Marine Structures 60 (2018) 201–217

Contents lists available at ScienceDirect

Marine Structures

journal homepage: www.elsevier.com/locate/marstruc

A global slamming force model for offshore wind jacket structures

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ARTICLE INFO

Keywords:
Wave slamming force
Jacket structure
Experiment
Global force
Plunging breaking wave

ABSTRACT

Under certain harsh environmental conditions, jacket structures supporting offshore wind turbines might be exposed to plunging breaking waves, causing slamming forces that affect the structural integrity and fatigue life. The slamming forces should thus be properly considered during the design, but a suitable force model specifically for jacket structures is currently in absence. In this study, a five-parameter force model is developed for estimating global slamming forces due to plunging breaking waves on jacket structures, based on statistical analyses of experimental data from the WaveSlam project. The force model is developed by considering a total of 176 individual breaking waves, under six wave conditions. For each individual breaking wave, the time history of the slamming force is calculated based on hammer test data in addition to wave test data, and the wave parameters are acquired from a wave elevation measurement. The acquired time histories and wave parameters are then used to determine the parameters involved in the force model, including two exponential parameters (i.e. α_1 and α_2) and three dimensionless coefficients for the expressions of wave-dependent parameters (i.e. duration coefficient ζ_1, rising time coefficient ζ_2, and peak force coefficient ζ_3). It is found that α_1, α_2, ζ_1 and ζ_2 are approximately constant, and ζ_3 follows a lognormal distribution. The quantile that determines ζ_3 should be carefully selected so as to provide a conservative prediction. A quantile of 95% is suggested in this paper, and it is found to be conservative based on the verification of the developed force model. Therefore, for a given sea state, this force model can give a deterministic and conservative prediction of the slamming force time history, regardless of the randomness of slamming forces. Challenges for the application of the force model are also addressed.

1. Introduction

Currently, the development of offshore wind energy is mainly in shallow or intermediate water, where bottom-fixed substructures (e.g. monopiles and jacket structures) are mainly used. Under harsh environmental conditions at certain locations, these substructures are exposed to plunging breaking waves, which cause slamming forces. The slamming force features an extremely high impact force within a very short time. It can affect the integrity and fatigue life of the substructures of offshore wind turbines (OWTs). Therefore, slamming forces should be properly considered in the design of OWTs that are likely to be exposed to plunging breaking waves.

Slamming, violent impact on offshore structures, is a strongly nonlinear phenomenon involving the interaction among water, air and structure. Slamming forces are affected by various factors, such as compressibility of water, hydroelasticity of the structure, air bubbles entrapped, cavitation and ventilation etc. [1]. In the past decades, a large amount of effort has been made to investigate this

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https://doi.org/10.1016/j.marstruc.2018.03.009
Received 4 December 2017; Received in revised form 26 February 2018; Accepted 19 March 2018

Table 1
Comparison of different slamming force models for cylindrical structures (modified from Ref. [7]).

Author	Theory	Maximum C_s	Slam duration, t_s	Time history of slamming coefficient, $C_s(t)$
Goda et al. [8]	von Karman	π	$\frac{D}{2C_b}$	$\pi\left(1-\frac{2C_b}{D}t\right)$
Campbell and Weynberg [9]	Experimental study	5.15	$\frac{D}{C_b}$	$5.15\left(\frac{D}{D+19C_b t}+\frac{0.107C_b t}{D}\right)$
Cointe and Armand [10]	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 [4]	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 $0\le t\le\frac{D}{16C_b}$) $\pi\sqrt{\frac{1}{12}\frac{D}{C_b t'}}-\sqrt[4]{\frac{16}{3}\frac{C_b}{D}t'}\tanh^{-1}\sqrt{1-\frac{2C_b}{D}t'\sqrt{\frac{12C_b}{D}t'}}$ $t'=t-\frac{D}{64C_b}$ (for $\frac{D}{16C_b}\le t\le\frac{13D}{64C_b}$)
WiFi formulation [6]	Wagner	2π	$\frac{13D}{64C_b}$	a symmetric load shape

Note that C_s is the slamming coefficient, D is the diameter of the cylinder, C_b is breaking wave celerity. In the WiFi formulation, the slamming force is assumed to be symmetric in time around the crest when the crest touches the structure surface.

complex phenomenon. The first work to study slamming forces theoretically was done by von Karman [2] on the estimation of forces on the floats of landing seaplanes. Later, Wagner [3] investigated the slamming forces on cylindrical structures, and in his study, the cylinder was approximated as a flat plate. The main difference between von Karman method and Wagner method is that the latter takes the local rise of free surface into account. This difference affects the duration and the magnitude of the calculated slamming force. Though the work by Wagner [3] was conducted 85 years ago, it is still widely used nowadays.

The von Karman method and Wagner method are usually used to determine the slamming coefficient of the slamming force for cylindrical structures, but the time history of the slamming force is also important when considering the effect of the slamming force. Several force models that can describe the time history of the slamming forces on cylindrical structures were thus developed, as given in Table 1. In these models, the slamming coefficients are time dependent. The Wienke and Oumeraci [4] model is recommended by the IEC 61400-3 standard [5] for designing OWT support structures. The WiFi formulation was newly developed in the WiFi JIP (Joint Industry Project Wave Impacts on Fixed turbines) in 2017 [6].

The models given in Table 1 were derived by using different approaches. The von Karman theory was implemented by Goda et al. [8], and Wagner theory was employed by Wienke and Oumeraci [4]. In addition to Wagner method, Cointe and Armand [10] 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. Campbell and Weynberg [9] determined the slamming coefficient by experimental study. The WiFi formulation was developed based on a combination of Wagner method and model tests at MARIN (Maritime Research Institute Netherlands) and at Deltares. It should be noted that these models were originally developed for a two dimensional (2D) slamming problem, hence the vertical distribution of slamming load was not taken into account. When applying these models to three dimensional (3D) problems, the vertical force distribution is usually assumed to be uniform or triangular.

The force models given in Table 1 were developed for cylindrical structures and can be used to estimate slamming forces on monopiles for OWTs. However, these force models might not be suitable for jacket structures, though they consist of several cylindrical legs and braces. One reason is that the water surface that approaches a leg or a brace is affected by other legs and braces, causing a more complicated slamming scenario than that for cylindrical structures.

The slamming forces acting on jacket structures are thus different from those on cylindrical structures. For jacket structures, wave slamming forces should be estimated both locally and globally. The local slamming forces are important for the design of e.g. individual legs, while the global slamming forces are essential for the design of e.g. foundation systems. Based on the experimental data from the WaveSlam project, Jose [11] discussed local versus global loads from breaking waves. Tu et al. [12] investigated the global slamming loads due to plunging breaking waves on jacket structures. A total of 3910 time series of slamming forces were reconstructed and statistically analyzed. The mean slamming coefficient was found to be about 1.30 at a curling factor of 0.4. In that study, two wave slamming load models were also proposed, i.e. a simplified force model and a refined force model, to represent the temporal development of global wave slamming loads on jacket structures. However, only one wave condition was considered in Ref. [12]. More wave conditions are thus required to further refine and verify the proposed force model.

In this study, six different wave conditions from the WaveSlam project are further analyzed to propose a more accurate global slamming force model for jacket structures for offshore wind applications. Under each wave condition, one or several wave test runs with a number of regular waves were carried out. Based on the experimental data, global slamming forces acting on a jacket structure model are inversely calculated by using the method developed by Tu et al. [13]. The parameters of the measured waves and the reconstructed slamming forces are then used to determine the parameters in the force model by statistical analysis. Verification and application of this developed force model are also addressed.