prevent disrupting the surface. Surface tension provides this normal force. The surface tension is proportional to the curvature of the interface, or the inverse of the radius of curvature. Looking at a two dimensional case, the mathematical representation of the pressure and surface tension balance is given by,

$$p - p_a = \sigma \left(\frac{1}{R_x} + \frac{1}{R_y} \right) \quad (18)$$

where σ is the surface tension, R_x and R_y are the radii of curvature in orthogonal directions and p_a is the pressure above the free surface. Curvatures are given approximately by the second derivative of the surface height. Upon replacement, the dynamic boundary condition becomes

$$p - p_a = \sigma \left(\frac{\partial^2 \eta}{\partial x^2} + \frac{\partial^2 \eta}{\partial y^2} \right) \quad (19)$$

For ocean waves, the wavelength is typically long enough that surface tension plays an insignificant role in the physics. When this is the case, the pressure above the free surface must match the pressure just below the surface. Bernoulli's equation on the free surface, given in Equation 9, is combined with the kinematic condition written in terms of the velocity potential, shown in Equation 20. The resulting equation for the dynamic free surface boundary condition is shown below, in Equation 21.

$$\frac{\partial \eta}{\partial t} + \frac{\partial \phi}{\partial x} \frac{\partial \eta}{\partial x} + \frac{\partial \phi}{\partial y} \frac{\partial \eta}{\partial y} = \frac{\partial \phi}{\partial z} \text{ on } z = \eta \quad (20)$$

Taking a total derivative of the Bernoulli equation, using the assumption that p_a is constant, and rearranging, produces the dynamic free surface boundary condition given below.

$$\frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} + \frac{\partial}{\partial t} (\vec{u})^2 + \frac{1}{2} \vec{u} \cdot \nabla \vec{u}^2 = 0 \quad (21)$$

The resulting formula is non-linear, and still leaves the position of the free surface as an unknown. It is shown that the problem of water waves is nearly impossible to describe analytically. We are left to solve the Laplace equation, as discussed earlier, which is a linear equation. However, because the boundary conditions are non-linear it becomes a very difficult problem to solve. The following section examines approximations that can be made in an effort to find useful analytical solutions.

2.3. Linearized Wave Theory

As previously noted, waves exist in many forms, including regular and irregular, linear and non-linear, and progression in varying depths. This section discusses the simplest possible type of wave, the linearized or small amplitude wave, which forms the basis for all other waves. The assumptions for linearized wave theory discussed here are that the wave is a two-dimensional, progressive gravity wave, with a constant period, height and length, traveling over a horizontal, smooth sea bed. Additionally, the wave is assumed to be inviscid, incompressible, irrotational with no temperature or salinity gradients, and is in the absence of wind and surface tension effects.

We begin with the Laplace equation discussed in Section 1.1, and three boundary conditions to describe the sea bed, and the kinematic and dynamic boundaries given in Equations 23, 24 and 25, respectively.

$$\nabla^2 \phi = 0 \quad (22)$$

$$\frac{\partial \phi}{\partial z} = 0 \text{ at } z = -h \quad (23)$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial \phi}{\partial x} \frac{\partial \eta}{\partial x} - \frac{\partial \phi}{\partial z} = 0 \text{ at } z = \eta \quad (24)$$

$$\frac{\partial \phi}{\partial t} + \frac{1}{2} \left[\left(\frac{\partial \phi}{\partial x} \right)^2 + \left(\frac{\partial \phi}{\partial y} \right)^2 \right] + g\eta = f(t) \text{ at } z = \eta \quad (25)$$

As was mentioned in the previous section, finding solutions to the Laplace equation with these non-linear boundary conditions is very difficult. To simplify this problem, assumptions are made in an effort to linearize the governing equations. Small amplitude wave theory assumes that the wave height is much smaller than the wave length and the water depth, and neglects non-linear terms. The kinematic and dynamic boundary conditions, given by Equations 24 and 25, in the problem statement then become

$$\frac{\partial \eta}{\partial t} - \frac{\partial \phi}{\partial z} = 0 \text{ at } z = \eta \quad (26)$$

$$\frac{\partial \phi}{\partial t} + g\eta = 0 \text{ at } z = \eta \quad (27)$$

Now, combining the kinematic (KBC) and dynamic boundary conditions (DBC) results in

$$\frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} = 0 \quad (28)$$

and

$$\eta = -\frac{1}{g} \left(\frac{\partial \phi}{\partial t} \right) \Big|_{z=0} \quad (29)$$

Via separation of variables, the velocity potential and surface elevation are found to be

$$\phi(x, z, t) = \frac{gH}{2kc} \frac{\cosh[k(z+h)]}{\cosh(kh)} \sin[k(x-ct)] \quad (30)$$

$$\eta(x, t) = \frac{H}{2} \cos(kx - \omega t + \psi) \quad (31)$$

where g is gravity, H is wave height, k is wavenumber, c is wave speed, h is water depth and ω is the angular frequency of the wave. It is important to note that non-trivial solutions for the velocity potential, which satisfy the boundary conditions given above, only exist when the dispersion relation is satisfied. The dispersion relation which uniquely relates the wave number to the wave frequency for a given water depth is given below, and it a result of the KBC given in Equation 28.

$$\omega^2 = gk \tanh(kh) \quad (32)$$

Simplifying assumptions can be made for shallow and deep water. In shallow water, as kh tends towards zero, the hyperbolic tangent of kh approaches kh , leaving the dispersion relation for shallow water as $\omega^2 \cong gk^2h$. For deep water, kh approaches infinity, and the hyperbolic tangent goes to one. The dispersion relation for deep water then simplifies to $\omega^2 \cong gk$.

The determination of the velocity potential, surface elevation and dispersion relation provides enough information for the calculation of numerous other physical quantities relating to linearized wave theory. A sample of physical quantities are outlined below, and a summary of linearized wave theory characteristics are provided in Table 2.

The pressure is found by plugging the solution for the velocity potential into the unsteady Bernoulli equation. Keeping the initial assumption to neglect non-linear terms, the Bernoulli equation is simplified by dropping the second order term. The resulting expression for the pressure is

$$p(x, z, t) = \rho g z + \frac{1}{2} \rho g H \frac{\cosh[k(z+h)]}{\cosh(kh)} \cos(kx - \omega t + \psi) \quad (33)$$

It is straightforward to determine the velocities in the x and y-directions by differentiating the velocity potential. The equations for the horizontal and vertical components of velocity are given below.

$$u(x, z, t) = \frac{gH}{2c} \frac{\cosh[k(z+h)]}{\cosh(kh)} \cos(kx - \omega t + \psi) \quad (34)$$

$$w(x, z, t) = \frac{gH}{2c} \frac{\sinh[k(z+h)]}{\cosh(kh)} \sin(kx - \omega t + \psi) \quad (35)$$

An expression for particle displacement follows from the calculation for particle velocities in the vertical and horizontal directions. Letting ζ_p be the particle displacement in the horizontal direction and η_p the particle displacement in the horizontal direction, and using the relations $u = \frac{\partial \zeta_p}{\partial t}$ and $v = \frac{\partial \eta_p}{\partial t}$, produces

$$\zeta_p(x, z, t) = \frac{H}{2} \frac{\cosh[k(z+h)]}{\sinh(kh)} \sin(\omega t - kx + \phi) \quad (36)$$

$$\eta_p(x, z, t) = \frac{H}{2} \frac{\sinh[k(z+h)]}{\sinh(kh)} \cos(\omega t - kx + \phi) \quad (37)$$

The particles follow elliptical clockwise orbits in progressive gravity waves. The shape of the elliptical path depends on the depth of the water, as can be seen in the equations for particle displacements and velocities. The horizontal particle displacement and velocity decreases with depth following $\cosh[k(z+h)]$. In a similar fashion, the vertical displacement and velocity decrease with $\sinh[k(z+h)]$. The profiles of the particle paths in shallow, intermediate and deep water are illustrated in Figure 1. Deep water is classified by a water depth that is greater than one half the wave length, shallow water is classified by a water depth of less than 1/20th the wave length. Intermediate water depth falls between the limits of shallow and deep water classifications [39].

2.4. Non-linear Waves

Next, non-linear wave theories are discussed. A sample of non-linear wave theories are presented here, including Stokes, cnoidal and solitary waves. Fundamental differences between linear and non-linear solutions are highlighted. Following the discussion of these wave theories, a diagram is given to outline the regions of applicability of various wave theories.

2.4.1. Stokes Theory

In 1847 Stokes published a paper on non-linear gravity wave theory using perturbation analysis to find approximate solutions for periodic progressive waves of permanent form in intermediate and deep water [21]. He made the important finding that periodic wavetrains are possible in a non-linear system, and also that the wave speed depends on wave amplitude, unlike in the case for linear waves. Stokes waves often serve as the basis for irregular wave modeling, and is seen in later discussions of ocean wave modeling.

Analysis begins with the potential flow formulation previously discussed, starting with the Laplace equation and boundary conditions for the seabed, kinematic and dynamic free-surface. First, the free-surface conditions are expressed as a Taylor series expansion

about a constant free surface elevation. For convenience and without loss of generality let the constant elevation be chosen as $z = 0$, which also ensures the expansion is done in proximity of the actual free surface elevation. Levi Civita proved the convergence of the series for small amplitude, steady wave motion [40]. The Taylor series expansion about $z = 0$ applied to the free surface boundary condition given in Equation 21, returns the expression

$$\begin{aligned} & \left[\frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} \right]_0 + \eta \left[\frac{\partial}{\partial z} \left(\frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} \right) \right]_0 + \left[\frac{\partial}{\partial t} (\vec{u})^2 \right]_0 + \\ & \frac{1}{2} \eta^2 \left[\frac{\partial^2 \phi}{\partial z^2} \left(\frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} \right) \right]_0 + \eta \left[\frac{\partial^2 \phi}{\partial z^2} (\vec{u}^2) \right]_0 + \\ & \left[\frac{1}{2} \vec{u} \cdot \nabla \vec{u}^2 \right]_0 + \dots = 0 \end{aligned} \quad (38)$$

Next, perturbation analysis is applied. Let $\epsilon = ka \ll 1$, so that we can expand η as

$$\eta = \epsilon \eta_1 + \epsilon^2 \eta_2 + \epsilon^3 \eta_3 + \dots \quad (39)$$

and let ϕ and u be expanded likewise. Substitution of these expansions into the Laplace equation and the three boundary conditions which have been expanded about $z = 0$, results in different ordered approximations to the solution of the non-linear wave problem. The first order approximation returns the linearized solution discussed in the previous section. The second order approximation is found by equating terms which are proportional to ϵ^2 . It is found that ϕ_2 satisfies the Laplace equation and the seabed boundary condition. The dynamic and kinematic free surface boundary conditions can be written, but are omitted here. Higher order approximations can also be carried out, which grow in complexity and contain more terms as their order increases.

Following the Taylor series expansion of the boundary conditions and the perturbation analysis, we can apply these results to the case of progressive waves of permanent form. Due to the assumption of permanence of the wave, it follows that the wave has constant speed, and the solution for the surface of the wave must contain only combinations of the term $(x - ct)$, where c is the phase velocity or wave celerity. Using the assumptions of periodicity and symmetry, the wave height can be represented as a Fourier series of the term $(x - ct)$,

$$\eta = \sum_{n=1}^{\infty} A_n \cos(n(x - ct)) \quad (40)$$

The wave heights for Stokes first and second order waves, respectively, are shown in the equations below.

$$\eta = A \cos(kx - \omega t + \psi) \quad (41)$$

$$\eta = A \cos(kx - \omega t + \psi) + \frac{H^2}{2L} \frac{\cosh(kh)(2 + \cosh(2kh))}{\sinh^3(kh)} \cos(2(kx - \omega t + \psi)) \quad (42)$$

A few important changes in the features of the waves due to non-linear approximations should be noted. The non-linear effects cause more peaked crests and shallower troughs, which more closely match the profiles of surface gravity waves. These changes are illustrated in Figure 2 below. Additionally, the wave speed now depends on both the amplitude of the wave as well as the wavelength. Finally, particle paths are no longer strictly elliptical, but now the particles travel in unclosed paths. This effect is known as Stokes drift, and it causes the particle orbits to translate over time.

2.4.2. Cnoidal Theory

In 1895 the Korteweg-deVries (KdV) equation was presented with the derivation of a nonlinear, exact solution called the cnoidal wave [22]. Cnoidal waves represent surface gravity waves with long wavelength to water depth ratios. These waves are often seen in ocean swells, and are marked by sharp crests and very shallow troughs.

The KdV equation in dimensional form is shown below,

$$\frac{\partial \eta}{\partial t} + c_0 \frac{\partial \eta}{\partial x} + \frac{3c_0}{2h} \eta \frac{\partial \eta}{\partial x} + \frac{c_0 h^2}{6} \frac{\partial^3 \eta}{\partial x^3} = 0 \quad (43)$$

where $c_0 = \sqrt{gh}$ and depth $d = h + \eta$. The solution for the surface elevation is

$$\eta(x, t) = \eta_2 + Hcn^2\left(\frac{x - ct}{\Delta} | m\right) \quad (44)$$

where η_2 is the trough elevation, H is the wave height, c is the phase speed and cn is the Jacobi elliptic function. Without familiarity with elliptic functions, it suffices to acknowledge that cn is a periodic function. Thus, the solution returns a periodic wave train.

2.4.3. Solitary Wave Theory

In the limit of infinite wave length, the KdV equation discussed in the previous section gives a solution in the form of a solitary wave. Solitary waves were first observed and reported by Scott Russell in 1844 [41], and expressions describing this phenomenon were later developed by Boussinesq and Rayleigh, in 1871 and 1876, respectively [19]. Solitary waves consist of a single peak which maintains its form and speed as it progresses. Solitary waves are sometimes referred to as solitons, a term which was coined by Zabusky and Kruskal in 1965 [42]. An excellent review of equations which admit solitary wave solutions, and important applications of these waves, is given by Scott, et al [43]. It should be noted that while a variety of equations admit solitary wave solutions, the Navier-Stokes equations do not. A comprehensive review of solitary waves can also be found in the work of Miles [44]. Sun provides a discussion the non-existence of solitary waves in water with small surface tension [45].

The surface height of a solitary wave is expressed as,

$$\eta = \frac{H}{(\cosh(\sqrt{\frac{3H}{4h^3}}(ct - \vec{x}))^2}$$

and the wave speed is given by,

$$c = \sqrt{g(H + h)} \quad (45)$$

where as before, H is the wave height, h is the water depth, g is gravity and $\vec{x}$ is the direction of the progressing wave.

2.5. Breaking Waves

Largely, wave breaking occurs due to wave crests becoming unstable. Many theories have been proposed to quantify wave breaking, including approaches based on wave steepness and acceleration. Breaking waves consist of the formation of a spilling region in front of the wave crest. Trailing behind the breaking wave is a turbulent wake in which the intensity decreases with distance from the wave crest. White-capping occurs because of air entrainment for particularly intense breaking waves.

Both Stokes and Michel came up with limiting configuration theories for breaking waves in 1880 and 1893, respectively [21][25]. Stokes's breaking wave criteria included that the particle velocity at the wave crest equal the phase velocity, the wave crest reach a sharp angle of 120° , a wave height to wave length ratio of $1/7$, and a particle acceleration of $0.5g$ at the wave crest [21]. Based on a limiting steepness criterion, Michel showed in 1893 that waves break when wave heights are greater than or equal to $0.027gT^2$ [25]. This was confirmed experimentally by Ochi and Tsai who found the empirical criterion $H \geq 0.020gT^2$ [24].

Later work by Longuet-Higgins gave a calculation demonstrating wave breaking at much smaller amplitudes than previously theorized [23]. An acceleration based criterion was proposed by Phillips that stated breaking would occur when the downward acceleration exceeded gravity [46]. Longuet-Higgins showed that white-capping occurs theoretically when the downward acceleration in all directions is within the Stokes 120° angle. Longuet-Higgins also derived that instabilities in regular waves occur when the wave steepness, ka , approaches 0.436. Rewriting this statement in terms of wave height gives $H = 0.022gT^2$ which is in good agreement with the work done by Michel and confirmed by Ochi and Tsai, mentioned earlier.

2.6. Regions of Wave Applicability

A variety of classic wave approximations have been discussed in this section. Understanding the limits of validity of each wave theory is important when selecting which equations to use. LeMéhauté compiled a useful diagram demonstrating the approximate regions of applicability, and is shown in Figure 3 [26]. The vertical axis shows the non-dimensionalized wave height plotted against the non-dimensionalized water depth on the horizontal axis. It is demonstrated that cnoidal theory is valid in regions of small wave height and water depth. In deeper water, linear wave theory is valid for small wave heights. As wave height grows, Stokes theory becomes applicable and the order of approximation grows with wave height. A line for breaking wave criteria is shown which bounds all the theories.

3. Ocean Physics

The previous section treated waves as a deterministic process. In reality, the surface of the ocean is composed of waves of many different parameters. The instantaneous sea surface can be described as the summation of deterministic waves if they act independently and interact weakly. The profiles of wind-generated waves vary continuously over space

and time in an irregular fashion. The description of the sea cannot be described on a single wave basis, but must be treated stochastically. Evaluation of statistical properties of waves can be done through frequency and probability domains. Waves in deep water follow a Gaussian distribution for their wave heights, while shallow water wave heights are non-Gaussian, but nonetheless can be described with a theoretical probabilistic distribution. The sea can be classified into ten sea states which increase with the significant wave height. The sea state classifications are shown in Table 3. This section begins with a discussion of the generation of ocean surface waves by wind. Spectral representation is covered, and commonly used ocean wave spectra are presented in some detail.

3.1. Ocean Wave Generation

Wind generated waves include both capillary and gravity waves. Capillary waves are ripples, where surface tension acts as the restoring force. Gravity waves are also wind driven, but as the name suggests, gravity acts as the restoring force. The type of ocean waves which affect the motion and forcing on offshore structures are gravity waves. Therefore the discussion of wind generated ripples, or capillary waves is omitted here, but an excellent source on the topic can be found in G.I. Taylor's paper from 1940 [47].

Phillips gives a comprehensive discussion on the generation of waves by wind in his text [16], which is summarized briefly here. Capillary waves are generated at the surface at very low wind speeds. These waves grow in space and time, until the wavelengths and amplitudes are large enough to categorize these waves in the gravity range, where the waves are on the order of centimeters. Once in the gravity range, continued growth is driven by forcing from wind pressure on the steep slopes of the waves. Additionally, shear stress from turbulent wind eddies, as well as tangential surface stress from the air spur further wave growth. Non-linear wave-wave interaction causes both smaller and larger waves to be formed. The generation of waves depends on the duration of the blowing wind as well as the distance from shore, or fetch. Additional details on the generation and growth mechanisms of waves by wind can be found in Jeffreys [27] [28], Miles [29] [30] [31] [32], Sverdup and Munk [33], and Pierson [34].

3.2. Random Waves

Profiles of wind generated ocean waves vary randomly in both space and time. The wave height as well as period vary randomly in time. Randomly changing waves must be considered as a stochastic process in order to evaluate wave properties in frequency and probability domains. Only statistical measures can be used as significant wave characteristics or predictive parameters. Because of the random behavior of ocean waves, it is necessary to understand the both probabilistic aspects of waves and the spectral representation of ocean wave characteristics.

In deep water, waves heights are Gaussian random processes, which has been demonstrated from collected measurements of ocean waves [48]. However, in shallow water the wave heights do not follow a Gaussian random process, but can still be described with alternative theoretical probability distributions. Random seas are generally due to energy transfer between waves and wind. Variations in wave properties can be attributed to variation in the wind. In the case of swell, waves with small wavelengths lose energy as they travel through space, causing less irregular waves to form over time.

The irregular surface height of ocean waves can be expressed by an infinite sum of sinusoidal wave components with differing wavenumbers (k), frequencies (f or ω) and

directions (θ). These wave properties must be representative of the ocean state, which can be determined by examining wave spectra.

To describe the surface of the ocean we begin with the profile of simple harmonic waves, which can be expressed as

$$\eta(x, y, t) = a \cos \left\{ \frac{\omega^2}{g} (x \cos(\theta) + y \sin(\theta) - \omega t + \psi) \right\} \quad (46)$$

where a is the wave amplitude, ω is the wave frequency and ψ is the phase. Now, we consider the random sea as a superposition of an infinite number of sine waves with different amplitudes a_j , directions θ_j and frequencies ω_j . The profile of the random wave is written as,

$$\eta(x, y, t) = \sum_j a_j \cos \left\{ \frac{\omega_j^2}{g} [x \cos(\theta_j) + y \sin(\theta_j) - \omega_j t + \psi_j] \right\} \quad (47)$$

Then, a spectrum that represents the contributions to the variance due to component waves with different speeds, frequencies and directions can be adopted. The potential and kinematic energy of waves can be represented with a spectral density function, otherwise known as a wave spectrum. The magnitude of the time averaged wave energy as a function of wave frequency is given in the spectral density function. The area under the spectral energy function gives the degree of sea severity. A very common measure of sea severity is given by the significant wave height, H_s or $H_{1/3}$, which is the average of the largest one-third of ocean waves. Sverdrup and Munk first introduced the term significant wave height in their discussion of random ocean waves in 1947 [33]. H_s is equal to four times the square root of the area under the spectral density curve. These spectra are discussed in more detail in the next section.

3.3. Spectral Representation

Wave spectra allow for the probabilistic prediction of wave properties. A few basic assumptions are usually made, including that waves are steady-state, ergodic random processes, which are also Gaussian random processes. An ergodic process is one in which the statistics of an ensemble of time histories can also be determined from a single sample. Additionally, it is assumed that the spectra are narrow banded, that is, a sharp concentration exists around a specific frequency. Finally, wave peaks and troughs are statistically independent [48].

We begin the mathematical discussion of wave spectra by defining the auto-correlation of a signal, $x(t)$, which is given below.

$$R_{xx}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T x(t)x(t+\tau)dt \quad (48)$$

The auto-correlation is a measure of how similar a function is to itself at some shifted time τ .

The time average of wave energy can be found by evaluating R_{xx} at $\tau = 0$, as is shown below.

$$R_{xx}(0) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T \{x(t)\}^2 dt = \bar{P} \quad (49)$$

To express the average energy in terms of wave frequency, ω , we can apply Parseval's theorem:

$$\int_{-\infty}^{\infty} x(t)^2 dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} |X(\omega)|^2 d\omega \quad (50)$$

where $X(\omega)$ is the Fourier transform of $x(t)$,

$$X(\omega) = \int_{-\infty}^{\infty} x(t) e^{-i\omega t} dt \quad (51)$$

Using Equation 49 with Parseval's theorem, the average wave energy can be expressed as

$$\bar{P} = \lim_{T \rightarrow \infty} \frac{1}{4\pi T} \int_{-\infty}^{\infty} |X_t(\omega)|^2 d\omega \quad (52)$$

where it is now a function of wave frequency, ω .

The spectral density function of random waves $x(t)$ is then defined as,

$$S_{xx}(\omega) = \lim_{T \rightarrow \infty} \frac{1}{2\pi T} |X(\omega)|^2 \quad (53)$$

Now, the time average of wave energy can be written as

$$\bar{P} = \frac{1}{2} \int_{-\infty}^{\infty} S_{xx}(\omega) d\omega = \int_0^{\infty} S_{xx}(\omega) d\omega \quad (54)$$

where simplifications have been made because the spectral density function is an even function. The relationship above shows that the area under the spectral density function represents that average wave energy.

The Wiener-Khinchine theorem says that for a weakly steady-state wave, the auto-correlation and the spectral density functions are Fourier pairs [48]. The result is the often given relationship between the auto-correlation and spectral density, shown here.

$$S_{xx}(\omega) = \frac{1}{\pi} \int_{-\infty}^{\infty} R_{xx}(\tau) e^{-i\omega\tau} d\tau \quad (55)$$

$$R_{xx}(\tau) = \frac{1}{2} \int_{-\infty}^{\infty} S_{xx}(\omega) e^{-i\omega\tau} d\omega \quad (56)$$

This result is important because it relates the auto-correlation in the time domain to the spectral density function defined in the frequency domain.

The discussion above can be summarized into a few steps, and is presented as a single relationship, shown below. We began with a wave record $x(t)$, and assumed it to be a steady-state, ergodic random process. The auto-correlation function was defined as $R_{xx}(\tau)$, given in Equation 48. The average of wave energy $\bar{P}$ was defined as $R_{xx}(0)$, which also gives the variance of the waves. Via Parseval's theorem, taking the Fourier transform of the auto-correlation returned the spectral density function. Finally, the Wiener-Khinchine theorem related the spectral density function in the frequency domain

to the auto-correlation defined in the time domain. The previous equations can be summarized as the following relationship:

$$\int_0^\infty S_{xx}(\omega)d\omega = \bar{P} = R_{xx}(0) = \text{Variance}[x(t)] \quad (57)$$

Minkenberg, et al, examined the effects of regular and irregular waves sampled from a wave spectrum on the motions of offshore structures [49]. The regular waves used in their analysis had equivalent statistical properties to the irregular sea. It was found that the results calculated with the regular wave concept yielded erroneous results. The work concluded that spectral analysis techniques return more realistic results and should be used when modeling ocean physics.

3.4. Commonly Used Wave Spectra

To accurately predict the linear and non-linear responses of structures in marine environments, wave spectra representing a variety of desired sea states are needed. Predictions of responses of marine structures, including motions, moments and forces, rely on the accurate modeling of random seas. Many spectral formulations have been developed since the 1950s to describe sea states. Two of the most commonly used spectra are discussed here. Both the Pierson-Moskowitz and JONSWAP spectra were developed based on analyses of measured data from the ocean.

Pierson and Moskowitz analyzed measured wave data taken by accelerometers on British weather ships in the North Atlantic in 1964 [35]. Only data taken in fully developed seas were used in the analysis. A fully developed sea is reached at the point of energy saturation in which there is a balance between the rate at which energy is gained from wind and lost by breaking or non-linear wave interaction. It was assumed that if the wind blew steadily over a long period of time and large area that waves would come into equilibrium with the wind, thus producing a fully developed sea. Five dimensionless spectra based on different wind speeds between 20 and 40 knots were produced, and an average of these was taken to find a general spectral formulation. The Pierson-Moskowitz spectrum is

$$S(\omega) = \frac{Ag^2}{\omega^4} \exp \left[-B \left(\frac{g/U}{\omega} \right)^4 \right] \quad (58)$$

where $A = 8.10 \times 10^{-3}$, $B = 0.74$, and U is the wind speed measured at 19.5m above the sea surface. The Pierson-Moskowitz spectrum depends only on wind speed.

In 1968 and 1969 measurements were taken by the Joint North Sea Wave Project (JONSWAP) on a 160km line in the North Sea. Analysis of the measured data was conducted by Hasselmann, providing a new spectrum for wind generated waves in fetch limited seas [36]. It was found that the wave spectrum is never fully developed. The waves continue to develop as a result of non-linear interactions over long times and distances. The JONSWAP spectrum is a modification to the Pierson-Moskowitz spectrum to account for fetch, resulting in a sharper peak. The JONSWAP spectrum depends on wind speed as well as fetch. The spectrum is given by,

$$S(\omega) = \alpha \frac{g^2}{\omega^5} \exp \left[-1.25 \left(\frac{\omega_m}{\omega} \right)^4 \right] \gamma^a \quad (59)$$

where,

$$a = -\frac{(\omega - \omega_m)^2}{2(\sigma\omega_m)^2} \quad (60)$$

and where the values for constants were determined from analysis of the collected data, and are listed below,

$$\begin{aligned} \gamma &= 3.3 \\ \alpha &= 0.07\bar{x}^{-0.22} \\ \sigma &= 0.07 \text{ for } f \leq f_m \text{ and } 0.09 \text{ for } f > f_m \\ \omega_m &= 7\pi(g/\bar{U})\bar{x}^{-0.33} \\ \bar{x} &= \text{dimensionless fetch} = gx/\bar{U}^2 \\ x &= \text{fetch length} \\ \bar{U} &= \text{mean wind speed} \\ g &= \text{gravity} \end{aligned} \quad (61)$$

The γ term is called the peak enhancement factor, and when multiplied with the Pierson-Moskowitz spectrum returns the JONSWAP spectrum. Analysis of the original data produces a peak-shape parameter value between 1 and 6, where γ is a random variable with a normal distribution. Generally the value is taken to be 3.3, which is the mean value taken from the normal distribution of γ .

The α term specifies the growth of waves with distance, distinguishing the JONSWAP spectrum from the Pierson-Moskowitz spectrum. To demonstrate these differences between the two commonly used wave spectra, a plot of the two spectra is shown in Figure 4. The increased peakedness of the JONSWAP spectrum should be noted.

4. Wave-Body Interaction

This section addresses the physical characteristics of time dependent flow around and interacting with bodies. Idealizations and simplifications are made in an effort to describe the physics in a straightforward manner. The physics of fluid loading and the dynamic response of offshore structures is presented mathematically, and in some places empirical data is provided for better understanding. Important non-dimensional quantities are provided in Table 4, and will be referred to throughout this section.

First, static loads are discussed, which includes hydrostatics, gravity and current. Next, dynamic loads are presented. Wave loads are considered for small and large bodies. Radiation and diffraction are discussed in the context of linearized hydrodynamics. The effects of added mass in fluid-structure interactions are considered. Finally, the section concludes with a review of recent research efforts in understanding offshore structures in the ocean. The next section presents a finite volume approach to modeling the loading and dynamic responses of structures in the ocean.

4.1. Static Loads

4.1.1. Gravity and Hydrostatics

We begin the discussion of fluid forces acting on a body with the simplest case possible, that of a body at rest. The structure will experience hydrostatic pressure acting normal to the submerged portion of its surface. The forces resulting from the hydrostatic pressure

in the vertical direction are balanced by the gravitational force acting on the mass of the structure. The net force is zero for a structure in static equilibrium. This simple case is represented mathematically below.

$$F_{pressure} + F_{weight} = 0 \quad (62)$$

4.1.2. Current Loads

Current is mainly the result of wind blowing across the surface, pressure variations in the atmosphere and tides. Currents alter the shape and size of waves. Under the wave crest the current is stretched, and is compressed under a wave trough. Stretching formulas can be applied to better model the shape and size of waves in the presence of a current. A good reference on adjusting wave formulations in the presence of current can be found in Chakrabarti's text on offshore engineering [50].

Current is generally assumed to be time invariant, and despite being turbulent in most cases, it is often approximated by a mean value. While current may be considered constant in time, it cannot be approximated as constant in space where it may vary with water depth. Pressure distributions on the structure are induced by the current, which generate drag forces in the direction of the flow. These pressure distributions may not be symmetric about the structure due to vortex shedding.

Hogben and Standing summarized the effects of currents on large structures into three modes [51]. These include a modification to the wave speed which depends on the magnitude of the current, a drag force which can be treated by Morison's equation and lastly wave-making resistance. The latter involves the waves which are produced upon impact with a surface piercing body. Potential flow calculations can be carried out to model these effects.

4.2. Dynamic Loads

4.2.1. Wave Loads

Interaction of waves with solid bodies includes the effects of reflection, refraction and diffraction. Refraction accounts for the bending or turning of waves when passing between two mediums or fluids of differing densities. Diffraction covers the effect of scattering waves upon impact with an impermeable boundary. Radiation is also be discussed, which treats the loads due to waves generated by a moving body. The shape, dimensions and relative motion of the barrier affects the magnification of these factors.

In wave-body interactions distinction must be made between small and large bodies. The character of the interaction differs significantly depending on the size of the body. Distinction between small and large bodies can be made by comparison between the size of the structure, D , and characteristic wavelength, $\lambda = 2\pi/k$, and wave amplitude, A . For small kD and a large value of A/D , the body is considered small. In this regime vortex shedding and flow separation dominate. Diffraction is insignificant for small bodies, as the bodies do not significantly alter the wave field. When kD is greater than order one, and A/D is small, diffraction is important and separation is insignificant [52]. A short discussion of small body interaction with the fluid is discussed here, followed by a more in depth discussion of large bodies interactions with the flow. An approximate mapping of the dominant loading regimes in terms of wave height, structure diameter and water depth is provided in Figure 5 below. The figure represents a very specific set of conditions

and should not be used as a general design guideline, but rather gives an idea for how wave and structure sizes influence the character of their interaction.

The exact boundaries for the regimes where inertial, diffraction, drag and wave-breaking dominant are somewhat nebulous, but can be categorized in a general sense as shown in Table 5, which is for the case of a circular cylinder.

Morison’s equation is commonly used to determine the loading on offshore structures. It is valid for slender bodies, more specifically cylinders which pierce the water surface. Morison’s equation is an empirically based calculation to determine the inline force of a body in an oscillating flow. The equation consists of two terms representing the drag and inertial forces of the body. While Morison’s equation has many limitations, which are briefly mentioned here, it still works surprisingly well for predicting loading on bodies in oscillatory flow.

Morison’s equation in its simplest form is the sum of an inertial force in phase with the flow acceleration and a drag force proportional to the square of the velocity. The equation is given below.

$$F = \frac{1}{2}\rho C_d A_p |U|U + \rho C_m V_0 \frac{dU}{dt} \quad (63)$$

where ρ is the density of the water, C_d is the drag coefficient, A_p is the projected frontal area of the object, U is the fluid velocity, C_m is the inertia coefficient, and V_0 is the displaced volume of the object. Morison’s equation can be modified to adjust for the case of a freely moving body, and furthermore in the presence of a current. Modifications for the case of a freely moving body are discussed at the end of this section, following a brief description of the Froude-Krylov hypothesis.

While Morison’s equation captures added mass, incident wave inertia and drag forces, it suffers from other limitations. Limitations of Morison’s equation include the inability to account for fluctuating lift force, as well as capture the inline force accurately. Furthermore, it ignores memory effects, and uses GI Taylor’s long wavelength assumption to simplify the treatment of diffraction [53]. It is inherently difficult to reconstruct the kinematics of the ocean due to uncertainties such as how to separate current and waves, omnidirectionality, and turbulence, among other parameters. Discrepancies between forces calculated with Morison’s equation and measured forces can be attributed to both the form of the Morison equation and the uncertainties of ocean wave characterization.

If wave scattering is ignored then a simplified representation of the pressure field around the body can be found. The force calculated from this simplification is called the Froude-Krylov force. The Froude-Krylov Hypothesis assumes a sufficiently small body so that the pressure field is not affected by incident waves, such that diffraction effects can be ignored. The Froude-Krylov force is the force that would act on a body if the body were not there, that is, if the body were to make no changes to the flow field. The force is expressed as,

$$F^{FK}(t) = -\rho \int \int \frac{\partial \phi}{\partial t} n dS \quad (64)$$

Closed form solutions for the Froude-Krylov force for a small sample of body geometries exist. A succinct summary of these solutions can be found in Chakrabarti [50]. The Froude-Krylov forces is an over-simplification of the hydrodynamic loading on a body,

and is in general not justified for use when more advanced computing resources are available. While the Froude-Krylov calculation is enticing due to its simplicity, much can be gained from a few additional considerations about body-wave interactions.

Morison's equation can be modified for the case of a freely moving body. An additional term is included in the inertial force term, seen in Equation 63. To account for the moving body, the inertial and drag force terms are adjusted by $\frac{dv}{dt}$. The modified Morison's equation takes the form, where the Froude-Krylov terms appears as the last term on the right hand side,

$$F = \frac{1}{2}\rho C_d A_p |U - v|(U - v) + \rho C_m V_0 \left(\frac{dU}{dt} - \frac{dv}{dt} \right) + \rho V_0 \frac{dU}{dt} \quad (65)$$

Morison's equation allows for an easy calculation of the forces on a small structure where pressure distributions due to complex flow and vortices would otherwise be difficult to calculate, and the Froude-Krylov force provides a simple treatment for the case where diffraction is ignored. But, if the flow remains attached to the structure, then it is actually easier to calculate the pressure field which causes the forces on the structure. For larger structures the flow around the body remains attached, and the incident wave scatters off the surface. In this regime of larger structures, Morison's equation assumptions are no longer valid.

For a linear treatment of the hydrodynamics of a floating object the problem can be divided into three separate problems: radiation, diffraction and hydrostatics. The radiation problem gives the loads for an oscillating body in the absence of waves. The loads are due solely to wave radiating away from the body. The diffraction problem finds the loads for a non-moving body in the presence of incident scattering waves. Finally, the hydrostatics includes the straightforward buoyancy and loads due to changes in the water-plane area. In the linearized treatment the three separate problems are mutually independent of each other. The total force is then given by the sum of radiation, diffraction and hydrostatics, which are each discussed further below.

$$F^{Hydrodynamics} = F^{Diffraction} + F^{Radiation} + F^{Hydrostatics} \quad (66)$$

First, we'll look at the diffraction problem for a vertical cylinder. The hydrodynamic problem can be linearized by using the same assumptions discussed in Section 1.3. This leads to a potential flow based approach which models the linear diffraction off a vertical cylinder. In this analysis, on top of the usual assumptions of inviscid, incompressible, irrotational flow, it is assumed that the flow is unseparated, and we neglect surface tension, cavitation and gradients in temperature and density in the vertical direction. We return to the Laplace equation for the velocity potential. We take the same boundary conditions discussed in the linearized wave theory section, that is the kinematic and dynamic free surface, the seabed and body boundaries. We define ϕ_w to be the incident wave potential, and ϕ_s as the scattered wave potential. The sum $\phi = \phi_w + \phi_s$ must satisfy the Laplace equation. Furthermore, the Sommerfeld radiation condition must be satisfied [54], which says that the outgoing wave must be represented by the scattered wave potential at long distances. This is given mathematically by,

$$\lim_{R \rightarrow \infty} r^{1/2} \left[\frac{\partial \phi_s}{\partial r} - ik\phi \right] = 0 \quad (67)$$

where the incident wave potential is given by,

$$\phi_w = \frac{-igH}{2\omega} \frac{\cosh[z(k+h)]}{\cosh(kh)} e^{i(kx-\omega t)} \quad (68)$$

The body-surface condition is

$$\frac{\partial \phi}{\partial n} = \frac{\partial \phi_s}{\partial n} + \frac{\partial \phi_w}{\partial n} = 0 \Rightarrow \frac{\partial \phi_s}{\partial n} = -\frac{\partial \phi_w}{\partial n} \quad (69)$$

where n is the outward normal vector to the surface of the body. This is the same no-permeation boundary condition that was presented earlier. An expression for pressure is derived from the unsteady Bernoulli equation,

$$p = -\rho g z - \rho \frac{\partial \phi}{\partial t} \quad (70)$$

The pressure distribution can then be determined, and the forces and moments calculations follow from there.

The above analysis is referred to as the diffraction problem. A similar analysis can be carried out to study the case of a body undergoing small oscillations and therefore radiating waves away from the body. The resulting motion and determination of wave amplitudes far away from the body can be studied, and is referred to as the radiation problem. Loads in the radiation problem include contributions from added mass and damping. An impulse in platform velocity causes waves to radiate. These radiating waves induce a pressure field which then results in a force which persists for all time while waves are radiating. Instead of the no-permeation boundary condition as was in the case of the diffraction problem, the normal derivative of the potential is prescribed by a non-zero value, and a similar analysis follows from there.

Closed form solutions to the linearized radiation and diffraction problems exist for a limited number of cases. Other geometries can be treated with integral methods to find approximate solutions, such as those based on Green's theorem. Force representations derived using Green's theorem are called the Haskind Relations, and details can be found in many texts on offshore engineering, including Sarpkaya and Issacson's book [55]. Additional methods for studying the diffraction and radiation problems exist, including hybrid element methods, as reviewed by Mei [52], and finite difference methods which are discussed in detail in the next section.

Generally wave diffraction reduces wave loads on the structure. It is important to note that even in the regime of diffraction dominated loading, flow separation can occur. Viscous forces may be important especially around sharp corners where separation is likely to occur. This factor must be considered for each geometry.

4.2.2. Added Mass

In 1828 Bessel conducted experiments with spherical pendulums in air and water, and noticed that the period of oscillation increased when the pendulum was placed in water as compared to air [15]. Bessel attributed the increase in period to the effect of an added mass in the system. This so called added mass is described in terms of the fluid displaced by the moving body. When dealing with the flow around objects or the unsteady motion of bodies in water, we must consider the effect of added mass. An accelerating or decelerating body must move mass (a volume of fluid) as it moves.

Obviously the mass of the system does not change, but rather changes occur in the acceleration or deceleration of the fluid, an increase or decrease in kinetic energy, or a negative or positive change in inertia per unit mass. Due to these physical explanations, the term added mass is sometimes replaced with added inertia.

The added mass moment of inertia in a viscous fluid exists only for a brief moment immediately following an acceleration or deceleration of the fluid, or a change from an initially steady state to an unsteady state. The added mass effects exist only before separation and viscous effects come into play. Furthermore, the effects only occur for a small displacement of the body.

A simple analysis for the case of a floating object with small motions which obey a linear behavior is presented below to demonstrate the effects of added mass. A simple harmonic motion model with a driving force is can be represented with the following equation,

$$m\ddot{x} + b\dot{x} + kx = f(t) \quad (71)$$

where m is the mass, b is the damping coefficient, k is the spring constant, f is the force acting on the mass and x is the displacement of the mass. The effect of added mass acts in opposition to the motion of the mass, so the equation of harmonic motion is adjusted to reflect that change,

$$m\ddot{x} + b\dot{x} + kx = f(t) - m_a\ddot{x} \quad (72)$$

or by rearrangement,

$$(m + m_a)\ddot{x} + b\dot{x} + kx = f(t) \quad (73)$$

Now, instead of the natural frequency going as

$$\omega_n = \sqrt{\frac{k}{m}} \quad (74)$$

it becomes

$$\omega_n' = \sqrt{\frac{k}{m + m_a}} \quad (75)$$

Thus, the effect of added mass is to decrease the natural frequency and increase the period, just as Bessel observed in his pendulum experiments. The force due to added mass can be expressed in three dimensions most elegantly with tensor notation.

$$\bar{F}_i = [m_{ij}]\dot{u}_i \quad (76)$$

where i,j = 1,2,3,4,5,6 and the first three indices represent the linear degrees of freedom, and the last three indices are the rotational degrees of freedom. The added mass matrix, $[m_{ij}]$ gives the mass associated with a force in i^{th} direction due to an acceleration in the j^{th} direction.

4.2.3. Impulse Loads

Much work has been done experimentally and theoretically on the wave impact loads on horizontal and vertical cylinders. Contributors to this topic include Miller [56], Faltinsen [57] [58], and Sarpkaya [59]. The flow field around a structure involving impacting waves is often very complicated. Empirical equations are often used in place of theory to calculate loads near the free surface due to breaking and broken waves.

For wave slamming, an empirical formula for a horizontal cylinder provides a rough estimate of the loading [50],

$$F = \frac{1}{2} \rho C_s A u_0^2 \quad (77)$$

where C_s is the wave slamming coefficient, ρ is the density of water, A is the cross-sectional area of the cylinder and u_0 is the maximum velocity in a wave cycle. The theoretical value of C_s is π and derivations of this value can be found in Sarpkaya's text [15]. Experimental work by Miller found a C_s value closer to 3.6 [56]. Further work by Sarpkaya showed that C_s depends greatly on the structural stiffness of the cylinder [59].

Furthermore, experiments on cylinders have been carried out to study the effects of breaking waves on structures. Ochi and Tsai conducted experiments with regular and irregular waves and found that the pressure field goes as

$$p = \rho \kappa_1 U^2 \quad (78)$$

where κ_1 is 5.98 for breaking waves, and 2.74 for an already broken wave approaching the structure [24].

4.3. Design and Analysis of Loads

Two main methods of analysis and design include deterministic (extreme) and stochastic (nominal conditions) wave loading. Deterministic analysis gives low-cycle fatigue. Typically, a design wave is chosen, Morison's equation is implemented by vertically integrating over the surface of the object to determine loading. This case is often treated as pseudo-static, and is calculated in time domain. A design wave is assumed to be uniformly crested and travel with constant speed and shape. Stochastic loads are generally calculated in the frequency domain using a spectral analysis. A force transfer function is calculated to determine the loading. More recent work using finite volume methods has analyzed deterministic and stochastic loading in a different framework. These approaches and research efforts are discussed in the next section. For now, a review of other approaches can be found in the following section.

4.4. Wind Turbine Platform Concepts

Before delving into a review of the literature on loading of offshore wind turbine platforms, it bears noting the range and definition of proposed and existing platform concepts. Offshore turbines include monopiles in shallow water, jacketed structures in transitional water, and finally, floating concepts in deep water. Floating platforms include tension leg platforms (TLPs), semi-submersibles, spar buoys, and barges. Shallow water is generally considered to be less than 30 meters in depth, transitional waters extend from about 30 to 60 meters, and deep water is anything deeper than about 60 meters. A helpful way to categorize floating platform concepts is by their stability strategy. TLPs

are stabilized by mooring lines, spar buoys are ballast stabilized, and have catenary mooring lines, barges are buoyancy stabilized and also have catenary mooring lines, and lastly, semi-submersibles are stabilized by both buoyancy and the mooring lines. A more detailed review of floating platform concepts is given by Thiagarajan [60].

4.5. Previous Research

Some analytical solutions exist from linearized theory for basic geometries, such as circular cylinders. Other methods have been developed for more general cases, including the integral equation method and the hybrid element method, which are presented in a review by Mei [52]. More recently, finite volume methods have become more feasible, and these methods along with a review of recent research is presented in the next section.

Integral equation methods using potential flow theory have provided exact analytical solutions for a small sample of geometries, and in more complicated cases, approximate results. Integral equation methods based on potential flow theory are popular due to their relatively inexpensive computational cost. Typically, the analysis begins with a single solution which satisfies the governing equations everywhere but on the surface of a geometry. Boundary conditions are applied on the surface of the body, resulting in an integral equation. In some cases an exact solution exists, but more commonly the surface is discretized and the solution is found numerically. The body surface is discretized into piecewise linear segments, often referred to as panels.

Work preceding floating offshore wind development includes research by Kleinman who used boundary value problem to model the generation of surface waves from a partially submerged body [61]. The linearized free surface condition is used with a radiation condition at infinity. In 1950 Fritz John gave an analytical solution for this problem under very strict assumptions, and Kleinman extends his work to show uniqueness for more general geometries. Two methods are introduced to modify the integral equation, including the addition of an integral on the water surface and another integral term representing only the submerged part of the floating body.

In 2005, Passon and Kühn presented a review of the state-of-the art simulation codes for offshore wind turbines [62]. A more recent review was given by Cordle and Jonkman, in 2013, that summarizes the most popular design tools for simulating floating turbines [63]. The review includes discussion of FAST, Bladed, SIMO/RIFLEX, HAWC2, 3Dfloat and SIMPACK, which will be discussed in more detail below.

There has already been a large effort to model the wave and wind loading on fixed bottom offshore wind turbines [64] [65] [66] [67] [68] [69]. Wave loading analysis on monopiles has largely been accomplished via Morison's equation, which is valid for vertically mounted cylinders. Research efforts in modeling floating offshore wind turbines have begun more recently, preceded by a history of research by the oil and gas industry, as well as the ship hydrodynamics community. Here, the focus is on work done for floating offshore wind turbines.

More recently, many wind turbine research efforts have made use of FAST, a non-linear aero-hydro-servo-elastic computer aided engineering (CAE) tool, which can be coupled with HydroDyn to simulate both fixed bottom and floating offshore wind turbines and is described in detail in Jonkman's dissertation [53]. FAST continues to be developed, verified and validated by the National Renewable Energy Laboratory (NREL) at the National Wind Technology Center (NWTC).

The latest release of FAST (version 8) provides a modularized framework, including a module for hydrodynamics called HydroDyn [37]. HydroDyn has the ability to model linear periodic waves as well as irregular waves sampled from various wave spectra. HydroDyn uses a combination of Morison’s equation with potential-flow theory to model the loads on the platform.

The latest release of HydroDyn includes the added capability of calculating Morison’s solutions on non-vertical and multiply interconnected members. Morison’s equation includes a term for radiation-induced added mass, diffraction-induced wave excitation forces (with a long wavelength approximation), and viscous drag forces. In the latest release of HydroDyn, each member of the platform is assigned a unique value for the viscous drag coefficient. Each member is discretized into segments, and FAST outputs a viscous force per unit length at each node along the length of each member. The total force is found by integration along the length of each member, and then a summation of the force on each member.

Radiation and diffraction solutions based on linear frequency-domain analysis can be imported from a code like Wave Analysis MIT (WAMIT), which is discussed below. The potential-flow panel method code, WAMIT, can be used as a pre-processor and internal frequency-to-time-domain transforms for time-domain-based potential-flow solutions. When WAMIT is used to provide potential-flow based solutions, Morison’s equations provide drag effect solutions frequency-to-time-domain transforms for time-domain-based potential-flow solutions.

The WAMIT hydrodynamics code was developed at the Massachusetts Institute of Technology [38]. WAMIT is a boundary integral equation method based on linear and second order potential theory, otherwise known as a panel method. The velocity potential and pressure fields are found on the submerged surface of the body. This model is used to solve the radiation problem, which generates a body-oscillation frequency-dependent set of coefficients, and the diffraction problem, which generates a vector of wave-frequency dependent coefficients.

Verification of HydroDyn, with preprocessing input from WAMIT, is presented via code to code comparison by Jonkman [70]. Additional work by Jonkman and Matha demonstrated the dynamic responses of three types of offshore floating turbine platforms, including a spar buoy, tension leg platform and barge [71]. Scavounos, et al, coupled WAMIT with the Aero-Hydro-Servo-Elastic design code FAST to study fluid loads on a floating wind turbine [72]. Scavounos has also investigated non-linear loads on bodies in irregular steep waves using potential flow theory [73].

Cermelli, et al, modeled the hydrodynamics on a floating wind turbine using WAMIT [74]. The potential flow based panel method was also applied by Zambrano, et al, to demonstrate the feasibility of smaller floating wind turbines with semi-submersible and tension leg platforms [75]. Gueydon, et al, simulated hydrodynamic loads using a panel method, coupled with catenary mooring lines and uniform wind, and found good agreement between numerical results and experimental results from a wave basin [76]. Wave drift on a semi-submersible platform was modeling using three-dimensional potential flow theory by Pinkster and Huijsmans [77].

A comprehensive offshore code comparison collaboration (OC3) was conducted for the dynamic loading responses of a 5 MW wind turbine mounted on a spar buoy in a depth of 320 meters [78]. A variety of environmental conditions were selected to simulate different model features. Results from seven codes were compared, and each code is summarized

in a table in the report. The hydrodynamics portion of each code consists of various combinations of Airy wave theory, linear potential flow with radiation and diffraction, Morison's equation and Streamfunction theory. None of the hydrodynamics modeling used in the code comparison includes finite volume methods, which are discussed in the following section.

Among the codes involved in the OC3 was the HAWC2 aero-elastic code developed at Risø-DTU, and the SIMO/RIFLEX code developed at MARINTEK. Work by Nielsen, et al, coupled HAWC2, which models fixed foundation wind turbines, with SIMO/RIFLEX, which simulates the dynamic response of marine structures, and found results to be in fairly good agreement with tank model experiments [79].

Although Morison's equation is most valid for cylinders that reach the ocean floor, or fixed-bottom wind turbines, it has been used for research on floating wind turbines as well. A spar buoy mounted wind turbine was modeled with a panel method and used Morison's equation to calculate hydrodynamics at instantaneous positions by Karimirad and Moan [80]. Further work by Karimirad presented hydroelastic code-to-code comparisons between his work using a combination of Morison's equation with a pressure integration method for the hydrodynamics of a tension leg spar buoy [81]. Fulton, Malcolm, and Moroz [82] and Withee [83] also used Morison's equation to model the hydrodynamics loads on tension leg platforms. Phuc and Ishihara modeled floating wind turbines as elastic bodies with an FEM code, using Morison's equation for hydrodynamics and quasi-steady theory for aerodynamics [84]. Mei gives a good review of earlier fluid-structure interaction work involving hybrid element methods for floating bodies that predates floating offshore wind turbine development [52].

5. Navier-Stokes Solvers

While the computational cost of CFD can be expensive for use as a design tool, it is still beneficial for its high-fidelity results. CFD has been more widely used to simulate wind turbine aerodynamics than hydrodynamics. Reviews of aerodynamic simulation tools have been given by Miller, et al, [85], as well as as a CFD focused review by Sanderse, et al [86]. However, as large-scale offshore wind development has grown in Europe, and begins to see development in other regions of the world, hydrodynamic modeling of offshore wind turbines has increased. Fixed bottom platforms for wind turbines, or monopiles, have been modeled with a variety of engineering tools as was discussed in the previous section. Additionally, wave run-up and loading on monopiles had been studied with CFD, and will be outlined here. CFD research on the hydrodynamics of floating offshore platforms is growing, and will be highlighted at the conclusion of this section.

This section begins with a brief review of Eulerian finite volume methods for modeling multiphase flows, including Volume of Fluid, Moment of Fluid, marker, and level-set methods. Next, computational schemes for modeling fluid-structure interaction are reviewed. Numerical instabilities in FSI coupling techniques are addressed, with summaries of monolithic and partitioned coupling approaches. FSI in the context of both free-surface and fluid interface finite volume methods is discussed next. A variety of finite volume codes and approaches are presented, including but not limited to immersed boundary methods, Volume-of-Fluid, fictitious domain method, CFDShip-Iowa, REFRESCO, and OpenFOAM. Following the more general discussion of FSI modeling with CFD, the focus

shifts to offshore wind turbine platforms beginning with monopiles and then concluding with floating platforms.

5.1. Eulerian Methods

Eulerian methods for multiphase flow modeling use a numerical grid that does not move with the fluid interface. The location of the fluid interface cuts through the cells in the mesh, and its location must be determined. There are two basic approaches in the determination of the interface location: interface tracking and interface capturing. Interface tracking explicitly describes the interface position. There are a variety of ways to do this, including use of supplemental Lagrangian surface-grids or marker particles. The interface capturing methodology does not explicitly track the interface. Instead, the interface location is determined implicitly, which can also be approached in a variety of ways. These include using volume fractions, as in the Volume of Fluid method, Moment of Fluid method, phase fields or distance functions, as are used in level-set methods.

This section describes some of the Eulerian methods for simulating multiphase flows. First, the Volume of Fluid (VOF) method is discussed, followed by the Moment of Fluid (MOF) method, level-set methods and finally marker methods.

5.1.1. Volume of Fluid

The Volume of Fluid (VOF) method is one of the most common methods for simulating multiphase flows. The VOF method is an interface capturing method in an Eulerian framework. Initial development of the method can be attributed to Woodward and Noh [87], Hirt and Nichols [88] and deBar [89].

In the simplest terms, the VOF method advects a fluid volume fraction on an Eulerian mesh. Each cell must have a fractional value between zero and one, where one represents fluid a , and zero represents fluid b . A pure cell is any cell which has a value equal of strictly zero or one. A mixed cell has a value between zero and one, meaning the cell is a mixture of the two phases and thus contains the interface between the two fluids. This information from the mixed cells is then used to reconstruct the interface between phases. The fluid volume fraction is advected with the flow via a transport equation. The transport equation is solved simultaneously with the mass and momentum conservation equations, which are elaborated upon shortly.

The mathematical representation presented here is for the flow of two immiscible, incompressible fluids, each with their own constant density and viscosity. The entire flow field is represented by a single set of conservation equations, where material properties vary discontinuously across the interface. Representations using two sets of conservation equations for each phase have also been done, but are omitted here.

As mentioned earlier, a volume fraction is used to represent the two fluids. The interface is represented as a mixture of the fluids instead of a sharp boundary. Physically the transition region is a sharp step, but is not treated as one in this method. The indicator function, α , is given by, [90]

$$\alpha = \begin{cases} 0 & \text{for a point inside fluid a} \\ 0 < \alpha < 1 & \text{for a point inside transitional region} \\ 1 & \text{for a point inside fluid b} \end{cases}$$

The indicator function, which is chosen to be the volume fraction, is advected with the flow, obeying a transport equation of the form,

$$\frac{\partial \alpha}{\partial t} + (\mathbf{U} \cdot \nabla) \alpha = 0 \quad (79)$$

Local material properties, such as density and viscosity, can be described using the indicator function as follows,

$$\rho = \alpha \rho_a + (1 - \alpha) \rho_b \quad (80)$$

$$\mu = \alpha \mu_a + (1 - \alpha) \mu_b \quad (81)$$

This method of determining local material properties, which jump in value across the interface, has its drawbacks. Taking the average of the viscosity as a simple weighted average of the indicator function can significantly reduce accuracy at the fluid interface [91]. An alternative to the arithmetic mean approach, given in above, is to use a harmonic mean represented mathematically in the equation below [92] [93] [94].

$$\mu = \frac{\mu_a \mu_b}{\alpha \mu_a + (1 - \alpha) \mu_b} \quad (82)$$

Issues with numerical diffusion arise when convecting a step function such as the volume fraction. To combat these issues, compression of the interface can be achieved via an artificial compression term. This term, proposed by Weller [90], is shown in the third term below.

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\mathbf{U} \alpha) + \nabla \cdot (\mathbf{U}_r \alpha (1 - \alpha)) = 0 \quad (83)$$

A velocity field, $\mathbf{U}_r$, compresses the interface. The compression term is only active in a thin region surrounding the interface, which prevents the compression from significantly affecting the overall solution. Further details on the compression of the interface can be found in Rusche [90].

The VOF approach evolves the volume of fluid in each cell, as the name suggests, but does not track the interface itself. In some cases, it may be desirable to geometrically reconstruct the fluid interface, for example, in scenarios where surface tension dominates. Geometric methods for reconstructing the interface will be discussed first, including simple line interface construction (SLIC) [87] and piecewise linear interface construction (PLIC) [95]. Next, work by Ubbink and Issa [96] will be discussed, where no explicit interface reconstruction is carried out. They proposed a method to avoid surface reconstruction altogether, as it can be computationally complex for unstructured meshes. Since the ocean is not dominated by surface tension, geometric reconstruction of the fluid interface is not required, such that Ubbink and Issa's approach is appropriate for modeling offshore wind turbines.

SLIC is a first order accurate reconstruction approach, that conserves volume, and was first presented by Noh and Woodward [87]. Fluid interfaces found in mixed cells are represented as compositions of one-dimensional components. Each component is represented as a straight line with is entirely perpendicular or parallel to the coordinate direction. Approximations of the interface are determined entirely by testing the volume

composition of the two fluids in the cells neighboring the mixed cell of reference. Interfaces satisfy the volume fraction in mixed cells. It is shown in Figure 6 that SLIC does not accurately describe the true interface for many cases. The fluid front can easily become fragmented, as is demonstrated in Figure 6, and this deterioration of the interface representation can lead to flotsam and jetsam, or small remnants of mixed fluid zones.

PLIC is an alternative approach to SLIC. PLIC reconstructs the interface in a mixed cell as a line in two-dimensions or a plane in three-dimensions. Unlike the SLIC approach, PLIC allows for lines or planes to be aligned in any direction. Line segments representing the fluid interface are usually described in Hessian normal form, $\hat{n} \cdot \vec{r} + d = 0$, where $\hat{n}$ is normal to the line segment, $\vec{r}$ is a point on the segment and d is the signed distance from the origin to the line segment. First the normal is computed, then the value for d satisfying the volume fraction of the cell is determined. This approach more accurately represents the interface, as shown in the Figure 6, despite the discontinuities between segments of neighboring cells. Errors of this method go as $O(\kappa h^2)$, where κ is the curvature of the true interface and h is the grid spacing [97].

Pilliod and Puckett proposed a second order accurate piecewise linear interface reconstruction algorithm. They demonstrated that a linear approximation to the interface is not sufficient to guarantee second order accuracy. They proposed the least squares volume-of-fluid interface reconstruction algorithm (LVIRA) and the efficient least squares volume-of-fluid interface reconstruction algorithm (ELVIRA), which use an error minimization approach to reconstruct the fluid interface exactly. The method reproduces lines and planes, in two-dimensions and three-dimensions, exactly, and allows the methods to maintain second order accuracy of the interface reconstruction [98].

Ubbink and Issa presented a non-geometric method to overcome the challenges associated with advecting a step function on an Eulerian grid [96]. These challenges include diffusion, dispersion and warping of the interface. The Compressive Interface Capturing Scheme for Arbitrary Meshes (CICSAM) method combines sharply resolved interfaces with boundedness of the volume fraction. Depending on the orientation of the interface with respect to the flow direction, the method switches between two high resolution discretization schemes. The method is fully conservative, implicit and theoretically second order in time.

Following interface reconstruction, and computation of volume fluxes from updated interface locations, the volume fraction is advected using the transport given in Equation 79.

5.1.2. Moment of Fluid

Dyadechko and Shashkov developed a Moment of Fluid method (MOF) which uses volume fractions as well as material centroid information to reconstruct interfaces [99]. The MOF method provides sufficient information to reconstruct an interface without the need for information from neighboring cells. MOF is able to resolve interface features on the order of the cell size. The computed interface is chosen to match the volume fraction and approximate the reference material centroid as best as possible.

Letting Ω define a material region, the zeroth moment (volume) and the first moment are defined as,

$$M_0(\Omega) = \int_{\Omega} dV \quad (84)$$

$$M_1(\Omega) = \int_{\Omega} \vec{x} dV \quad (85)$$

The material centroid can then be represented in terms of the zeroth and first moments, as,

$$\vec{x}_{\Omega} = \frac{M_1(\Omega)}{M_0(\Omega)} \quad (86)$$

The interface is computed to match the reference volume exactly and to approximate the centroid as closely as the possible. The interface normal, $\hat{n}$, is computed by minimizing the functional,

$$E_c^{MOF}(\hat{n}) = |\vec{x}_c^{ref} - \vec{x}_x(\hat{n})|^2 \quad (87)$$

where $\vec{x}_c^{ref}$ is the reference material centroid and $\vec{x}_x(\hat{n})$ is the reconstructed material centroid with interface normal $\hat{n}$. The centroids are advected with the local velocity, and the reference material centroid is found from the volume weighted sum of these forward traced centroids.

The minimization of $E_c^{MOF}(\hat{n})$ is calculated as follows; first, an initial guess for the interface normal is calculated by defining a vector between $\vec{x}_c^{ref}$ and the actual cell centroid. The signed distance, d , is then calculated to match the reference volume in each cell exactly. The centroid of the resulting polyhedron is then computed, and the distance between the actual and reference centroids is determined.

Interface reconstruction in the MOF method is efficient due to the fact that no neighboring cell information is needed. Reconstruction of the interface in each cell is determined from volume fraction and material centroid of the reference cell only. Shashkov and Ahn extended the work of MOF to include an adaptive mesh refinement strategy [100]. The adaptive meshing is based on errors in the centroid positions. Furthermore, they extended MOF for multi-material cases in which the number of materials exceeds two.

5.1.3. Level-set methods

Osher and Sethian were the first to formulate a level-set method for calculating the motion of an interface under a velocity field [101]. Level set methods implicitly represent boundaries, or in the case of two phase flow, the interface between the fluids using a zero level-set of the function ϕ . The level-set function ϕ is a signed distance function. The interface is defined by $\Gamma(t)$, which exists in R^n and bounds a region Ω . The smooth level-set function ϕ is defined such that

$$\phi(\vec{x}, t) = 0 = \Gamma(t) \quad (88)$$

$$\phi(\vec{x}, t) > 0 \text{ for } x \in \Omega \quad (89)$$

$$\phi(\vec{x}, t) < 0 \text{ for } x \notin \Omega \quad (90)$$

The motion of the interface is tracked by advecting the level-set function using a transport equation lacking a diffusion term. The dissipation must be carefully treated by use of an appropriate convection scheme.

The level-set field must be reinitialized at each time step following the evolution of Γ . The steady-state solution to the following equation is used to reinitialize the level-set field [102]

$$\frac{\partial \psi}{\partial t} + \text{sign}(\phi)(|\psi| - 1) = 0 \quad (91)$$

with the initial condition,

$$\psi(\vec{x}, 0) = \phi(\vec{x}, t) \quad (92)$$

The curvature of the interface is found by calculating the divergence of the normal gradient of ϕ at the interface. Mathematically this relation is given by,

$$\kappa = -\nabla \cdot \hat{n}, \text{ where, } \hat{n} = \frac{\nabla \phi}{|\nabla \phi|} \quad (93)$$

Properties of the two fluids, such as density and viscosity, are given by the smooth Heaviside function,

$$\rho = \rho_{liquid} + (\rho_{gas} - \rho_{liquid})H(\phi) \quad (94)$$

$$\mu = \mu_{liquid} + (\mu_{gas} - \mu_{liquid})H(\phi) \quad (95)$$

Adalsteinsson and Sethian introduced the narrow-band approach, which focuses the computational effort about the fluid interface region [103]. Similar work was also done by Peng, who developed an algorithm to track the evolution of the interface, that is, the level-set function [104]. A region is defined with a cut off width, γ , defining where the evolution of the level-set function will be computed. This method is $O(N)$ where N is the number of grid points inside of the cut-off region. The points outside of the cut-off region must be masked at each time step, and this step is $O(N^2)$.

Changes in the interface topology are well defined in the Level-set method. Additionally, level set methods are computationally inexpensive, as it is sufficient to solve the level-set function only near the interface, as Peng demonstrated [104]. While level set methods are beneficial in these ways, they do suffer from mass conservation issues. A variety of hybrid methods have been proposed to combat issues with mass conservation as well as improved accuracy. Combinations of level-set and VOF methods have been put forth by Sussman and Puckett [105], Bourlioux [106], Sussman and Fatemi [107] and van der Pijl [108] which make an effort to overcome mass conservation issues. For improvement to the solution accuracy Enright proposed a hybridized method of level-set with particle methods [109]. Despite improvements in some areas, these approaches introduce artificial fluctuations in the interface curvature as a result of local corrections to the level-set field.

5.1.4. Marker Methods

The marker and cell method (MAC) uses Lagrangian marker particles which are advected with the local fluid velocity to locate the presence of a fluid interface. Marker particle methods were first developed by Harlow and Welch in 1965 [110]. Marker methods can be surface-based, in which particles are only on surfaces, or volume-based when

markers exist in entire domain. Surface-based marker methods offer the benefit of being far less computationally expensive than volume-based methods.

Information is exchanged between the Eulerian grid and the Lagrangian particles at each time step by conservative interpolation. A typical computation begins by setting initial conditions and solving for the fluid momentum in the Eulerian grid. Then the momentum is transferred to the Lagrangian grid and advected. Following the advection of the momentum, surface tension forces are calculated and then interpolated back to the Eulerian grid. Once the transferred forces are applied to the momentum equation, the next time step is computed and the cycle repeats.

While surface-based methods are computationally less expensive, they suffer from the need for numerical surgery in the case of topological changes [101]. Volume-based methods are able to avoid numerical surgery, but are more expensive. Marker methods are good at conserving volume. In general, marker methods are valued for the ability to capture subgrid scale features, such as fluid ligaments. However, grid refinement is often necessary to accurately calculate other physics anyway, negating the benefit of subgrid scale feature capturing. Kothe and Rider argue that practically the marker particle method is costly and suffers from accuracy issues due to the interpolation between the Eulerian grid and the particles [111].

Marker particles have been used with supplemental triangular surface meshes in an arbitrary Lagrangian Eulerian (ALE) framework by Unverdi et al [112], Tryggvason et al [113] [114] and de Sousa et al [115] to calculate surface tension on the supplemental mesh and transfer the solution back to the Eulerian grid. A variety of applications which use extensions of these methods have been performed. Esmaeeli, et al, simulated bubbly flows [116][117], Juric, et al, utilized this method for boiling applications [118], and Glimm, et al, simulated Rayleigh-Taylor and Richtmeyer instabilities [119][120].

This method has also been used for wave modeling applications. Non-linear waves generated by a piston-type wavemaker were simulated by Huang, et al, using a MAC method in two-dimensions [121]. Numerical results were compared with experimental and theoretical results, and good agreement was found at small wave steepnesses, and agreed less well for steeper waves. Park, et al, simulated non-linear waves interacting with a stationary cylinder and compared their numerical results with experimental data [122]. Non-linear multidirectional waves were investigated with a MAC method by Kim, et al [123]. Results were compared to potential-based theory and experimental measurements, and the results were generally found to be in good agreement. MAC methods have also been used to investigate breaking waves [124] [125] [126].

5.2. Previous CFD Research: Wave-Body Interaction

As mentioned previously, there is a longer history of offshore structure hydrodynamics from both the oil and gas industry, as well as the ship hydrodynamics community. More recently, research efforts have begun to focus more closely on offshore wind farms, both with fixed bottom and floating platforms. Because so much of the hydrodynamics research on offshore wind turbines draws from the experience of oil and gas applications, and ship hydrodynamics research, the discussion of Navier-Stokes approaches to offshore wind will begin with a broader scope. We'll work towards examining recent research in Navier-Stokes approaches to the hydrodynamics of offshore wind turbines by first exploring the broader problems of FSI coupling, multiphase flow modeling with FSI coupling, and then finally conclude with research on monopiles, and lastly on floating platforms.

5.2.1. Fluid-Structure Interaction

The choice in the overall computational scheme for FSI problems is non-trivial. Numerical instabilities are a well known challenge in FSI problems, where the computational method plays a major role in determining whether the system will be stable or not. Causin discusses numerical instabilities in loosely coupled FSI schemes in the context of a blood flow problem, but the ideas in his paper affect a wider range of FSI problems too [127]. Causin points out that numerical instabilities depend on both the density of the structure as well as the domain size. It is proposed that explicit couplings may be unconditionally unstable, and that implicit couplings should perform more stably. Förster, et al, provide a proof for the role of the density ratio in numerical instabilities in the sequentially staggered solution framework for FSI problems [128].

The computational approach for FSI problems can be divided broadly into two categories based on the coupling of the fluid and the structural equations. The first method is the monolithic approach in which the entire coupled system is solved implicitly and the solution is converged at each time step [129] [130] [131] [132]. Alternatively, partitioned solvers allow separate treatment of the fluid and the structure. These methods are beneficial due to their flexibility, and often are less computationally expensive as well.

A variety of coupling schemes have been derived in the context of partitioned approaches [133]. In a sequentially staggered scheme, shown on the far left hand side of Figure 8, the fluid and solid equations are solved one after the other. In this approach, one code must use the solution of the other code from the previous timestep, making this method explicit. The center of Figure 8 illustrates a parallel staggered, explicit, approach, in which both codes are solved simultaneously. Both of these explicit approaches exchange information only once per time step. Lastly, the far right side of Figure 8 shows a strong coupling approach in which data are exchanged multiple times per time step. This iterative approach performs multiple coupling steps within each timestep. The updated time step solutions to both codes make this approach implicit in nature.

Work by Wall, et al, is an example of a iterative staggered, strongly coupled implicit approach to the FSI problem [134]. Wall, et al, simulated a basin with an elastic bottom. An approximate solution was determined from a staggered coupling scheme, and then the solution was iterated upon using updated boundary conditions. The fluid was computed with a free-surface that was treated with a deforming mesh. The equations for the fluid and structure are solved using a tightly coupled algorithm. The fluid and structure equations are solved sequentially, in an iterative fashion. The deformation of the structure is updated in each iteration by using the fluid stress from the previous iteration. The fluid is updated following changes in the structure boundary. Iteration and under-relaxation are implemented to ensure convergence of the solution.

Malan and Oxtoby presented a fully coupled, partitioned FSI scheme which was computed in parallel [135] [136]. Their work used a dual-time stepping method in which the fluid and structure equations are solved simultaneously, but separately. At the fluid-solid interface, fluid traction is applied to the boundary of the solid body, and the body velocity is applied to the fluid. Following mesh motion, residuals are recalculated, and the solid and fluid solutions are recalculated until the residuals drop below the convergence criteria. Matthies and Steindorf also used a partitioned approach for solving an FSI problem [137] [138], and their work follows a very similar approach to that of Malan and Oxtoby. Their work used separate treatments for the fluid and the structural computa-

tions, and coupled the two components with an algebraic coupling condition. Habchi, et al, used a partitioned solver approach in which the fluid, structure and internal mesh motion were all treated separately [139]. The work simulated structural deformation due to incompressibility, as well as a flap excited by a Von Karman vortex street. Additional work using partitioned approaches for FSI problems have been done by Mok and Wall [140], Kuttler [141], Kassiotis [142], von Scheven [143], Dettemer and Peric [144] [145], Nicholls-Lee [146], Ruprecht [147] and Tezduyar [148] [149]. Partitioned approaches to the FSI problem are revisited below when discussing VOF approaches to FSI problems.

5.2.2. *Finite Volume Methods with FSI*

A variety of finite volume methods have been implemented to treat the fluid part of the FSI problem. Some methods treat the fluid problem with a free-surface, neglecting the air phase, while others simulate both the air and water with a fully two-phase treatment. Discussion of both the free-surface and fluid interface methods are mentioned here. Finite volume methods with FSI coupling have been applied to a variety of applications, largely outside of offshore wind energy. While the work reviewed in this section does not directly cover offshore wind applications, but rather presents similar FSI problems, the same methods can be applied to offshore wind modeling.

Immersed boundary methods provide one approach for solving the fluid flow problem in the presence of a body. Peskin first developed the immersed-boundary (IB) method for biological fluid dynamics applications in 1972, when he simulated cardiac mechanics and blood flow [150]. Detailed reviews of the method have been given by Peskin [151] and Mittal [152]. Peskin’s review provides a mathematically rigorous review of the method, while the latter review by Mittal covers applications of the method, including flow past a truck and sphere, a body tumbling in free fall and flow past flapping filaments. In general, the IB method solves the Navier-Stokes equation on a Cartesian grid. The body’s effect on the fluid flow is treated with a force density which represents the force supplied by the surface of the body onto the fluid. One benefit of this method is the elimination of the need for a body fitted grid. However, IB methods do suffer from various weaknesses, including challenges with stability, volume conservation and efficiency [153].

Gilmanov and Sotiropoulos implemented a hybrid Cartesian immersed boundary method to simulate flow past moving objects [154]. The code was validated using a rotating sphere. Simulations of flow past a undulating fish-like body and planktonic copepod were carried out. In all cases, the motion of the body was prescribed. Ilinca and Hetu presented results for the flow around rigid bodies using an IB method, but only for the case of static objects [155]. IB methods have been applied to a variety of applications, including blood flow, aquatic animals, and rigid bodies, can be also be extended to modeling floating platforms for offshore wind turbines.

Further work with FSI coupling problems has been carried out without the use of an immersed boundary method. For example, Peric, et al, presented results for the motion of rigid bodies with a free surface RANS approach coupled with an iterative solution method for the 6 DOF motion [156]. The fluid flow was predicted with a commercial CFD software package, and was coupled with a user-coding interface for the 6 DOF motion. In each time step the fluid equations were solved first, followed by a predictor-corrector method for the motion of the rigid body by integration of pressure and shear forces along the body surface. The fluid velocity solution was re-solved after motion of the body, and a new time step was begun.

CFDShip-Iowa is a code that is frequently encountered in the literature for the modeling of ship hydrodynamics. The CFDShip-Iowa code uses the unsteady Reynolds averaged Navier-Stokes (URANS) equations to solve for the liquid phase. A level-set method is implemented for capturing the free surface. The fluid flow equations are solved, and the forces and moments acting on the ship are found by integrating the elemental forces along the surface of the body. The ship is treated in a non-inertial ship-fixed reference frame with the origin located at the ship center of mass, on to which the forces and moments are projected. A predictor corrector approach is used to compute translational and rotational ship velocities. Rigid overset grids are used, and two to five iterations are performed to achieve convergence of the flow field and ship motions within each time step. Weymouth simulated a Wigley hull in regular waves with the CFDShip-Iowa code [157]. Good agreement was found between CFD predictions and experimental data for a wide range of Froude numbers. Experimental damping and added mass coefficients also showed agreement with the numerical work. Castiglione, et al, simulated a multi-hull catamaran in regular waves using the CFDShip-Iowa code [158]. Maximum response conditions were studied by varying the wavelengths at a fixed ship speed. The CFD predictions showed good agreement with experimental data.

Further development of the CFDShip-Iowa code was done by Yang, et al [159]. A level-set and immersed boundary (IB) method were combined with a sharp interface Cartesian grid solver for simulating ship hydrodynamics. A level-set method was used to find the solution for the free-surface, while an IB method was employed for simulating the motion of the ship. Wave fields around steady forward moving ship hulls were produced. This work was later extended with a strong-coupling scheme to solve fluid-structure interaction problems again in the framework of an embedded boundary [160]. In the later work, the fluid and the structure are treated as part of a single dynamical system where all governing equations are integrated simultaneously. More recently, Yang and Stern devised a simpler and more efficient formulation in which the fluid solver was moved outside of the predictor-corrector loop [161]. Prescribed motion cases were provided as initial validation cases for this work. Strongly coupled interactions, such as vortex induced vibrations and galloping, were presented as well and were in good agreement with experimental measurements.

The Reynolds averaged Navier-Stokes code developed at MARIN, called ReFresco (Reliable and Fast RANS Equations (solver for) Ships, Cavitation and Offshore), has also been popular for ship hydrodynamics, as well as oil and gas platform simulations. ReFresco has been applied and validated for propeller flows, flow around complex ships, offshore structures in current and wind loads and submarine maneuvers and cavitating flows. Jaouen, et al, simulated the flow around a forced rolling body and investigated the added mass and damping coefficients [162]. The two-dimensional CFD predictions from ReFresco were compared with experimental data, as well as results from the commercial CFD package CFX, and excellent agreement was found between all three.

These same RANS based solvers can be applied to the problem of offshore wind turbines. The ship geometries can be replaced with offshore wind turbine platforms to examine the interaction of the waves and the structure. The loading on offshore wind platforms can be investigated in the same manner as is it on ships.

Ship hydrodynamics have also been modeled using the Volume of Fluid approach discussed in the previous section, with a deforming grid. Yang, et al, used a body fixed reference frame with the origin located at the ship center of mass to simulate motion of

a LNG carrier in regular waves [163]. Also a VOF method was employed which typically models two phase flow, Yang's work modeled only the water, and used extrapolation methods to compute the velocity and pressure fields of the air in order to properly model the fluid interface. In each time step the hydrodynamic forces on the body were computed and then the position was updated, followed by a final update of the flow solution. Mesh topology changes were made when necessary.

Gerrits and Veldman developed, and named, the improved Volume-of-Fluid method (iVOF) for the study of sloshing liquid fuel in satellites [164]. The iVOF method uses a structured, non-boundary fitted grid, allowing for the easy generation of the grid around complex structures. The authors argue that the iVOF method improves upon the original VOF method which suffers from the production of flotsam and jetsam, as well as gain or loss of water due to rounding the VOF function. In the iVOF method, a local height function is introduced in conjunction with the original VOF method. This work was extended by MARIN for the application of green water loading [165]. The iVOF method has since been used for anti-roll tank simulations [166], water entry problems for a wedge [167], dam break problems [168], free-hanging subsea structures in regular waves [169], and oil tension leg platforms in extreme waves [170].

Other work carried out with VOF methods includes the approach of body attached meshes, as opposed to deforming grid methods. Panahi, et al, have used VOF with a fractional step method to model a variety of hydrodynamics problems [171][172]. In their work the mesh is fixed to the body, and moves with the body as the body moves due to forces and moments from the fluid flow. This method has been applied to sloshing, dam breaking with obstacles, as well as cylinder and wedge water-entry problems. Additionally, steady-state forward ship motion has been simulated with this method. All of the work mentioned has been validated with experimental data. Sato, et al, have also implemented a VOF method with a body attached mesh [173]. Ship motion in regular head waves for a Wigley Hull and Series 60 model was simulated. The pitch and heave amplitudes, as well as phase angles, were compared to experimental data and reasonable agreement was found.

Maki, et al, simulated the constant velocity impact of a wedge-shaped body using a VOF method and a one-way fluid-structure coupling approach in OpenFOAM [174]. More recent work by Piro and Maki presented a tightly coupled approach for fluid-structure interactions [175]. In this approach, information between the structure and fluid is exchanged in a manner that achieves better time accuracy. Under-relaxation and iteration are used at each time step. The under-relaxation factor is selected with a method presented by Causin, et al [127]. Three wedge entry problems are presented as validation cases; one with constant entry velocity of an elastic wedge, another is an entry and exit of a rigid wedge, and finally exit and entry of a hydroelastic wedge. While this work does not present a method for 6 DOF motion, the under-relaxation and iterative solution approach could be extended for freely moving bodies.

Again, these approaches can be applied to model offshore wind hydrodynamics. VOF coupled with a structural solver can simulate the two-phase flow of the ocean and the wind, while treating the platform geometry with a rigid body solver. These methods have been applied to ship hydrodynamics, as well as offshore oil and gas platforms, and can be extended to study offshore wind applications.

Other less common methods for modeling the fluid component of the FSI problem include the fictitious domain method, and the constrained interpolation profile method,

which are both mentioned here briefly. Fictitious domain methods have been developed for simulating fluid-structure interactions. Quantities are transferred between Eulerian and Lagrangian frames. The basic idea of the fictitious domain method is that the interior of the solid is assumed to be filled with the fluid. The fictitious fluid moves at the same velocity as the solid by a pseudo-body force, aka the Lagrangian multiplier. Shi and Lim simulated a variety of flexible bodies in fluid flows using a Lattice Boltzmann Method - Distributed Lagrangian Multiplier/Fictitious Domain (LBM-DLM/FD) method [176]. Yu and Shao also used a fictitious domain method to simulate flow past flexible bodies [177]. Hu and Kashiwagi studied the heave and pitch motion for a Wigley hull in regular head waves using a constrained interpolation profile method (CIP) [178]. This less common approach to fluid-structure interactions was first developed by Yabe [179]. Hu and Kashiwagi found good agreement between their numerical predictions and experimental data, except at large wavelengths.

While none of the work presented in this section directly modeled offshore wind applications, each approach can be extended to model the interaction of waves with offshore wind platforms.

5.3. Dynamic Meshing

The numerical domain in the FSI problem can be treated in a variety of ways, one of which is through dynamic meshing in which the domain adapts to follow the movement of the structure. A brief overview of dynamic meshing classifications are covered here, as well as mention of the challenges and difficulties related to moving meshes. These difficulties include factors such as mesh quality, robustness, efficiency, and numerical errors.

Dynamic meshing can be classified broadly into two categories – the first, where the mesh motion is known *a priori* and the second, in which the mesh motion is determined alongside the flow solution. Externally drive mesh motion includes cases like the prescribed motion of a wing, or a piston. The other type of dynamic meshing, in which the mesh moves with the flow involve cases like 6 degree-of-freedom body motion. Dynamic meshing can also be classified by two major mesh actions, which apply to both external and flow driven mesh motion. Mesh actions can be categorized as mesh deformation or topological changes. Mesh deformation involves simply moving points, where topological changes alters the number of connectivity points, faces and cells. Furthermore, due to the changing number of cell volumes, topological changes require data remapping which is prone to errors [180]. While mesh deformation is easier to implement and less prone to errors, sometimes it is not sufficient. Large mesh deformations and rotating motions can lead to mesh quality issues, necessitating topological changes to avoid numerical errors.

One of the main challenges in dynamic meshing is maintaining geometric validity, which includes mesh quality. Geometric validity requires all cells to be convex, and bounds mesh orthogonality to a specified tolerance [181]. Mesh quality can be judged by a variety of indicators, including but not limited to skewness, orthogonality, aspect ratio, smoothness, and condition number [182].

A variety of deforming mesh algorithms have been proposed. One of the most popular approaches to defining mesh motion is the spring analogy. Blom gives a review of the advantages and weaknesses of the spring analogy [183], and Farhat presents the addition of torsional springs to improve robustness of the method [133]. Other approaches

to achieving robust mesh motion include Laplacian smoothing with varying diffusivity algorithms [184].

Issues arise with conservation of mass, and other conserved terms, when the mesh moves and mass fluxes are calculated with grid velocities. Difficulties with conservation can be overcome through the *Space Conservation Law* (SCL), which mathematically describes the conservation of space for a control volume that changes position and shape. The SCL gives the relationship between the rate of the change of the volume of a control volume and the velocity of its surface [185],

$$\frac{\partial}{\partial t} \int_{\Omega} d\Omega - \int_S (v \cdot n) dS = 0 \quad (96)$$

A more detailed discussion of the SCL is presented by Demirdzic and Peric [186], including an emphasis of the importance of satisfying the SCL and some test cases to demonstrate the point.

5.3.1. CFD of Hydrodynamics on Wind Turbine Platforms

The majority of installed offshore wind turbines use fixed-bottom platforms in shallow waters, however, for transitional to deep water, floating platforms show great potential. Research on the hydrodynamics of monopile support structures has a longer history, due to the greater number of farms that have been proposed and installed with fixed bottom structures. More recently, research efforts have begun to study floating platforms, which are subject to increased motion due to current and wave interactions.

Just as there was a large effort to model wind and wave loading on monopiles with non-CFD engineering tools, there has also been ample work with CFD. Research on monopiles has focused around not only wave loads, but also wave breaking, which can play a significant role for structures in relatively shallow water. Wave run-up has also been a point of focus for research on gravity based foundations in shallow water.

Christensen, et al, presented research on extreme wave forces and wave run-up on monopiles [187]. The work implemented the Navier-Stokes equations, but neglected viscous effects, thus reducing the modeling to the Euler equations. A vertical cylinder placed on a sloping bed was modeled, highlighting the effects of breaking waves. It was shown that breaking waves greatly influence wave run-up and forces on the structure. Further work by Christensen was carried out to study irregular wave loading on gravity based foundations specifically sited on Thornton Bank in Belgium [188].

Bredmose, et al, simulated wave loads on a gravity wind turbine foundation using a 3D Navier-Stokes solver which treated the fluid interface with VOF [189]. Load predictions from CFD were compared with Morison's equation and good agreement was found for wave load history, but not for extreme loads. Later work by Bredmose and Jacobsen used a 3D CFD model to investigate extreme loads from breaking waves on monopile foundations [190]. CFD results were compared to load predictions from Morison's equation, and found that loads from CFD predictions were larger. Bredmose and Jacobsen presented further work on wave impacts on monopiles, again with a VOF method from OpenFOAM [191]. Wave run-up on monopiles was also investigated by Peng, et al, with the commercial CFD software ComFLOW [192].

Wave forces on a single cylinder, and on a pair of cylinders, which is representative of monopiles for offshore wind turbines, as well as oil and gas support structures, was

modeled by Kamath, et al [193]. CFD results were computed with RANS and a level set method modeling the free surface of the water. Load predictions from CFD were compared with Morison's equation and MacCamy-Fuchs theory, and good agreement was found.

Additional research on wave impacts on monopiles was carried out by Zhou, et al, specifically for the Shanghai Donghai-Bridge offshore wind farm in China [194]. OpenFOAM was used to model waves with VOF and RANS, and wave run-up as well as load predictions were examined. Lara, et al, also studied wave interaction with single- and multi-piled structures using an OpenFOAM based approach [195].

CFD research on platforms other than monopiles has been carried out as well, though not in as great of volume. Koop and Berezniński presented results for a semi-submersible modeled with 10 different grids in three different headings (180, 150 and 90 degrees) [196] using the REFRESCO code, which was discussed earlier. The CFD predictions for loads on the semi-submersible in current were compared with experimental data, and good agreement was found.

Vortex induced motions (VIM) are known to affect the fatigue life of platforms such as TLPs and semi-submersibles. Work has been carried out with CFD to study VIM on a variety of platforms in current and waves. Kim, et al, used CFD to investigate VIM on a TLP platform, building upon previous work on spar VIM [197]. Tan, et al, studied VIM on a multi-column floating platform [198]. Commercial CFD software was used to investigate VIM, and good agreement was found between calculations and experimental tank measurements. Lefevre, et al, presented VIM studies of a spar with strakes, pipes, chains and anodes using the Improved Delayed Detached Eddy Simulation turbulence model [199].

The CFDShip-Iowa code, discussed earlier in the context of ship hydrodynamics modeling, was utilized by Quallen, et al, to simulate a spar mounted wind turbine [200]. The spar buoy was simulated in free decay tests, as well as in regular waves. The crowfoot and added yaw-stiffness mooring line models were investigated. CFD results were compared to motion predictions from FAST, and good agreement was found for most of the degrees of freedom, with the largest differences seen in the yaw motion.

Free decay tests of a spar buoy were simulated by Beyer, et al, [201]. The multi-body aero-servo-hydro-elastic wind turbine simulation tool, SIMPACK, was coupled with the commercial CFD code, ANSYS-CFX, which was used to model the hydrodynamic loads. The hydrodynamic modeling in ANSYS-CFX used a VOF approach to treat the two-phase flow. Surge, sway, roll, pitch and yaw DOFs were enabled, and surge and pitch motions from a free decay surge motion test were compared between CFD and HydroDyn. Future work will look at more complex geometries, and interaction of geometries with incident waves.

6. Concluding Remarks

Offshore wind turbines show great potential for capturing energy, in a way that reduces greenhouse gas emissions and diversifies the energy portfolio. Large-scale offshore energy projects have been installed in Europe and Asia, with proposed farms on the rise in the United States. All of the existing offshore wind farms make use of fixed bottom platforms, which rely on siting the structures in relatively shallow water. In

deep water, it is no longer cost-effective to install fixed bottom structures, thus, floating platforms have been proposed in their stead. Two prototype floating offshore wind turbines have been installed in Europe, and another off the east coast of the United States. Floating platforms allow for the siting of wind farms in locations far from shore, where the structures can no longer be seen from land, thus reducing public opposition based on visual impacts. Furthermore, the wind resource is greater offshore, and the better resource is often in close geographic proximity to high population densities.

While offshore floating wind turbines show promise as a source of clean energy, we first must overcome economic and technical barriers. Studying floating platforms for offshore wind turbines is just one part of the challenge to decrease the cost of energy. Both the capital cost of the projects must be reduced, while also increasing energy production and improving reliability of the entire system. Part of the reduction of capital costs includes smarter design of these floating platforms. This necessitates a detailed understanding of the loads and displacements of these structures in the ocean environment, where platforms are subjected to waves, current, wind and even ice. The development of cost-effective and reliable floating offshore wind turbines requires engineering models, which are computationally inexpensive, as well as higher-fidelity models, like CFD, to provide detailed insight to guide the engineering models.

The creation of engineering models and higher-fidelity CFD models for studying offshore hydrodynamics requires the agglomeration of many topics, including water wave theory, ocean mechanics, hydrodynamics, and fluid-structure interaction, to name a few. A variety of modeling approaches exist, beginning with the straightforward Morison's equation, and growing in complexity towards potential flow theory, and finally with fully three-dimensional finite volume methods. While a variety of CAE tools provide methods to quickly model the hydrodynamics on offshore wind turbines, simplifying assumptions may reduce the accuracy of the solution. CFD methods provide higher-fidelity results, where less assumptions are required, but may be too computationally expensive for some design processes. The chosen approach depends on the desired outcome.

Engineering models and CFD toolboxes have been widely used for oil and gas applications, as well as in the ship hydrodynamics community. More recently, offshore wind turbines with fixed bottom platforms have been simulated with both engineering and CFD tools. However, less research has been carried out to study floating platform designs with engineering models, and even fewer studies have been done with CFD methods. While the lessons and experience from the oil and gas industry, and the ship hydrodynamics community, can be applied towards simulating offshore floating wind turbines, there are differences which must be acknowledged. In general, offshore oil and gas applications experience a reduced degree of motion as compared to floating platforms for offshore wind turbines. In ship hydrodynamics, it is often the case that ships are simulated in forward motion, where the displacement of the body is prescribed. Floating platforms for offshore wind may be subjected to large displacements, which should be modeled with free 6 degree of freedom motion. In light of the discussion of instabilities in FSI coupling problems, simulating free 6 DOF motion is a known challenge due to stability concerns.

Looking towards the future, data measured in wave tanks tests and on deployed platforms in the ocean environment will support forthcoming numerical results from CFD and CAE tools. Model scale measurements, such as DeepCwind [7], provides verification and validation opportunities for computer codes at reduced scales. At full scale, there

is hope that prototype and full scale measurements from installed platforms will become publicly available for validation of codes at the same scales.

The opportunity to enhance our knowledge of floating wind turbine platforms is great, and also prudent. Floating platforms for offshore wind energy are an emerging technology that show great potential for energy production. The relative infancy of this technology leaves an opening for new research and understanding. Furthermore, wind energy has already proven itself as a viable resource as the world seeks to diversify its energy supply and diminish greenhouse gas emissions. There is great potential for existing knowledge from onshore and fixed bottom projects to inform floating offshore wind energy. Ensuring viability of offshore floating wind farms relies upon modeling efforts from the scientific and engineering community. These modeling efforts will include and be enhanced by the theories and research efforts discussed in this review.

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TABLES

Table 1: Wave type classification table. Reproduced from Mei. [14]

Wave Type	Physical Mechanism	Typical Period	Region of Activity
Sound	Compressibility	$10^{-2} - 10^{-5}$ s	Ocean interior
Capillary ripples	Surface tension	$< 10^{-1}$ s	Air-water interface
Wind waves and swell	Gravity	1 – 25s	
Tsunami	Gravity	10 min - 2 h	
Internal waves	Gravity and density stratification	2 min - 10 h	Layer of sharp density change
Storm surges	Gravity and Earth rotation	1 - 10 h	Near coastline
Tides	Gravity and Earth rotation	12 - 24 h	Entire ocean layer
Planetary waves	Gravity, Earth rotation and variation of latitude or ocean depth	$O(100days)$	

Table 2: Summary of Linearized Wave Theory Characteristics.

Characteristic	Mathematical Representation
Linearized KBC	$\frac{\partial \eta}{\partial t} - \frac{\partial \phi}{\partial z} = 0$ at $z = \eta$
Linearized DBC	$\frac{\partial \phi}{\partial t} + g\eta = 0$ at $z = \eta$
Velocity Potential	$\phi = \frac{gH}{2kc} \frac{\cosh[k(z+h)]}{\cosh(kh)} \sin(\omega t - kx + \psi)$
Surface Elevation	$\eta = \frac{H}{2} \cos(kx - \omega t + \psi)$
Dispersion Relation	$\omega^2 = gk \tanh(kh)$
Horizontal Particle Displacement	$\zeta_p = \frac{H}{2} \frac{\cosh(k(z+h))}{\sinh(kh)} \sin(\omega t - kx + \psi)$
Vertical Particle Displacement	$\eta_p = \frac{H}{2} \frac{\sinh(k(z+h))}{\sinh(kh)} \cos(\omega t - kx + \psi)$
Horizontal Particle Velocity	$u = \frac{gH}{2c} \frac{\cosh[k(z+h)]}{\cosh(kh)} \cos(kx - \omega t + \psi)$
Vertical Particle Velocity	$w = \frac{gH}{2c} \frac{\sinh[k(z+h)]}{\cosh(kh)} \sin(kx - \omega t + \psi)$
Pressure	$p = -\rho g z + \frac{1}{2} \rho g H \frac{\cosh(k(z+h))}{\cosh(kh)} \cos(kx - \omega t + \psi)$

FIGURES

Figure 1: Particle orbital paths which vary depending on water depth. Reproduced from Holthuijsen [202].

Figure 2: The surface elevation for first and second order Stokes waves. The second order waves demonstrate the non-linear effects of more peaked crests and shallower troughs.

Figure 3: Approximate regions of applicability for different wave theories, depending on wave height and water depth, from LeMéhauté [26].

Table 3: Sea States. Adapted from the UK Meteorological Office Fact Sheet [203].

WMO Sea State Code	Significant wave height (m)	Characteristics
0	0	Calm (glassy)
1	0 to 0.1	Calm (rippled)
2	0.1 to 0.5	Smooth (wavelets)
3	0.5 to 1.25	Slight
4	1.25 to 2.5	Moderate
5	2.5 to 4	Rough
6	4 to 6	Very rough
7	6 to 9	High
8	9 to 14	Very high
9	Over 14	Phenomenal

Figure 4: The Pierson-Moskowitz and JONSWAP spectra. Both spectra shown here have a significant wave height of 0.475 meters and peak spectral period of 4 seconds.

Table 4: Important non-dimensional numbers relating to fluid-structure interactions.

Dimensionless Number	Formula	Physical Significance
Reynolds	$Re = \frac{UD}{\nu}$	Characterize laminar and turbulent flow regimes
Froude	$Fr = \frac{U}{gL}$	Resistance of bodies moving through fluid
Keulegan-Carpenter	$KC = \frac{U_m T}{D}$	Compares the drag coefficient to inertial forces

Figure 5: Classification of small versus large structures and their limits of applicability. The vertical axis shows H/D which is equivalent to the Keulegan-Carpenter number. The horizontal axis is the diffraction parameter, $\pi D/L$. Adapted from Chakrabarti [50].

Table 5: Relative dominant wave loading regimes for a circular cylinder, adapted from Sarpkaya [15]. D is the diameter of the body, L is the wavelength, and H/D is the Keulegan-Carpenter number.

Dominant Regime	Range
Inertia	$0.01 < H/D < 0.25, \pi D/L < 0.5$
Small-drag, large-inertia	$0.25 < H/D < 1.5, \pi D/L < 0.5$
Morison region (comparable drag and inertia)	$H/D > 20$
Diffraction	$\pi D/L < 0.5$

Figure 6: Volume of fluid representations of an interface(a), represented by volume fraction values (b), reconstructed with SLIC (c) and reconstructed with a piecewise-linear approximation (d). Reproduced from Pilliod and Puckett [98].

Figure 7: Representation of the MOF method in two-dimensions. The true interface is represented by the solid curved line, the dotted line represents the piecewise-linear reconstruction and the normal is label as $\hat{n}$. Reproduced from Shashkov and Ahn [100].

Figure 8: Partitioned schemes for loose and tight coupling of fluid and structural codes. The diagram represents the computation fluid dynamics (CFD), and the computational structural mechanics (CSM) solvers at the top and bottom, respectively. The far left illustrates a sequential, staggered, explicit coupling scheme. The middle portion of the diagram shows a parallel, staggered, explicit approach. Finally, the far right side shows a strong coupling scheme, where an iterative approach couples the codes a number of times within each time step. From Ruprecht [147].