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A review of slamming load application to offshore wind turbines from an integrated perspective

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Abstract

In harsh sea conditions, it is possible for offshore wind turbines (OWTs) to be exposed to slamming loads due to breaking waves, especially plunging breaking waves. These slamming loads lead to significant structural responses and can affect the ultimate limit state (ULS) design and the fatigue limit state (FLS) design of OWTs. However, detailed consideration of slamming loads is not a common practice in the design of primary structures in offshore wind industry. Studies on integrated dynamic analysis of OWTs with consideration of slamming loads are very limited. When applying slamming loads on OWTs, several aspects should be considered, such as the detection of breaking waves, the calculation of slamming loads, and the approaches to integrate the slamming loads in fully coupled analysis, etc. This paper provides an extensive review of key issues concerning these aspects, which can benefit the application of slamming loads on OWTs.

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Keywords: Breaking waves; slamming loads; integrated dynamic analysis; offshore wind turbine

1. Introduction

Slamming loads resulting from plunging breaking waves are dangerous for offshore wind turbines (OWTs) exposed to certain wave conditions. Although many studies have been carried out in the past decades about slamming loads and their application to OWT designs, detailed consideration of slamming loads is still not a common practice in the design of primary structures in offshore wind industry. The slamming load application involves many research topics in oceanography and ocean engineering, which have been elaborated separately in their respective fields. However, a state-of-the-art method that takes different aspects of the application problem into account is still in absence; accord-

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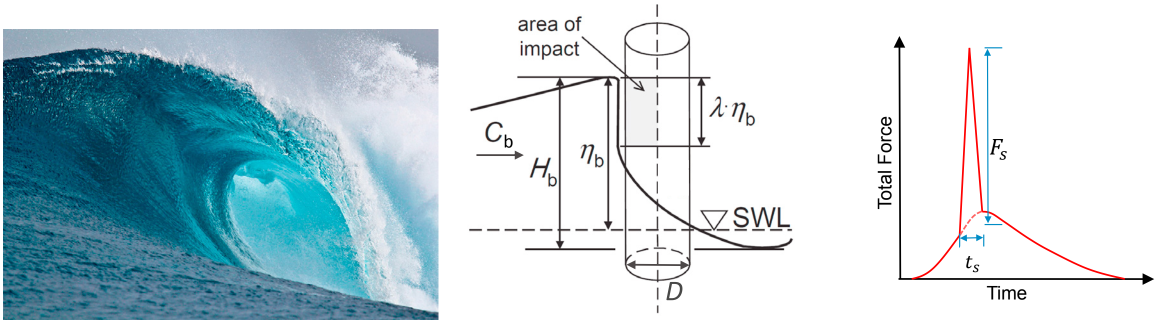
ingly, the numerical tools used in offshore wind industry usually do not have a function to include slamming loads in the simulations. These limitations restrain the application of slamming loads in the design practice of OWTs.

This study starts from an general introduction of breaking waves and slamming loads. Then, how to include the slamming load in the integrated dynamic analysis of OWTs is thoroughly reviewed and discussed, including the detection of slamming events, the calculation of slamming loads and the integration of slamming loads in fully coupled analyses. The status and issues of slamming load applications are discussed and some improvement possibilities are proposed.

2. General slamming force characteristics

2.1. Breaking waves

A breaking wave is a wave whose amplitude reaches a critical level at which it becomes unstable and dissipates large amounts of wave energy into turbulent kinetic energy. It may occur at certain sites, depending on the local water depth, the breaker height, the local wave length, the wave steepness, the sea bed slope and probably some other parameters. Among different types of breaking waves, the plunging breaking wave is most relevant to slamming loads on the offshore wind turbine supporting structures. It features a relatively small dissipating area, a very high local pressure and a high impulsive load. In this paper, wave slamming loads due to plunging breaking waves are mainly reviewed and discussed.



(a) Plunging breaking wave (b) Sketch of a breaking wave [28] (c) Typical wave slamming force

Fig. 1. Breaking wave and wave slamming force on a circular cylinder

2.2. Slamming load

The quasi-static wave force on a slender cylindrical structure is normally calculated by the Morison's equation as

$$F_{qs} = F_D + F_M \tag{1}$$

where F_D and F_M are the drag and inertia forces, respectively, and they are expressed as

$$F_M = \int_{-h_b}^{\eta_b} \rho \pi C_m \left(\frac{D}{2}\right)^2 a_x dz \tag{2}$$

$$F_D = 0.5 \int_{-h_b}^{\eta_b} \rho C_D D u \left|u\right| dz \tag{3}$$

in which ρ is the water density, η_b is the wave elevation at the breaking point, D is the diameter of the cylindrical structure, u and a_x are the velocity and acceleration of water particle. C_D and C_m are the drag and inertia coefficients, respectively, and they are dependent on Keulegan-Carpenter number, Reynolds number, roughness parameters and interaction parameters.

However, the Morison's equation is not sufficient to represent the wave force due to the plunging breaker on the structures. The force coefficients in the Morison's equation cannot describe the wave impact force of very short duration, typically of the order of milliseconds. A common engineering practice is to add an extra term F_S in Eq. 1 to represent the slamming load in the total wave force.

$$F = F_D + F_M + F_S \tag{4}$$

In the most general case, F_S is expressed as

$$F_S = \int_l C_s(z)\frac{1}{2}\rho U(z)^2 W(z)dz \tag{5}$$

where C_s is the slamming coefficient; U is the velocity of the water particles impacting the structure; and W is the effective width of the structure. The values of these three parameters depend on the height z. By integrating the line force at different z over the whole impact height l, the total slamming force is obtained.

There are many simplified expressions of Eq. 5, depending on the used slamming load model to be discussed in Section 3.2.3. For example, by using the model proposed by Wienke and Oumeraci [28], Eq. 5 for a cylinder is expressed as

$$F_S = C_s\frac{1}{2}\rho C_b^2 D\lambda\eta_b \tag{6}$$

The impact height range l is a portion of the breaking elevation $\lambda\eta_b$, where λ is the curling factor which indicates how much of the wave crest is active in the slamming load, as shown in Fig. 1. η_b is the wave elevation at the breaking point. The line force is considered to be constant over the impact height range. The water particle velocity U is approximated by the breaking wave celerity C_b, and the width W is the diameter of the cylinder D.

3. Slamming load application for offshore wind turbines

Three indispensable aspects should be considered for slamming load application on OWTs, i.e. how to detect a slamming event, how to calculate the slamming load and how to integrate it into fully coupled analysis. In each of the aspects, there are various issues that should be considered in more detail as shown in Fig. 2.

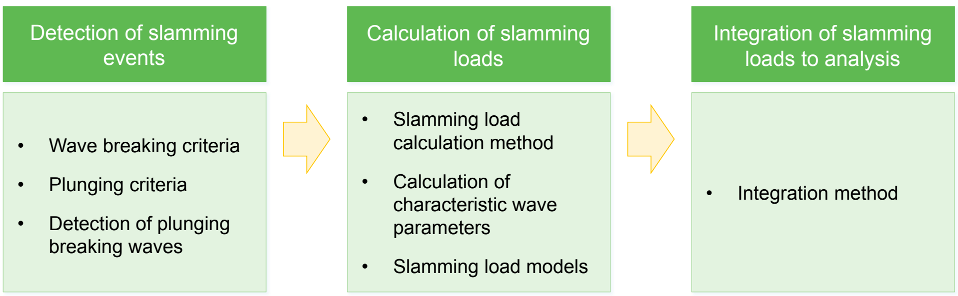


Fig. 2. Three aspects involved in slamming load application on OWTs

3.1. Detection of slamming events

The slamming load should only be considered when this event occurs in the vicinity of the structure. For a certain wave condition, a suitable breaking criterion should first be applied to judge whether a wave is broken or not. If the wave is broken, the plunging breaking criteria should then be applied, since plunging breaking waves are most relevant to slamming loads. These criteria are commonly developed for regular waves, however, OWTs are usually exposed to irregular waves, a suitable approach is then required to detect the incidence of plunging breaking waves from large amounts of irregular waves.

3.1.1. Wave breaking criteria

A large amount of effort has been made to identify the criteria for the inception of wave breaking. Robertson et al. [24] summarized the characteristic relationships of breaking waves theorized by different authors and their regions of applicability. Perlin et al. [23] reviewed the state-of-the-art progress of breaking waves in deep and intermediate waters, including the prediction of their geometry, breaking onset, and especially energy dissipation.

However, to find an intrinsic relation for a wave breaking in a general form is not easy. Liu et al. [15] extensively reviewed the existing formulas for the inception of wave breaking. By defining different breaking index, these formulas can be classified into four types, i.e. the McCowan [18] type, the Miche [19] type, the Goda [7] type, the Munk [20] type.

- The McCowan [18] type:

$$\frac{H_b}{h_b} = \gamma\,(s, \lambda_0) \tag{7}$$

- The Miche [19] type:

$$\frac{H_b}{L_b} = \alpha\,(s, \lambda_0) \tanh\left[\xi\,(s, \lambda_0)\,\frac{2\pi h_b}{L_0}\right] \tag{8}$$

- The Goda [7] type

$$\frac{H_b}{L_0} = \alpha'\,(s, \lambda_0)\left\{1 - \exp\left[-1.5\xi'\,(s, \lambda_0)\,\frac{2\pi h_b}{L_0}\right]\right\} \tag{9}$$

- The Munk [20] type

$$\frac{H_b}{H_0} = \beta\,(s)\left(\frac{H_0}{L_0}\right)^m \tag{10}$$

where H_b, h_b, and L_b are the wave height, water depth, and wave length at the breaking point, H_0 and L_0 are the wave height and wave length in deep water. s is the bottom slope and $\lambda_0 = \frac{H_0}{L_0}$ is the wave steepness. γ, α, α', ξ, ξ' are coefficients that are dependent on s and λ_0. β is a coefficient as a function of s.

Within each type, several authors developed different formulas, The assumptions and regions of applicability for each formula should be aware of when the formula is employed. In addition, to compare the accuracy of these four types [15], one representative formula in each type was chosen and verified by a total number of 1193 experimental cases, covering a wide range of beach slope from 1/100 to 1/3. It was stated that the Goda's formula proposed in [8] is the best among the selected four criteria if excluding the data with the beach slopes larger than 1/10.

Liu et al. [15] also proposed a new predictive formula for the inception of regular wave breaking, by introducing a new breaking index, $\frac{gH_b}{C_b^2}$. By analyzing a large number of data, a breaking criterion was achieved. This criterion was claimed to be highly accurate for predicting the inception of regular wave breaking.

It should be noted that these wave breaking criteria are related to the bottom slope s, which implies breaking waves are more pronounced in the slope region. The above wave breaking criteria have been used in recent studies on slamming load application to OWTs. Marino [17] employed the Miche [19] type criterion, i.e. $\frac{H_b}{L_b} = 0.142 \tanh\left(\frac{2\pi h_b}{L_0}\right)$. Hallowell et al. [10] used four criteria, including the McCowan [18] wave limit $\frac{H_b}{h_b} = 0.78$, the Miche [19] wave limit $\frac{H_b}{L_b} = 0.142 \tanh\left(\frac{2\pi h_b}{L_0}\right)$, the Goda [7] wave limit $\frac{H_b}{L_0} = 0.17\left\{1 - \exp\left[-1.5\frac{\pi h_b}{L_0}\left(1 + 15s^{4/3}\right)\right]\right\}$, and the Battjes [11,13] wave limit $\frac{H_b}{h_b} = 0.78 \tanh\left(\frac{0.14g}{2\pi(0.78h_b)}T_z^2\right)$. By comparing these criteria with breaking events measured, it was stated that the Goda limit identifies fewer false positives than Miche and Battjes limits [10].

3.1.2. Plunging criteria

Another important aspect for slamming event detection is plunging criteria. The breaking waves are usually classified into three types: spilling, plunging and surging [11] (or sometimes four types with an additional collapsing type). The wave profile of each type is different. The plunging breaking waves are the ones that cause the impulsive slamming loads. For slamming events to occur, the waves should not only fulfill the breaking criteria but also the plunging criteria.

The most common way to categorize the breaking waves is through surf similarity parameters [12].

$$\xi_o = \frac{\tan\alpha}{\sqrt{\frac{H_o}{L_o}}} \tag{11}$$

or

$$\xi_b = \frac{\tan\alpha}{\sqrt{\frac{H_b}{L_o}}} \tag{12}$$

in which α is the sea floor slope in radians.

According to IEC 2009 [11], the criteria for plunging breaker are

$$0.45 < \xi_o < 3.3 \tag{13}$$

or

$$0.4 < \xi_b < 2.0 \tag{14}$$

In fact, many studies have been carried out to discuss and correct the critical values for the criteria, and the results are different, depending on e.g. the bathymetry.

In order to apply the plunging criteria based on surf similarity parameters, the seabed slope has to be known, which is not always the case in reality. This limits the application of the criteria in practice. In another classification system, which is proposed recently by Yao et al. [29], a ratio of breaker depth to offshore wave height $\frac{h_b}{H_o}$ is used. The plunging breaker occurs if $\frac{h_b}{H_o} < 1.8$.

In the recent studies about slamming load application in OWTs, the plunging criteria are not used for slamming detection. Both Hallowell et al. [10] and Marino [17] assume that the slamming events occur as long as the breaking criteria are fulfilled regardless of the breaking type. This approach is reasonable, since the available research results on the plunging criteria and the available information about the site are not enough for detecting the plunging breakers. Nevertheless, it is essential to use proper plunging criteria in order to detect the slamming events more accurately, and further investigations on the criteria are therefore desired.

3.1.3. Detection of plunging breaking waves

The ideal approach to detect the breaking wave is based on the spatial evolution of wave breaking. Such kind of spatial evolution can be captured by computational fluid dynamics (CFD) methods, as those done by Christensen et al. [4], Corte and Grilli [6], Nielsen et al. [22], Bredmose and Jacobsen [2], Jose et al. [14] and Alagan Chella et al. [1]. However, the CFD methods are usually time consuming.

The detection of wave breaking can be simplified given the wave elevation. When performing the numerical simulations, it is possible to simulate the irregular wave field around the structure. At every time step in the time domain simulation, the spatial variation of the waves is acquired and can be analyzed by zero up- or down-crossing methods. The zero-crossing analysis divides the sequential wave into a series of individual waves, and for each individual wave,

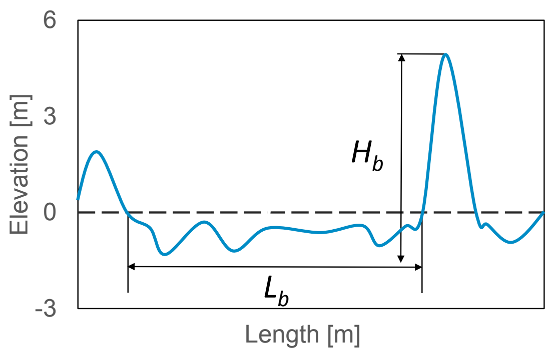


Fig. 3. Zero-crossing analysis of wave profile to get wave height H_b and wave length L_b

the characteristic parameters, such as the wave height, wave length, wave period, etc. can be determined. Then, by applying a suitable breaking wave criterion and a plunging criterion, the individual breaking wave that is likely to break is identified. Such method is adopted by Marino [16,17] to identify the likely breaking waves. However, such method cannot capture the wave profile when it breaks.

When analyzing the measured data from an offshore site, the approach for breaking wave detection is quite different. Currently the wave elevation or sea surface data usually include measurements from a single point, which cannot capture the spatial evolution of wave breaking. Other indicators, such as the measured structural response, are therefore required to detect the slamming events. Hallowell et al. [10] employed the measured mudline bending moment as an indicator. If one peak in the measured moments is several times higher than the rest of time history, it implies that a wave has broken at or near the structure and it is a slamming event.

3.2. Calculation of slamming loads

3.2.1. Slamming load calculation method

In order to calculate and to include the slamming loads in the general wave loads, both an engineering approach and a numerical approach can be used. Based on the CFD, the numerical approach models the interaction of breaking waves with the structure. This approach costs tremendous simulation time and is therefore not suitable during the primary design phase of OWTs.

The engineering approach calculates the slamming load by employing a wave slamming load model. The slamming force model features a slamming coefficient and a certain force distribution pattern in space and in time. It also requires certain characteristic wave parameters, for instance the wave celerity in the model by Wienke and Oumeraci [28]. The engineering approach estimates the slamming load very quickly, hence it is a desirable way to integrate the slamming load into fully coupled analyses. However, this approach is highly dependent on the used wave slamming load model. In Sections 3.2.2 and 3.2.3, the characteristic wave parameters and wave slamming load models involved in the engineering approach are further discussed.

3.2.2. Calculation of characteristic wave parameters

During the detection of wave breaking by zero-crossing analysis of a wave field, the characteristic wave parameters can be acquired as well. However, as mentioned above, zero-crossing analyses can only detect likely breaking waves, but the characteristic parameters of the wave cannot be estimated very accurately. A possible way to improve the accuracy of the estimation is to use advanced methods to further simulate the evolution of likely breaking waves. Marino [16,17] used the domain decomposition technique to achieve this. The computational field was divided into two sub-domains. In the sub-domain without the structure, a potential flow theory was used. In the sub-domain containing the structure, a mixed-Eulerian-Lagrangian (MEL) method was used to further simulate the likely breaking waves. In this way, the wave profile at the breaking instance is simulated, so the accuracy of the characteristic breaking wave parameters is improved at a relatively small cost of computational time.

In the field measurements, these characteristic breaking wave parameters cannot be directly achieved. Assuming that the spatial evolution of waves can be approximated by their temporal evolution, these parameters can be calculated approximately. This is the method used by Hallowell et al. [10], which involves the following steps:

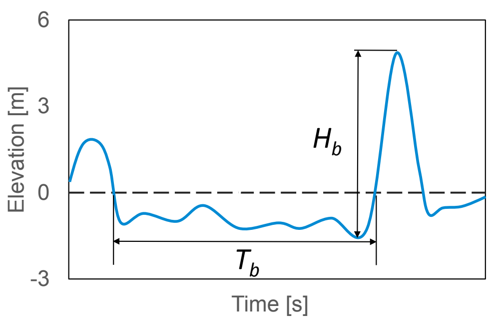


Fig. 4. Zero-crossing analysis of wave time history to get wave height H_b and wave period T_b

1. Data processing is carried out to remove any tidal or surge variance in the sea surface data, so as to obtain a zero-mean wave profile and identify individual waves and their associated parameters, such as height and period. The data are smoothed using a 1 s moving average to remove high-frequency noise from the wave measurements.
2. Down-crossing analysis is carried out to obtain individual wave characteristics, such as the height, the period and the depth. The structural response data recorded are synchronized with the wave profile data.
3. The slamming events are detected from the record of the structural response, and the wave parameters are determined for each of these events.

3.2.3. Slamming load models

Cylindrical structure

Wave slamming loads act on offshore substructures in a very short time and with a very high amplitude, as illustrated in Fig. 1. It is a strongly nonlinear phenomenon and is affected by various factors, such as compressibility of water, hydroelasticity of the structure, air bubbles entrapped, cavitation and ventilation etc.

One of the first attempts to theoretically investigate the wave slamming load was performed by von Karman [26]. The cylinder is approximated as a flat plate with a width equal to the immersed width of the cylinder. However, the local raise of the free surface during the impact is neglected, which affects the duration and magnitude of the slamming force. Later, Wagner [21,27] took the local raise into account. Currently there are several common wave slamming load models, as given in Table 1. Among them, the von Karman theory is implemented by Goda et al. [7], and Wagner theory is employed by Wienke and Oumeraci [28]. In addition to Wagner's method, Cointe and Armand [5] also derived the asymptotic expressions for the inner domain and outer domain at the spray root during the impact and further solved the problem by matching the inner and outer asymptotic expressions. Experimental study is another approach to determine the slamming coefficient, as conducted by Campbell and Weynberg [3].

Table 1. Comparison of different wave slamming models for cylindrical structures and jacket structures (modified from [10])

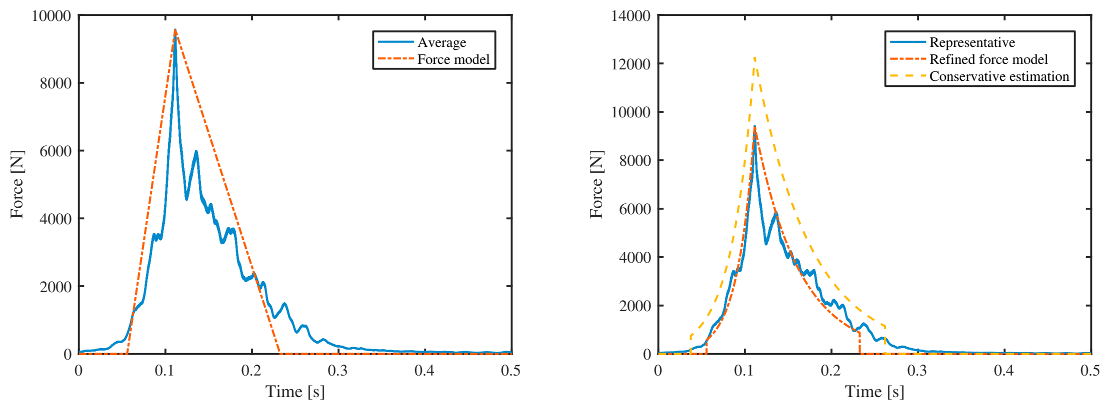
	Author	Theory	Maximum C_s	Slam duration, t_s	Time history, $C_s(t)$
Cylindrical structure	Goda et al. [9]	von Karman	π	$\frac{D}{2C_b}$	$\pi\left(1 - \frac{2C_b}{D}t\right)$
	Campbell and Weynberg [3]	Experimental study	5.5	$\frac{D}{C_b}$	$5.15\left(\frac{D}{D+19C_bt} + \frac{0.107C_bt}{D}\right)$
	Cointe and Armand [5]	Wagner and matched asymptotic expansions	2π	$\frac{3D}{2C_b}$	$2\pi - \left(4.72 - \ln\left(\frac{2C_b}{D}t\right)\right)\sqrt{\frac{2C_b}{D}t}$
	Wienke and Oumeraci [28]	Wagner	2π	$\frac{13D}{64C_b}$	$2\pi - 2\sqrt{\frac{2C_b}{D}t}\left(\tanh^{-1}\sqrt{1 - \frac{C_b}{2D}t}\right)$ (for $0 \le t \le \frac{D}{16C_b}$) $\pi\sqrt{\frac{1}{12}\frac{D}{C_bt'}} - \sqrt[4]{\frac{16}{3}\frac{C_b}{D}t'}\tanh^{-1}\sqrt{1 - \frac{2C_b}{D}t'\sqrt{\frac{12C_b}{D}t'}}$ $t' = t - \frac{D}{64C_b}$ (for $\frac{D}{16C_b} \le t \le \frac{13D}{64C_b}$)
Jacket structure	Tu et al. [25] Simplified	Experimental study	2.05	-	Triangular
	Tu et al. [25] Refined	Experimental study	2.05	-	Exponential

These four wave slamming models provide time dependent slamming coefficient as well as the slamming duration, which are very helpful for slamming load application in the design practice. However, these four models are originally developed for a 2D slamming problem, hence the vertical distribution of slamming load is not taken into account. When applying these models, the vertical force distribution is usually assumed to be uniform or triangular. These models do not consider many factors that affect the wave slamming loads, such as nonlinear irregular waves, water particle velocities at free surface and the spatial variation of slamming loads. But laboratory experiments has shown that slamming loads approximated by these models are reasonable [28]. Additionally, the IEC 61400-3 standard [11] recommends the Wienke and Oumeraci [28] model for designing OWT support structures.

Jacket structure

Jacket structures are made of several cylindrical legs and braces. The waves approaching the aft legs and braces are affected by the front legs and braces. This will cause a more complicated slamming scenario than for a cylindrical structure. Consequently, the global response of jacket structures subjected to wave slamming force is different. Based on the experimental data from the WaveSlam project, Tu et al. [25] investigated the global slamming loads due to plunging breaking waves on jacket structures. A total of 3910 time series were reconstructed and statistically analyzed. The mean slamming coefficient is found to be about 2.05 at a curling factor of 0.4. Tu et al. [25] also proposed two wave slamming load models, i.e. a 3-parameter triangular force model and a 5-parameter exponential force model, to represent the temporal development of global wave slamming load on jacket structures, as demonstrated in Figure 5.

However, these two models by Tu et al. [25] are proposed for breaking waves impacting the front legs of the jacket structure. They are not applicable to estimate the slamming load on the aft legs of the jacket structures. Actually, the waves acting on the hind legs are influenced by front legs, especially when the waves are broken.



(a) 3-parameter simplified force model [25]

(b) 5-parameter refined force model [25]

Fig. 5. Two models for the wave slamming loads on the front legs of jacket structures [25].

Comparison of the models

In order to compare the slamming force models described above, the models in Table 1 are applied to one study case, and the results are compared. The case is taken from a model scale wave test of the WaveSlam project. The vertical front side of a jacket model was exposed to shallow water breaking waves in the test. Two legs and two braces of the same diameter in this side were exposed to the plunging breakers. The model scale parameters of the wave case and the structure are given in Table 2.

In the application of the slamming force models for cylindrical structures, the wave is assumed to impact the four cylindrical legs and braces simultaneously. So the results are basically four times the slamming forces on one cylinder. The forces are assumed to be uniform along the axial length of cylinder, and calculated by Equation 6, where $C_b = \sqrt{g(d + \eta_b)}$. The results of the slamming force models for jacket structures are obtained directly from the analysis of the experimental data of the case.

Table 2. Parameters of the wave case and the structure.

Parameter	Symbol	Value	Unit
Wave period	T	4.9	s
Wave height at the structure	H	1.83	m
Elevation at the breaking point	η_b	1.28	m
Water depth	d	2	m
Curling factor	λ	0.4	-
Gravitational acceleration	g	9.81	m/s^2
Water density	ρ	1000	kg/m^3
Diameter of braces and legs	D	0.14	m
Number of braces and legs exposed to the breaker	N	4	-

The time series of the slamming forces calculated from different models are compared in Figure 6. The peak forces, durations and impulses derived from the time series are compared in Figure 7.

The peak forces are proportional to the maximum slamming coefficient of the models (see Table 1). Therefore, the slamming models for jacket structures, which have lower maximum slamming coefficients, lead to lower peak forces. In reality, the breaker does not impact different parts of the braces and legs simultaneously as we assumed. The impact is neither vertically nor horizontally uniform. So, it is reasonable to have lower maximum slamming loads on jacket structures than those calculated with simultaneousness assumption.

On the other hand, the duration obtained from the models for jacket structures are much higher than those from the models for cylindrical structures. The non-uniform impact of the breaker on different parts of the braces and legs is again partly the reason for this difference. Moreover, the breaking locations were decided by human observation during the experiment, whose data were used for developing the slamming models for jacket structures. The waves might have broken slight before or after the front side of the structure, so the durations calculated from those models can be longer than the ones from the idealized models. It also worth noticing that the models for cylindrical structures are mainly or partly based on theory, and they do not match the whole time series of the experimental data which were used for developing the models very well. The agreement is best inside the peak force region and less accurate outside of it. So, the estimated durations from these models can be shorter than in reality.

The impulses obtained from the models for jacket structures are also higher than those from the models for cylindrical structures. This difference results from the different peak forces, durations and the shape of the time series.

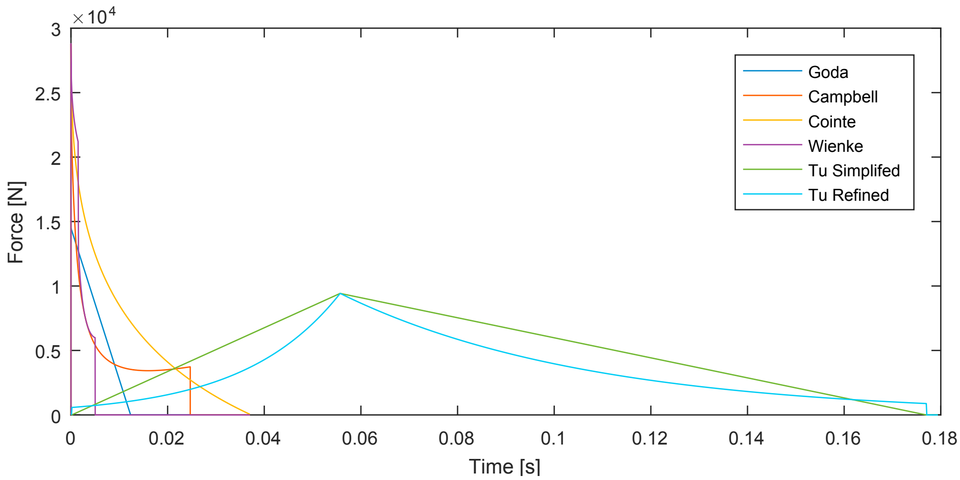


Fig. 6. Time series comparison among different slamming force models for one jacket structure and one wave case.

3.3. Integration of slamming loads in fully coupled analysis

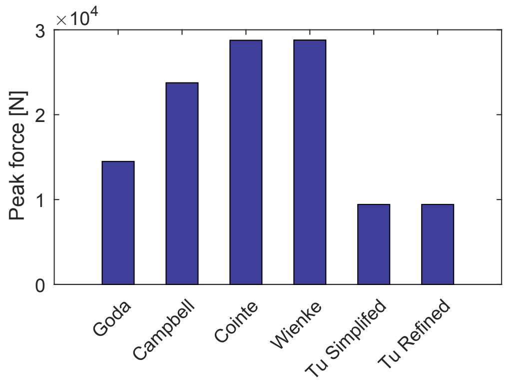
In the design practice of OWTs, the effect of slamming loads should be assessed by integrated dynamic analysis, which is commonly based on the engineering approach. The slamming loads can be estimated directly according to Eqs. 5 or 6, given the slamming coefficient, wave celerity, impact area and vertical force distribution pattern. However, most fully coupled simulation tools for OWTs, such as FAST, SIMO-RIFLEX-AeroDyn, BLADED, do not have the option to directly include the slamming loads. A possible way to consider the slamming loads in the existing tools without modifying the codes is to add the slamming load as an additional inertial or drag term in the Morison's equation.

Including slamming loads as an additional inertial term has been used in several publications, such as Hallowell et al. [10] and Marino [16]. This is achieved by modifying the acceleration in Eq. 2 as

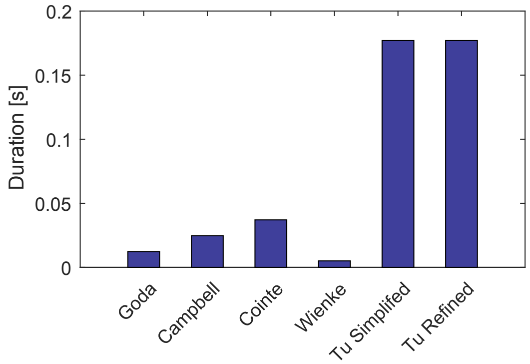
$$a_x^{new} = a_x + a'_x \tag{15}$$

where a'_x is due to the slamming load and is estimated by

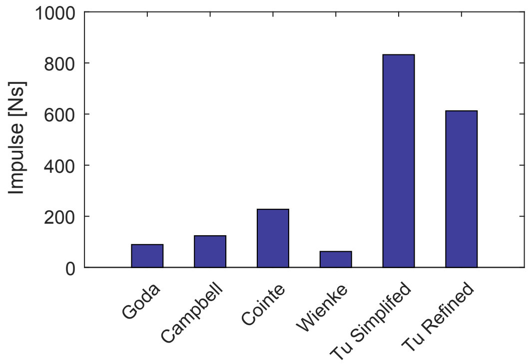
$$a'_x = 2\frac{C_s}{C_m}\frac{C_b^2}{D\pi} \tag{16}$$



(a) Peak force



(b) Duration



(c) Impulse

Fig. 7. Parameter comparison among different slamming force models for one jacket structure and one wave case.

4. Conclusions

Aiming at facilitating the application of slamming loads in the design practice of offshore wind turbines (OWTs), this paper reviewed the three most important aspects: the detection of slamming events, the calculation of slamming loads, and the integration of slamming loads into analysis.

There are some critical issues worth highlighting in these aspects. The first issue is about slamming detection. When identifying the breaking wave through zero-crossing analysis, it is assumed that the presence of the structure

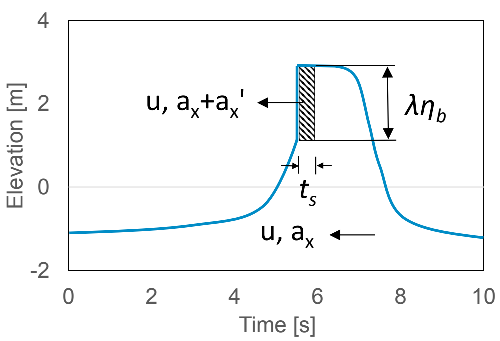


Fig. 8. Illustration of modified wave kinematics for wave slamming load application through Morison's equation.

does not affect wave evolution, even in the vicinity of the structure. In realistic ocean conditions, wave breaking is significantly affected by local bathymety, currents, wind-wave interaction, and other parameters. Therefore, using a suitable wave breaking criterion and plunging criterion is of significant importance. The second issue is about identifying the parameters that are required in the wave slamming load models. The parameters can be estimated by using, for instance, stream function method. But since the detected breaking waves are irregular and strongly nonlinear, it is challenging to have an estimation that is accurate enough. By using advanced methods, e.g. the MEL method, the detection of likely breaking waves and associated parameters can be circumvented. However, these methods are usually very time consuming. The third issue is about selecting a reliable wave slamming load model, including the slamming coefficient, impact area, vertical force distribution pattern and temporal development pattern, etc. The existing wave slamming load models present much difference in these factors. The issues discussed above affect the critical structural responses in the integrated dynamic analysis of OWTs, and have an impact on the ultimate limit state (ULS) and fatigue limit state (FLS) design of OWTs. They should be carefully taken into account in the design practice.

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