A Review of Slamming Load Application to Offshore Wind Turbines from an Integrated Perspective

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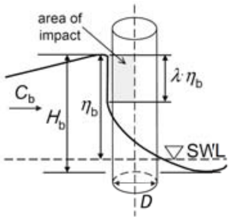
Abstract

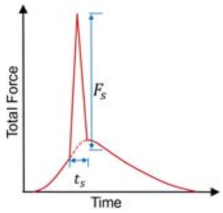
In harsh sea conditions, it is possible for offshore wind turbines (OWTs) to be exposed to slamming loads due to breaking waves, especially plunging breaking waves. These slamming loads lead to significant structural responses and can affect the ultimate limit state (ULS) design and the fatigue limit 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.

Plunging Breaking Wave and Slamming Load

Plunging breaking wave



Sketch of a breaker interacting with a cylinder [5]



Typical wave slamming force

In engineering practice, the total force from a plunging breaking wave on a cylinder is usually calculated by: $F = \underbrace{F_D + F_M}_{\text{Morison's force}} + \underbrace{F_S}_{\text{Slamming force}}$

A general expression of slamming force: $F_S = \int_l C_s(z) \frac{1}{2} \rho U(z)^2 W(z) dz$

C_s slamming coefficient; ρ water density; U water particle velocity; W project width of the structure; l height range of the impact

Depending on used slamming model, it can be simplified for example as:

$F_S = C_s \frac{1}{2} \rho C_b^2 D \lambda \eta_b$ Wienke and Oumeraci's model [5]

C_b celerity of the breaking wave; D diameter of the cylinder; λ curling factor; η_b elevation of the breaking wave

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Detection of slamming events

Four types of breaking criteria [3]

- The McCowan type: $\frac{H_b}{h_b} = \gamma(s, \lambda_0)$
- The Miche type: $\frac{H_b}{L_b} = \alpha(s, \lambda_0) \tanh\left[\xi(s, \lambda_0) \frac{2\pi h_b}{L_0}\right]$
- The Goda type: $\frac{H_b}{L_0} = \alpha'(s, \lambda_0) \left\{1 - \exp\left[-1.5\xi'(s, \lambda_0) \frac{2\pi h_b}{L_0}\right]\right\}$
- The Munk type: $\frac{H_b}{H_0} = \beta(s) \left(\frac{H_0}{L_0}\right)^m$

Two types of plunging criteria

- Through surf similarity parameters:

$$\xi_o = \frac{\tan\alpha}{\sqrt{H_o/L_o}} \text{ and } \xi_b = \frac{\tan\alpha}{\sqrt{H_b/L_o}}$$

According to IEC 61400-3, if $0.45 < \xi_o < 3.3$ or $0.4 < \xi_b < 2.0$, plunging breaker occurs

- Through breaker depth to offshore wave height ratio:

Plunging breaker occurs, if the ratio $\frac{h_b}{H_o} < 1.8$

Detection approach

- Apply zero-crossing analysis to irregular wave field to determine the wave parameters
- Apply suitable breaking and plunging criteria selected based on bathmetry, water depth, etc
- If necessary, conduct CFD simulations for better parameter estimation, and use additional indicators for the detection

Calculation of slamming loads

Slamming load calculation method

- Numerical approach (e.g. CFD), which is more time consuming.
- Engineering approach by using slamming load models, which is suitable for the design practice.
    - Estimate characteristic wave parameters by e.g. zero-crossing analysis
    - Select a slamming load model according to the structure type

Different slamming load models for cylindrical structure and jacket structure

	Author	Theory	Maximum C_s	Slam duration, t_s	Time history, $C_s(t)$
Cylindrical structure	Goda et al.	von Karman	π	$\frac{D}{2C_b}$	$\pi\left(1 - \frac{2C_b}{D}t\right)$
	Campbell and Weynberg	Experimental study	5.5	$\frac{D}{C_b}$	$5.15\left(\frac{D}{D+19C_b t} + \frac{0.107C_b t}{D}\right)$
	Cointe and Armand	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	Wagner	2π	$\frac{13D}{64C_b}$	$2\pi - 2\sqrt{\frac{2C_b}{D}t}\left(\tanh^{-1}\sqrt{1 - \frac{C_b}{2D}t}\right)$
Jacket structure	Tu et al.	Experimental study	2.05	-	Triangular
	Tu et al.	Experimental study	2.05	-	Exponential

Integration of slamming loads to analysis

Current simulation tools for integrated analyses, such as FAST, do not have the option to directly include the wave slamming loads.

Solution 1: Modify the codes to include the slamming loads

Solution 2: Do not modify the codes, but include the slamming loads as an additional term in the Morison force, usually as an additional inertia term.

$$a_x^{new} = a_x + a'_x$$

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

Key Points on Slamming Load Application

For detecting the slamming events

- The effect of the structure on the waves is not considered, when zero-crossing analysis is used.
- Criteria should be carefully selected according to the individual local conditions

For calculating the slamming loads

- Characteristic wave parameters required in the slamming load models can only be estimated approximately by using zero-crossing analysis
- A reliable slamming load models should be carefully selected

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