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Prediction of Wave-in-Deck Loads on Offshore Structures Using CFD

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Abstract

The reduction in design air gap has been considered as a threat in the amplification of wave-in-deck loads on both fixed and floating offshore platforms. In this paper, the wave-in-deck forces on a fixed plate of a rigidly mounted box-shaped structure due to monochromatic regular waves are computed by means of a computational fluid dynamics (CFD) approach based on the volume of fluid (VOF) method implemented in the commercial CFD codes. Different parameters including wave steepness and air gap are tested. The obtained results are validated against tank experiments. The measured peaks of force components were analysed using one-way ANOVA (analysis of variance) in order to test the force variation over time. CFD force predictions were found to be in good agreement with the measured forces.

Introduction

This paper reports on the continuation of previous analysis [2] using a CFD solver to predict the wave-in-deck loads on a simplified deck box. In the previous analysis the maxima (peaks) of measured force components due to monochromatic regular waves were varied with time and were inconsistent in the tested time frame. Therefore, there was a need to address this using a statistical technique for the purpose of analysis of peak variance and its effect on the mean value. The measured peaks of horizontal and vertical force are analysed using one-way ANOVA (analysis of variance).

Tank Experiments

Kali [5] conducted small scale model tests at the towing tank of AMC. The AMC towing tank is 100 m long and 3.55 m wide and is equipped with a hydraulically driven flap-type wavemaker. The tank can be operated at different water depths of up to 1.5 m. A sketch of the towing tank and the experimental setup is given in Figure 1. The tested deck box measures 450 mm × 450 mm × 75 mm in length, breadth and height (L × B × h) respectively. The deck was instrumented by two AMTI MC3A Model-100-Series load cells. The wave height was measured using four capacitance-type (Churchill Model) wave probes; denoted as WP in Figure 1. The model was tested in monochromatic waves propagating in positive x-direction with crests exceeding the air gap without overtopping. Regular waves with a wave height of 125 mm and three wave periods of 1.2, 1.3 and 1.4 seconds were tested (Table 1). The wave parameters were selected so that the wave steepness $S = H/\lambda_0$ was less than 10 %. During the testing a constant water depth, d, of 1.5 m was maintained.

Experimental Results

The measured forces were captured at a sample frequency of 5 kHz and acquired for 45 seconds. The data collected at different air gaps including wave crest height at the leading edge of the tested deck (WP2), horizontal force (Fx) and vertical force (Fz) is discussed in this section.

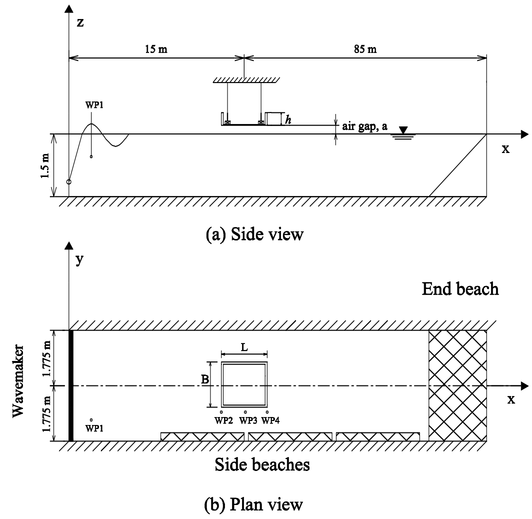

Figure 1. Sketch of experimental setup [not to scale].

Condition	Air gap, a [mm]	Incident wave parameters		
		H [mm]	*T* [sec]	S [%]
1	56	125	1.2	5.52
2	56	125	1.3	4.75
3	56	125	1.4	4.04
4	49	125	1.2	5.52
5	49	125	1.3	4.75
6	49	125	1.4	4.04
7	41	125	1.2	5.52
8	41	125	1.3	4.75
9	41	125	1.4	4.04

Table 1. Air gap and wave conditions tested.

Figure 2 and Figure 3 show a scatter diagram of Fx and Fz as a function of crest height, respectively. The wave parameters of H = 125 mm and T = 1.4 sec are used for these plots. A single run consisting of force peaks of 32 impacts in x- and upward z-direction is presented. Even though the deck experiences high forces when the air gap reduces, a clear correlation between the force component and crest height cannot be obtained. The wave skewness was found to be varied from 0.51 to 0.77. As a result, only a few waves were found with the approximately theoretical crest height of 62.5 mm. Both figures reveal strong nonlinearities associated with wave impact. The variation in wave crests can be attributed to the amount of wave diffraction produced by the presence of the deck structure, although B/λ_0 = 14.5 %. Even with an incident regular wave 4.04 % steep, it is difficult to obtain consistent force peaks, particularly in the z-direction resulting from multiple wave-in-deck events. Therefore, variation in the mean value of force peaks should be tested.

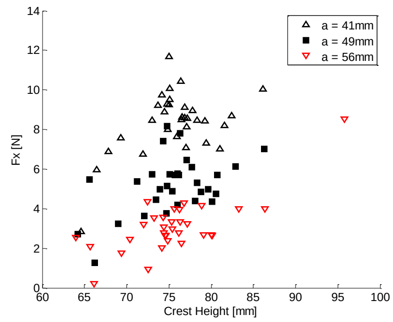

Figure 2. Measured horizontal force peaks versus crest height of WP2 at different air gaps [H=125 mm, T=1.4 s].

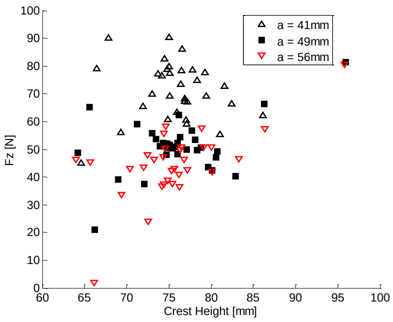

Figure 3. Measured vertical upward force peaks versus crest height of WP2 at different air gaps [H=125 mm, T=1.4 s].

Analysis of Variance (ANOVA)

Tank experiments are often conducted using multiple runs for each test condition to ensure the repeatability and accuracy of the measured parameters. In regular wave tests, the measured wave deck loads are commonly evaluated over a certain amount of time by using the mean loads of a number of load peaks. However, there is still considerable uncertainty about impact loads on structural members near the water surface. This uncertainty could be in the form of odd measures or outliers. These outliers may be due to pressure spikes from entrapped air and/or gas dynamics associated with a complex aeration process of air-water-structure interaction. Previous research showed that force peaks, even with regular waves, were varied with time and not consistent in the force time history of two tested runs having the same condition [2]. Referring to Figure 2 and Figure 3 some outliers do exist, for instance at a crest height equal to approximately 75 mm, a maximum peak in x-direction (Figure 2) and a number of odd peaks at 65 – 70 mm and at 95 mm (Figure 3) can be noticed. Statistically, outliers can be usually ignored when one wishes to obtain the mean value because they do not follow the general trend of the relation/correlation between the independent and dependent variables. However, this may not be the case when we analyse wave-in-deck impact forces where the safety of structure has a high priority and can be severely affected by eliminating load peak(s). Table 2 summarises the averaged peaks of upward vertical force (Fz) at condition 4 through 9 [1, 2]. When outliers are removed from force time histories, a significant difference/drop in mean values was obtained ranging from 16.84 % (condition 7) to 25.92 % (condition 9). The source of variation in mean value of force peaks is unknown.

Condition	a (mm)	T (sec)	Fz without outliers	Fz with outliers	Difference (%)
4	49	1.2	51.4	61.8	20.23
5	49	1.3	61.4	75.4	22.8
6	49	1.4	41.2	50.8	23.3
7	41	1.2	78.4	91.6	16.84
8	41	1.3	73.8	89.9	21.82
9	41	1.4	57.1	71.9	25.92

Table 2. The effect of exclusion of outliers on the mean value of upward Fz peaks.

ANOVA is employed to study the changing patterns of the response variable (herein forces) and the factors that influence those changes both within and between subjects. Within subject effects in wave-in-deck events are those values that differ from impact to another. Between subject effects are those values that change only from subject to subject (herein from run 1 to run 2).The variance is the average squared deviation i.e. difference of a data point from the distribution mean [4]. Therefore, the sum of squares (SS) is the variance without finding the average of the sum of the squared deviations and can be calculated as:

$$s^2 = \sum (x - \mu)^2 \tag{1}$$

The total/overall SS can be partitioned into two components including the sum of squares between groups (herein runs) $SS_{between}$ and the sum of squares within each group/run SS_{within}. Mean squares for each source of variation can then be calculated from:

$$MS_{between} = \frac{SS_{between}}{df_{between}} \tag{2}$$

$$MS_{within} = \frac{SS_{within}}{df_{within}} \tag{3}$$

where $df_{between} = C - 1$, $df_{within} = N - C$. C is number of related groups/runs and N is total number of observations/peaks. The nomenclature df refers to the degrees of freedom in each source of variation. The null hypothesis (H_o) states that the means are all equal and can be written as: H_o: $\mu_1 = \mu_2 = \mu_3 = \ldots = \mu_C$, where μ is population mean and C is number of related runs (= 2). The alternative hypothesis (H_A) states that at least two of the means are different. All analyses are conducted assuming p-value equal to 0.05. If the resulting p-value is less than this threshold, there will be a significant difference between the means and a strong evidence to reject H_o. To show the significance of variation F ratio is usually presented as an indicator given by:

$$F = \frac{MS_{between}}{MS_{within}} \tag{4}$$

It is obvious that F statistic governs the relationship between the variance between runs and the variance within runs. This will test the effect of both test repeatability and time i.e. consecutive wave impacts on the mean value of force peaks. The analysis is demonstrated on condition 6 and 9 where N in each condition is equal to 32 × 2. The statistical results are tabulated in Table 3. Both conditions were found to satisfy H_o with p-value > 0.05 indicating that all data points including outliers in both runs were important for estimating the mean value of force peaks.

Condition 6: H = 125 mm, T = 1.4 sec, a = 49 mm			
Force component	F	p-value	H_o
Fx	0.22	0.64	Accepted
Fz	0.055	0.82	Accepted
Condition 9: H = 125 mm, T = 1.4 sec, a = 41 mm			
Fx	1.05	0.31	Accepted
Fz	0.24	0.62	Accepted

Table 3. ANOVA results for condition 6 and 9.

Air Gap Reduction

The air gap was reduced gradually using two steps. The first step was achieved by lowering the deck 7 mm and the second by 8 mm resulting in a total reduction of 15 mm from the original air gap (56 mm). Figure 4 shows the effect of air gap reduction on the vertical force in the upward direction. The change in air gap Δa represents the air gap reduction from 56 mm to 49 mm and to 41 mm. The change in force is given by the percentage in relation to F_o which is the averaged peak of Fz when the deck was originally located at 56 mm above still water level. Different values of wave steepness S are used to establish the relationship between Δa and $\Delta F/F_o$. A clear trend can be seen such that the deck structure is impacted by higher vertical forces when its level above water line is lowered. As can be seen the total reduction, 15 mm, results in as twice as the force experienced by the deck structure at the original air gap (56 mm) when S = 0.055. This large change in Fz indicates the complexity and threat of wave deck impact due to air gap reduction.

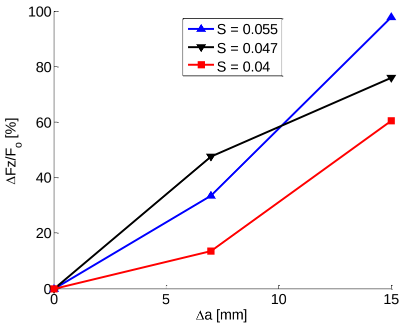

Figure 4. The effect of air gap reduction on upward Fz at different values of wave steepness (S).

CFD Techniques

In this work, the commercial Navier–Stokes, CFD code STAR-CCM+ (Release 8), was used for simulating wave-in-deck impacts. Based on isothermal and laminar flow assumptions, a system of partial differential equations governing the conservation of mass and momentum of incompressible fluids was solved numerically using finite volume method. In addition, the free surface equation and its motion were solved and captured using the volume of fluid (VOF) model. For further details, it can be referred to STAR-CCM+ user guide [3]. A numerical wave tank (NWT) of 14 m in length, 2 m in height and 1.775 m wide (with a symmetry plane) was created based on the previous studies [1, 2]. The origin of the coordinate system was located at the lower left corner (Figure 5). Mesh generation starts with a base cell such that the cell has a uniform size in 3D throughout the domain. In this study, different sizes of base cell were tested throughout the domain. In addition, in order to simulate fine flow details in way of wave free surface and around the deck structure, two volumetric controls using refined mesh depending on the selected base cell were created. Table 4 summarises the mesh parameters tested and the final selections recommended for this investigation. In order to model the desired wave characteristics, an incoming wave with appropriate height and wave period was specified based on Stokes fifth order wave theory at the inflow boundary (left side in Figure 5). Hydrostatic pressure boundary condition was specified at the top of the tank, i.e. the outflow boundary. The no-slip boundary condition was used on both the deck and the remaining tank surfaces along the exterior of the domain. The second order implicit time discretization was adopted in all simulations. Besides, it was found that time step of 0.001 sec with 5 iterations per time step is adequate to maintain optimal High Resolution Interface Capturing (HRIC) for the solution of the volume fraction equations. Each simulation required an approximated run time of 28 hours to obtain 20 seconds physical time on the AMC Cluster using 12 processors.

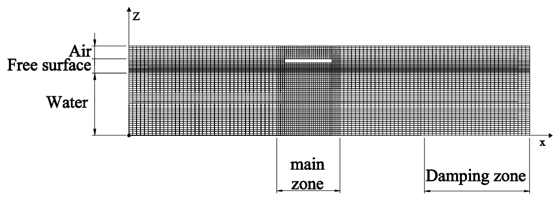

Figure 5. Mesh density distribution within the numerical wave tank shown at the symmetry plane of y = 0 m [not to scale].

Parameter	Tested sizes	Selected size
Base cell (m)	0.02, 0.03, 0.04	0.04
Δz in free surface zone (m)	0.004, 0.005	0.004
Length of damping zone (m)	2, 3, 4	3

Table 4: Mesh size tested within the computational domain.

Comparison of CFD and Experimental Results

The wave elevation at the leading edge of the model, 4.5 away from the inlet boundary condition, was studied using different sizes of base cell. Mesh I through Mesh III was created using a base cell size of 0.02, 0.03 and 0.04 m resulting in a total number of cells of approximately 1.47 million, 576,000 and 422,000, respectively. Other mesh parameters and solver settings were kept constant during mesh convergence study (Table 4). Figure 6 shows a good match between CFD wave elevation and the theoretical one obtained based on Stokes fifth order. However, the numerical wave elevation failed to reproduce the non-linear behaviour at wave troughs, underestimating the wave amplitude. Having tested the mesh density, a non-significant difference in wave amplitude at both crest and trough was obtained. Consequently, with the deck model present mesh III was employed in order to compute wave deck impact forces.

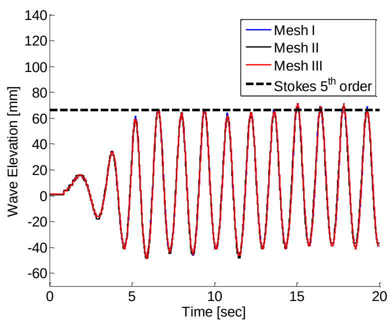

Figure 6. CFD wave elevation at 4.5 m from the inlet using different mesh sizes compared with Stokes fifth order [H = 125 mm, T = 1.4 sec].

The predicted and measured forces in 9 conditions (Table 1) are compared including peak values in x- and z-direction (Table 5). The Fz component in upward and downward directions is denoted by Fz(↑) and Fz(↓), respectively. Conditions 4 through 9 are extracted from [1, 2]. In a few conditions such as 1, 2 and 7 CFD results seem to underestimate the force peaks measured at the towing tank. The deviation between CFD and measurements may be attributed to the replication of wave elevation.

Condition	Experiment			CFD		
	Fx	Fz(↑)	Fz(↓)	Fx	Fz(↑)	Fz(↓)
1	2.6	46.3	-21.9	1.2	30.8	-17.1
2	5.4	51.1	-20.0	1.8	41.8	-16.3
3	3.1	44.8	-22.2	2.0	42.8	-15.9
4	4.5	61.8	-19.3	3.23	64.7	-20.4
5	5.6	75.4	-19.7	6.6	66.5	-25.6
6	4.2	50.8	-19.5	4.84	57.8	-20.8
7	11.5	91.6	-16.4	4.6	88.8	-23.8
8	6.3	89.9	-16.4	6	89.6	-20.1
9	7.5	71.9	-16.8	6.8	66.6	-17.1

Table 5: Predicted and measured of wave-in-deck forces [N].

For condition 3, Figure 7 shows the measured wave elevation at WP1 and WP2 compared with the theoretical wave height approximated by Stokes fifth order. The incident wave height (WP1) was found to be approximately 7 % higher than the theoretical one. This may be due to the interference, within a close distance of 2 m, between incoming waves and the wavemaker. However, the deviation in wave amplitude at some crests and troughs is more noticeable at WP2. The variation in wave amplitude differs from wave to wave indicating that data analysis should be conducted on a basis of individual waves when dealing with such problems.

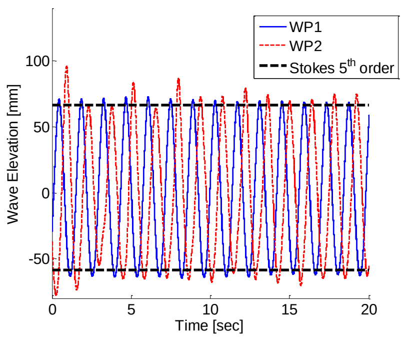

Figure 7. Measured wave elevation at WP2 compared with Stokes fifth order for condition 3 [H = 125 mm, T = 1.4 sec, a = 56 mm].

Figure 8 shows a single wave period comparison between wave elevations computed and measured at the leading edge of the deck. Good agreement is achieved in terms of time and amplitude of wave profile, particularly at the crest. The associated wave-in-deck force components are presented in Figure 9 for Fx and Figure 10 for Fz.

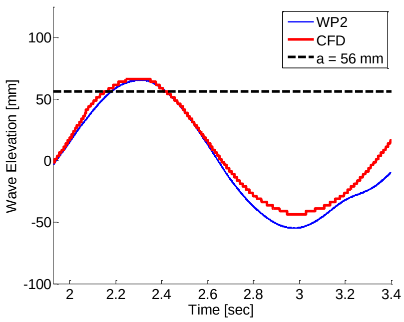

Figure 8. A single wave period comparison between predicted and measured wave elevation for condition 3.

Despite the small force magnitude of Fx, CFD force is in good agreement with the measured forces corrected by level 7 and level 8 using the Daubechies (db) wavelet family [2]. Good agreement is also obtained between CFD force in z-direction compared with the measured one corrected by level 6 using the Daubechies (db) wavelet family (Figure 10). A slight trade-off can be noticed in the downward direction where CFD was found to underestimate the force magnitude due to the under-prediction of wave amplitude at trough (refer to Figure 6 and Figure 8).

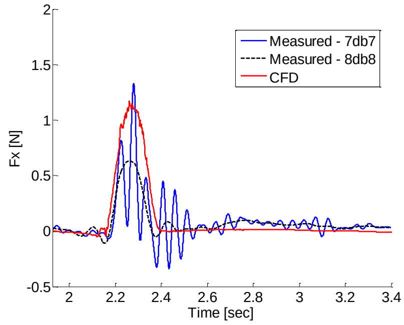

Figure 9. Time history of horizontal force for condition 3.

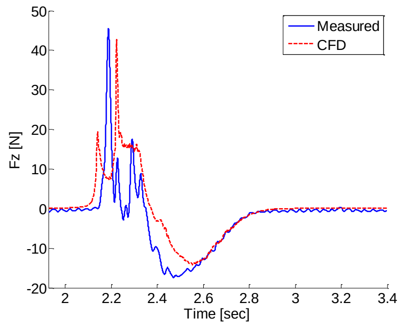

Figure 10. Time history of vertical force for condition 3.

Conclusions

In this paper, it was found that even a small reduction in air gap can largely amplify the wave-in-deck loads on offshore structures. Whilst the CFD force predictions were found to be in good agreement with the measured forces, the authors recommend that further investigation is required.

Acknowledgments

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References

[1] Abdussamie, N., Amin, W., Ojeda, R., Thomas, G. & Drobyshevski, Y, Vertical Wave-in-Deck Loading and Pressure Distribution on Fixed Horizontal Decks of Offshore Platforms. In: *The 24th Int. Offshore and Polar Engineering*, 2014, ISOPE-I-14-058.

[2] Abdussamie, N., Thomas, G., Amin, W. & Ojeda, R, Wave-in-Deck Forces on Fixed Horizontal Decks of Offshore Platforms. In: *The ASME 33rd Int. Conf. on Ocean, Offshore and Arctic Eng.*, 2014, OMAE2014-23629.

[3] CD-Adapco, *User guide - Star-CCM+ Version 7.04*, 2012.

[4] Huck, S.W., *Reading Statistics and Research*. Sixth edition. Pearson Education, 2012.

[5] Kali, V., *Investigation into Wave Slamming Loads on a Deck Box*, Final year Project in Ocean Eng. Dept., Australian Maritime College, 2012.