Technical Meeting — 4 March 2020

Structural Integrity of Ships

Bruce Cartwright, Research Associate, University of Newcastle, and Senior Simulation Engineer, Pacific ESI, gave a presentation on *Structural Integrity of* Ships to a joint meeting with the IMarEST attended by 28 on 4 March in the Boardroom at Engineers Australia, Chatswood.

Introduction

Bruce began his presentation by saying that it would be in two parts: some of the initial work in smoothed-particle hydrodynamics (SPH), and then an example using a typical frigate, as presented at Pacific 2019 IMC. The software used is Virtual Performance Systems (VPS) from ESI Group in Paris. The motivation was to use commercial-off-the-shelf software to provide unprecedented engineering results for the maritime industry, based on tried-and-proven techniques in use in the automotive and aerospace industries.

The overall aim of the project was to develop a tool to give asset owners and operators a more confident method to predict the likelihood of a given asset surviving a given service load. The perceived applications were life extension of existing assets, and/or survivability of aged assets.

More specifically, the aim was to reveal the non-linear stress response of a ship as it traverses a wave in order to understand, from an engineering perspective the response of:

- a vessel to limit-state incidents;
- a damaged or compromised vessel to a given sea-state; and
- a vessel that is not able to be analysed by conventional tools — i.e. not a "ship" shape.

The results may be used for risk assessment, survivability assessment or life predictions by way of fatigue assessment.

The technique *can* be used for linear responses, but is not efficient compared to other tools for this purpose.

VPS Software

The VPS software is used for virtual prototyping of manufacture, testing and real-life. The largest user-base is automotive industry, and the interface reflects this. It has explicit and implicit solvers, and the explicit solver has inbuilt controls for determining stable timesteps. There are numerous material models for most material types including composites. Advanced material failure laws are included for the prediction of progress of non-linear failures.

Here Bruce showed an example of the results, an animation of a typical frigate proceeding at 9 kn into a regular head sea of 4 m wave height.
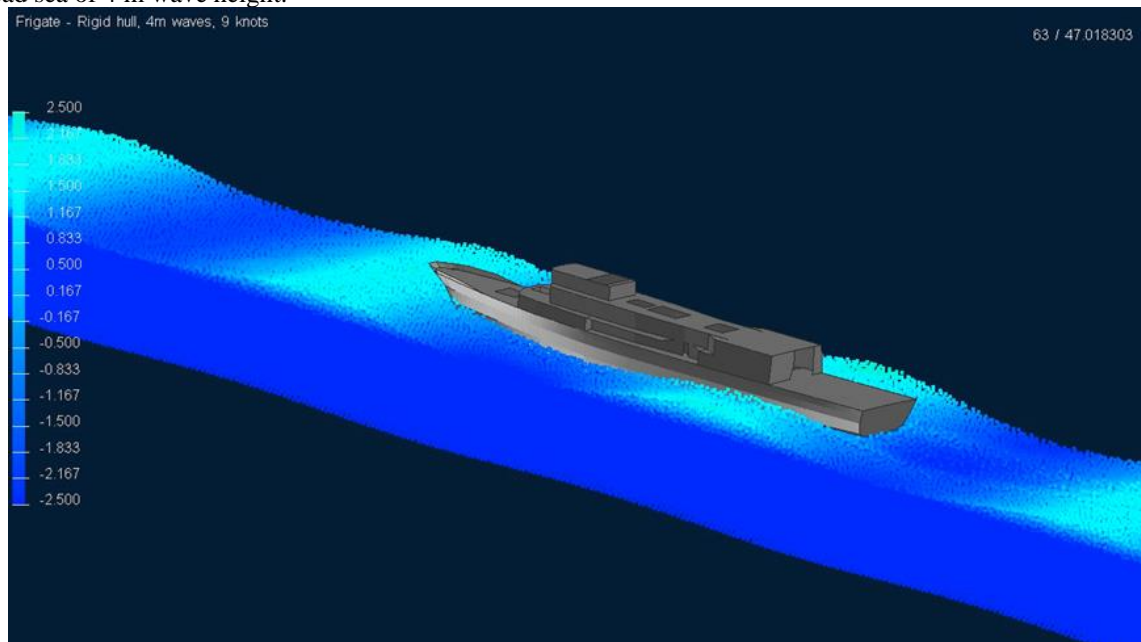
Animation of typical frigate at 9 kn into 4 m head sea
(Image courtesy Pacific ESI)

How does Smoothed Particle Hydrodynamics Work?

You need to define physical things, such as a boat, water and a tank, give each of them properties and loads, define how they interact with each other, and then see what happens.
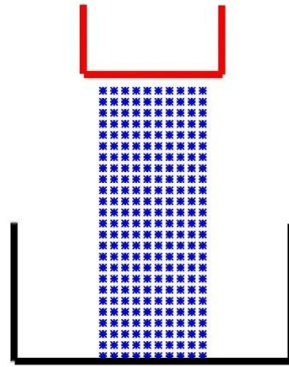
How SPH works
(Image courtesy Bruce Cartwright)

In general, everything falls under gravity, the water stays in the tank (mostly), the boat floats on the water, and the boat deflects under the hydrostatic and hydrodynamic loads.

Where does the smoothing come in? The properties of particle *i* are determined by the properties of its neighbours, weighted by a "smoothing" function. Those particles closer have greater effect, and those further away have less effect. This also implies that each particle influences its neighbours to a degree, and within a 'sphere of influence'.

The first uses of SPH were in astrophysics for studying the formation of galaxies from large volumes of gas.
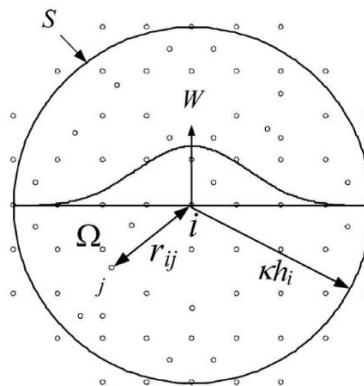

Smoothing in SPH
(Image courtesy Bruce Cartwright)

Early Days

Some of the first commercial applications of SPH to fluids (in the early 2000s) were in Europe to analyse the ditching of commercial aircraft; where SPH was used for the water together with a deformable fuselage.

At about the same time, bird strike on aircraft was also being considered; SPH was used for the bird, impacting a flat plate with pressure sensors. The break-up of the bird, and the distribution of pressure with time, enabled the SPH material to be calibrated against real bird impacts.
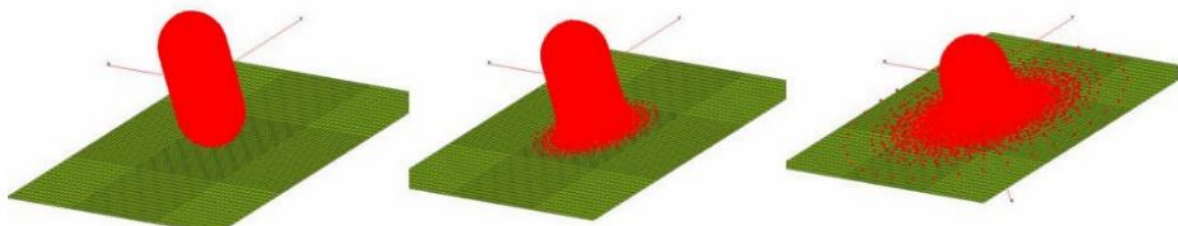
Modelling of bird strike on aircraft
(Image courtesy Bruce Cartwright)

In 2006, Boeing in Australia, with assistance from Pacific ESI and the Cooperative Research Centre for Advanced Composite Structures, combined the SPH bird model with composite materials. The main focus of the numerical simulation was damage prediction. Simulation provided failure prediction of the composite skins and

composite structural members. After rigorous evaluation, the Boeing 787 was the first commercial aircraft in the world to use numerical simulation of bird strike for certification with the FAA.
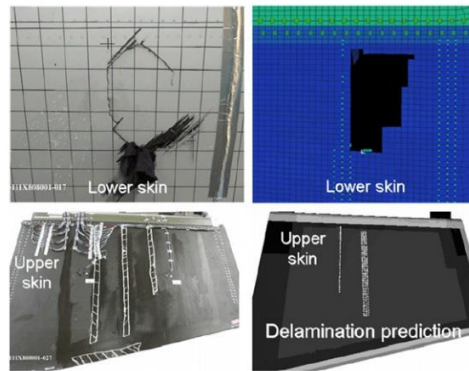

Bird strike penetration of lower skin and delamination of upper skin,
test panel (L), SPH simulation (R)
(Image courtesy Pacific ESI)

Other Examples

Bruce then showed a series of fluid-structure interaction (FSI) problems to which SPH had been applied. All came up with physically-realistic results, inspiring confidence in the method and the outcomes. These included:

- Helicopter ditching in water: Helicopters have a high centre of gravity, and tend to roll over and sink very quickly on impact with the water. Survivability is low without emergency flotation devices. The VPS software contains an airbag facility for automotive use, so this was employed to make super-sized airbags for upright helicopter flotation. The airbags commence in the folded position and inflate just prior to impact.
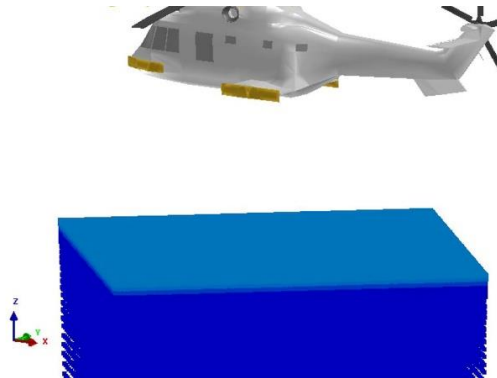
Helicopter ditching with airbags to be deployed
(Image courtesy Pacific ESI)

- Dropped soda can: This involved dropping a soda can (with its axis horizontal) half-full with fluid onto a vee-shaped metal edge. They were interested in the material deformation, the slosh/splash inside the can, and the impact forces.
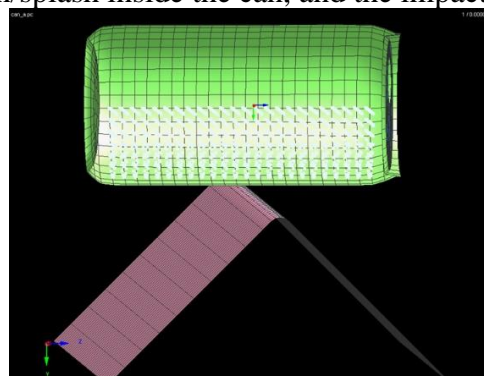

Soda can dropped onto vee-shaped edge
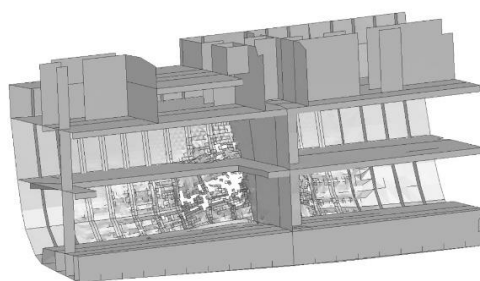(Image courtesy Pacific ESI)

- Water in a falling bottle: A rigid soft-drink bottle was modelled with a rubber end-cap like a half tennis ball, part filled with water, and dropped. This showed the sloshing of the water, with interesting transfer-of-momentum effects depending on the initial conditions of the water.

- Interaction with waves: A Volvo 70 hull was modelled, with a force on the mast to represent the sails, balanced for the yacht to be upright and driving forward into waves.

- Planing hull: A planning hull was accelerated from rest, and found that the pitch and heave changed realistically with velocity. There was an indication of dynamic lift, so the planing response was generically correct. However, no validation performed on this.

- Disabled submarine on surface: Here a typical submarine was modelled at zero forward speed on the surface of the water, with motion in six degrees of freedom induced by waves only. Here they could explore passive devices for damping of motions.

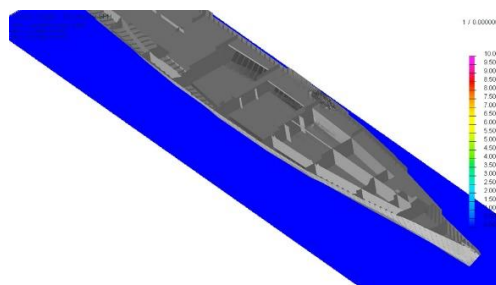**Underwater Explosion and Flooding**

Here a typical frigate hullform was used, with an explosive charge placed in the water some distance away. The water was modelled with SPH and the ship hull was elastic-plastic with strain-rate dependent failure. The explosion took place in 10 ms, and the pressure wave was transmitted through the water (SPH) and interacted with the hull, with element elimination on failure.
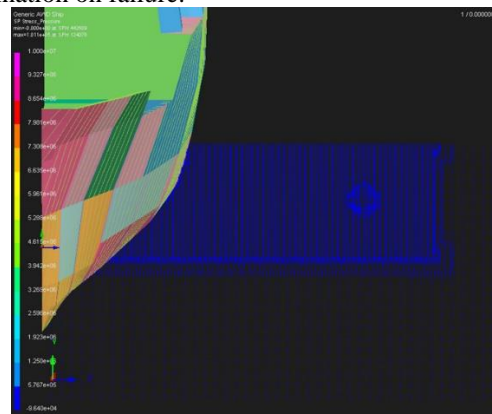
Model of underwater explosion close to typical frigate
(Image courtesy Pacific ESI)

SPH prediction of damage sustained by typical frigate in underwater explosion
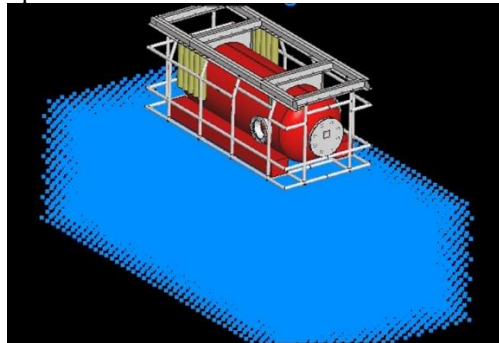(Image courtesy Pacific ESI)

SPH prediction of flooding of typical frigate following underwater explosion
(Image courtesy Pacific ESI)

Flotation of Unconventional Vessels

SPH is particularly useful for the flotation of unconventional vessels, as there is no restriction on the type or shape of the vessel, and or if it is in the water or not. Contact interfaces define the interaction of water and the structure, to produce momentum/impact forces when at speed, and hydrostatic/buoyancy forces when at rest.

Bruce used the example of a hyperbaric chamber on board a vessel where, if a fire or other emergency necessitates evacuation of the ship, then the chamber with its occupant(s) needs to be jettisoned overboard. Issues such as acceleration of occupant(s), and the flotation of the chamber needed to be confirmed for certification for use on board a ship.


Model of hyperbaric chamber about to be jettisoned
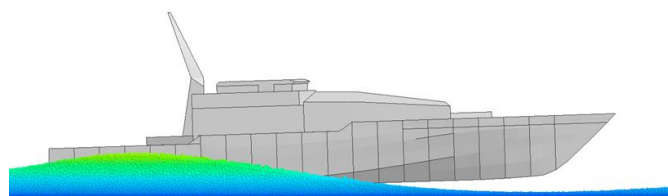(Image courtesy Pacific ESI)

Another example was of a SWATH (small-waterplane-area twin-hull) vessel, with six degrees of freedom proceeding obliquely at 20° to the oncoming waves. Thrust was provided by a constant force acting normal to the transom at all times (like a waterjet); if the boat changed direction, so did the thrust. The result is visible corkscrew motion over the waves, with variations in forward speed with waves, and coupled pitch/roll/yaw behaviour.
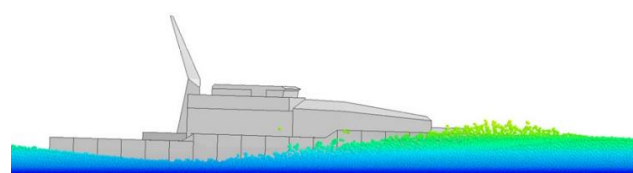
Hydrodynamic Loads

Bruce then used the example of a typical patrol boat. By dividing the hull into equi-spaced strips, we can extract the force acting between the hull and the water on that strip and, hence, the forces acting on the ship to generate motions. He showed eight separate predictions of the motions as the vessel progressed through the waves (only Positions 1 and 4 are shown here).
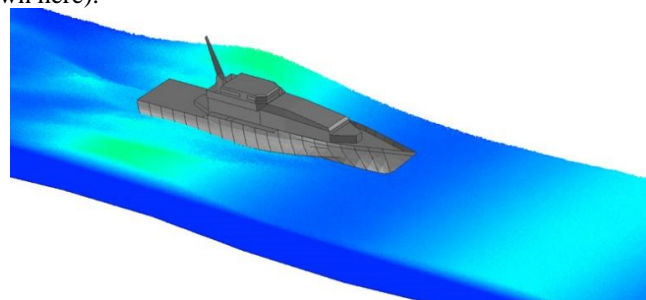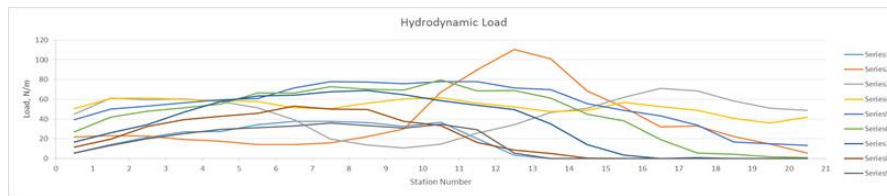

Model of typical patrol boat in waves
(Image courtesy Pacific ESI)

SPH motion prediction of typical patrol boat in waves — Position 1
(Image courtesy Pacific ESI)

SPH motion prediction of typical patrol boat in waves — Position 4
(Image courtesy Pacific ESI)

SPH prediction of hydrodynamic loads on typical patrol boat in waves
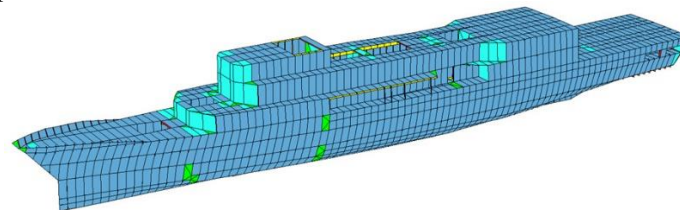(Image courtesy Pacific ESI)

Seaway Loads Applied to a Frigate

Bruce then turned to the second part of the presentation, the application of seaway loads to a typical frigate, as presented at Pacific 2019 IMC. This is an ARC-funded project, involving collaboration between the University of Newcastle, Pacific ESI, Defence Science and Technology, and UNSW Sydney, and is due for completion in June 2020.

The project aims to deliver a tool to give asset owners and operators a more confident method to predict the likelihood of a given asset surviving a given service-load. It aims to achieve this by having a detailed knowledge of the state of the specific asset at a given time, being able to induce loads in that asset as a consequence of a specific sea state or wave loading (now or in the future), and performing a structural assessment of the asset under those loads. The structural assessment can be used to assess the likelihood of surviving a specific incident now or, in combination with conventional structural deterioration theories, for fatigue or corrosion, to assess the expected life of the vessel.

Project Methodology

The model was set up to accommodate time-varying hydrodynamic loads through fluid-structure interaction using mesh-free methods, i.e. with the fluid modelled using SPH. The fluid and structure are modelled simultaneously in the commercial software package VPS.

A finite-element structural model of a typical frigate with no appendages was provided incorporating non-linear finite elements, with local refinement for failure modelling. Distributed nodal loads were used in order to represent maximum displacement. The model initially represented the ship as built, i.e. with no defects. Only the areas of the ship of known high stress will be modelled in detail in order to reveal stresses around cracks which appeared in the real ships.

Structural finite-element model of typical frigate
(Image courtesy Pacific ESI)

The finite-element model will be refined by the provision of approximately 600 documents describing various defects. These were reviewed to identify strength-degrading defects, and only the defects in high-stress regions of the ship will be accounted for in the FE model. Loss of material by corrosion will be modelled by local thinning of structural members, and cracks will be modelled directly as fissures in the material.

The sea state was modelled using SPH, with waves generated by the moving-floor concept, i.e. using the FE technique of a sub-domain, the lower boundary of the domain of interest is assigned boundary conditions (motions or velocities) identical to the behaviour of the full domain at that point. This has the advantages of reduced computational domain, due to the reduced depth, and there is no wave maker on the surface.
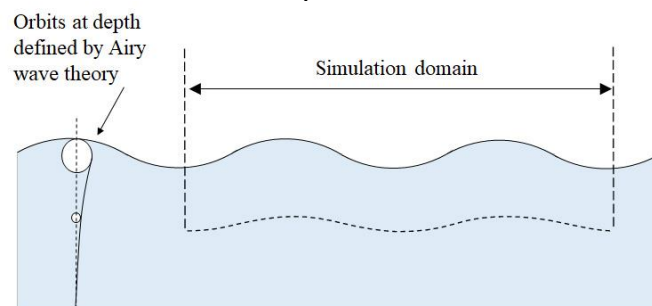
Modelling of the sea state
(Image courtesy Pacific ESI)

The model was initially set up for hydrostatic and still-water bending moment checks, and comprised:

- A tank for containment of SPH.
- The FE model, free to pitch, heave and roll.
- Gravity acting on the water (SPH) and the ship.
- Interaction of the underwater shape of the ship, where the mass distribution and the displacement of the water (SPH) determined the final resting position of the ship.
- Time duration to allow the ship to settle.
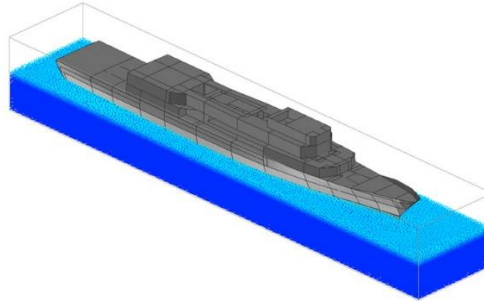
Model for hydrostatic and SWBM checks
(Image courtesy Pacific ESI)

Simulation Results

The model achieved hydrostatic equilibrium, floating at the datum waterline and with the correct trim. Shear forces and bending moments were extracted at ten central locations on the FE model and compared with the results from MAESTRO [*Owen Hughes' ship structural analysis software* —Ed.] The correlation between the VPS results and MESTRO were good, with a maximum of 4% difference.
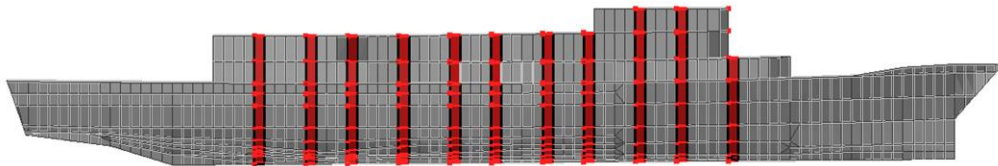
Model for hydrostatic and SWBM checks
(Image courtesy Pacific ESI)
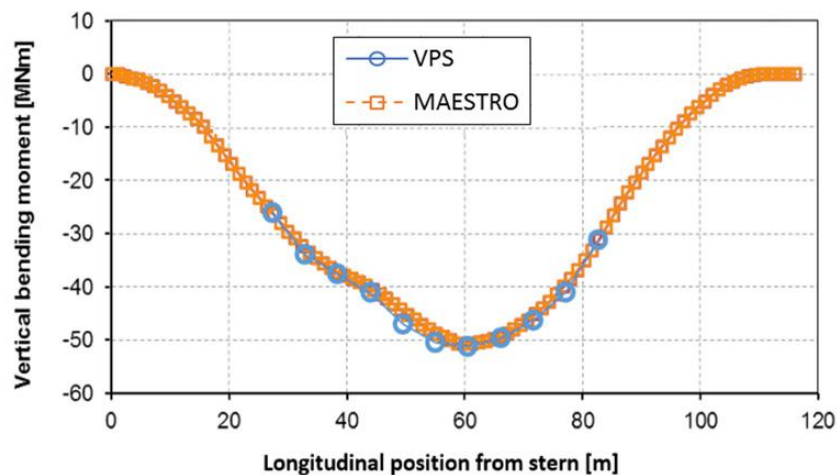
SPH simulation results for SWBM
(Image courtesy Pacific ESI)

With successful results for still water, the attention turned to the vessel moving with forward speed into head seas. This was modelled with the moving floor for the lower domain boundary, periodic boundary conditions up- and down-stream, the vessel velocity provided by a boundary condition and with either a rigid-body or fully-flexible ship model.

A parameter sensitivity study was performed, as there were many variables in the simulation setup: the size of the SPH particles, i.e. discrete particles of water, the tank parameters of width and depth, the wave length, wave height and ship speed. The output parameters were normalised (non-dimensional) pitch and heave. It was found that the tank width and depth had some effect on the ship response , but also that the SPH particle diameter had a significant effect. Smaller SPH particles approach a continuum, and so give better results and less-noisy interface reactions, but also mean more particles requiring more CPU effort. Present computers (36 cores) are limited to about 500 000 particles for reasonable (24 h) solution time.

The conclusion of the sensitivity study was that a reasonable compromise between CPU effort and accuracy for engineering solution would be achieved for the case of 109 m wavelength and 9 kn into a head sea with a tank width of 50 m, depth of 20 m, and particle diameter of 1.2 m.

When run with these parameters, the SPH simulation result is a bending moment which varies with time as the ship passes over the waves.
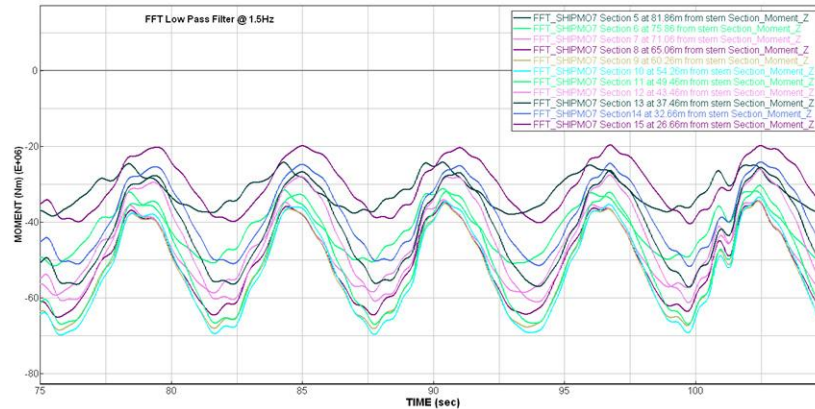
Total bending moment results at λ/L_{WL} = 1.0, v = 9 kn, h = 1 m in head seas
(Image courtesy Pacific ESI)
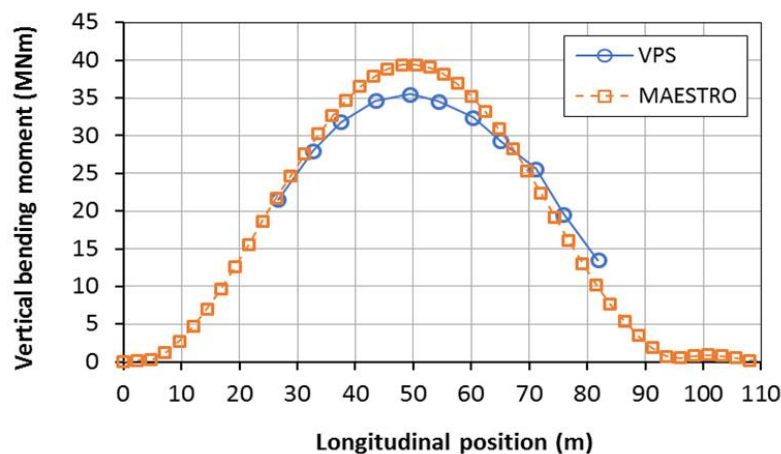
BM comparison with MAESTRO at λ/L_{WL} = 1.0, v = 9 kn, h = 1 m in head seas
(Image courtesy Pacific ESI)

Stresses in Waves

Stresses in plates can be visualised as a wave passes a ship. In this case, with zero forward velocity, high stresses are noted where the aft deck meets the superstructure. Work is underway to develop similar stress states for a ship with forward velocity

Animations of Ships in Motion by VPS

Visualisation is a valuable tool to aid understanding of wave-induced stresses. The output from VPS can produce animations which show the motion of the vessel. An important aspect to consider is that the simulation results account for non-linear interactions between the vessel and the water. In addition, totally un-realistic behaviours can be observed, such as specifying impractical speed through high sea states, or realistic behaviours such as flooding through water ingress.

Here Bruce showed some animations of the frigate proceeding at 9 kn into head seas of varying heights of 1, 2 and 4 m, and then at 27 kn into an 11 m head sea [*possibly unrealistic — Ed.*]!

Conclusion

Results to date using smoothed-particle hydrodynamics are promising. Ship motions and bending moments show good correlation to MAESTRO results. Current work to complete the project involves refining the mesh to provide 'as-built' detail, which can then be 'degraded' to represent real 'aged' defects, and developing the stress state in a ship with forward velocity.

Questions

Question time was lengthy and elicited some further interesting points.

As in FE calculations, when using SPH the size of the particles can be varied as required to home in on areas of interest, e.g. away from the vessel the particle diameter could be large, while in an area of interest the particle diameter could be one-tenth that size; both would generate the same sized waves.

Class societies require structural design assessment (SDA) using detailed FE models with still-water bending moments specified by IACS. However, this project is looking for an independent way to specify the loads on the vessel, and to be verified by experiments.

SPH can handle the air-water interaction at the free surface and, in particular, can handle the slamming effects of the air cushion in an air-cushion vehicle.

The vote of thanks was proposed, and the certificate and "thank you" bottle of wine presented, by the President of the Australian Division of RINA, Martin Renilson. The vote was carried with acclamation.

Bruce Cartwright (L) accepting his certificate and
"thank you" bottle of wine from Martin Renilson
(Photo Phil Helmore)