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Motion Prediction of Ships and Yachts by Smoothed Particle Hydrodynamics

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Abstract. Smoothed Particle Hydrodynamics (SPH) is a (relatively) recent numerical analysis technique that facilitates the development of a virtual towing tank for the analysis of ship and yacht motions. SPH is a mesh-free interpolation method in which particles follow the motion of the material and its interfaces. Although the accuracy of the method merits further work, the SPH method when used to model fluid flow suffers neither from the inaccuracies of the Eulerian finite difference solution, nor from the large deformation limitations of Lagrangian finite elements. When water is analysed using mesh-free techniques, the simulation can model many non-linear phenomena including breaking waves as well as dispersion in splash-like events. The combination in the one analysis package of both mesh-based and mesh-free capabilities makes feasible the analysis of ship and yacht behaviour in waves. This physics-based analysis technique yields an approach that is unrestricted in its ability to model conventional displacement vessels, multi-hulled wave-piercing vessels, planing vessels or even submarines. Furthermore, airborne events such as those leading to slamming of yachts can also be analysed. This paper will present a number of recent case studies to demonstrate the flexibility of the SPH numerical towing tank for the analysis of ships and yachts in waves.

1. INTRODUCTION

The design of ships and yachts for severe conditions is not a trivial matter. Life is at risk, often at times when no outside assistance is available. Yet to err on the safe side from a design perspective carries cost penalties in terms of the cost of the structure initially, and the running cost over the life of the vessel. So we strive to continually reduce the risk of vessel design by understanding the science of the severe events.

The severe events of interest in this paper is the encounter of a severe wave, or perhaps the repeated encounter of lesser but significant waves that bring cumulative damage to a vessel. Typically the response of the vessel to such a wave will be non-linear, involving a change of speed or direction, often associated with large amplitudes of roll and/or pitch. Consequently this response is outside the regime of most ship motion analysis software packages, and so an alternate approach is required.

The analysis approach to the response of a vessel adopted in this paper is similar to the state-of-the-art computer simulation of the crash-testing of a car. In the automotive, rail and air transport industries where human safety is paramount, considerable cost of a new vehicle is associated with the physical crash-testing of a new design. Crash-testing is a requirement to demonstrate compliance with the safety regulations governing that industry. These physical tests are expensive to prepare, conduct and analyse. There is tremendous financial pressure on the designers to pass the crash-test with the first test-piece. The designers from these industries improve the chance of passing the crash-test by a process called “simulation”. The simulation process involves conducting numerous “virtual” crash-tests by computer models. By running numerous simulations the designers are able to evaluate the design iterations, and so choose the design that represents the best balance of survivability, weight, manufacturability and economics.

For the application of ships or yachts in water the simulation process is similar – the water and the vessel are allowed to interact based on the principles of physics and material behaviour. The response of the vessel is not restricted by empirical relationships or presumed responses. In this way extreme behaviour can be modelled with a stable computation process that places no restriction on vessel shape, motion or behaviour. The result is a simulation that can model a vessel that can fully submerge, become airborne or capsize as a consequence of the forces acting on it.

This un-restricted simulation capability may be applied to ships and yachts in such cases as extremely high-speed vessels, slow-speed vessels encountering large waves, or the assessment of damage survivability.

This paper highlights some of the development work being conducted by the authors to develop the technique for naval architecture applications.

2. THE MESH-FREE APPROACH

In 1977 Lucy [1], and Gingold and Monaghan [2] first demonstrated the concepts of a mesh-free approach to describe behaviour of a fluid. These authors developed the concept for studies in astrophysics involving gases, large distances and limitless volumes of space.

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The concept of the mesh-free approach is that the fluid domain is represented by discrete particles that have with them the associated fluid properties. Each particle moves with the velocity of the amount of material it represents. The forces that generate this motion are derived from the weighted average of the pressures of the neighbouring particles within a specified radius. Thus the properties are smoothed, and the name Smoothed Particle Hydrodynamics (SPH) is used. The smoothing effect of the weighting function is depicted graphically in Figure 1, where the 'kernel' is the weighting function.

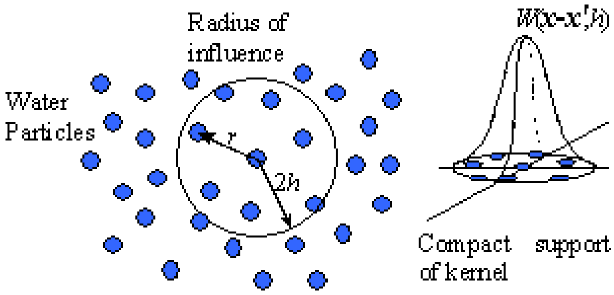

Figure 1. Local properties are the weighted average of the particle properties [3].

For the solution of the conservation equations the unknown gradients of the relevant fluid properties i.e. density and velocity components may be replaced by the gradients of the kernel. This avoids the need to evaluate gradients by numerical differentiation as for finite difference methods. This also explains why no grid is needed.

In conventional grid-based analysis of fluid flows, the analysis is very efficient when the flow is steady and uniform. When the flow is rapidly changing and strongly non-uniform, or when the shape of a free surface becomes complex such as for breaking waves, traditional grid-based methods may encounter serious difficulties. In contrast, the SPH technique can handle highly dynamic, non-uniform flow or surface breaking effects, as there exist no fundamental restrictions to the motion and topology of the particle distribution. Within the limitations of the spatial discretisation allowed by the computer resources, the particles are able to model rotational flow or splash.

The SPH technique quickly showed new capabilities to modelling gases, liquids and also solids. Some problems with the SPH technique, in particular related to stability, convergence or dealing with boundaries have been identified and to some extent been resolved by some modifications to the details of the method [4, 5]. There have been numerous studies showing reasonable to good results for flow of compressible or (nearly) incompressible fluids. The method has proven to be especially valuable for simulations involving complex fluid domains and moving interfaces [6, 7] The implementation used here employs a number of modifications to allow modelling of near-incompressible fluids using more efficient computations [8].

3. COMMERCIAL SPH SOLVER

The SPH used for the present study was implemented within the PAM-SHOCK commercial software package, from Engineering Systems International, France [8]. The commercial software code provides for a functional and robust environment to study the SPH behaviour. The software environment has advanced graphical user interfaces to conveniently prepare models and view results in an animated form, and many advanced finite element features such as "contact" routines that allow various material parts to interact. The code also combines mesh-free and grid-based elements in the one solver environment, providing SPH/FE hybridisation. This facilitates the study of fluid-structure interactions by allowing a structural entity such as a ship, yacht, oil platform, to be modelled using conventional shell elements, either deformable or rigid, and the water to be modelled as particles.

The combination of these features makes the use of a commercial software package an attractive tool for an applied user such as a ship or yacht designer.

SPH techniques are currently in a state of development with advancements and enhancements routinely being reported in the scientific literature. A commercial piece of software might therefore not have the most recent advancements implemented. The results presented here were achieved with software released in February 2005, 12 months before this conference. Nonetheless, it is worthy to explore the potential of commercial software packages, because as the applications for the software develop, the software authors will respond to industry interest and enhance the usability of the software for that industry – through industry-specific interfaces or improved scientific modelling of the material behaviour if that is found to be required.

4. RELEVANT SPH EXAMPLES

4.1 Hydrostatic Response of a Planing Hull

With so many examples of water behaviour modelled by SPH in the open literature [9,10,11], these are not reproduced here. Instead we will present here the more complex scenario of a body floating within the water. Specifically this paper will focus on extracting the response of the floating body that is relevant to the assessment of the floating body as a ship or yacht design.

Firstly we consider the hydrostatics of a planing hull, typical of a small sports-fisher or workboat. It is essential that the SPH technique demonstrate that the hull will sit on its design water line at rest, and show typical trim response with a shift in the centre of gravity. The general lines of the workboat are shown in Figure 2, with the particulars of the vessel noted in Table 1.

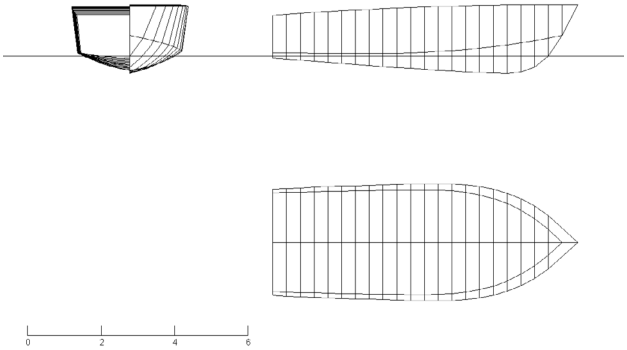

Figure 2. Lines of an 8.3m Planing Hull

LOA	8.30 m	Beam Max	3.184 m
LWL	7.45 m	Beam WL	2.814 m
Displacement	4042 kg		

Table 1. Particulars of the Planing Hull

Simulating the hydrostatic response of a simple hull like this using SPH is a complex process compared to the instantaneous results obtained from a basic hull hydrostatics programme. The difference here is the hydrostatics programme is tailored to find an equilibrium position of the distribution of the mass and the distribution of buoyancy. The hydrostatics programme is optimised to produce those results and nothing else.

In contrast, the SPH process is a time-based physical modelling system, where a complete physical system is defined, with initial conditions and time-based controls prescribed to everything in the system. After this initialisation stage, the interaction of the system components can begin, until an equilibrium position is obtained. If the design is reasonable, the boat will float on the water, but if not, the boat will sink, roll over, or do whatever the physics says it should do. All this takes time to define, and takes time to solve for the computer also. However, once the system is defined and works for one case, the system is easily modified for another case.

The model shown here consisted of the boat hull, a tank to hold the water, and the water particles. All of these parts were in a 3-dimensional space, and placed initially such that each part did not contact another. For simplicity here, the model had symmetry along its centreline, implying only half the hull was modelled. The boat hull consisted of about 400 shell elements and the water was modelled with about 18,000 particles of 150 mm diameter each. An interval of 15 seconds was allowed for the hull to achieve an equilibrium position in the water. At the start of this 15 seconds simulation process, the boat hull and water fell into the tank due to gravity, where they then interacted to obtain an equilibrium position. The configuration of the system, and the results, are shown in Figure 2.

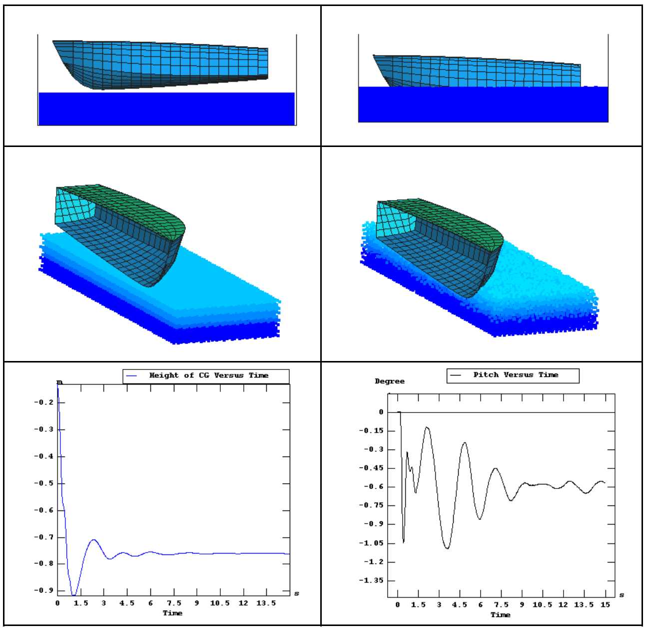

Figure 2. Balancing of the planing hull by SPH. The vessel begins the simulation period out of the water, and then drops into the water under gravity, producing an oscillating pitch response which soon damps out. The bottom left image is the vertical height of the CG, the bottom right image is the pitch of the vessel, trimming by the bow (bow down, negative pitch).

The top left illustration of Figure 2 shows a side view of the hull, water particles (blue mass) and the tank at the commencement of the simulation period. The middle left image is a perspective view of the initial conditions. Here it is visible that this is a real 3-Dimensional problem, except the hull has been restricted in motions across the line of symmetry, otherwise it would roll over, fill with water and sink, because it is only half a hull.

The right hand images of Figure 2 illustrate the equilibrium position of the hull. The bottom left curve is the height of the centre of gravity with time. Although the text is illegible due to small size of graphic in this paper, the shape of the curve is important. It starts at an arbitrary position, and then falls under gravity until the buoyancy of the hull brings it up again. There is a slight oscillation around the equilibrium position as would be expected from a real system. The curve on the right is the pitch of the hull, which oscillates around a value of about –0.6 degree from the initial position. The oscillations at the end of the time period may be due to some water sloshing within the tank, but are very small, at about 0.05 degrees.

The pitch and heave oscillation periods revealed here are a function of the period of oscillation of the water in the tank and the response of the hull in the water. The water is confined in a relatively small tank for these simulations, so it is likely the oscillation period may be close to the natural frequency of pitch oscillations for the hull. However, the periods may not be accurate here as the hull inertias were calculated by the PAM-SHOCK code based on the distribution of mass associated with the shell elements defining the hull, which would be different to a hull with engine, gearbox, fuel and stores. If the exact inertias of the vessel were known, these could be defined, and the resulting oscillations should then be accurate.

Next, the centre of gravity of the hull was shifted, first aft by one metre, and then forward by one metre to observe the response in SPH. These results are shown in Figure 3 with the previous neutral trim results for comparison. The curves under each hull show the pitch of the hull with time. Each scenario shows a similar behaviour, oscillating to an equilibrium positions consistent with the location of the CG.

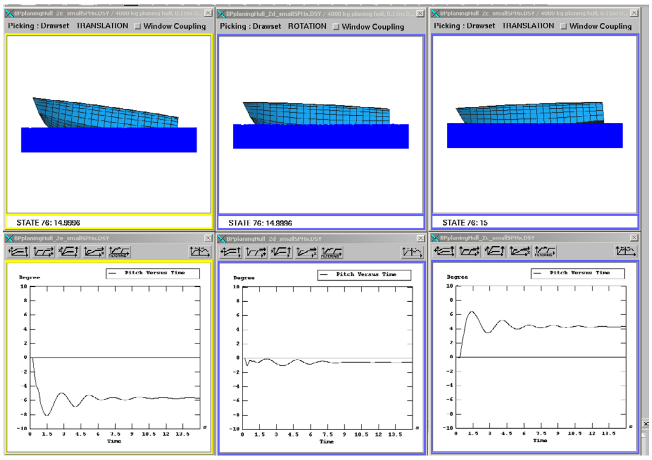

Figure 3. The planing hull adopts a new attitude with a shift in the CG. The lower curves are pitch versus time, the interesting feature being the oscillations and equilibrium value.

The verification of these results is currently in progress as part of a larger validation and verification programme of SPH in PAM-SHOCK for maritime applications.

4.2 Hydrodynamic Response of a Planing Hull

The same 8.3 m planing hull was then accelerated to a cruising speed in calm water to observe the response of the vessel. For this trial the CG was placed to achieve a near level trim when at rest, and a longer tank of water was used. The vessel was free to pitch and heave, but fixed in the other motions except forward motion that was prescribed by a linearly increasing function with time.

The result is shown in Figure 4. Initially, the vessel adopts a near-level 'at-rest' attitude. After a few seconds, the vessel moves forward increasing in speed. The simulation results illustrate the pitch angle changing as the boat accelerates.

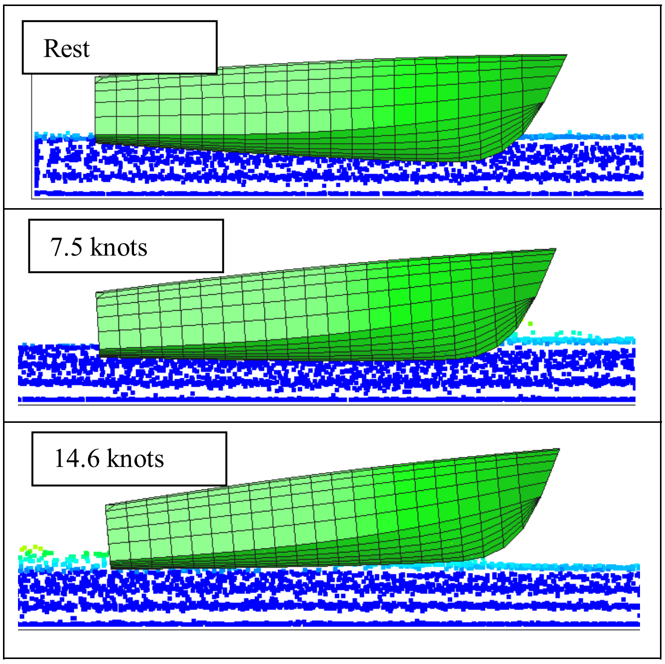

Figure 4. Change in attitude of the planing hull as it accelerates.

Eventually, the pitch angle becomes steady. Visible changes in pitch correspond to the vessel riding over its bow wave, and then settling at a constant trim as the hull continues to plane. This is qualitatively a realistic response for a planing hull being accelerated in calm water.

4.3 Balance of a Sailing Yacht

The next scenario illustrates the potential of the SPH technique in accounting for dynamic loads on a sailing yacht. The yacht used here is a 34m catamaran, similar to those which took out first, second and third place of the first edition of "The Race", the non-stop, no-restrictions race around the world in 2001 [12].

The aim here is to illustrate that the effects of lateral resistance and buoyancy can be modelled by the simulation process. The model yacht is a catamaran and so has two rudders, and two dagger-boards. The hulls are symmetric with a length to breadth ratio of about 17:1.

In the simulation here, the yacht commences the time period out of the water, and then is lowered into the water to attain a static balance. Once this is achieved, a force acting on the centre of the sails is applied. This force increases steadily until the boat acquires forward speed. As the force is increased further, the yacht will begin to heel. At this point the yacht will also turn into the wind slightly. Unfortunately in this basic simulation there was no feedback systems, so the load on the sail continued to increase until the vessel capsized. However, the value of the simulation had been realised by this point – that being that the balance of the yacht in sailing configuration was demonstrated. Although this simulation was performed in calm water, the next step is to demonstrate the behaviour in waves.

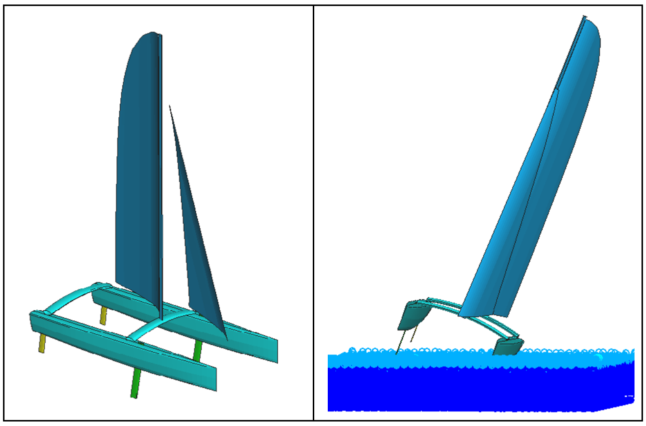

Figure 5. The 3D model of the sailing catamaran, and right, with an increasing force to represent the sail loads, the vessel will sail in a straight line for considerable distance before capsizing.

5. SHIPS IN WAVES

5.1 Regular Waves in SPH

Before SPH simulations may be used for the design of ships subjected to wave forces, the propagation of relevant waves has to be verified. The waves of interest are more or less regular deep water waves with a wave length of a fraction of the boat length to many times the boat length. As the SPH technique is intended to be applied to vessels from model size to super-tankers, there is a need to demonstrate good wave propagation irrespective of wavelength.

Early simulations by some of the authors [13] showed some loss of wave amplitude as the wave propagated. This was concerning but was dismissed at the time as the focus was the severe event, not the response of the ship in regular waves. It has since been realised that the ship response in regular waves is essential to illustrate correct wave behaviour, and consequently correct ship response in those waves. Other researchers have also noted that the propagation of waves by the classical method such as a wave maker at one of the sides of a constant depth, parallel-sided tank, has been problematic in SPH [14]. A loss of wave amplitude in some experimental results of a solitary wave have also been reported [15] suggesting the SPH simulation might not be as grossly inaccurate as originally thought. The authors are currently reviewing this experimental data for similarities to the SPH waves.

To investigate whether the SPH method is capable of simulating wave propagation over long distances without significant change of wave shape, a solitary wave has been modelled in 2D [16]. With an appropriate choice for numerical parameters and material model, the wave amplitude was maintained reasonably well (until it is disturbed by reflecting waves from the boundary) and the wave speed is in accordance with the theory. The simulation of this solitary wave also produced a small reduction in wave amplitude, and it was of similar order of magnitude to that seen in the experiments of the solitary wave [15].

To progress the analysis of ships in waves, a technique whereby waves could be propagated with negligible loss of amplitude for many wavelengths was required.

To achieve this an empirical approach has been developed in the present study whereby the wave in the SPH particles was excited along its length by applying a boundary condition on the tank floor as suggested by classical Airy wave theory. The boundary condition applied to the tank floor mimicked the motion of a deep-water wave at the depth of the tank floor. Thus the excitation energy to create the propagating wave was added to the system continuously along the length of the tank. If the wave profile was being altered as a consequence of energy loss through the SPH, then the profile alteration should be less where the energy has only to traverse the depth, and not the entire length of the tank.

This empirical approach allows wave to propagate up to 10 wavelengths without loss of wave height whilst using current SPH formulisations. A possible argument for the validity of this approach is the mathematical description of the particle motions of regular waves as a function of the depth [17].

An added advantage of exciting the wave through movement of the tank floor is that the depth of water required for a deepwater-like wave propagation is much less than that required for a stationary deep tank floor [17]. This results in a faster simulation than if a stationary floor was used.

Using this technique, a one-metre amplitude wave of 100 metres wavelength may propagate over one kilometre in 15 metres of water depth without any loss of amplitude. This is deepwater behaviour of a wave, evidenced by the circular motion of the particles down to the tank floor as shown in Figure 6. This circular motion of the water particles would usually only be seen in water of at least 50 metres deep. To model 15m of depth requires only about 30% the CPU effort of the full 50m depth, and so this moving-floor technique of wave excitation is attractive in terms of computational efficiency.

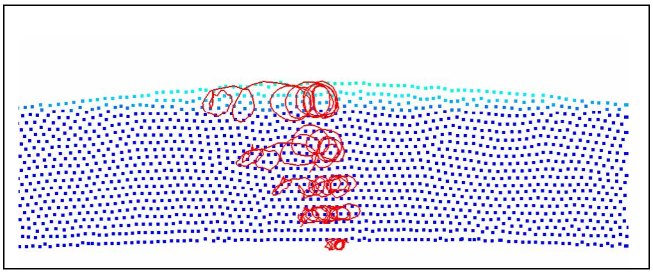

Figure 6. Circular motion of the SPH particles in a wave generated using the moving floor technique, suggests good deep-water wave behaviour despite the shallow depth.

Although the issue of possible losses in the wave propagation are not yet completely resolved, the moving floor concept described here enables a steady wave state to be created. It is proposed that the interaction of the ship with the waves can then be considered as a series of short duration events, for which the loss of energy characteristic of the classical SPH formulation is acceptable in terms of assessing the response of the vessel. Further work is being done to verify this approach by the authors, but examples of the technique to illustrate the potential will be illustrated.

5.2 Fast Displacement Ship in Waves

Having generated a non-diminishing regular wave it was then possible to drive a ship through the waves to observe the ship response. Figure 7 illustrates the response of a generic frigate in seas of 3 metre height and 110 metre wavelength. Wave height is depicted by the shade of the SPH particles – dark blue for the wave trough and light blue tending to green for the wave crests.

For this simulation the vessel speed was determined by an applied velocity boundary condition. The final speed was far in excess of the service speed of this type of vessel. Nonetheless, this excess in speed further displays the versatility of the SPH technique, in that the simulation proceeded, and gave a prediction of the response of the vessel if such a speed could be attained. A very distinct wave profile of the high-speed frigate is easily visible in the surface topology of the wave shown in Figure7.

5.3 Multihull in Oblique Waves

The previous simulations had the vessel being forced through the water at a speed irrespective of the vessel response. The next simulation employs a more realistic scenario where a constant thrust is applied to the transom.

Figure 8 illustrates the response of a high-speed catamaran under constant power in an oblique sea of 3 metre height and 110 metre wavelength. The vessel illustrated is based on the US Navy experimental catamaran called the X-Craft. For this simulation the catamaran had a full 6 degrees of freedom, with the forward thrust provided by a force vector that was always normal to the transom – thus replicating the thrust from a water jet. The resulting motion shows considerable corkscrew motions as the vessel moves over the waves. Similarly there is notable surge, yaw and heave associated with the passing of each wave. These motions would contribute to a very unsavoury, not to mention uncomfortable, environment for passengers and crew.

Severe non-linear ship motions resulting from a near-breaking wave have previously been demonstrated in [13]. Again, much of this work needs to be validated before use for engineering assessment.

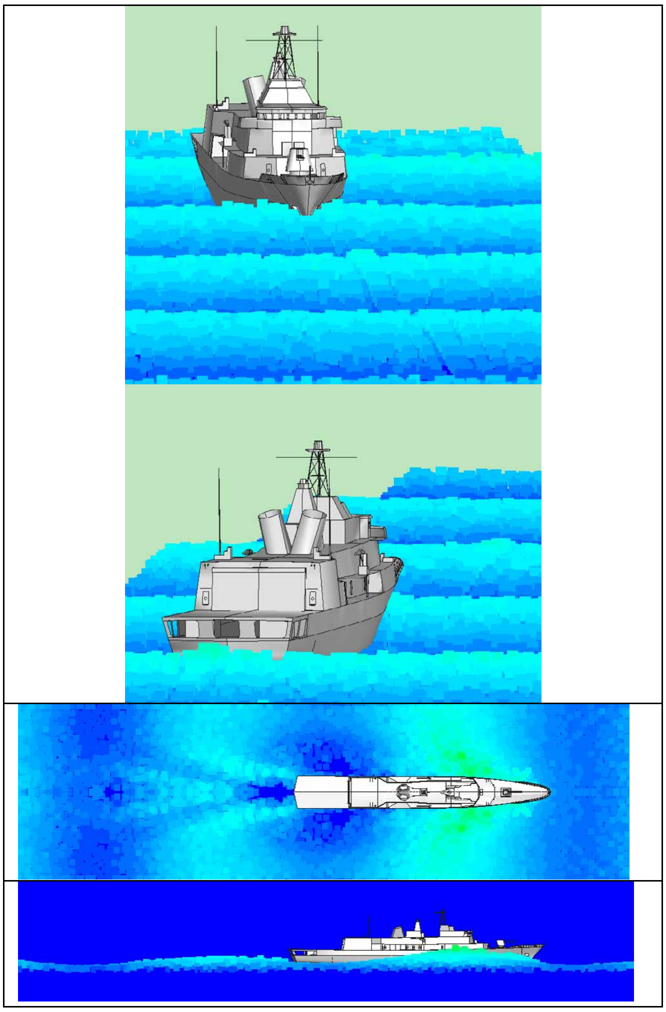

Figure 7. A generic frigate displays typical responses and wave-making tendencies when traversing waves generated by the moving floor boundary conditions. The upper images are as the vessel begins to move, the lower images depict top and side view of the vessel at a speed of 30+ knots.

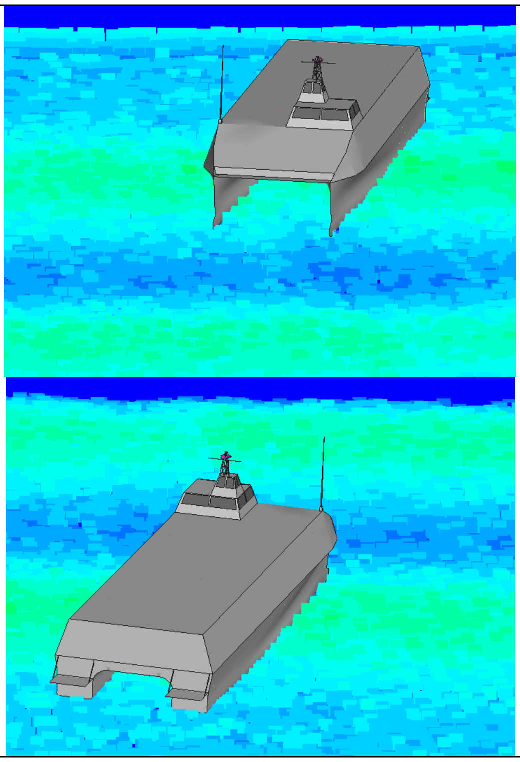

Figure 8. A catamaran with 6 degrees of freedom demonstrates considerable corkscrew motions when traversing these slightly oblique waves under self-power.

6. CONCLUDING REMARKS

The SPH technique has been shown by example to be a versatile modelling technique to reveal global motions of ships in severe conditions.

When modelled in the classical sense, waves propagating down a channel were found to dissipate too quickly to be useful for the assessment of global ship motions. This is an area of ongoing research for both the SPH techniques and other mesh-free particle methods.

To progress the study of ship motions, a kinematic boundary condition was applied to the tank floor that produced a regular wave over many wavelengths without loss of amplitude. The resulting wave appears to be useful for ship motion studies. If the ship encounter with each wave is considered as a short-duration event, then this approach to wave generation and ship response may prove suitable.

The numerical simulations presented in this paper require further validations.

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