Ocean Engineering 131 (2017) 263–271

Contents lists available at ScienceDirect

Ocean Engineering

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

# Wave impact loads on wave-piercing catamarans

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## ARTICLE INFO

*Keywords:*
Slamming
Catamaran
Whipping
Modal frequencies
Mode shape
Hydroelastic segmented model
Slam loads
Bending moments

## ABSTRACT

Wave slamming is investigated for the 112 m INCAT wave-piercer catamaran with reference to experimental work conducted at full scale, numerical computation by CFD and FEA and testing at model scale using a 2.5 m segmented hydro-elastic model. The segmented model was tested in regular head seas to investigate the magnitude and location of the dynamic wave slam force and slam induced hull bending moments. The model consists of rigid segments joined by elastic hinges designed to match the scaled first longitudinal modal (whipping) frequency measured at full-scale on the INCAT 112 m vessel. Effects of forward speed and wave encounter frequency on slamming and whipping were investigated. Scaled slam forces of up to 2150 t weight (21.1 MN) were measured during model tests for a full-scale vessel with a loaded displacement of 2500 t. These slams can impart impulses on the bow of up to 938 t weight-seconds (9.20 MNs) and strain energy of up to 3.5 MJ into the ship structure based on scaled model test data. The impact energy is transferred primarily to the main longitudinal whipping mode, which decays with an overall structural damping ratio of 0.02–0.06, this being strongly dependent on internal frictional mechanisms within the ship structure.

## 1. Introduction

The most common design of catamaran has a flat wet-deck section joining the two demi-hulls and extending to the bows of the demi-hulls. This design is effective during operation in smaller waves. However, this conventional catamaran design is prone to deck diving when operating in following seas. Deck diving causes the wet-deck to encounter the wave surface, imparting an impulsive slam load on the bow that may cause substantial structural damage (Fig. 1). This occurs because conventional designs do not have substantial bow flare above the waterline and the forward end of the superstructure is very exposed to water entry. Designs of the semi-SWATH type with submerged bow sections are relatively soft at the bow, that is having a smaller increase of buoyant upward force on the forward hull sections with vertical displacement as the bow enters the water more deeply. As a result there is a smaller upward force as the bow enters a wave and such designs are thus more vulnerable when operating in large seas.

The severity of slamming can be significantly reduced with a centre bow, as in the INCAT wave-piercer catamaran (Fig. 2), with substantial reserve buoyancy above the waterline. The wave-piercing design adopted by INCAT is configured to reduce wave response in moderate head seas while providing inherent forward buoyancy, which ensures that complete bow immersion of the demi-hulls and water over the upper deck of the central bow are avoided during large wave encounter or when overtaking following seas. It is an essential part of the vessel response that significant bow forces are generated in order to prevent deck diving and bow entry. Operations in severe sea conditions thus expose the vessel to wet deck slamming when the bow entry is sufficiently deep that the wet deck comes into contact with the water surface. Such extreme conditions with wet deck slamming need not necessarily present a hazard to the vessel or the passengers provided that the structure is adequately strong and loads are well sustained.

The hydrodynamic interaction between a moving wave-piercer bow and moving water surface is clearly a complicated process involving three-dimensional transients. For this reason identification of slam loads is best carried out by full-scale vessel trials and model testing as describe by Davis et al. (2007). However, continuing advancements in computing resource are enabling the application of simulations based on the Reynolds-averaged Navier-Stokes (RANS) equations (McVicar et al., 2014, 2015). The aim of the present paper is to give an overview of the various aspects of slamming in the bow area of Wave Piercing Catamarans by means of full scale sea trials, through scale model testing and through computation of transient hydrodynamics and structural response to impact loads. The combination of full scale, model scale and computational investigation gives a more comprehensive perspective on the wave slamming process for these vessels and its

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http://dx.doi.org/10.1016/j.oceaneng.2016.11.015
Received 26 November 2015; Received in revised form 30 September 2016; Accepted 12 November 2016
0029-8018/

**Fig. 1.** Damage sustained by Ocean LaLa following an extreme wet-deck slam event on 9th August 2010 en route from Penghu to Taichung. 311 passengers and 22 crew were on-board the vessel when Mayday was sent at 19:04 local time 8.7 miles from port. Although there were no serious injuries recorded, 8 passengers were sent to hospital. (http://www.chinapost.com.tw/taiwan/national/national-news/2010/08/10/268041/Ferry-accident.htm).

**Fig. 2.** INCAT Hull 069 – Liquified Natural Gas (LNG) 99 m wave-piercer catamaran commissioned in June 2013.

implication for structural design. This paper in particular extends previous investigations in the area of combined computation of both the transient hydrodynamics in the bow area and the dynamic response of the ship structure by finite element analysis.

## 2. Review of wave slamming on full-scale vessels

Sea trials have been conducted on several INCAT catamarans fitted with a TSK wave radar to measure wave elevation, accelerometers to measure vessel motion and strain gauges to measure unsteady stresses in the ship structure. Wave slamming causes an impulsive load on the structure resulting in virtually instantaneous flexure followed by whipping vibratory response as described by Kapsenberg and Brizzolara (1999). Slam impulse loads applied to the centre bow of the catamaran in head seas most strongly excite the first longitudinal mode of vibration in the vertical plane (Thomas et al., 2008). However, the very short duration of the slam impulse which acts on INCAT catamarans can induce responses from higher frequency modes (McVicar et al., 2015). The effect of higher order modes can be very localised and only observable in measurements close to the localised slam loading. Full-scale trials undertaken on the 112 m INCAT catamaran identified the first longitudinal modal frequency during an extreme wave slam (Lavroff et al., 2009). Fig. 3 shows a typical accelerometer response during sea trials of INCAT hull 064 (112 m) when a wet deck slam occurred (Lavroff, 2009). It is seen that the slam transient loading leads to excitation of the main whipping mode of the vessel, in this case at a frequency of 2.44 Hz or period of 0.41 s. The decay of the whipping motion is due to internal frictional mechanisms within the structure (Thomas et al., 2008) and in this case indicates an overall structural damping ratio relative to critical damping of 0.065.

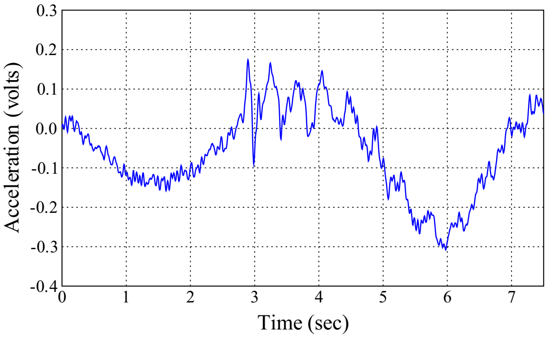

**Fig. 3.** Wave induced slam upward acceleration recorded on the bow of INCAT Hull 064, 112 m wave piercer catamaran during a delivery voyage to Japan in August 2007, Lavroff (2009). The slam occurred at time, $t$=2.9 s. Accelerometer sensitivity 0.78 V/$g$, where $g$ is gravitational acceleration (m/s$^2$).

Thomas et al. (2008) determined values of the first longitudinal bending mode frequency and damping ratio for 86 m, 96 m, 98 m and 112 m INCAT wave-piercer catamarans at speed while encountering slams and while moored in calm water using anchor drop tests. Table 1 provides a summary. INCAT have developed a NASTRAN/PATRAN finite element model of the ship structure to predict frequencies of the main longitudinal bending mode – LBM (Fig. 4), lateral torsional mode - LTM (Fig. 5) and split mode – SM (Fig. 6). The associated frequencies are shown in Table 1.

The 98 m catamaran was analysed in more detail than the other vessels by Amin (2009). The finite element model predicted nine dominant longitudinal bending modes in the range 1.97–2.67 Hz, five distinct split modes in the range 1.62–1.73 Hz and two lateral torsion modes at 1.10 and 1.13 Hz. The various modes in each case can best be described as variants of the dominant mode, this being a particular characteristic of complex structures with dominant overall forms and dimensions. While the computed frequencies are generally higher than those measured, the finite element analysis clearly confirms the physical identity of the various modes. The fundamental LBM was observed in the whipping responses of all vessels while the LTM was only observable for the 86 m and 96 m vessels and the SM was only observed in the 98 m vessel sea trials. The 98 m catamaran had horizontal cross bracing on the portal top level extending further forward and further aft. This appears to have increased the lateral stiffness of the structure therefore raising the response frequency of the split mode. Due to the general similarity of these vessels, it would be expected that similar modes be excited in each vessel. It is therefore likely that strain gauge placement and the similarity of the LTM and SM frequencies inhibited the identification of the unobserved modes. The longitudinal bending modes of the 86 m and 96 m vessels were further identified in zero speed anchor drop tests using four accelerometers located along the vessel centre line by Thomas et al. (2003), as shown in Table 1. The finite element analysis showed little effect of speed using added water mass calculated by the boundary element method. Damping ratios are also presented in Table 1. Sources of damping were investigated by Thomas et al. (2008), who reported that hydrodynamic wave making, viscous effects and compressive pressure waves radiated through the body of the surrounding water are all negligible. It was concluded that major damping originates from structural sources such as the anti-vibration mountings that isolate the upper passenger deck structure from the main ship structure, bolted connections, the internal fit-out and furnishings.