20th Australasian Fluid Mechanics Conference
Perth, Australia
5-8 December 2016

The Effect of Air Content and Compressibility on Wave-in-Deck Impact Pressures

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Abstract

Numerical simulations of an extreme wave impact on a topside deck structure were conducted to ascertain the effect of air content and its compressibility on the magnitude of the wave-in-deck impact (slam) pressure. The topside deck was investigated as both a fixed structure and as a topside structure of a typical Tension Leg Platform (TLP) exposed to unidirectional regular waves. The volume of fluid model implemented in STAR-CCM+ was used to capture the free surface interface. CFD results were validated using different levels of mesh resolution against 1:125 model-scale experiments. In all simulated cases, the deck area exposed to a wave slam event was found to be in contact with a water-air mixture with a significant proportion of air, which revealed that two-phase models are necessary to accurately simulate wave-in-deck problems.

Introduction

Offshore installations such as those located in the Australian North West Shelf (NWS) and the Gulf of Mexico are exposed to cyclones/hurricanes which can generate severe wave events including wave-in-deck impact (slam) events. Such events can cause damage to decks of fixed and floating offshore structures [1]. Nevertheless, the current engineering knowledge required to accurately predict the magnitude and distribution of wave-in-deck loads and the resulting global response of floating structures such as Tension Leg Platforms (TLPs) and semi-submersibles remains limited. The slam events and the associated global effects (forces) and local effects (localised pressures) must be correctly and accurately accounted for in the design stage.

In this paper, numerical simulations of an extreme wave impact on a topside deck structure were conducted to ascertain the effect of air content and its compressibility on the magnitude of the wave-in-deck impact pressure. The topside deck was investigated as both a fixed structure and as a topside structure of a typical TLP exposed to unidirectional regular waves. The volume of fluid (VOF) model implemented in STAR-CCM+ was used to capture the free surface interface. To account for large platform motions in the floating structure, the overset mesh technique was utilised, whilst the platform tendons were modelled as massless spring lines. CFD results were validated using different levels of mesh resolution against 1:125 model-scale experiments.

Experiments

Model Configurations

In this study, three models including a fixed platform deck, a fixed multicolumn platform (rigidly mounted TLP) and a compliant TLP were investigated at a model scale of 1:125 (Figure 1). All models were subjected to an extreme unidirectional regular wave condition at a deck clearance of 120 mm or 15.0 m at full-scale (vertical distance from the still-water level to the deck underside). The objective was to examine how wave-in-deck impact loads differ amongst the three models. For more details in regards to experimental setup and model dimensions please refer to [1].

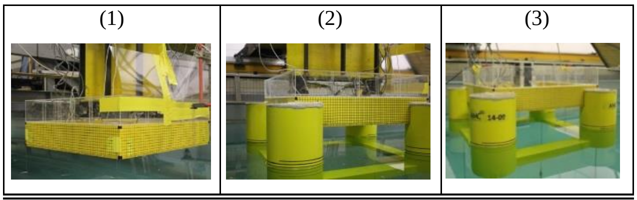

Figure 1. (1) Fixed deck model, (2) Fixed multicolumn platform model and (3) Compliant TLP model.

Instrumentations

The localised slamming pressures at the deck underside were measured by means of sixteen piezoresistive pressure transducers (denoted by PT); see Figure 2 for the fixed deck. The pressure transducers had the same *xy* locations for the other two models. The tip of each transducer (approximately 4 mm in diameter), was mounted flush with the underside of the deck. A sampling frequency of 20 kHz was used to capture slam pressures.

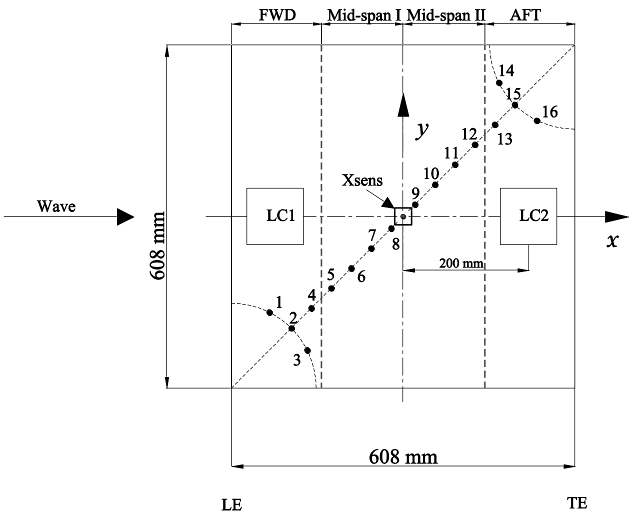

Figure 2: Distribution of pressure transducers (PT) and load cells (LC) on the deck underside of the fixed deck model [not to scale]. LE: Leading edge, TE: Trailing edge, LC: Load cell, FWD: Forward section, AFT: Aft section. Xsens: Accelerometer.

Test Matrix

An extreme wave condition was generated at the Australian Maritime College (AMC) towing tank (Table 1). All models were subjected to the same wave condition. A water depth of 1.5 m was maintained constant during experiments. Model testing was conducted based on the following procedure:

1- *Condition 1*: The deck structure was attached to a heavy and stiff beam mounted on the tank rails.
2- *Condition 2*: The same deck structure tested was supported by four circular columns and four submerged pontoons to represent a fixed multicolumn platform.
3- *Condition 3*: The TLP model was then de-attached from the cross beam and tethered from each column base to the tank floor using four tendons.

Full-scale		Model scale		Conditions tested
Wave height, H (m)	Wave period, T (s)	Wave height, H (mm)	Wave period, T (s)	
28.88	17.0	231	1.52	1, 2, 3

Table 1. Test matrix.

Data Analyses

Uncertainty analysis of pressure measurements is introduced in this section by demonstrating the impact pressures associated with a single wave impact measured in three repeated runs for condition 1 (fixed deck). The repeatability of wave elevations measured at approximately 0.7 m from the deck leading edge is given in Figure 3. Low variability can be seen when the time history of wave elevations is compared using the three repeated runs. Using the time history of a single wave (time = 32 s – 33.5 s), standard deviations of 1.23 mm and 0.76 mm were obtained for the amplitude of wave crests and troughs, respectively.

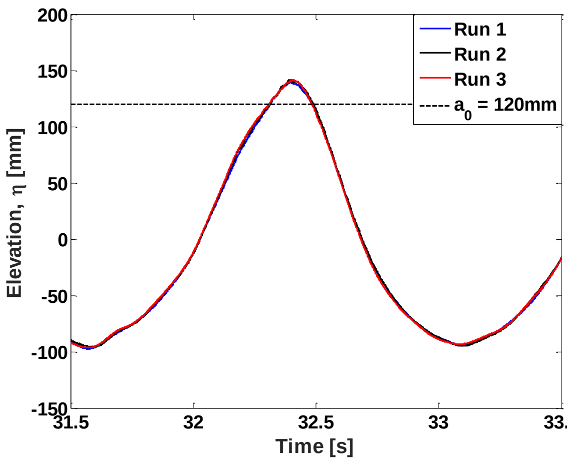

Figure 3. Time history of wave elevation measured at 0.7 m in front of the deck model using three repeated runs. a_0 = deck clearance.

The corresponding time histories of wave-in-deck pressures measured by PT#15 and PT#16 are presented in Figure 4 and Figure 5, respectively. The maximum pressure (slam pressure) captured by PT#15 had a mean value of approximately 800 Pa. A standard deviation of 541.2 Pa was obtained for PT#16. This implied that impact pressures varied for repeated runs having almost identical wave conditions.

Two-Phase CFD Simulations

The commercial Navier-Stokes CFD code STAR-CCM+ (Release 10) developed by CD-adapco was used for simulating the physics of the wave-in-deck problem. Laminar flow was assumed for all numerical simulations because the CFD results were aimed at reproducing the model test results.

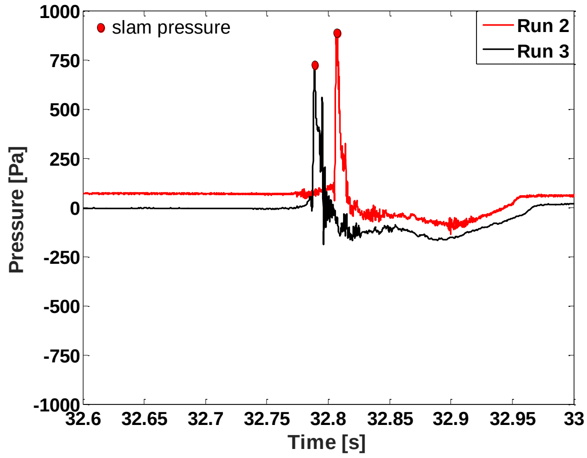

Figure 4. Time history of pressure transducer # 15 for 2 repeated runs. Slam pressures are denoted by dots.

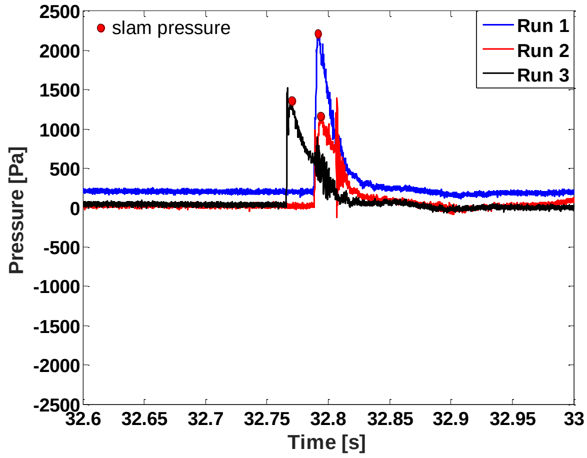

Figure 5. Time history of pressure transducer # 16 for 3 repeated runs. Slam pressures are denoted by dots.

The interface between water and air phases was captured with the aid of VOF model. The physical properties (e.g., density) of water and air were expressed as a volume of a fraction of each fluid during the solution; see the STAR-CCM+ user guide [2] for further theoretical details. In this work, the following main steps were performed for simulating the wave-in-deck problem:

1- *Mesh convergence study*: A numerical wave tank (NWT) was generated (22.0 m × 1.775 m × 2.0 m) and fine mesh size was applied at the free surface zone in the *x*- and *z*-directions ($dx \geq \lambda/100$ and $dz \geq H/20$). λ is the wavelength.

2- *Wave impact tests*: the model's centroid was placed in the middle of the tank (3λ upstream and 3λ downstream). Fine mesh size was applied at all model's surfaces (3.125 mm). A finer surface mesh at the deck underside was also tested (an example is shown in Table 2 and Figure 6).

3- *Air compressibility*: Both water and air phases were firstly modelled as incompressible fluids. The air compressibility was finally tested; the air density and its pressure derivative were defined by means of *user-defined field functions*.

Mesh	Surface mesh size at the deck underside	Total no. of cells ($\times 10^6$)
1	3.125 mm	2.33
2	1.5625 mm	2.69

Table 2. Surface mesh size tested at the deck underside.

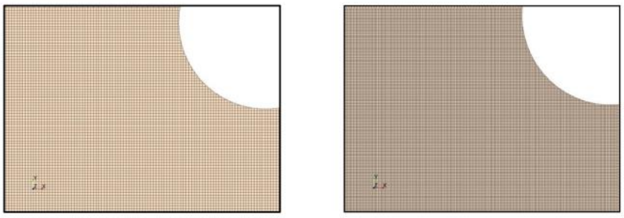

Figure 6. A plan view (*xy* plane) of the deck underside showing the local refinement of surface mesh near the aft column: Mesh 1 (left) and Mesh 2 (right).

To account for large rigid-body motions in the CFD simulations of the compliant TLP model, the overset mesh technique was utilised, whilst the platform tendons were modelled as massless spring lines. A time step of 0.001 s with 5 iterations per each time step was used for all simulated cases.

Comparisons of CFD and Experimental Results

Figure 7 demonstrates the effect of mesh resolution on the magnitude of slam pressure at PT#16. CFD simulations with Mesh 1 (≈ 1.3 cells per transducer diameter) predicted approximately 88% of the measured slam pressure of 1793 Pa, whilst the predicted slam pressure increased to 95% using Mesh 2 (≈ 2.6 cells per transducer diameter). This implies that fine surface mesh was necessary to capture such slam pressure at a discrete point. Mesh 2 was, therefore, selected for further analysis.

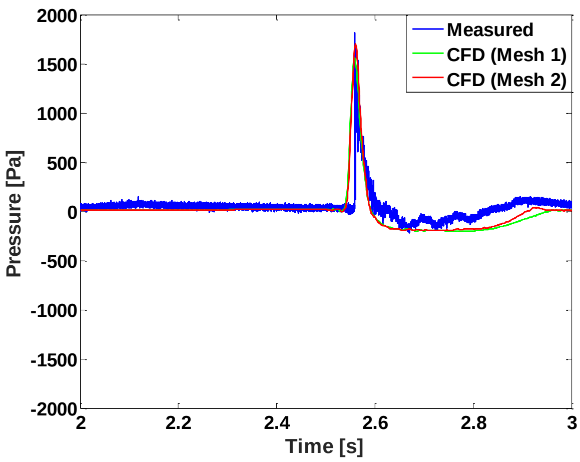

Figure 7. Time history of wave-in-deck pressure on fixed multicolumn platform model at PT#16 (condition 2). CFD models used incompressible air.

Air Compressibility

The effect of air compressibility on the magnitude and time history of wave-in-deck impact pressure at a discrete point (PT#16) can be seen in Figure 8. When the air was modelled as a compressible phase, the predicted peak pressure reduced from 1700 Pa to 1334 Pa (≈ 21.7% reduction).

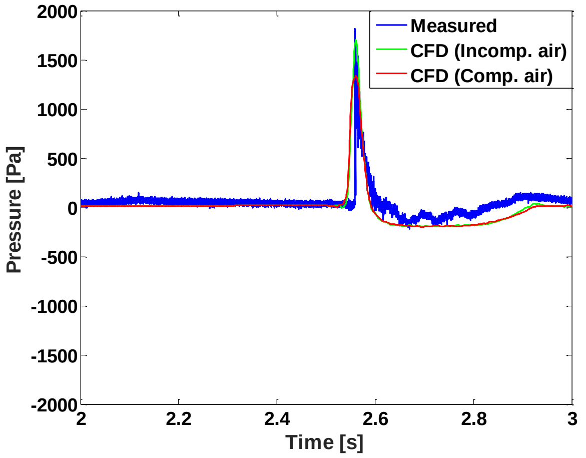

Figure 8. Time history of wave-in-deck pressure on fixed multicolumn platform model at PT#16 (condition 2).

Air Content

In order to quantify the air content associated with the wave impact, the maximum pressure over the whole deck area and the volume fraction of the water phase were obtained at each time step using CFD models. This technique proved to be more effective and less sensitive to mesh resolution than the prediction of slam pressure at a discrete point. Figure 9 shows a single wave impact in the deck area for conditions 1, 2 and 3 computed with incompressible air. Each wave impact caused at least two consecutive slams at the deck underside i.e. a sharp increase in the pressure magnitude (denoted by letters a – f). Table 3 summarises the predicted peak pressures and the associated water content (%) for all wave slam events a – f depicted in Figure 9.

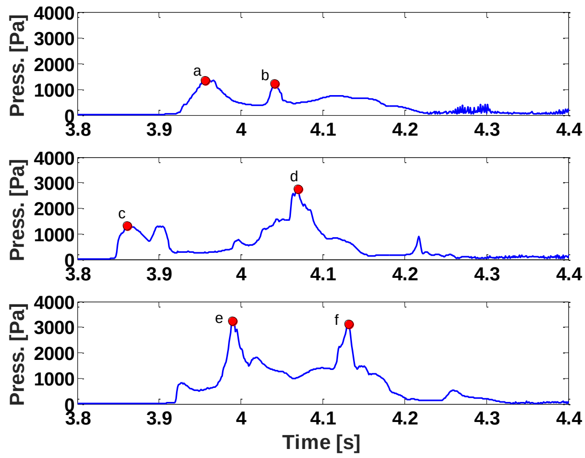

Figure 9. Time history of maximum pressure at the deck underside. From top to bottom: fixed deck, fixed TLP and compliant TLP.

Model	Slam	Peak pressure (Pa)	Water content (%)
Fixed deck	a	1334	50
	b	1140	65
Fixed TLP	c	1337	80
	d	2770	30
Compliant TLP	e	3248	65
	f	3134	20

Table 3. Maximum pressure over the deck area and the associated water content. Figure 9 shows the wave slam events a – f.

Pairwise comparisons between the peak pressure and the water contents (volume fraction) are presented in Figs. 10 – 12 (only half of the deck underside models are shown due to symmetry).

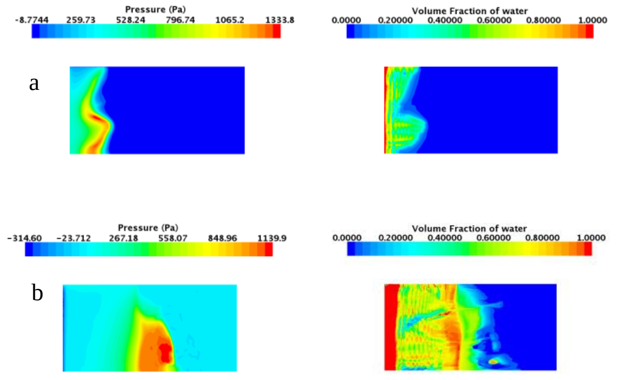

Figure 10. Snapshots of wave slam pressures and water content on fixed deck model.

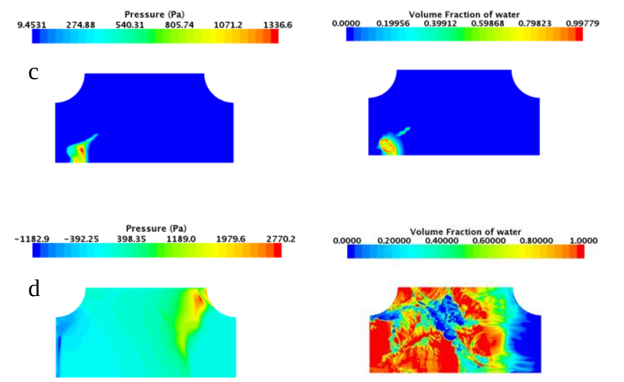

Figure 11. Snapshots of wave slam pressures and water content on fixed TLP model.

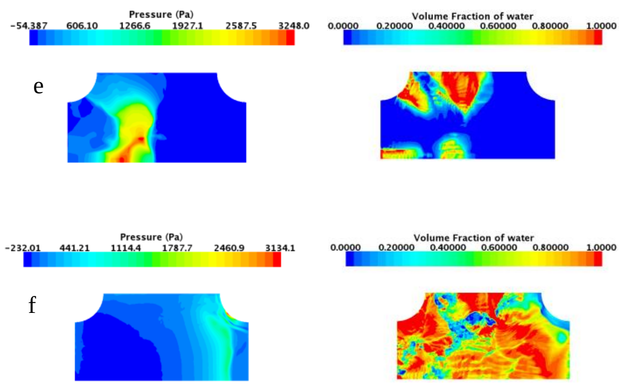

Figure 12. Snapshots of wave slam pressures and water content on compliant TLP model.

It should be noted that the two consecutive pressure peaks occur in the forward and the aft section of the deck underside, respectively. On both occasions, the part of the deck experiencing the pressure peak was exposed to a mixture of water and air phases. For instance, a volume fraction of the water phase of approximately 0.5 (50% air) was found with the wave slam on the fixed deck (Figure 10a).

By investigating the volume fraction of the air underneath the deck structure, it was found that not only the air phase filled the interface cells with the water phase but an actual air cavity was also formed during the deck impact. In all simulated cases, the deck area exposed to a wave slam event was found to be in contact with a water-air mixture with a significant proportion of air phase. This highlights the necessity for numerical two-phase simulations to accurately model the wave-in-deck problems.

Another observation is that the presence of the hull (columns + pontoons) had a large effect on the pressure magnitude, as the second pressure peak significantly increased (almost doubled). By also comparing conditions 2 and 3, the compliant TLP model received larger slam pressure than that was predicted for the model fixed. This can be attributed to the model set-down caused by its surge motion while being restrained vertically by the tendons.

Conclusions

Numerical simulations of an extreme wave impact on a topside deck structure were conducted to ascertain the effect of air content and its compressibility on the magnitude of the wave-in-deck impact (slam) pressure. The topside deck was investigated as both a fixed structure and as a topside structure of a typical TLP exposed to unidirectional regular waves.

Impact pressures were obtained at a discrete point and over the whole exposed area of the deck. Because the slam pressure is an extremely localised phenomenon, predicting wave impact pressure at a discrete point, both in model tests and CFD-based codes, remains challenging.

Obtaining the wave-in-deck slam pressures over an exposed area using CFD simulations was more effective and provided insights into the pressure changes due to air compressibility and its content. In all simulated cases, the deck area exposed to a wave slam event was found to be in contact with a water-air mixture with a significant proportion of air phase.

Further numerical analyses using different wave conditions should be conducted to examine the effect of air content on the slam pressure magnitudes.

Acknowledgments

The authors would like to acknowledge the assistance from Mr Tim Lilienthal, Mr Kirk Meyer and Mr Liam Honeychurch at the AMC towing tank.

References

[1] Abdussamie, N., Towards Reliable Prediction of Wave-in-Deck Loads and Response of Offshore Structures, PhD Thesis in Maritime Engineering and Hydrodynamics, 2016, University of Tasmania: Launceston, Australia.

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