A Passive Flow Separation Approach for Reducing Slamming Loads on Large Catamarans – Experimental Investigation

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Abstract

High-speed catamarans have, over the past three decades, extended their service areas from protected waters to the open ocean where impacts with waves can result in structural damage. This work is aimed at addressing the lack of high-quality three-dimensional (3d) experimental data suitable for benchmarking catamaran vessels impacting with water in a 3d regime, as well as establishing an understanding of the key elements influencing the severity of wetdeck slamming loads. A series of experimental tests were conducted on a high-speed catamaran's bow section during water entry using a constant speed drop testing facility.

The water impact facility allows the water/model interaction to occur at relatively high-velocities up to 10m/s and with two angles of trim, e.g. 0° and 5°. The tested model was constructed with two interchangeable centrebows to study the influence of flow separation prior to slam events. It was found that limited pressure transducers that are localised in space and time could be important for validating numerical techniques but should not be used as a basis for structural design. The findings of this study would also provide designers and classification societies with an approach to predict pressure distributions along the archway of non-uniform structures.

Key-words:
Water impact; Wetdeck slam; Experimental tests; Fluid Structure Interaction (FSI)

1. INTRODUCTION

This paper aims at addressing wetdeck slamming, one of the principal mechanisms for wave induced loads on catamaran ships. A catamaran experiences this type of slamming when operating in large waves as the wetdeck, the exposed deck area between the two demi hulls of the catamaran, impacts the water surface with a high relative vertical velocity (see Fig. 1). Wetdeck slamming is a significant design issue for catamarans since it can cause major structural damage and avoiding its occurrence is one of the main reasons a vessel's master reduces speed or changes course in heavy weather, adversely affecting the vessel's operation and schedule.

The main area of interest in the design of large wave-piercing catamarans is the impact loading in the vicinity of the centrebow during immersion (Davidson et al., 2006, Faltinsen, 2006). Several large high-speed catamarans have suffered damage due to wetdeck slamming, although these vessels were designed to classification society rules (Rothe et al., 2001, Steinmann et al., 1999, Thomas et al., 2002).

Some prominent examples of damage due to wetdeck slam events are as follows:

- Cracks in MS Sollifjell (Wang and Guedes Soares, 2013);
- localised buckling of plates, stiffeners and distortion of centrebow stiffeners of Incat Hull 050 (Thomas et al., 2002); and
- extensive structural damage to the bow of HSS Stena Discovery (Thomas, 2003).

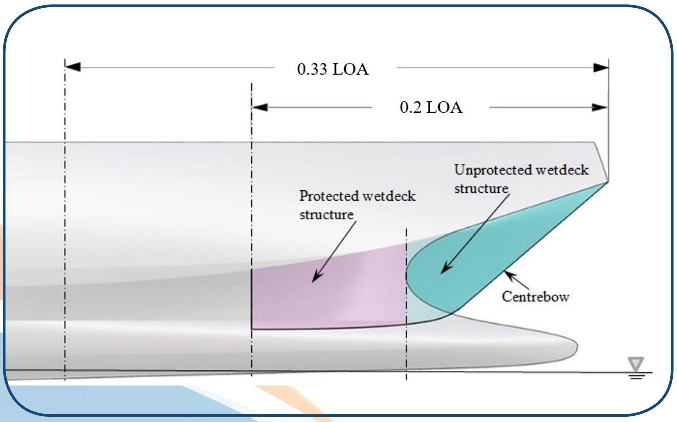

Fig. 1. Schematic diagram of bow section for a catamaran.

To eliminate the prospect of structural damage and to secure insurance cover in case of damage, high-speed craft are designed to rule-based design loads. Currently, classification societies (Cummings and Roden, 1998, LR, 2019, DNV-GL, 2018, ABS, 2016), provide designers with a range of empirical formulae that are based on quasi-static pressure predictions due to the impact on high-speed catamaran's wetdeck, which may over- or underestimate the actual impact pressure distributions.

The wetdeck slamming problem is significantly more complex than that for monohull slamming as it involves rapid changes of local loads in time and space, air inclusions, and the compressibility of mixing fluids (water and air) over a non-uniform surface in three dimensions.

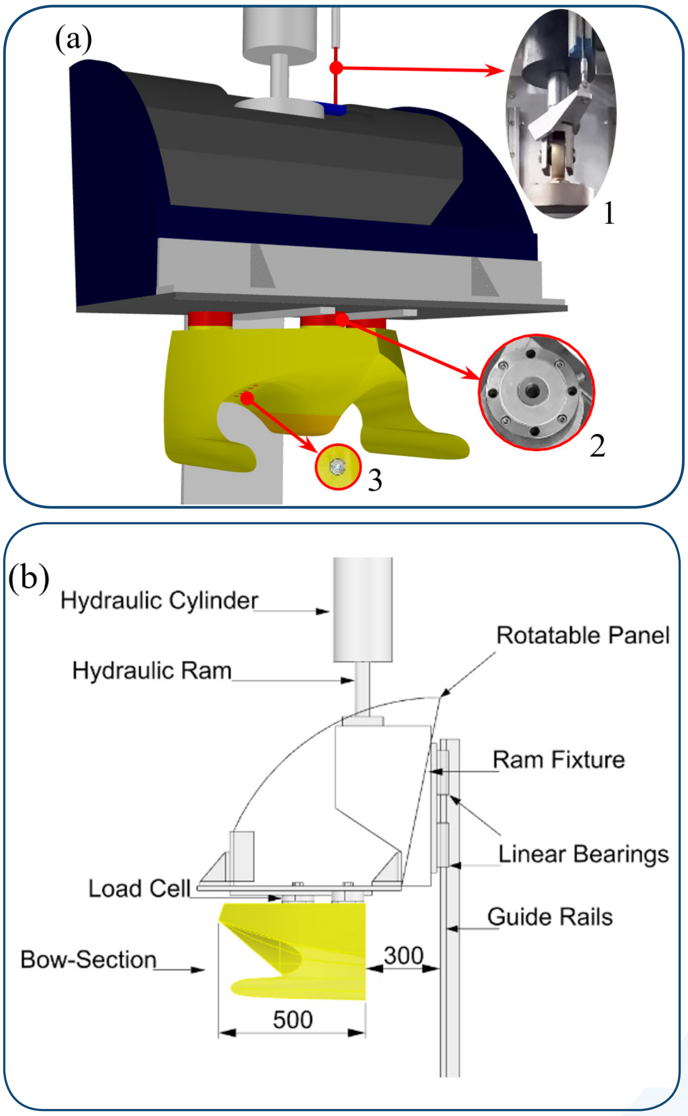

Fig. 2. The experimental test setup instrumentation; Subplot (a) showing 1 = longitudinal vertical displacement transducer (LVDT) and hydraulic ram cylinder, 2 = Load cell and 3 = Pressure transducer and fitting surface. Subplot (b) illustrates a set of linear bearings, dimensions are in mm.

With increasing capabilities in Computational Fluid Dynamics (CFD) and High-Performance Computing (HPC), CFD 3-d tests are becoming more affordable and well suited to supplement empirical formulae, experimental studies, and full-scale trials although validation of computed results would still require data.

The drop test technique is used extensively to characterise slam loads in a more controlled environment. However, there are limited data available in the public domain, which is just limited to 2-d multihull vessels (Davis and Whelan, 2007, Swidan et al., 2014, Swidan et al., 2013). An exception is the study conducted by Swidan et al.(2016) and Swidan et al. (2017), where two series of 3-d drop tests were performed to evaluate the behaviour of a catamaran bow section during the water-impact phase at a range of constant speeds from 2.5m/s up to 5m/s in 0.5m/s increments. The aim of this study is to characterise the wetdeck slamming phenomenon and to provide designers and classification societies with an approach to predict impact loads magnitudes and pressure distributions, based on reliable experimental work and test bench data that would allow researchers to validate the numerical results.

The present work extends upon the experimental works conducted by Swidan et al.(2016) and Swidan et al. (2017) through providing non-dimensionalised pressure coefficients of the maximum pressure peaks of a catamaran during water-entry at two relative impact angles and range of impact velocities. It is very useful to represent pressure in terms of a dimensionless quantity, like that of lift and drag, as a step forward to eliminate the uncertainty related to experiments with scaled models, which is an issue currently being discussed by the international scientific community (Rizzo et al., 2018).

2. EXPERIMENTAL SETUP

To provide high-quality experimental data suitable for validation purposes a series of drop-test experiments were conducted using the Servo-hydraulic Slam Testing System (SSTS), at Industrial Research Limited, Auckland, New Zealand (Swidan et al., 2016).

Fig. 2 illustrates the main mechanical components of the SSTS. The hydraulic system can achieve a range of controlled water-entry velocities up to 10 m/s, with the required hydraulic power for each target velocity that is controlled by a servo-proportional control valve.

For the purpose of the present study, the impacts were conducted with the model at two fixed trim angles (⊠) of 0° and 5°. The water depth and temperature during tests were 1.15 m and 11°, respectively. All tests were performed in a controlled environment and with an initially calm water-surface.

The main particulars of the test model shown in Fig. 2 are: length (L) 500 mm, beam (B) 638 mm, height (H) 327.6 mm and total mass 14.8 kg, while the expected flow behaviour during water penetration of both parent centrebow and the amended centrebow is shown in Fig. 3. It was sized to ensure that there would be a gap between the model and the tank wall of double the model's overall beam. This was to minimise boundary condition effects and the possibility of wave reflections.

A three-dimensional Computer Numerically Controlled (CNC) router was used to cut the model out of 15 layers of glass reinforced plastic giving a total shell thickness of 10 mm with minimal surface roughness. Details of the used instrumentation on the test rig are given in Table I. However, further details about the device and uncertainty analysis can be found in Swidan et al. (2016).

Table I. Instrumentation Details

Gauge	No. of Channels	Manufacturer	Model	Maximum Range
High-speed video camera	0	Photron	Fastcam SA5	7500 fps
Position sensor	1	Vishay	REC 139L	3 m
Load cell	3	Precision transducers	LPC 5t	5000 kg
Pressure transducers	5	PCB piezotronics	113B- 26.68950	kNm^{-2}

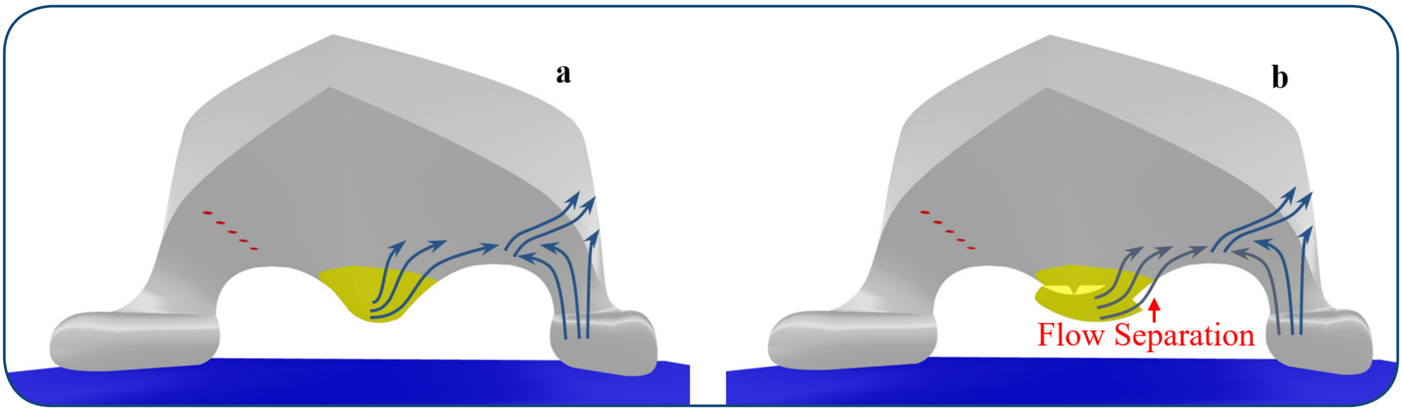

Fig. 3. Schematic drawing showing the expected low behaviour on one side during water penetration of; (a) parent centrebow and (b) amended centrebow (Swidan et al. (2016b).

Fig. 4. The new centrebow design of Saint John Paul II, Incat catamaran, length overall = 110m. (Swidan et al., 2019). Note: that all Incat manufactured vessels had previously a smooth centrebow without any appendigies for water separation during water-entry and to enhance her vessels' seakeeping performance.

3. RESULTS AND DISCUSSION

This section discusses experimental results to characterise the wetdeck slamming phenomenon and to gain knowledge with regard to the flow behaviour beneath an arched wetdeck, the work exerted, the slam load magnitudes, and pressure distributions when using two interchangeable centrebow configurations. The parent hull form is a generic wave-piercer catamaran (presented in Fig. 3.a), similar in style to those designed by Revolution Design Pty Ltd and manufactured by Incat Tasmania.

Swidan et al. (2017) proposed the second winged-centrebow (named in this study amended hull) as a new design for the centrebow and aimed to induce water separation at the tip of wings during water entry, as presented in Fig. 3.b and was implemented by Incat Tasmania in her new vessels starting from year 2019, as shown in Fig. 4. The objective of this early water separation is to generate an air cavity that can work as damper during wetdeck slamming. Another feature is the larger exposed area with a reduced deadrise angle to try and provide greater resistance during water-entry and reduce the impact velocity. Additionally, the winged shape of the amended centrebow is designed to increase the drag force during water-exit after slamming events, reducing the pitch motions.

3.1 Experimental Results

All the data presented starts at 0 immersion, e.g. the model touches the initially calm free-surface.

Fig. 5a illustrates the velocity traces of the tested model at an angle of trim of 0° on the left hand side and an angle of trim at 5° on the right hand side of the figure. The area under the curve (Fig. 5b) presents the energy exerted on both hull models due to hydrodynamic loads. Saving this energy reduces the probability of structural failure and the ability to design lighter weight ships without hull deformations (Payne, 1988). Although Fig. 5.b demonstrates that the measured force traces of the amend hull are with a slight reduction of 6% in slam force peaks when compared with parent hull at the same condition.

It is also interesting to see a great influence of the trim angle, which is the relative angle between the model and the initially calm water surface, on the severity of slam loads and pressure peaks. In contrast, Fig. 4c, illustrates that the peak slam pressures increase by 15% when utilising the amend centrebow over the parent hull.

Though the pressure peak distributions close to the impact region depend on the distribution of the normal component of relative velocity over that region (Cooker and Peregrine, 1995), this observation confirms the finding of Faltinsen et al. (1997) that large pressure peak magnitudes do not necessarily mean large stresses on the structure. Thus, integrating a limited number of pressures can lead to in-accurate force predictions, except where complete pressure mapping is provided.

Fig. 6. demonstrates the mean velocity of pressure pulses in the longitudinal direction that was evaluated on the basis of pressure transducer longitudinal locations as a gradient of corresponding slam pressure spiking times. This 3-d plot demonstrates that the wetdeck water impacts create a rapid change in water velocities. The related slam pressure peaks increase with the increasing rate of change of hydrodynamic momentum, which is strongly dependent on relative water impact velocity as well as transducer longitudinal location, with the maximum pulse velocity (vy) is at P1 being more than double the P5, as shown in Fig. 6.

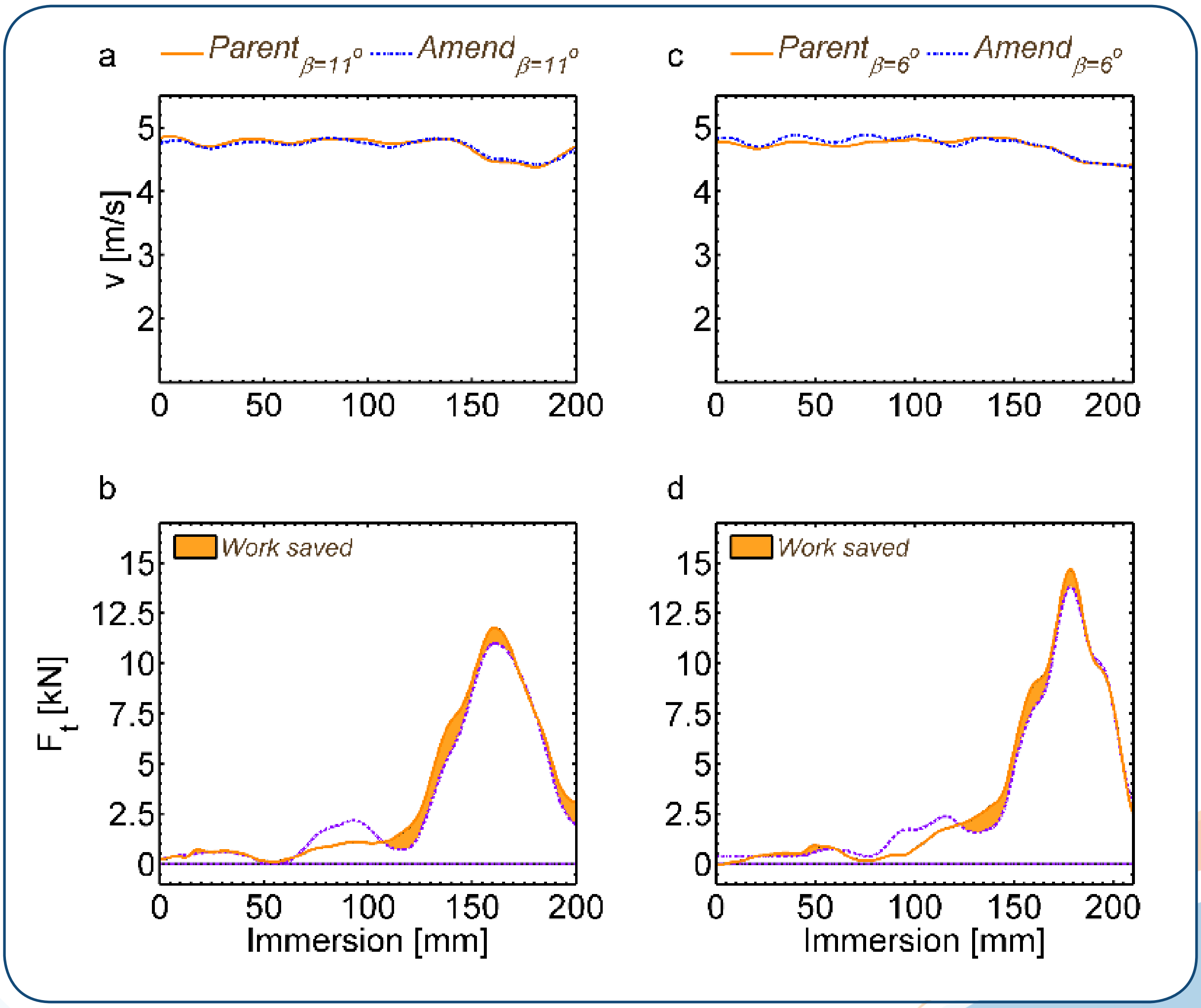

Fig. 5. Showing the experimental measurements of a catamaran bow hull model during water impact tests at approximately 4.5 m/s. Subfigures (a) show the measured velocity profile, (b) the measured forces and the work saved, (c) the mean pressure traces with respect to model immersion.

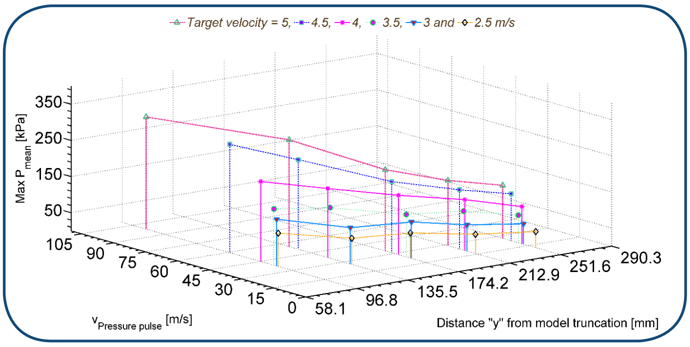

Fig. 6. 3-d plot showing the effect of the transducer location on both the peak slam pressures and the corresponding pressure pulse velocities (vy) in the "y" direction in relation to six water impact velocities. The x-scale presents the longitudinal locations of the five pressure transducers against the y-scale that presents the range of the calculated mean vy and the z-scale that presents the mean slam peak pressures of 26 tests.

The pressure pulse velocity, which could be extracted from Fig. 6, correspond to the development of water jet along the archbow during water entry at relatively high-speeds. The measured pressure as function of time was analysed and the pressure pulse was presented in Fig. 6. This would provide researchers with the water jet velocity along the archway, which would help them in solving boundary layer regimes and selecting adequate turbulence model for validating further numerical simulations based on calculated longitudinal velocity. These 3-d effects would not have been captured in the model experiments if the model had been simplified to 2-d sections.

Although, the pressure distributions demonstrate the possibility of finding a relation between the maximum peak pressure magnitude that occurs at a certain location, e.g. Pressure transducer number 1 (P1, see Fig. 7), and the rest of the five pressure transducers, the localised nature of such a transient slam pressure peaks makes the repeatability of those data uncertain, especially at less controlled environments, e.g. seakeeping tests or full-scale trials. Thus, it could be of an importance to find the maximum pressure coefficient of each hull model. This study is limited to finding the pressure coefficients of the parent hull for a minimum of three repeated water impact tests for the at relative impact angles of ***β*** = 11° and 6°, that are equivalent to angles of trim of 0 and 5 degrees respectively, and for all relative velocities, e.g. from 3 to 5m/s in 0.5 m/s increments.

The mean traces of maximum pressures at P1 are aligned using the cross-correlation function in Matlab that can detect and align the peaks of a number of signals and has allowed accurate calculation of the average of maximum pressure time histories.
From this, designers could be able to calculate the pressure coefficient at the two relative impact angles using the traditional Wagner formula, as presented in Eq. 1 and 2 (The terms mentioned in Eq. 1 and 2 are defined in Fig. 7`

(1) $$\xi_{\beta^\circ} = \frac{z_{Pmax(\beta^\circ)} - z_{\beta^\circ}}{z_{\beta^\circ}}$$

(2) $$C_{P(\beta^\circ)} = \frac{2P_{max(\beta^\circ)}}{\rho v^2}$$

The repeatability of the experiments is acceptable since ***CP*(*β*°)** traces are in very good agreement. The maximum pressure coefficients of parent hull model ***CP(0°)max*** = 26 ±2 and ***CP(5°)max*** = 34.5 ± 1.5 are found approximately constant and uniform and it does not depend on impact velocity. It is interested to know that this was also noticed previously by a number of researchers, e.g. (Dobrovol'Skaya, 1969), (Zhao and Faltinsen, 1993), (Zhao.R, 1996), (Yettou et al., 2006) and (Lewis et al., 2010) but for other hull model shapes.

Fig. 8 demonstrates that the smaller the relative impact angle ***(β)***, the sharper the pressure coefficient trace, the more significant the pressure coefficient is ***CP(β°)*** (***max***) and the shorter the peak, this correlates well with slam force traces for ***β* = 6°.** Further numerical simulations are necessary to understand the disconnect between the slam force peaks and the pressure distributions using both hull model shapes. As, utilising a high-speed camera to capture the flow behaviour deemed to be limited for 3-d catamarans with protected hull structure.

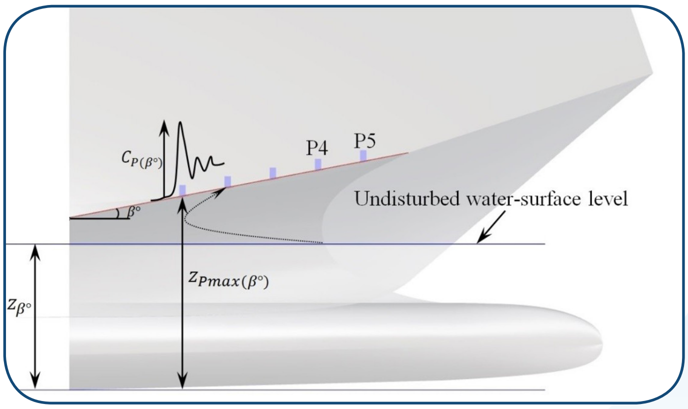

Fig. 7. Side profile view of model defining the variables used to non-dimensionalized the maximum slam pressure peaks at P1. Also shown on the archway are the locations of the five pressure transducers

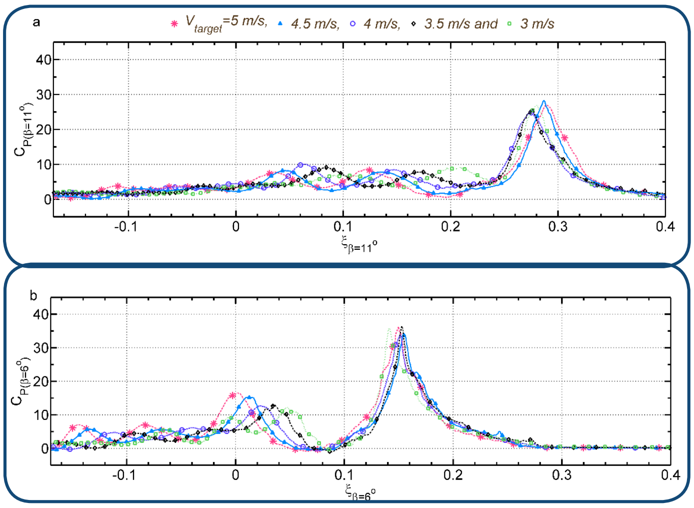

Fig. 8: Catamaran pressure coefficients at two relative impact angles with non-dimensionalisied catamaran entry-depth.

4. CONCLUSIONS

The presented work reports on a series of experimental tests that were conducted on a 3-d bow section of a catamaran model impacting with water in a 3-d regime. The catamaran model is constructed with two interchangeable centrebows. The experimental data and CFD results including flow behaviour, pressure distributions, vertical force, applied work and corresponding immersions gave new insights into the wetdeck slamming phenomenon.

It is important for classification society rules to consider the influence of pitch angle on wetdeck impact load severity, as it was found through utilising computational and experimental tests that an increase of 5 degrees in trim angle can increase the vertical slamming force on the entire model by up to 30%.

As a result of using the amended centrebow, flow on the tips of the wings separation was reported during centrebow-water entry. Thus, the larger air-cushioning effect between the wetdeck and water surface showed a decrease in the resultant force by 6% in comparison to the parent centrebow. This inventory idea has been implemented by Incat in her new built vessels.

It was observed that limited pressure distributions should not be used to assess slam loads due to the finding that localised pressure measurements are more dependent on flow behaviour than on the entire slam load magnitudes. Thus, larger peak pressure magnitudes (at selected locations) do not necessarily lead to a larger total force. The 3-d water-impact experiments can be extended by implementing scaled-velocity traces recorded from full-scale sea trials rather than conducting constant-speed water impact tests. This will enable further investigation on the issue of scaling of slam loads.

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