Advanced Experimental Techniques for Solving Maritime Hydrodynamic Problems

Gregor J. Macfarlane[1] and Alan N. Fleming[1]
[1] Australian Maritime College, University of Tasmania, Launceston, Australia; gregorm@amc.edu.au

Abstract
The past two decades has seen a marked shift in the primary purpose of performing physical scale model experiments in hydrodynamic facilities to help solve a range of maritime hydrodynamic problems. It is now commonplace for experimental programs to utilise complex measurement techniques to investigate highly non-linear phenomena, often to provide high-quality data from a controlled environment to aid the validation of numerical techniques, such as potential flow and computational fluid dynamic (CFD) models. This has resulted in a significant increase in the usefulness of relatively small- to medium-sized experimental facilities due to their versatility and cost effectiveness in (a) developing and verifying innovative measurement techniques, and (b) applying these techniques to perform complex experiments to solve hydrodynamic problems for the maritime industry. This paper presents examples of several state-of-the-art measurement techniques that can now readily be performed within the National facilities at the Australian Maritime College, including the 100 m long towing tank and 35m long x 12m wide shallow water wave basin. Also described are examples of how these techniques have recently been applied to a range of industry-driven research projects.

Keywords: maritime hydrodynamics, scale model experimentation, videogrammetry, particle imaging velocimetry, 6DoF force measurement.

1. Introduction

Gone are the days when the most common experiments performed in the Australian Maritime College (AMC) towing tank are simple calm water resistance tests to predict the powering required for a new design or modification to an existing ship hull. These experiments, which were once the primary reason for having such a facility, accounted for almost 50% of the projects undertaken during the first decade of the AMC facility's operation (1985 to 1995). The past two decades has seen a gradual but clear shift towards much more complex experiments, to such an extent that the once "bread and butter" calm water resistance experiment occupies only about 5% of the available time in AMC's heavily utilised towing tank and shallow water wave basin (technical details related to these hydrodynamic facilities can be found at [3]).

There has been an observed decline in demand for basic hull resistance testing as established naval architects acquire reliable model and full scale data for their 'stock' hull forms, but this is a relatively small part of the move towards much more complex and challenging experiments. Measurement technologies and analysis techniques for testing ship models and other marine structures have rapidly developed in recent years. This has been partly driven by the introduction of new digital measurement technologies and the increasing demands of the maritime industry in some emerging areas of application. A significant proportion of this effort has been to provide vital support in validating numerical techniques, such as potential flow codes and computational fluid dynamic (CFD) models.

This paper briefly describes some of these measurement and analysis techniques and how they have been used to solve a wide range of applications for the maritime industry.

2. Measurement Technologies

A description of several new measurement techniques, and the hydrodynamic problems they have been applied to solve, are described in this section. They have been arranged in three broad groups; the first two are based on the primary type of measurement methodology adopted: stereo videogrammetry and particle imaging velocimetry. The third group covers several examples where the primary focus is on interaction effects when multiple vessels operate in close proximity to one another. All experiments follow International Towing Tank Conference (ITTC) recommended procedures [13].

2.1 Stereo Videogrammetry

Surface flow and wave field analysis is an emerging area of interest in the fields of coastal hydrodynamics and marine renewable energy. AMC has developed a bespoke stereo videogrammetry system to quantify wave patterns and elevations over a wide surface area. This non-contact system uses two strategically located digital cameras and a precise calibration technique to monitor the motions of a large quantity of custom-made positively-buoyant ultraviolet fluorescent flake particles (of approximate size 5 x 5 x 0.8 mm). Videogrammetry data is processed using the '*SurfaceFlow*' module of the software DaVis (version 8.3.1) [31].The accuracy of the technique has been validated against measurements from many conventional resistive type wave probes.

This technique has recently been used to capture radiation and diffraction effects from the presence of multiple submerged wave energy converter (WEC) models [25]. The purpose of the radiation experiments was to quantify the effect of the energy radiated from one WEC model in the array on the others. The experiment consisted of a single 'active' model with up to five other 'static' models in an array configuration. The active model was driven for ten sinusoidal cycles, in both pure heave and surge independently, with the effect of the radiated waves being measured on the passive models in the array.
A monopolar pattern is characterised by a perfectly axisymmetric wave emitting from the device. This is the characteristic pattern for a heaving device, or from a practical point of view, the effect of the dynamic pressure in an oscillating water column (OWC) chamber. On the other hand, the dipole pattern has two poles generating waves of same amplitude but opposite phase. This is the characteristic pattern for a surging or pitching device. A photograph from these experiments in shown in Figure 1 and an example of the resultant dipole radiated wave fields acquired from stereo videogrammetry can be seen in Figure 2.

Figure 1 A photograph of the experimental set-up for the stereo videogrammetry. The cameras and UV lights are mounted on the raised trusses and the surging active WEC model lies submerged beneath the pink fluorescing particles floating on the water surface.

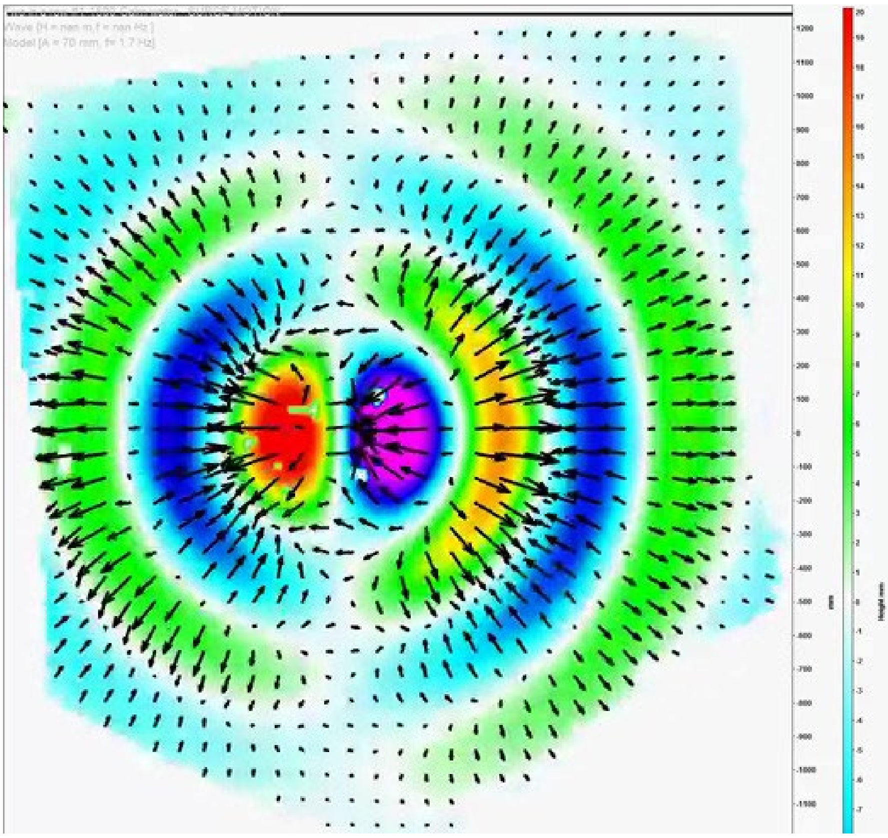

Figure 2 Example of experimental measurement of a dipolar radiated surface wave field from the submerged surging WEC model using stereo videogrammetry [25].

In what is believed to be a world-first, AMC has pioneered the adaptation of digital videogrammetry for underwater operation to quantify the deformation of a flexible membrane. The membrane was an air/water interface for a novel sea-floor mounted WEC, the concept of which has been patented by the Australian company Bombora Wave Power [28, 1] (refer Figure 3 for a photograph of the scale model used in the experiments). This short range underwater trinocular videogrammetry system consists of three synchronised cameras mounted in separate underwater housings acquiring images of the same location at a frame rate of 50Hz. Equi-spaced markers of diameter ~4mm on a 15mm rectilinear grid on the membrane surface were then solved to give the time series motion of the membrane. This data has been used to validate a CFD model of the WEC system which has allowed non-linear effects to be explored and to estimate the stresses in the membrane under the action of idealised hydrodynamic and system loads [14].

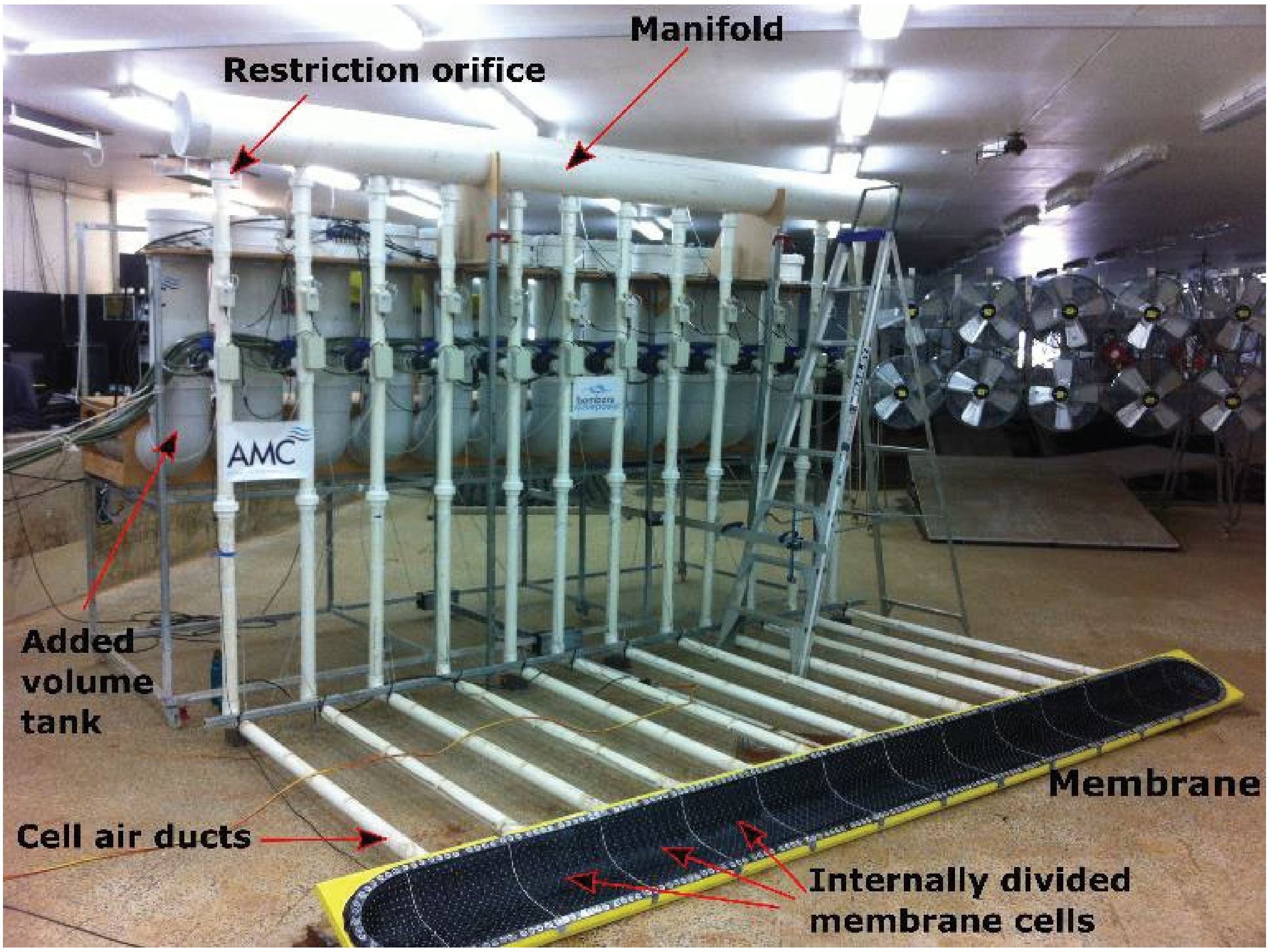

Figure 3 A photograph of the experimental set-up for the Bombora WEC model (while the basin was drained). The flexible membrane is the black material in the foreground. The pipework behind the WEC model provided a means of measuring air flows and pressures in the system (and to correctly scale the required air volumes) [1].

2.2 Particle Imaging Velocimetry

Particle Imaging Velocimetry (PIV) is a flow measuring technique which allows full field measurement in a plane of velocity fields without interfering the flow itself. The fluid is seeded with very small neutrally buoyant fluorescing particles and a laser generated light sheet is used to illuminate the particles in the area of investigation. Two images are captured at a small time offset which are compared using cross correlation to determine the displacement of the fluid and therefore the fluid's velocity. This technology has been adopted to investigate a wide variety of maritime applications, particularly in the field of marine renewable energy.

Possibly the most promising of the various marine renewable energy technologies currently being developed is the oscillating water column (OWC). Traditionally, the majority of physical experiments conducted within Australia and around the world have treated various OWC geometries simply as a 'black box' where the input energy (ocean waves) is known and the available output energy is predicted, usually through the simple measurement of quantities such as air pressure, air velocity and water level within the chamber. One of the advances that AMC has made is the application of PIV to quantify the flow fields inside the OWC 'black box' [9, 10]. When applied to experimental analysis of OWCs, standard 2-dimensional PIV can reveal phenomena associated with the transformation of the oscillatory flow of the wave to the linear (or near linear) oscillation of the free surface within the OWC. This has led to the optimization of the geometry of the device for improved performance [9] and a new understanding of the energy balance (the flow of energy from incoming waves into the device and extracted at the power take-off)[11]. In doing so, viscous energy losses (energy converted into other forms, such as heat, which cannot be extracted) due to the generation of vortices were identified and we found that these could be reduced by modifying the geometry of the column.

PIV experiments have also been performed to compare the performance characteristics between differing OWC geometries with the aim to investigate conversion losses and device performance by modifying the underwater geometry [8]. Four models were tested in total; a base model (used in much of the abovementioned studies) and three variations that had additional segments to afford different chamber length and lower/upper lip angles (10, 20 and 30 degrees). An example of the output is shown in Figure 4 where the velocity fields for the base geometry and one of the variations are presented. This study concluded that replacing sharp edges with a softer transition is effective at reducing energy loss via the production of vorticity and angling the upper-lip upwards improves energy capture. Both of these improvements have been implemented within the revised geometry adopted by the first full-scale commercial device currently under development by Wave Swell Energy.

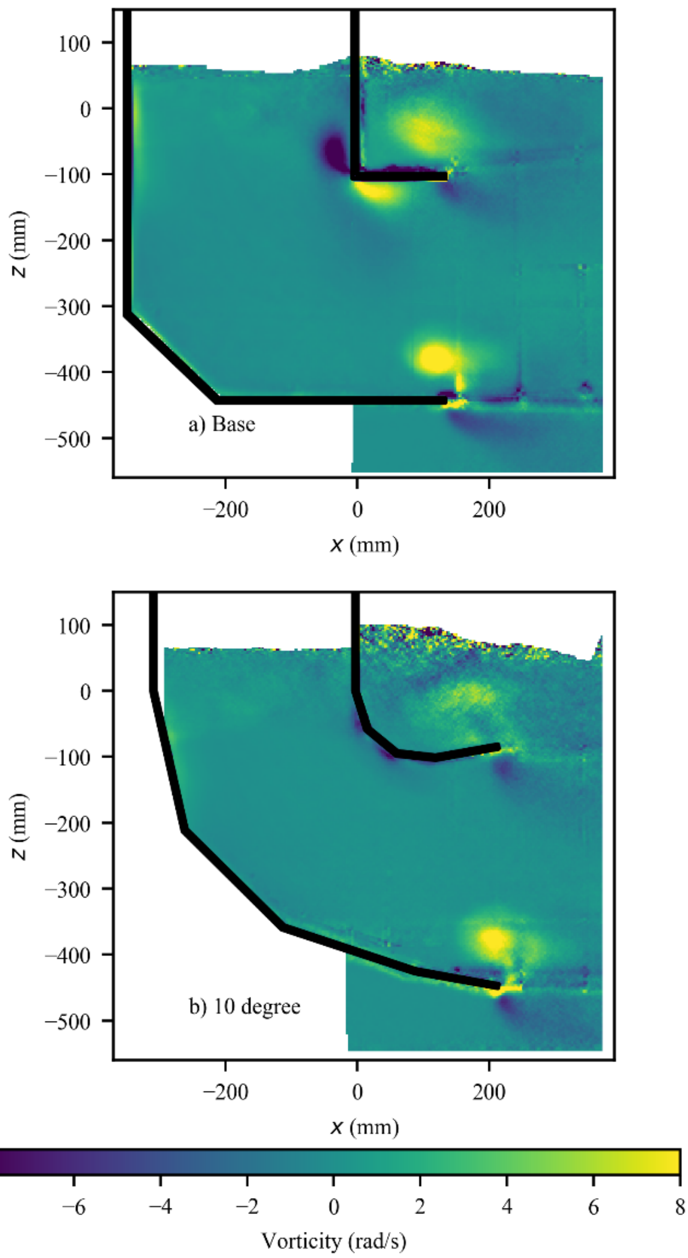

Figure 4 PIV results showing the average vorticity (energy losses) within two different OWC geometries. The significant reduction in losses around the upper lip is evident between the base geometry (top) and the smoother transition of the 10 degree lip case (bottom). The PIV data can also be used to examine the average kinetic energy of the velocity fields which can identify inefficiencies as an uneven distribution is likely to result in further energy loss [8].

Similar PIV data has also been acquired to investigate the effect that wave type (regular, polychromatic and irregular wave spectra) and 3-dimensional flow effects have on the power-generating performance of OWC WECs [21, 22, 23]. It is also being used to validate 2D and 3D CFD models for undertaking parametric studies on OWC design. These numerical models have successfully been used to assess many design and performance parameters for stationary, near-shore and floating offshore OWCs [6]. Recent work has used the validated 3D CFD model to assess the survivability of an offshore floating-moored OWC which experiences mooring line failure in extreme seas [7].

Experiments using PIV have also been applied to assess a very unusual maritime hydrodynamic scenario presented by the new and novel transhipment concept known as the floating harbour transhipper (FHT). The FHT is a concept of transferring bulk materials from shore to an offshore floating transfer facility by use of a low draught transfer vessel, which has the potential to revolutionise the export of bulk cargo from remote areas where no deep-water port currently exists. The FHT concept is described in detail elsewhere [17, 18, 19] but a key aspect of the FHT is the open stern well dock on the transhipper which provides shelter for a shallow draught feeder vessel that shuttles cargo between the shore-based facilities and the FHT, and onto an export vessel moored alongside the FHT.

The FHT well dock represents a tightly confined space in which the feeder vessel must manoeuver. The cross-sectional area of the feeder vessel is relatively large compared to that of the well dock so a large body of water is displaced when the feeder vessel enters the well dock, all of which must exit via the limited space between the feeder vessel and the well dock floor and sides. The resultant flow velocities around the feeder and its propulsors makes for very unusual operational conditions that the Master of the vessel must understand in order to safely manoeuvre the feeder in and out of the well dock. Acquiring PIV measurements inside the well dock as a feeder vessel enters (and exits) has increased our understanding of the complex flows involved and led to some innovative design features being implemented within the well dock that have greatly mitigated the operational challenges (Figure 5) (findings will soon be published).

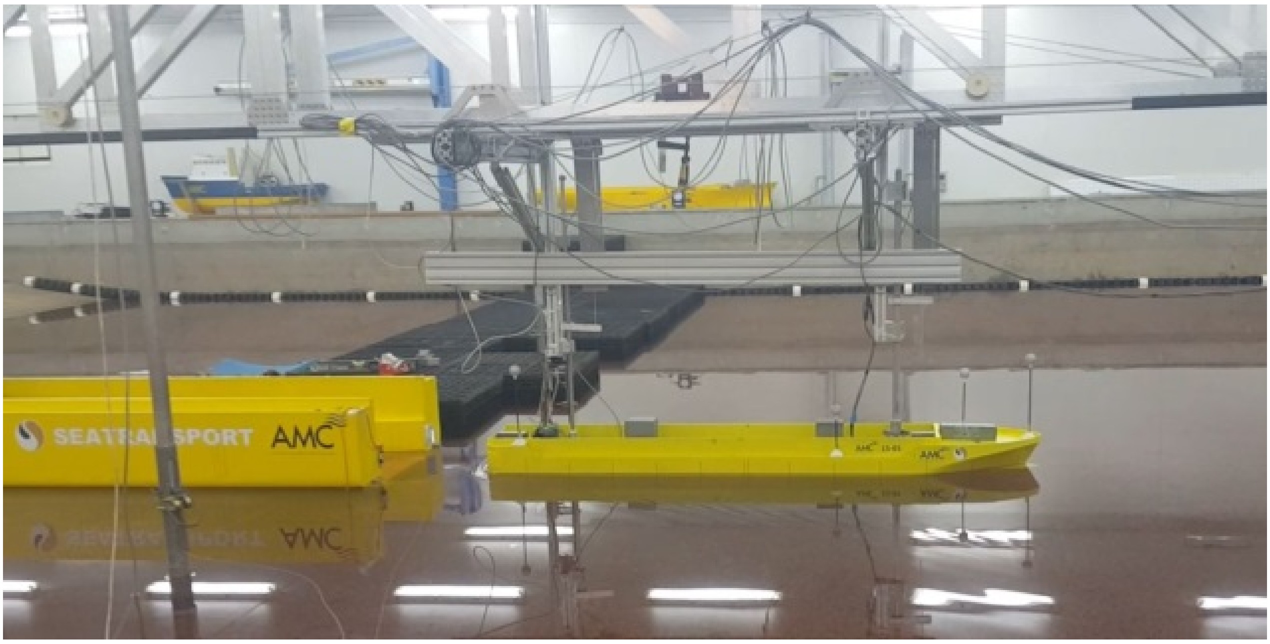

Figure 5 Photograph showing the scale model of the feeder vessel (right) about to travel astern to enter the stern well dock in the model of the FHT (left). In addition to acquiring PIV data of the complex flow inside the well dock as the feeder performs this manoeuver, the dynamic effects on the hull resistance (powering requirements) and motions were also quantified.

In a very different project, PIV has been used to measure velocity fields around a series of tidal turbines to assess the performance and effects of parameters such as blade shape, number of blades and the interaction between the turbine hub and blades. The commercial nature of this work has prevented this from being published at this stage.

The International Towing Tank Conference [13] have developed a standard series of 2D and 3D experiments from which to benchmark PIV measurements and analysis between facilities. Results from tests performed in the AMC tank to quantify the wake flow around the tip of a surface piercing flat plate at an angle of incidence was studied using 2D PIV and found to have excellent agreement with results from the much larger facilities of MARIN and INSEAN used by the European Hydro Testing Alliance [2].

A key factor in the successful use of either stereo videogrammetry or PIV for all of the above-mentioned projects are the characteristics and quality of the seeding particles. AMC have perfected the in-house production of fluorescing particles that are customised to the precise needs of the experiment. For example, the fluorescent particles used in the OWC tests (Figure 4) were all within the range of 38 – 75 microns in diameter, doped with Rhodamine dye and neutrally buoyant. These particles fluoresce at a different wavelength to the excitation wavelength from the PIV laser; enabling blocking of reflected laser light from the acquired images through the use of optical high pass filters. Filtering the reflected light enables capture of the flow field in close proximity to reflection from bubbles, vortex filaments with entrained air and the free surface, all of which may occur during some of the experiments described here. The method of seeding the water prior to any experiment must also be considered: this is relatively simple for a case like the stationary OWC models, but is a challenging task to obtain the desired and consistent seeding density when capturing unsteady phenomena from a high-speed hydrofoil that may require running nearly the full length of the 100 m long towing tank.

The relatively large and positively-buoyant particles (flakes) used in the stereo videogrammetry experiments seen in Figure 1 have also been used for other projects where there has been a need to capture the free surface waves. For example, to investigate the generation of waves for a surfing wave pool [29] and extremely rare ship-generated soliton waves in a restricted channel - the latter has resulted in an online educational tool [12].

2.3 Multi-Vessel Interaction: Motions & Loads

In this section, four examples of multi-vessel interaction are described. In each case the forces and moments experienced by the ship models are measured using load cells and all 6 degree of freedom motions using a non-contact optical infrared video motion capture system. We have acquired and developed a large suite of load cells and force balances to suit every application, from small single-axis force transducers, to small 6-DOF force balances (where small forces are expected), to a large 6-DOF force balance that can restrain a ship model that displaces 800 kg and is exposed to large incident waves. For motion measurements, our wave basin has a fixed 8-camera Qualisys system with inbuilt calibration markers to allow rapid set-up and calibration [27]. We also have an 8-camera portable system that can be used in either the tank, basin or off-site.

A scenario that we are regularly asked to study is the interaction between large cargo ships when manoeuvring within very restricted waterways. For example, when one ship passes a berthed ship in a shipping channel it causes hydrodynamic interactions which can result in the berthed ship ranging on its moorings. This is often a critical factor in the design and/or operation of ports where entering or departing ships are required to pass those already moored. Not only is it important to accurately model the channel width and depth, but recent work has highlighted the importance of the local bathymetry surrounding the berthed ship as the type and location of banks and wharves can have a significant effect on the berthed ship motions and loads [5]. It is not unusual for this berthed ship - passing ship interaction to restrict loading/ unloading operations, and in extreme cases it has resulted in damage to mooring infrastructure, vessels and dangerous situations for crew and passengers [30].

For the past 15 years, we have generally addressed these problems by performing physical scale model experiments to accurately measure the interaction forces and moments and use this as input to a numerical simulation software package to predict the motions and mooring loads experienced by the berthed ship due to a passing ship. It is common to consider various different mooring arrangements (each of which may typically involve 16 mooring lines, of specific type, quality and pretension) and to assess this against PIANC and OCIMF safety criteria [26, 24]. In recent years we have used our experimental data to successfully validate CFD predictions using an inviscid double body model, thus providing a cheaper and quicker alternative to experiments for acquiring reliable and very site-specific interaction forces and moments [4].

Another ship interaction scenario investigated, usually for defence applications, are replenishment at sea (RAS) operations. These typically involve the transfer of fuel, supplies and/or personnel between vessels operating in close proximity at moderate forward speeds (approximately 12 to 16 knots). Due to the close proximity of the vessels, hydrodynamic interaction forces develop between the hull forms which impact both the ship motions and the manoeuvring capability of the vessels (Figure 6). Recent developments have seen these experiments also include incident waves at various headings to assess the effect of the sea state [20].

The interaction between surface ships during a RAS operation, such as that described above, is not dissimilar to the scenario when dealing with submarine applications. Fully submerged missions often necessitate an autonomous underwater vehicle (AUV) and submarine to operate in close proximity in order to launch, recover, and recharge the AUV, in addition to the ability to communicate data between them during operations. The interaction effects acting on an AUV operating close to a moving submarine have been investigated, predominantly using CFD but suitably validated and supplemented through physical model experiments [15, 16]. The resulting simulation model is intended to be coupled with a control system in a dynamic manoeuvring simulation to evaluate the motion behaviour of the AUV and develop the necessary algorithms to maintain the desired trajectory of the vehicle when in operation near a moving submarine.

Figure 6 Photograph of RAS experiments to investigate the influence that both lateral and longitudinal separations between vessels have on the interactions. It was found that this can lead to large supply vessel (left) roll motions in head seas and that variations in lateral and longitudinal separation between vessels had a large influence on the peak roll response of the supply vessel [20].

The physical experiments in the towing tank, with known constant forward speed, use a horizontal planar motion mechanism (HPMM) capable of generating horizontal motion (pure sway and/or yaw) on the AUV model. The AUV model was mounted to the HPMM using a 'sting' arrangement that connects to the model through the aft end, with the forces and moments acting on the AUV model recorded via two 6-DOF load cells located inside the model. The submarine model was mounted directly onto the carriage by means of rigid supports as shown in Figures 7 (CFD model) and 8 (experimental set up).

The fourth (and final) example of multi-vessel interaction covered in this paper involves the FHT concept previously outlined in Section 2.2, which considers the interaction effects between three ship models all in close proximity: the FHT (mothership), the feeder vessel that will be docked inside the FHT well dock, and an ocean-going export vessel that moors alongside the FHT (Figure 9). One aspect of the current investigation is to quantify the relative motions between the docked feeder vessel and the FHT, as this must be understood to determine the operational window in terms of maximum sea state. Related to this is the operation of materials handling equipment onboard the FHT to extract the bulk cargo from the docked feeder vessel. It has already been determined that the sheltered location inside the well dock significantly reduces the motions of the feeder vessel when compared to a more traditional side-by-side transhipment operation, thus decreasing downtime due to inclement weather [17]. A similar study is underway to assess the relative motions between the FHT and the export vessel moored alongside.

3. Summary

This paper has discussed the growing demand for more advanced measurement techniques and how they are being used to solve complex maritime hydrodynamic problems. Examples provided cover a wide range of specific applications that have adopted stereo videogrammetry and PIV to investigate hydrodynamic phenomena previously beyond conventional measurement technology. Also discussed are several novel experimental programs to study interaction effects between multiple vessels operating in close proximity.

Complex experiments such as these, especially those that acquire vast quantities of digital images over a prescribed area, are often best suited to relatively small to medium-sized facilities due to the high cost and time involved to develop and fine tune the measurement techniques. The facility staff and researchers at AMC will continue to utilise their versatile and cost effective facilities to develop innovative measurement techniques to solve hydrodynamic problems for the maritime industry.

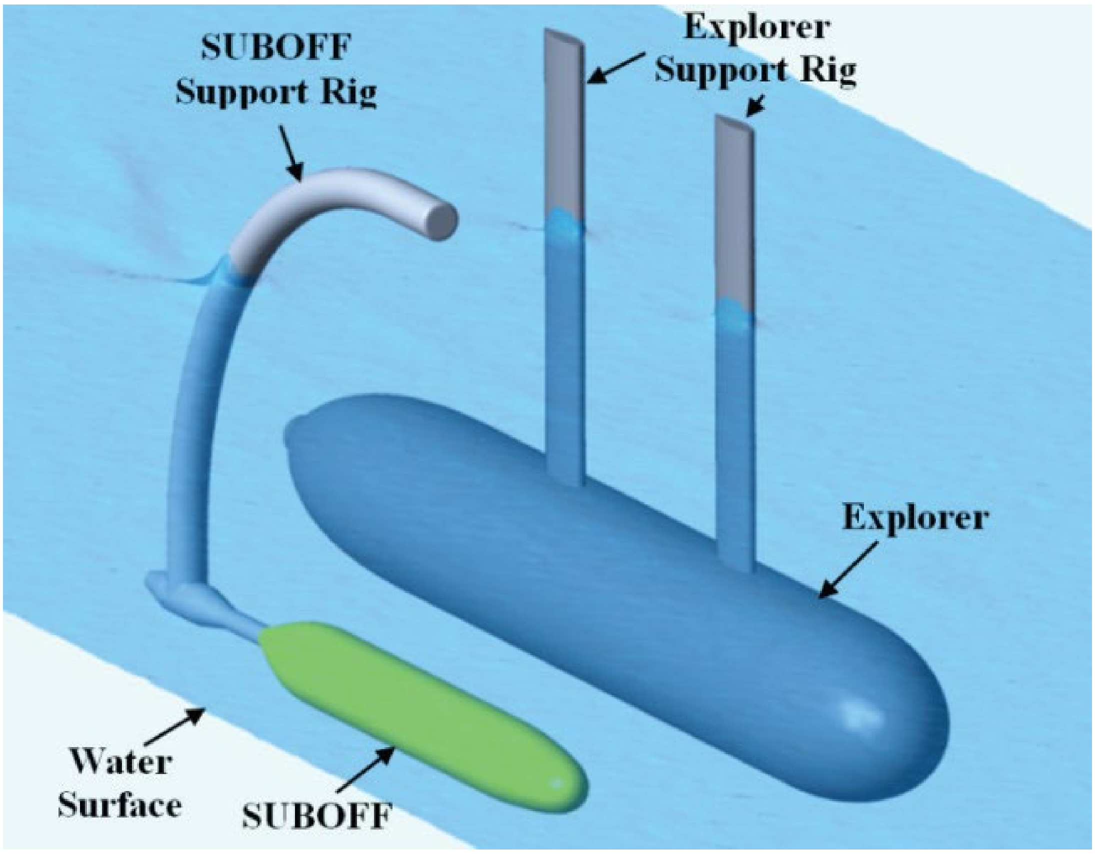

Figure 7 CFD model of the experimental setup for an AUV (SUBOFF) operating in close proximity to a submarine (Explorer). The support rigs used during the physical experiments are included in the CFD simulation (as shown) to quantify their effect on the measurements and to assist in describing the physical test rig. The experiments considered various lateral separations and longitudinal positions for the two models. Further scenarios were investigated using CFD, once validated against the experimental data [15].

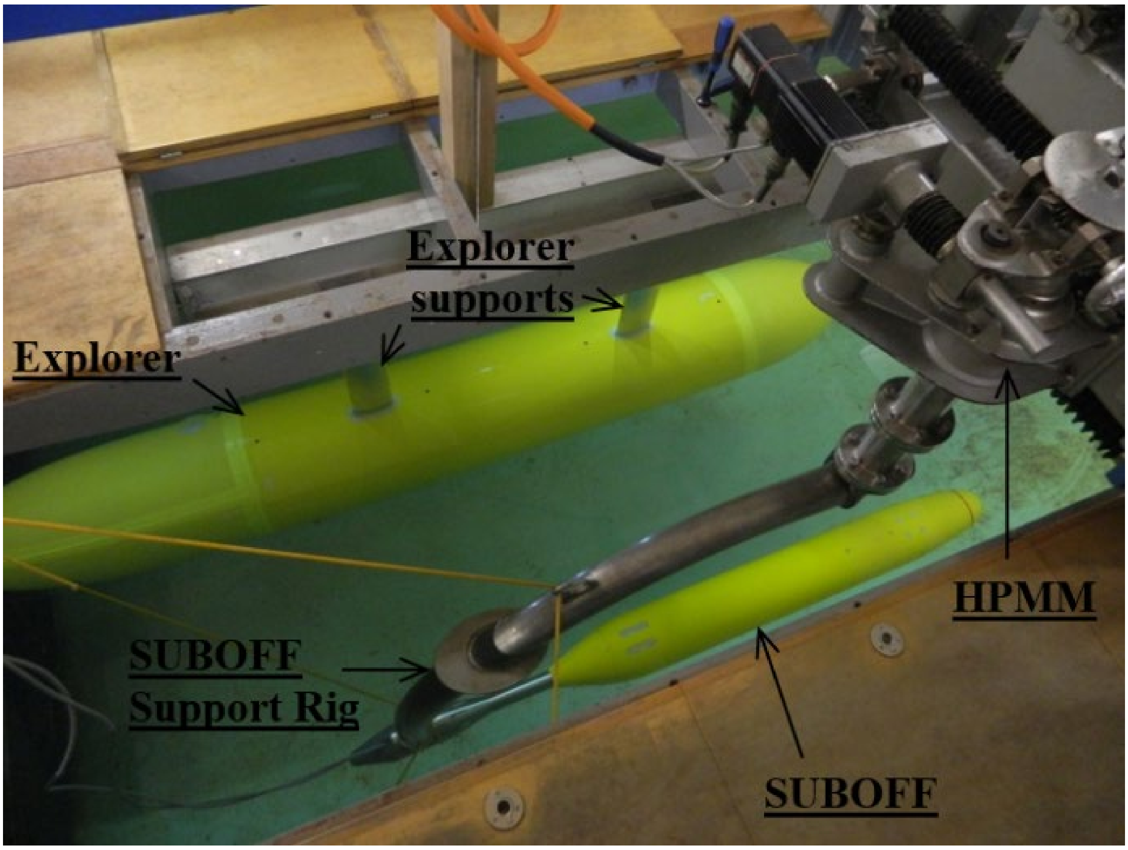

Figure 8 Photograph of the experimental setup for an AUV when operating in close proximity to a submarine [15].

Figure 9 A photograph from recent experiments involving the 5m long scale model of the FHT, feeder vessel and ocean going vessel in the AMC shallow water wave basin. The bow of the feeder vessel can be seen protruding from the FHT well dock (left). Both Panamax and Capesize ocean going vessels are under consideration: the smaller Panamax size is shown here. A minimum of four markers (silver spheres) are fixed to each of the three models to allow the Qualisys optical motion tracking system to measure all six degrees of motion for each ship model. The incident waves seen here are regular head seas, but the study is investigating a number of irregular wave spectra and wave headings.

4. Acknowledgements

Many of the experimental techniques described in this paper have been developed through projects supported by the Australian Government through the Australian Research Council (Grant numbers ARC LP0990307, LP110200129, LP130100962, LP150100502) and the Australian Renewable Energy Agency (ARENA).

We acknowledge our colleagues and collaborators who contributed to the work outlined in this paper. Where appropriate, the relevant publications have been referenced.

When preparing for any physical experiment, but especially when they are highly novel and as complex as all those outlined here, good technicians are worth their weight in gold. Many personnel assisted with this work, but the talents and efforts of AMC technicians, Liam Honeychurch and Kirk Meyer, deserve special mention.

5. References

[1] Algie, C., Fleming, A.N. and Ryan, S., Experimental and numerical modelling of the Bombora wave energy converter, Proc. 3rd Asian Wave & Tidal Energy Conf., Singapore, pp. 246-253, 24-28 October 2016.

[2] Ashworth Briggs, A., Fleming, A., Ojeda, R. and Binns, JR,, Tracking the vortex core from a surface-piercing foil by particle image velocimetry (PIV) using fluorescing particles, Proc. 19th Aust. Fluid Mechanics Conf. 8-11 December, Melbourne, Australia, pp. 1-4. 2014.

[3] Australian Maritime College (AMC), http://www.amc. edu.au/facilities/towing-tank, http://www.amc.edu.au/ facilities/model-test-basin, [accessed 23 January 2017]

[4] Denehy., S. Duffy, J.T, Ranmuthugala, D. and Renilson, M, Squat in berthed ship – passing ship interaction for restricted water cases, Proc. 4th Int. Conf. on Ship manoeuvring in Shallow and Confined Water, Hamburg, Germany, 23-25 May 2016.

[5] Denehy., S. Duffy, J.T, Renilson, M. and Ranmuthugala, D., An experimental and numerical investigation into berthed ship – passing ship interaction in a channel: methods to increase safe passing ship speeds, PIANC Year Book 2016 [in press].

[6] Elhanafi, A., Fleming, A., Macfarlane, G.J. and Zhi Leong, Underwater geometrical impact on the hydrodynamic performance of an offshore oscillating water column–wave energy converter, [in press] *Renewable Energy*, 2017.

[7] Elhanafi, A., Macfarlane, G.J., Fleming, A. and Zhi Leong, Intact and damaged survivability of an offshore floating–moored OWC, Proc. 27th Int. Ocean and Polar Engineering Conference, San Francisco, California, USA, 25-30 June 2017.

[8] Fleming, A. and Macfarlane, G.J., Experimental flow field comparison for a series of scale model oscillating water column wave energy converters, [in press] *Marine Structures*, 2017.

[9] Fleming, A., Macfarlane, G.J., Penesis, I., Bose, N. and Hunter, S., Experiment based underwater geometry optimisation programme for an oscillating water column ocean wave energy converter, Proc. 18th Australasian Fluid Mechanics Conference, Launceston, Australia, 3-7 December 2012a.

[10] Fleming, A., Penesis, I., Goldsworthy, L., Macfarlane, G.J., Bose, N. and Denniss, T., Phase averaged flow analysis in an oscillating water column wave energy converter, *Journal of Offshore Mechanics and Arctic Engineering*, Vol. 135, No.2, May 2013.

[11] Fleming, A., Penesis, I., Macfarlane, G.J., Bose, N. and Denniss, T., Energy balance analysis for an oscillating water column wave energy converter, *Ocean Engineering*, Vol. 54, pp 26-33, July 2012b.

[12] Forrest, S., Soliton Waves, BEng Thesis, UTAS, 2016. https://www.youtube.com/watch?v=D14QuUL8x60

[13] ITTC, International Towing Tank Conference, Quality Systems manual, http://ittc.info/downloads/quality-systems-manual/ [accessed 23 January 2017].

[14] King, A., Algie C, and Ryan, S. (2015), Modelling of large deformations in membranes for analysis of wave energy converters, 3rd Symposium on Fluid-Structure-Sound Interactions and Control, July 2015.

[15] Leong, Z.Q., Ranmuthugala, D., Penesis, I. and Nguyen, H., Quasi-static analysis of the hydrodynamic interaction effects on an autonomous underwater vehicle operating in proximity to a moving submarine, *Ocean Engineering*, 106, 175-188, 2015.

[16] Leong, Z.Q., Ranmuthugala, D., Penesis, I. and Nguyen, H., Transient analysis of hydrodynamic interaction effects on an autonomous underwater vehicle in proximity of a moving submarine, *Trans. RINA*, Vol. 157, Part A4, *Int. J Maritime Eng.*, Oct-Dec 2015.

[17] Macfarlane, G.J., Ballantyne, R.J., Ballantyne, S.E. and Lilienthal, T., An experimental study on the relative motions between a floating harbour transhipper and a feeder vessel in regular waves, *Trans RINA*, Vol. 154, Part A2, *Int. Journal of Maritime Eng.*, Apr-Jun 2012.

[18] Macfarlane, G.J., Johnson, N.T.M., Clarke, L.J., Ballantyne, R.J. and McTaggart, K.A., The floating harbour transhipper: new-generation transhipment of bulk ore products, Proc. ASME 2015 34th Int. Conf. on Ocean, Offshore and Arctic Engineering, OMAE2015, St. John's, Newfoundland, Canada, May 31-June 5, 2015.

[19] Macfarlane, G.J., Matsubara, S., Clarke, L.J., Johnson, N.T.M. and Ballantyne, R.J., Transhipment of bulk ore products using a floating harbour transhipper, Proc. of the Australasian Coasts & Ports Conference, Auckland, New Zealand, 15 - 18 September 2015.

[20] Mathew, J.L., Sgarioto, D.E., Duffy, J.T., Macfarlane, G.J., Denehy, S.P. and van Walree, F., An experimental study of ship motions during replenishment at sea operations between a supply vessel and a LHD, [under review] *Trans. RINA, Int. J. of Maritime Engineering.*

[21] Mitchell Ferguson, T., Macfarlane, G.J., Penesis, I., Fleming, A.N., PIV investigation of 3-dimensional flows within an oscillating water column, *International Journal of Marine Energy*, 2015.

[22] Mitchell Ferguson, T., Penesis, I., Macfarlane, G.J. and Fleming, A.N., A PIV investigation of OWC operation in regular, polychromatic and irregular waves, [In Press] *Renewable Energy*, 2016.

[23] Mitchell Ferguson, T., Penesis, I., Macfarlane, G.J. and Fleming, A.N., Improving OWC performance prediction using polychromatic waves, *Energy*, 93, (Part 2) pp. 1943-1952, 2015.

[24] OCIMF, Mooring equipment guidelines", 3rd Edition, Livingstone, United Kingdom: Witherby Seamanship International, ISBN: 9781905331321, 2008.

[25] Penesis, I., Manasseh, R., Nader, J-R., De Chowdhury, S., Fleming, A., Macfarlane, G.J. and Hasan, MK., Performance of ocean wave-energy arrays in Australia", Proc. 3rd Asian Wave & Tidal Energy Conf., Singapore, pp. 246-253, 24-28 October 2016.

[26] PIANC, Criteria for movements of moored ships in harbours, a practical guide'', Report of Working Group no 24 of the Permanent Technical Committee II, Supplement Bulletin no 88, 1995.

[27] Qualisys, http://www.qualisys.com/ [accessed 23 January 2017].

[28] Ryan, S., Algie, C., Macfarlane, G.J., Fleming, A.N., Penesis, I. and King, A., The Bombora wave energy converter: a novel multi-purpose device for electricity, coastal protection and surf breaks, Proc. Aust. Coasts & Ports Conf., Auckland, New Zealand. 15-18 Sept. 2015.

[29] Schmied, S.A., Binns, J.R., Renilson, M.R., Thomas, G., Macfarlane, G.J. and Huijsmans, R. A novel method for generating continuously surfable waves – comparison of predictions with experimental results, *Journal of Offshore Mechanics and Arctic Engineering*, Vol. 135, Issue 3, August 2013.

[30] Seelig, W. N., Passing ship effects on moored ships, Tech. Report, TR-6027-OCN, Naval Facilities Eng. Service Center, Port Hueneme, California, USA, 2001.

[31] *SurfaceFlow*, *Product Manual 1003019 for DaVis 8.3*, LaVision GmbH, 2015

[32] Wave Swell Energy, http://waveswellenergy.com.au/ [accessed 29 January 2017].