Prediction of Slamming Behaviour of Monohull and Multihull Forms using Smoothed Particle Hydrodynamics

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ABSTRACT: High-speed catamarans are increasingly being used for transportation in both defence and commercial purposes due primarily to their advantages in fuel efficiency, speed and flexible mission applicability. Improving their seakeeping behaviour to reduce discomfort as well as keeping the structure as light as possible are two of the major issues naval architects are extensively investigating. The impact of the bow into the water when operating in large waves, better known as slamming, is a phenomenon which can cause serious damage to the structure as well as reducing passenger comfort in high-speed catamarans. Therefore an understanding of this phenomenon is crucial, as is the development of a method for accurately predicting the slam load magnitude. Model wedge water-entry experiments, CFD, mathematical and empirical formulations are conventional methods currently being employed to investigate slamming and predict drop velocity, accelerations and pressure profiles on the hull surface. More recently, the Smoothed Particle Hydrodynamics (SPH) technique has been applied to simulate wedge water-entry problems due to its advantages in capturing rapid and large deflections in fluids. In this work, SPH has been successfully used to simulate water-entry of a wedge in two-dimensions. Also, the effect of important parameters such as artificial viscosity and numerical speed of sound are investigated and comparisons with experimental results are presented. A wedge with side plates has been simulated as a simplified representation of a catamaran bow section with centrebow.

1 INTRODUCTION

Catamarans currently have a wide range of applications including use as car and passenger ferries, pleasure boats and military vessels. Use of lightweight materials, such as aluminium and composites, provides these vessels an opportunity to travel at high speed efficiently; however, passenger comfort, vessel operability and structural strength in waves are major issues which still need further research. This is particularly important for large high speed catamarans since the design criteria are not yet clear or sufficiently accurate (Heggelund et al. 2002).

High length to beam ratios and high Froude numbers of catamaran demihulls suggest that the tendency of the vessel to have large motions in the longitudinal plane is high, thus large vertical velocities and displacements are expected at both ends of the vessel. When the vessel motion in large waves causes an impact on the underside of the cross deck structure, severe slam events occur for high speed catamarans; these are known as wetdeck slams (see Figure 1). Local wetdeck and global damage can occur in rough seas due to this phenomenon (Lloyd 1989; Thomas et al. 2003).

Figure 1: An outline section of a large high speed catamaran.

Since the demihulls are slender, there is often insufficient reserve buoyancy to act as a restoring force when it is needed to resist against large pitch motions. This is a particular problem in following...
seas when deck diving can occur with water coming over the bow structure of a conventional catamaran. The short centrebow acts as a solution to this problem; a volume in the bow part which is added to the cross deck between the demi-hulls, stretches vertically downwards (see Figure 2).

For large high-speed catamarans fitted with centrebows, there are several parameters affecting the wet deck slamming behaviour, including tunnel height and the position of the centrebow. Several configurations of the centrebow in catamarans are available, which have been designed based on the designers’ experience or their perception of the phenomena. There is often not a coherent approach to design the centrebow due to a lack of available information about its effects on vessel behaviour. Hence, there is a need for further research on the effects of different centrebow shapes and tunnel heights on the behaviour of the vessel at the sea.

Full-scale trials, model experiments and numerical simulations are the common methods employed to model slamming behaviour. A brief discussion on each of these methods is presented in the following sections.

Previous collaborative work between the University of Tasmania and INCAT Tasmania, has investigated the performance of wave piercing catamarans in full-scale measurements and model scale tests. The investigations have been focused on the seakeeping, global wave loads and slamming behaviour (Roberts et al. 1997; Thomas et al. 2003; Davidson et al. 2006; Davis et al. 2007; Thomas et al. 2008; Amin et al. 2009). In the present work numerical simulations using Smoothed Particle Hydrodynamics (SPH) to model slamming behaviour of wedge and catamaran sections will be introduced and the results will be compared to experimental data.

2 BACKGROUND

2.1 Full scale trials

Whilst slamming is of concern in many marine applications (Faltinsen et al. 2004), in this work, the special interest is on ship bow slamming. Due to the importance of the phenomenon, much work has been done to investigate the probability of its occurrence or the effects of slamming (Lloyd 1989).

Conducting measurements on full-scale vessels is an important method for investigating slamming behaviour. A key finding has been the identification of the range of slam events experienced by high-speed catamarans. Full scale tests on catamarans provide real measured data and environmental conditions which can provide an understanding of actual slam loads and their effects on the ship. There have been a considerable number of investigations on catamaran motions and slamming behaviour at full scale. For example Haugen and Faltinsen (1999) worked on a 30m catamaran in which vertical acceleration and other strains of the vessel during slamming were measured and compared with a hydroelastic wet deck model.

Full-scale tests were conducted by Roberts et al (1997) and Thomas et al. (2001; 2003; 2005) on an 81m, a 96m and an 86m INCAT catamaran and the slamming loads were found to be significantly larger than the regular wave loads.

![Figure 2: Condor Express, INCAT Hull042, an 86m car-passenger wave piercing catamaran, the centrebow in front is obvious (Photo: Barry Quince).](image)

Although full-scale data is extremely valuable, there are also some concerns connected with conducting full scale experiments. Firstly data acquisition is difficult; secondly, when analysing the data it can be difficult to identify the slam loads and to distinguish slam loads from global wave loads. Also there is often little or no control on environmental conditions and trial parameters at the sea (Thomas et al. 2003). In the case of new designs there is a need to investigate the problem using other methods such as model experiments or numerical simulations.

2.2 Model tests

Model tests are widely used to predict motions and forces in marine applications. Wedge water-entry (drop tests) and segmented model tests are used for the investigation of slam events in model scale.
There are advantages in model scale tests: all the environmental conditions can be controlled and most of the required information can be captured by sensors. Moreover, it is easier and cheaper to change the test parameters and model configurations. By means of model experiments, a good understanding of the phenomena can be gained and the basis for theoretical or numerical formulations established. Dynamics and kinematics of the model tests can then be scaled to full size and used to predict the vessel’s full scale behaviour.

### 2.2.1 Drop tests

Von Karman (1929) and, shortly after, Wagner (1932) introduced the wedge water-entry problem for wedges with small deadrise angles and also suggested some analytical approaches which today are considered fundamental solutions. Many works have followed and improvements to Wagner’s solutions have been presented in literature due to the importance of the phenomenon. Zhao et al. (1993; 1996; 1998) and Faltinsen (2002; 2004) conducted a relatively intensive investigation including experiments and analytical solutions on the wedge water-entry problem and slamming. Free falling and forced dropping of straight and inclined sections were investigated.

To simulate the slamming of catamarans, drop tests were performed by Whelan et al. (2004) and Davis et al. (2007) for several centrebow configurations at the University of Tasmania. A two-dimensional study of drop kinematics of bow sections was carried out, both theoretically and experimentally. Drop speed, pressure distribution and vertical acceleration were measured. Despite the advantages of wedge water-entry tests the predicted loads and pressures were found to be unrealistically high when compared to full scale results, especially for catamaran sections.

### 2.2.2 Hydroelastic segmented models

There have also been some investigations of the slamming and whipping response of catamarans at model scale, using hydroelastic segmented models to examine the vessel structural response. Ge et al. (2002) used a 5m segmented catamaran model which had two transverse cuts and two longitudinal cuts with strain gauges fitted to trace the global response due to wetdeck slamming.

Lavroff (2009) developed a 2.5m hydroelastic segmented scaled model of a 112m INCAT wave-piercing catamaran. The model was tested in both calm water and waves and the slamming, whipping and motion response of the model was investigated. The whipping modal response and damping coefficients of the model were analysed and important parameters which affect them were demonstrated (Lavroff et al. 2007).

Hydroelastic segmented model tests are more realistic than the wedge water-entry tests, since the whole three-dimensional geometry and environmental conditions are represented. Local and global slam effects on the vessel can be investigated and results are very useful in terms of defining criteria for slam events and for predicting the loads on the full vessels based on model test results.

### 2.3 Numerical simulations

Computational Fluid Dynamics (CFD) has been used for the simulation of the wedge water-entry problems. Different approaches using CFD are available to analyse the fluid-structure interaction phenomenon (Brizzolara et al. 2008).

The FORTRAN program BEAMSEA is a software package developed at the University of Tasmania which applies the Boundary Element Method (BEM) and strip theory in time domain to analyse the motions and behaviour of the vessel in waves. Currently, work is being done to add a slamming predictor to the program.

Smoothed Particle Hydrodynamics (SPH) is a mesh-free particle method that has been shown by several authors (Doring et al. 2004; Oger et al. 2006; Viviani et al. 2009) to capture large deformations in free surface flows due to its Lagrangian nature, as well as its faster generation of input data. Whilst Veen (2011) has applied SPH to the problem of a wedge with side plates, the outcome was uncertain due to the singular nature of conditions at the point where the cross section fills with fluid particles completely. In the present work a further attempt is made to simulate entry of a wedge with side-plates as a pre-cursor to investigating the section of a catamaran with centrebow.
mesh-free Lagrangian method (where the coordinates move with the fluid), and the resolution of the method can easily be adjusted with respect to variables such as the density.

It has several benefits over traditional grid-based techniques as it guarantees conservation of mass since the particles themselves represent mass; and computes pressure from weighted contributions of neighboring particles rather than by solving linear systems of equations. Also, unlike grid-base techniques it creates a free surface for two-phase interacting fluids directly since the particles represent the denser fluid (usually water) and empty space represents the lighter fluid (usually air). For these reasons, it is possible to simulate fluid motion using SPH in real time. Therefore, as long as the inter-particle relations are defined correctly, the particles are free to go anywhere (Liu et al. 2003).

Monaghan (1988; 1992) was first to introduce SPH to astronomical problems, and shortly after applied it successfully to free surface flows (Monaghan 1994). A number of notations and mathematical approaches to describe SPH are documented. A brief overview is presented here with notations similar to that of Liu et al. (2003).

A function $f(x)$ can be represented as an integral form of the three-dimensional position vector $x$ as shown in Equation (1):

$$f(x) \equiv \int_W f(x') W(x-x', h) \, dx'$$

in which $W$ is smoothing function or kernel function and $h$ is the smoothing length. The kernel function has similar properties to the Dirac Delta function.

One of the common kernel functions is the Gaussian, which is shown in Equation (2):

$$W(r, h) = \alpha_D \exp \left(-q^2\right)$$

where $\alpha_D$ is given as $\frac{1}{\sqrt{\pi}h^2}$ in two-dimensions.

The momentum conservation equation in a continuum field is given by

$$\frac{D\vec{v}}{Dt} = -\nabla P + \vec{g} + \vec{\Theta}$$

where $\Theta$ in Equation (3) refers to the diffusion terms and $P$ is the pressure. To complete the momentum equation, there are different approaches to the diffusive terms. Artificial viscosity proposed by Monaghan (1992) is the most common and is given as Equation (4)

$$\frac{d\vec{v}_i}{Dt} = -\sum_j m_j \left( \frac{p_j}{\rho_j} - \frac{p_i}{\rho_i} + \Pi_{ij} \right) \vec{v}_i W_{ij} + \vec{g}$$

where $\vec{g}$ is the gravitational acceleration and $W_{ij} = W(x_i - x_j, h)$. $\Pi_{ij}$ is the viscosity term defined as

$$\Pi_{ij} = \begin{cases} -\frac{\alpha \mu_{ij}}{\rho_{ij}} & \vec{v}_{ij} \cdot \vec{r}_{ij} < 0 \\ 0 & \vec{v}_{ij} \cdot \vec{r}_{ij} > 0 \end{cases}$$

where $\mu_{ij} = \frac{\eta \vec{v}_{ij} \cdot \vec{r}_{ij}}{\vec{r}_{ij}^2 + \eta^2}$ with $\eta^2 = 0.01h^2$ and $\vec{v}_{ij} = \vec{v}_i - \vec{v}_j$ is the relative velocity between the particles. The term $\vec{c}_{ij} = \frac{c^2_{\rho} + c^2_{\rho}}{2}$, where $c$ is the speed of sound in each particle and $\alpha$ is a constant chosen according to the problem. Artificial viscosity is used to stop the unphysical behaviour of fluid particles, smears out the shocks and contact discontinuities.

To develop the continuity equation, fluid density changes can be calculated in SPH using Equation (6).

$$\frac{d\rho_i}{Dt} = -\sum_j m_j \vec{v}_j \cdot \vec{v}_i W_{ij}$$

The equation of state for determining the fluid pressure is given by Equation (7)

$$P = B \left( \frac{\rho}{\rho_0} \right)^\gamma - 1$$

where $\gamma = 7$ and $B = \frac{c^2_{\rho} \rho_0}{\rho_0}$ in which $\rho_0 = 1000kg \, m^{-3}$ the reference density and $c_0 = c(\rho_0) = \sqrt{(\frac{\rho}{\rho_0}) \rho_0}$ the speed of the sound at the reference density. The speed of sound, $c_0$, is a numerical speed of sound which is always taken as less than the actual speed of sound in water and normally more than 10 times the fluid maximum bulk velocity (Viviani et al. 2009). Equation (7) is derived from the assumption that the fluid is weakly compressible, so there is no need to solve Poisson’s equation.

Particle movements are smoothed using the XSPH formulation proposed by Monaghan (1989),

$$\frac{d\vec{r}_i}{Dt} = \vec{v}_i - \epsilon \sum_j \frac{m_j}{\rho_{ij}} \vec{v}_{ij} W_{ij}$$

where $\epsilon$ is a constant normally $0 \leq \epsilon \leq 1$, but with most incompressible fluids chosen as 0.3 (Liu et al. 2003). This correction keeps the particles more orderly and prevents unphysical particle interaction.
3.2 Water-entry of vessel sections with SPH

Drop tests are a common technique for investigating the slamming problem experimentally.

Figure 3. experimental facilities of drop tests at University of Tasmania (Whelan 2004).

Comprehensive results of drop test experiments are available from previous works by Whelan (2004). Figure 3 shows the drop test facility at the University of Tasmania used in these experiments. It consists of a vertical tower with guide tracks to drop the entry section from various heights. The tank is of 2.4m length and 0.3m width, filled with water of 1m in depth. Different wedge and other cross-sectional models were fitted with pressure sensors and an accelerometer and the tests were filmed with a high-speed camera. The tank is made from glass to allow the water-entry to be filmed. Some of the water-entry sections of Whelan’s experiments (such as Figure 5) are modelled using SPH. Pressure sensor positions, named P1 to P4 are shown on the body plans. The 25 degree wedge is the same as the section shown in Figure 5 but without the side-plates.

The open source code of SPH called SPHysics (SPHysics http://www.sphyisics.org) has been adopted as a base code with significant changes introduced to model the different wedge geometries and allow for the dropping of a rigid section from a certain height above water level. The governing equations in the SPHysics solver are shown in Section 3.1. The code has been validated for a number of benchmark cases available on the website.

To simulate the drop test, a two-dimensional tank with dimensions 2.4m length and 0.3m width (as used by Whelan (2004)) has been adopted.

Figure 4. Dimensions of the 25 degree deadrise angle wedge with side-plates. P1, P2, P3 and P4 are the position of pressure transducers (Whelan 2004).

Figure 5 shows the particle arrangement in the bottom right corner of the domain. The fluid particles and boundary particles were modelled using a staggered approach to prevent unnecessary penetration of particles through the boundary walls. The Dalrymple dynamic boundary condition (Gomez-Gesteira et al. 2010) was adopted to model the solid walls of the tank and unlike the fluid particles these are fixed. As the fluid particles approach the boundary, the pressure increases and generates a repulsive force which prevents the particles escaping.

Figure 5. Particle arrangement on the bottom right corner of the tank.
The wedge drop section as seen in Figure 10 is simulated using the same type of particles used to create the boundary. The weight per length and the drop height was extracted from Whelan’s (2004) experimental results. These were determined by scaling and non-dimensionalising slam events of real ocean vessels. For the 25 degree deadrise angle wedge, the drop height was chosen so that the wedge velocity when it hits the water was the same as in the experiments.

Due to the weakly compressible assumption of the fluid in the equation of state, the speed of sound and the coefficient of artificial viscosity play significant roles in the accuracy as well as computational time of the SPH simulations. Therefore, a set of simulations was completed to investigate the effect of these parameters with two particle spacing’s (P.S.) of 0.01m and 0.005m. In these simulations the kernel function was chosen to be Gaussian \((h = 0.93\sqrt{2(P.S.)^2})\) and the time stepping scheme was the Predictor-Corrector described by Monaghan (1989).

To investigate the accuracy of the SPH simulations, the accelerations, vertical velocity, submersion and pressures relative to time are predicted and compared to experimental results by Whelan (2004). These parameters are of importance as the general structure and seakeeping of the ship in waves is of interest. In the slam events, if the amount of kinetic energy which the vessel needs to absorb is to be simulated, the vertical velocities and accelerations must be considered. The peak local pressure is also important if the local structure stiffening is of interest. Also, the progressive submersion relative to time is a good indicator to assess the motions predicted by SPH.

4 RESULTS AND DISCUSSIONS

4.1 25-degree wedge water entry

A sample comparison of drop distance, vertical velocity, vertical acceleration and pressure time history (at location P3) of the 25 degree wedge of 72.25kg/m and drop height from water level to the side knuckles of 0.192m is shown in Figure 7 to Figure 10.
Also from equation (8) $\varepsilon$ is chosen as 0.5.

**Figure 9.** Plot of the vertical acceleration comparing numerical results obtained using SPH with experiments by Whelan (2004) for the 25 degree wedge.

A drop in water level between 0 to 0.005m occurs when a low speed of sound is used. This arises because the fluid particles leak through the fixed tank wall due to the small repulsive forces or the compression of fluid caused by gravity (the lower the speed of sound is, the more compressible the fluid becomes).

**Figure 10.** Plot of the pressure at P3 comparing numerical results obtained using SPH with experiments by Whelan (2004) for the 25 degree wedge.

Figure 11 and Figure 12 show the relative error (in time) in the results obtained for the vertical velocity, distance travelled and peak acceleration associated with changing the artificial viscosity coefficient ($\alpha$) and speed of sound ($c_0$) respectively for both particle spacing’s 0.005m and 0.01m. The relative error was calculated using relative error $= \frac{X_{\text{exp}} - X_{\text{num}}}{X_{\text{exp}}}$ and averaged over the complete simulated drop time. Maximum values were used to determine the relative error for the acceleration.

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As is shown in Figure 11, for the lower artificial viscosity, the vertical velocity and drop distance travelled matches quite well with the experimental results, with the accuracy reducing as the artificial viscosity increases. It could be concluded that the lower artificial viscosity is more suitable for such simulations, since the particles are more free to move based on momentum equation. Unphysical behaviour does not occur from the fluid particles here since there is no large discontinuity or phase change. With the particle size of 0.005, the peak acceleration has greater accuracy when a low viscosity is used. Whilst in the case of the drop peak acceleration, for a particle size 0.01m, the error is high at low viscosity, decreasing with increasing viscosity. This behaviour in acceleration does not follow the other trends, thus needs further investigation.
The effect of varying the speed of sound is shown in Figure 12. The relative error does not show a monotonous trend. For a speed of sound of 40m/s the error trends have a local peak. The reason could be found in the trend of acceleration results, as shown in the Figure 13 (c₀ = 40m/s). There is a large local minimum after the first and highest peak and this could be due to the effect of the tank walls. The total drop time is very small; therefore, in lower speed of sounds, pressure waves take longer to hit the tank walls and return. Specifically for the case when c₀ = 40m/s, when it strikes the side wall of the drop section, there is an effect on the drop motion. The higher the speed of sound is, the higher are the frequency of the acceleration fluctuations; therefore, the submersion and vertical velocity accuracy changes. As in the experiments, due to the real speed of sound (around 1500m/s), the frequency of these oscillations in accelerations is much higher and does not change the overall trend. Further work is needed to be done on the effects of speed of sound and tank dimensions on wall reflections and energy absorptions.

For a speed of sound of 15m/s there is a reduction in the error for the wedge displacement, vertical velocity and peak acceleration. This could be a good basis on which to commence simulation of further geometries.

Running the simulations using smaller particles increases the computational time significantly (more than 10 days) so the larger particle size was adopted for the simple wedge geometries. Overall, the simulations show satisfactory accuracy in determining the motions for a simple wedge. Further work is being conducted for more complex geometries in an aim to predict catamaran slamming phenomena.

4.2 Water-entry of a 25 degree wedge with sideplates

A 25 degree wedge with two side-plates with a section weight of 72.25 kg/m and drop height from central wedge bottom of 0.082m was simulated in SPH. The snapshot of the slam is shown in Figure 14. The best results were obtained for a particle size of 0.005m, α = 0.01, c₀ = 15m/s and ε = 0.3. Results are shown in Figure 15 to 19.
Figure 16. Plot of the drop velocity comparing numerical results obtained using SPH with experiments by Whelan (2004) for the 25 degree wedge with side-plates.

Figure 17. Plot of the vertical acceleration comparing numerical results obtained using SPH with experiments by Whelan (2004) for the 25 degree wedge with side-plates.

Figure 18. Plot of the pressure at P4 comparing numerical results obtained using SPH with experiments by Whelan (2004) for the 25 degree wedge with side-plates.

The results show that the numerical results obtained using SPH follow the overall trend of the experimental results, but with less accuracy than achieved for the simple wedge. Although the deceleration trend has some deviation the prediction of peak drop acceleration is quite good. The peak acceleration for the wedge with side-plates is higher than that measured in the experiments by Whelan (2004). The most likely cause of this the effect is the air cushion generated underneath the highest point of the section by entrained gas elements which do not vent freely in the model tests. In SPH this effect could be represented by increasing the compressibility of the water so as to compensate for the compressibility of the air bubbles trapped within the section at the top of the arch. There are also some fluctuations in the predicted pressure profile, which could have been caused by the movements of separate particles at the spray root around the measured area.

5 CONCLUSIONS

Investigation of slamming for surface piercing catamarans is an ongoing subject of research. However, not much work has been done on the effect of hull form, specifically the presence of a centrebow and magnitude of the tunnel height. Smoothed Particle Hydrodynamics, as a numerical approach has been used here successfully on simple wedge water-entry to simulate a monohull vessel slamming. Simulations achieved errors of less than 5% in drop velocity and progressive submersion and approximately 30% in drop peak acceleration. Pressure on the side walls were predicted by averaging fluid particles pressure around the desired point. To approach the slamming of a catamaran with a centrebow, a simple wedge with two side-plates was also investigated in SPH, the results are less accurate but promising. Further work is needed to improve the results for two-dimensional simulations of realistic ship cross sections.

6 REFERENCES


