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An Overview of Wave Impact Forces on Offshore Wind Turbine Substructures

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Abstract

Offshore wind turbines are always subjected to highly varying aerodynamic and hydrodynamic loads which dictate the design phase of the wind turbine substructures. The breaking wave forces yield the highest hydrodynamic loads on substructures in shallow water, particularly plunging breaking waves. Due to the complex and transient nature of the impact forces, the description requires more details concerning the physical properties of breaking waves and the response of the structure. The objective of this paper is to give an overview of the previous and recent research on wave impact forces and the key issues pertaining to these forces on offshore wind turbine substructures.

Keywords: Breaking waves; slamming force; offshore wind turbine substructures; wave forces.

1. Introduction

The offshore wind turbine structures are slender and wave and wind loads act on the lower and the upper part of the tower. Near to the free surface zone, the wave forces may obtain their maximum values. Most of the recent substructures for wind turbines are monopiles, truss structures, tripods, gravity based structures etc. The substructures exposed to the harsh sea environment, experience the extreme impact force, run-up, scour etc. Breaking waves exert very high impact forces in very short duration on the substructures and the analysis is extremely intricate. Due to the impact force on the substructures, the

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performance and fatigue life of the offshore wind turbine is affected [1]. Wave run-up affects the design of boat landing and platform facilities of the offshore wind turbine structures.

Many laboratory and numerical studies have investigated the impact forces caused by breaking waves for oil and gas structures. The offshore wind structure is a long slender member, extending high above the mean water level and it carries the mass at the tip (rotor and nacelle). Hence, it is obvious that the dynamic characteristics of the wind turbine substructures are completely different from fixed oil and gas structures. Hence the effect of breaking wave forces on an offshore wind turbine needs to be investigated in more detail to improve the current design methods. The aim of this paper is to discuss the previous and recent research on the experimental results, numerical modeling, theoretical description of wave impact forces, design guidelines and the key issues concerning the wave impact forces on offshore wind turbine substructures.

2. Breaking wave force characteristics

2.1 Breaking waves

Breaking is initiated when the wave gains more energy, becomes unstable and dissipating the energy in the form of turbulence. During the wave breaking process, the energy of the wave system is focused close to the crest of the wave and a spatial spread of wave energy occurs [2].According to the Stokes criterion for wave breaking the particle velocity at the crest of the wave reaches the celerity. The common ratio of the wave height to the water depth at breaking is between 0.8 and 1.2. Breaking waves may occur at the site depending on the water depth, wave height, sea bed slope, wave period and steepness. Breaking waves are classified as spilling, plunging, surging and collapsing where the latter is the combination of plunging and surging [3]. The spilling and surging wave forces can be approximated as a quasi-static force. The breaking waves most relevant to offshore wind turbine structures are spilling and plunging breakers [4]. The energy from the plunging breakers is dissipated over a relatively small area, and high impulsive loads and high local pressures are exerted. Breaking wave properties are also depending on the wind-wave interaction, wave-wave interaction and wave-current interaction. There are two major uncertainties in breaking wave forces: the kinematics of the flow and the relationship between the flow and the breaking wave forces [5].

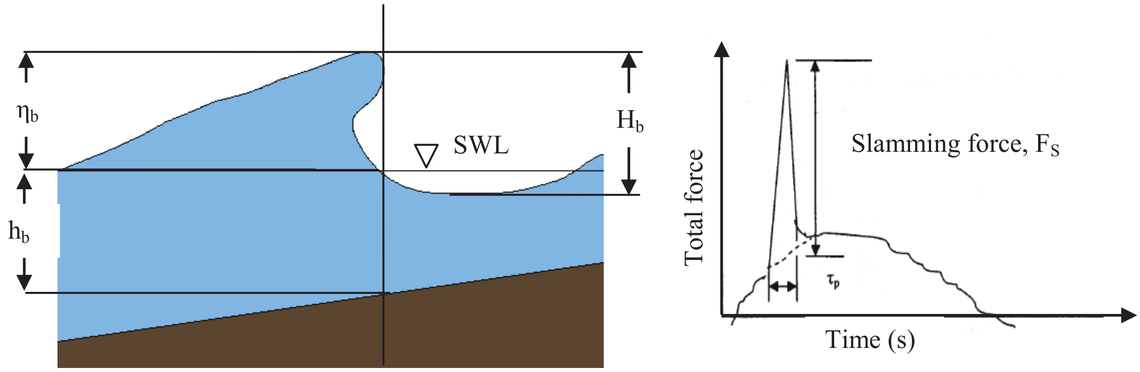
2.2 Breaking wave forces

The non-breaking wave force is normally calculated using Morison equation as the sum of the quasi static inertia and drag force, and the values of the inertia and drag coefficients are dependent on Keulegan-Carpenter number, Reynolds number, roughness parameters and interaction parameters [6]

$$F = F_D + F_M = \frac{1}{2}\int_{-d}^{\eta} \rho_w C_D D u|u| \, dz + \int_{-d}^{\eta} \rho_w C_M \frac{\pi D^2}{4}\frac{\partial u}{\partial t} dz \qquad (1)$$

where F_D is the drag force, F_M is the inertia force, C_D is the drag coefficient, C_M is the inertia coefficient, ρ_w is the mass density of water, D is the pile diameter, u is the water particle velocity and t is time. The Morison equation is generally valid for small diameter members that do not considerably modify the incident waves, and it depends on the ratio of the wave length to the member diameter. The Morison equation is applicable when this ratio is larger than 5.0.

For design purposes, the impact force is previously approximated by considering only the drag force component and multiplying by a factor of 2.5 [7]. The total wave force on a sub-structure due to breaking waves can be divided into a quasi-static force and an impact force called slamming force. The quasi-static force can be well described by the Morison equation and the impact force component must be added with



the Morison equation to determine the total wave force due to the breaking waves.

Figure 1 (a) Breaking wave parameters (SWL= Sea water level) and (b) The nature of the slamming force.

Three different approaches are used to account for the impact forces due to breaking waves in the structural design. First, a simple approach to estimate the impact force by applying the non-linear wave kinematics (non-linear wave theory) in the breaking zone to the structural members using Morison equation with conventional force coefficients [8].

Second, the impact force can be represented by the drag term of Morison's equation based on the relative velocity of the member to the water particle and with a suitable drag coefficient, because of the uncertainty involved in the prediction of accelerations caused by breaking waves [5, 9, 10]. In the splash zone, submerged structural members are vulnerable to wave impact due to the action of breaking waves. Moreover, the influence of the change in the momentum (inertia forces) is very important to account for the impact forces.

Third, if the wave breaks against the structure the Morison equation ought to be modified or expanded to include the wave breaking effect, especially due to plunging breakers on the slender structure. The nature of the slamming force is indicated in Fig. 1(a). However, the force coefficients in the Morison equation cannot describe the impact force of very short duration typically of the order of milliseconds. Hence it is imperative to add an extra term in Eqn. (1) to include the impact force effect (slamming force) in the total wave force [5, 11],

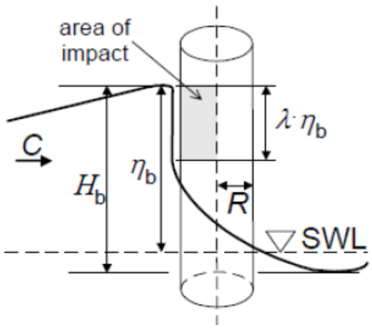
$$F = F_D + F_M + F_S \tag{2}$$

$$F_S = 0.5\rho_w C_s D C_b^2 \lambda \eta_b \tag{3}$$

Here F_s is the slamming force, C_s is the slamming force factor, C_b is the breaking wave celerity (the water particle velocity is set equal to the wave celerity at breaking), and λ is the curling factor which indicates how much of the wave crest is active in the slamming force as shown in Fig. 1(a).

2.3 Impact force characteristics

Basically, the impact force is caused by the collision of the upright wave front with a structure leading to a change in the forward momentum which yields a force of large magnitude in a short duration [11]. A particular characteristic of plunging wave impacts is the considerable variation of the peak between different impacts. Fig. 2 shows a circular cylinder exposed to a breaking wave and the various parameters of the breaking process. The wave breaking is always associated with extreme velocities and accelerations with high surface elevations.



C is the wave celerity

H_b is the wave height at the breaking location

η_b is the maximum free surface elevation

R is the radius of the cylinder

λ is the curling factor

Figure 2 Breaking wave impact force on a circular cylinder [13]

Hence the structural members in the splash zone experience the severe loading due to breaking waves [5].The rising time is the time at which the impact force reaches its maximum value and it plays a vital role in the dynamic response of the structure. In fact, the rising time distribution affects the slamming force amplification since it is nondeterministic. Further, the maximum impact force response may be driven by the dynamic response of the structure [10]. According to Goda's theory [11], the rising time is zero as in the case of vertical wall. Later, the importance of the wave front inclination is addressed by Sawaragi et al. [12]. The angle of inclined wave front is an important parameter to find the rising time and the initial sudden rise in the impact force [12]. In addition to that the surface roughness of the structure also tends to increase the rise time and reduces the magnitude of the amplification. The factors affecting the impact forces are the compressibility of the air between the cylinder and the water surface, water depth, curling factor, entrapped gases in the water, cylinder surface irregularities, rise time etc. [10].

3. Wave impact models

The wave impact acts for a very short time relative to the wave period and with high amplification. In general various factors affect the wave impact force such as irregular sea, the compressibility of air between the structural member, the compressibility at the beginning of impact, three-dimensional shape of the sea surface, size and shape of the air bubbles near the free surface and sea bed slope [13]. Hence the description of the wave impact model becomes complex. One of the first attempts to investigate the impact force on a body during landing on the water was performed by von Karman [14]. The impact force on the cylinder is approximated as a flat plate with a width equal to the immersed width of the cylinder and integrating the force over the height of the impact area results the impact force. In his theoretical model, the raise of the free surface elevation during the impact, the so called pile-up effect, is neglected, which affects the duration and magnitude of the impact force [2]. Later, the model developed by Wagner [2] includes the pile-up effect. Thus, the wetted surface estimated by Wagner's model is higher than the von Karman's model and hence the slamming coefficient is also higher in the former case. The maximum inline force at the beginning of the impact can be obtained by applying the approach of von Karman and Wagner. The von Karman model is implemented by Goda et al. [11] and Tanimoto et al. [15] to calculate the wave impact forces on vertical cylinders. The theoretical model presented by Wienke and Oumerachi, [7] is based on the Wagner's theory. The non-linear velocity terms in the Bernoulli equation are considered in order to account for the temporal development of the impact. The description of the shape of the body is very important to predict the immersed width of the cylinder and is approximated as an ellipse by Fabula [7] and a parabolic shape by Cointe and Armand [7].

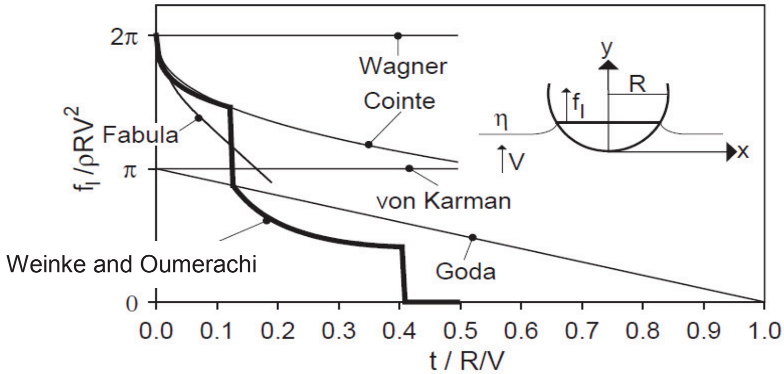


Figure 3 Comparison of time histories of the inline force, (t=time, R=cylinder radius, V=cylinder velocity) [7]

For the direct impact force on the upright cylinder, the quadratic parabola representation is applicable at the beginning of the impact; it is not valid for the total duration of the impact [7]. To improve the approximation, Wienke and Oumerachi [7] described it as a circular shape and introduced a polynomial stepwise function to describe the wetted surface of the circular cylinder. In the case of impact with an angle (oblique), then the shape of the body has to be described as an elliptical shape instead of a circular shape. The comparison of time histories of inline force for the different theoretical models is shown in Fig. 3.

There are two theoretical models based on the study of the penetration of a horizontal circular cylinder entering into calm water at various constant down ward velocities: Sarpkaya [10] and Campbell-Weynberg [16]. The theoretical model by Sarpkaya [10] predicts the design forces on a horizontal cylinder subjected to impact, but this model does not describe the impact area and the curling factor [13]. Though, the wave slamming coefficient depends on the rising time and the natural period of the structure. The impact model by Campbell and Weynberg [16] recommends that the slamming coefficient of the fully submerged cylinder is 0.8, but the model does not define the curling factor [16].

4. Experimental investigations of impact forces due to breaking waves

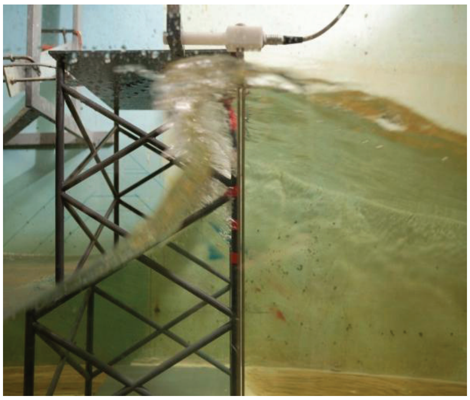
4.1 Investigations on cylindrical structures

Goda et al. [11] investigated the impact forces on the circular and triangular vertical cylinders and the study includes the information of force-time relationship. They assumed that the impact force is the result of the change in momentum of the water mass of a vertical wave front and they have not considered the rising time of the impact force [12]. The experiments by Sawaragi and Nochino [12] revealed that the wave front is not always vertical and that the front shape of breaking wave determines the rising time of the impact force. Moreover, its magnitude depends on the wave breaking pattern and the wave breaking point. The vertical distribution of the peak values was found to be a triangular shape whose peak appears at the height about 70% of the wave crest above the still water level. They defined the total force as the sum of three forces; the impact force, the force by Morison's equation and the static pressure caused by the difference of water levels between the leeward and the seaward sides of the cylinder, and the largest value of the total force is seven times as large as the Morison's force. Watanabe and Horikawa [11] observed that the phase difference between the accelerations of the water particles and the inertia forces must be considered for the estimation of both the drag and the inertia coefficient.

All the previous tests, except those by Wienke and Oumeraci [7], have been carried out at a fairly small scale with cylinder diameters typically 5–10 cm. They carried out tests in a large wave flume with a cylinder with diameter 0.70 m, water depths approximately 4 m and with wave heights up to 2.8 m. They found that the pile-up effect considerably affects both the duration and the magnitude of the impact force. Further, they observed that the distance between wave breaking and cylinder greatly influences the magnitude of the impact force, and the impact force is proportional to the curling factor, which depends on inclination angle of the cylinder and on the angle of the wave front inclination. Ros [17] and Arntsen et al. [18] carried out tests on the wave slamming forces on a single pile where local force responses were measured at different elevations.

4.2 Investigations on truss structures

The wave forces on a truss structure on this scale are subjected to scale effects, especially the Morison type forces. However the results obtained are nevertheless of interest and suggest that tests on a larger scale are needed before any final conclusion on wave slamming forces on truss structures can be made. There has not been carried out any major investigation on the wave impact forces on truss structures. Results from an introductory experimental study carried out to find impact forces on truss structures in scale1:50 by Aune [19] are shown in Fig. 4(a). Aune [19] made a brief analysis of the wave forces and used these forces to calculate the response of a full scale structure. Tørum [20] has made some additional analysis of the responses measured by Aune [19]. As seen in the Fig.4 (b), there is a low frequency part and a high frequency part of the response. The low frequency part is the Morison force part, while the high frequency part is from the wave impact. The recorded response force is corrupted from dynamic effects on the model from the impacts. The challenge is to extract the wave impact force from the force response signal, taking the dynamic effects of the model-measuring system into account. This is normally done by using a convolution technique, e.g. similar to what Ros [17] did for a monopile. However, this has not been pursued so far on the truss structure model. As aforesaid, the wave slamming force on a monopile occurs when the crest region of the wave hits the pile.



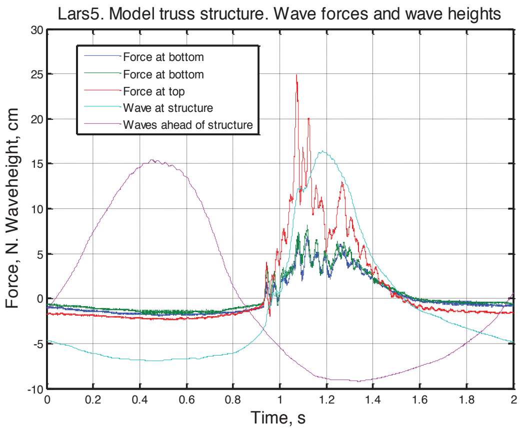


Figure 4 (a) Wave impact test at NTNU (b) General appearanse of the wave and response force recordings.

Table 1 Comparison of different wave impact models

Authors	Theory	C_S	Vertical force distribution
Goda et al. [11]	von Karman	π	Uniform
Sarpkaya [10]	A method by Kaplan [16]	For dynamic analysis: π or otherwise 5.5	Depends on the rise time and natural period
Sawaragi and Nochino [12]	Experimental study	π	Triangular
Tanimoto et al. [15]	Von Karman and Wagner	π	Triangular
Weinke and Oumerachi [7]	Wagner	2π	Uniform
Ros [17]	Experimental study	4.3	Triangular

In the case of truss structures, there are apparently some impacts caused by low wave surface elevations from the mean water level (approximately) as shown in Fig. 4(b). A truss structure has been designed for the Thornton bank outside the Belgian coast, where plunging breakers have been specified, and that the wave slamming forces from plunging breakers are governing the stresses in this structure [22]. Table 1 provides a comparison of different experimental and theoretical wave impact models for single circular cylindrical structures.

5. Numerical simulations of impact loads due to breaking waves

The estimation of the total wave force using Morison equation with the von Karman or the Wagner impact models requires the input of wave kinematics. Nevertheless, there are many uncertainties in the application of the wave theories to describe steep and breaking waves in shallow water [21]. Hence the numerical simulation may be an alternative to the exact description of the shallow water impact forces. The numerical description requires the modeling of wave-structure-air interaction during the impact [22]. The most destructive impact occurs when a breaking wave approaches the structure with almost vertical front and entrapping a small air pocket at the wall [23]. Numerical simulations of offshore wind turbines should include a fully non-linear model to account for breaking wave impact loads on offshore wind turbines.

Wu et al. [24] simulated the impact wave force due to breaking waves without entrapped air on a vertical wall by describing the complex free surface and splashing, and breaking by the Volume of Fluid (VOF) technique. Zhang et al. [25] studied the impact of a two-dimensional plunging wave on a rigid vertical wall using a Boundary Element Method (BEM) and scaled the maximum impact pressure by the breaker parameters. BEM has some limitations in modeling the post-breaking and the extreme turbulent impacts. Hence the model must include the complete flow physics based on the solution of Navier-Stokes equation [26]. Christensen et al. [22] demonstrated the coupling of a Boussinesq wave model with a Computational Fluid Dynamics (CFD) solver for the wave-structure interaction problems. This model is applied to calculate the wave loads on the wind turbine substructures and the new model reduced the computational time. Mokrani et al. [26] investigated the impact force and the overtopping flow generated by plunging breaking waves on a vertical wall by combining Navier-Stokes equations and VOF technique (NS-VOF).

Bredmose and Jacobsen [23] studied the extreme spilling breaking wave loads on a monopile foundation of an offshore wind turbine using Open Field Operation and Manipulation (OpenFOAM).
Christensen et al. [22] studied the extreme wave run-up and wave forces on monopile for offshore wind turbines using the NS-VOF. It was observed that the run-up caused by nearly breaking waves is higher than the run-up due to periodic waves. Corte and Grilli [27] modeled the extreme wave slamming on monopile offshore structures using a NS-VOF for two-phase flow. Nielsen et al. [28] studied experimentally and numerically the effect of three-dimensional waves on the wave run-up and predicted the maximum run-up using a fully non-linear NS-VOF technique. Bredmose and Jacobsen [29] investigated the vertical wave impact force and subsequent run-up on a monopile sub-structure using a VOF method.

6. Recommendations from standards for the wave impact forces

There are several design guidelines for the prediction of design wave impact forces from wave breaking on vertical cylinders. Though, there are limited guidelines for design impact forces on truss structures. The IEC 61400-3 [4] standard recommends that extreme events for the design load phase should account for the stochastic nature of both wind and wave loading, the flexibility of the structure and the non-linear nature of waves simultaneously. The load due to the wave run-up should be considered to the design of the low level platforms. If an offshore turbine is located near a coastal breaking wave zone, the coupled wave and current model should take into account the surf currents generated by the breaking waves. API RP 2A-WSD [30] suggests the slamming coefficient value between 0.5π and 1.7π depending on the rise time and the natural period according to Sarpkaya [10]. Slamming forces affect the local structural member design. According to DNV- OS-J101 [15] and DNV-RP-C205 [16], slamming on horizontal cylinders can be predicted using a method described by Kaplan [16] and slamming on vertical cylinders can be represented by the Campbell and Weynberg [16] impact model.

The air entrainment increases the rise time and reduces the maximum impact forces. In sea water, the bubbles are smaller and disappear slowly where as in fresh water, the bubbles are larger and disappear quickly. Hence it is recommended that the water properties should be considered for the slamming experiments [16]. Table 2 shows the comparison of design guidelines for the impact loads.

7. The key issues in the performance of an offshore wind turbine under the influence of wave impact forces

First, in the case of impact forces, the reaction forces are highly important and do distinctly depend on the structural response and the shape of the structure [32]. Breaking waves may potentially cause significant dynamic amplifications of the structural response on substructures.

Table. 2 Comparison of design guidelines for the impact loads [14]

Design standards	IEC 61400-3 [4] GL [31] ABS [21]	DNV-OS-J101[15] DNV-RP-C205[16]	API RP 2A-WSD [30]
Theoretical model	Wienke and Oumerachi model [7]	For Horizontal cylinders-Kaplan [16] For Vertical cylinders-Campbell & Weynberg [16]	Sarpkaya [10]
Slamming Coefficient (C_S)	2π at t=0 for force per unit length	5.15 at t=0 for force per unit length	0.5π to 1.7 force per unit length

	Time invariant	Time invariant	For dynamic analysis- π Otherwise 5.5

The consequence of large breaking wave forces would increase the probability of fatigue failure and affect the design of the offshore wind turbine structures, which will result in large stiff structures that are more expensive [1]. Moreover, breaking waves affect the global dynamic load and responses [13].

Second, wave run up indicates a complex process that is dependent on a number of wave characteristics, structure conditions and local effects. The strong wave run-up induces an additional inline force and overturning moment on the lower level platforms. Moreover, the short duration vertical impact forces may excite structural ringing at very high frequencies [23]. The report [28] has shown that wave run-up has removed the grating at the access platforms located 9m above mean sea level and affected the access ladders at the Horns Rev offshore wind farm [28]. Experiments have shown that the long waves with higher crest velocities have large influence on the wave run-up [33]. The important design parameters of these platforms are maximum wave run-up height and the associated forces.

Third, the scour process around the base of the sub-structure is due to erosion of the bed soil due to the combined wave and current induced flow velocities and it is the complex interaction between the incoming flow, the base of the sub-structure and the sea bed. The depth of this scour is in the order of 1.5 times the pile diameter. However, combination of a current with waves in the same direction is relative long waves, results in an increase of scour around the base of truss structure, so called "dish pan scour" [34]. It is clear that the scour affects the stability and the dynamic behavior of the offshore substructures. Hence the substructure design should consider the wave and current induced scour.

8. Summary

A detailed literature review is carried out to study the influences of the breaking waves and the associated effects on offshore wind turbine structures. The considerable uncertainties in the estimation of hydrodynamic loads, fatigue life and the extreme loads are caused by the breaking waves. The design loads of offshore wind turbine are more sensitive to the dynamic characteristics than the offshore oil and gas structures [21]. Hence the design methods and guidelines need to be investigated in detail for offshore wind turbine substructures.

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