Hydrodynamics Design Considerations for Underwater Vehicles

D Ranmuthugala # and Z Leong

Australian Maritime College, a Specialised Institute of the University of Tasmania, Australia
#dranmuth@utas.edu.au

Abstract *— Underwater vehicles, such as Unmanned Underwater Vehicles (UUVs) and submarines, require a number of considerations during their design, such as operational requirements including range, speed and profile; weight balance; structural integrity; construction capability; stealth including acoustic and visual signatures; platform efficiency; sensors fit; payload; and costs. One of the major aspects that influences the final design is the hydrodynamic characteristics of the hull and the influence of the appendages. Although this cannot be considered in isolation, the hydrodynamics will dictate to a large extent the shape of the vehicle's hull and casing, the location and shape of the fin or sail, and the appendage configuration.*

The operational and manoeuvring performance of the platform, both submerged and surfaced, is heavily dependent on the hydrostatics, hydrodynamics, and seakeeping capabilities of the vehicle. They dictate how the vehicle reacts to internal and external influences during normal and extreme manoeuvers. These requirements also influence the shape, location, and the configuration of the forward and aft control surfaces, as well as the proplusor configuration, as the flow into the latter affects its hydrodynamic performance and acoustic signature. In addition to the vehicle's performance, the flow past the hull, appendages, and propulsor contribute to flow noise that makes the vehicle susceptible to detection as well as affecting the efficiency of the on-board sensors. Thus, the vehicle and its external appendages need careful hydrodynamics consideration during the design and operational phases to ensure that the platform will meet its design objectives and maintain them throughout its lifecycle.

Keywords — **underwater vehicles, hydrodynamics, Computational Fluid Dynamics, captive model testing.**

I. INTRODUCTION

Today's underwater vehicles operate in hazardous environments and are required to withstand significant external fluid pressures and manoeuvre within extremely narrow operating envelops. In addition, many vehicles have limited on-board power sources thus requiring energy conservation measures, which includes reducing their propulsion load by increasing the vehicle's hydrodynamic and propulsion plant efficiencies.

To achieve hydrodynamic efficiency, it is important that vehicle designers and operators are aware of the hydrodynamic characteristics of the vehicles, their manoeuvring behaviour in design and off-design conditions, and the influence of the hull and appendages on performance. Figure 1 shows the complex flow structure around the appended SUBOFF (Groves et al., 1989) generic submarine geometry at an angle of yaw to the flow.

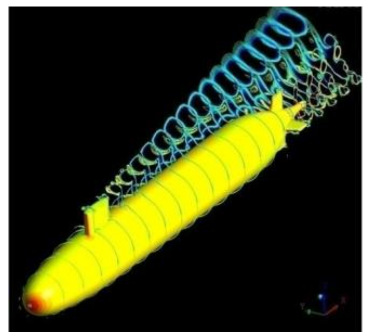

Figure 1. Flow vortices around the fully appended SUBOFF generic submarine geometry at 10 degrees yaw.

In practice, it is difficult to hydrodynamically optimise the hull shape due to operational requirements such as the payload and sensor fit (Renilson, 2015). In addition, operational conditions may adversely affect the performance and the efficiency of the appendages. Through the years, many tools and methods have evolved to assist the designer to improve the vehicles' hydrodynamic capabilities. This paper discusses the tools, together with the key vehicle characteristics that affect their design and operation.

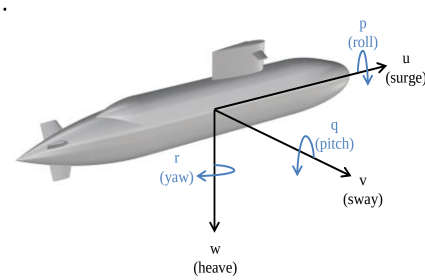

Figure 2. Coordinate system for an underwater vehicle.

The manoeuvring of surface ships is obtained about their midship; however, for underwater vehicles this tends to be about the centre of gravity of the vehicle (Feldman, 1979; Fossen, 2011), with all six degrees-of-freedom usually considered. Figure 2 shows the coordinate system for an underwater body, including the positive directions for the translation and rotational degrees-of-freedom.

II. HORIZONTAL MANOEUVRING EFFECTS

When turning in a horizontal plane, an underwater vehicle will experience both sway, yaw, and roll. The resultant steady state transverse local vectors acting on the body (shown in Figure 3) have a relatively large transverse velocity at the stern. As seen in the figure, there will be a location, usually forward of midship, where there is no transverse velocity. This is referred to as the Pivot Point (Renilson, 2015) and is of importance when designing the location of appendages such as the sail, fins, and control surface.

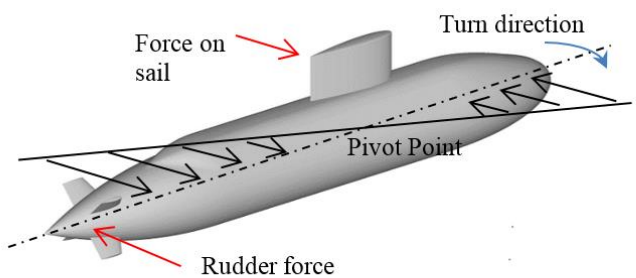

Figure 3. Forces on a turning vehicle.

Consider the location of the sail on the vehicle shown in Figure 3. To turn the vehicles to starboard its rudders are moved to starboard. This will initially cause the whole vehicle to move laterally towards the port side, resulting in an opposing distributed hydrodynamic force along its length. As the body is not axisymmetrical about the horizontal plane, the lateral force on the sail will cause the vehicle to roll inwards. As the vehicle continues into the turn, the velocity distribution will change to that shown in Figure 3. Thus, if the sail location is close to the Pivot Point, the roll will diminish due to its low lateral velocity.

A further complication is the effects of the wake generated by the body, sail, and other appendages. Usually most underwater vehicles are symmetric about the vertical plane, but not so about the horizontal plane. Figure 4 shows the wake generated when the vehicle is at an angle of yaw to the flow.

As seen in Figure 4(a), the sail tip vortex over the stern of the vehicle interacts with the afterbody vortices, weakening the upper afterbody vortex in comparison to the lower vortex. This induces a circulation around the aft hull, Figure 4(b), which creates 'lift' due to the resulting pressure variation shown in Figure 4(c). This pressure difference results in a downward force on the stern of the vehicle and is considered an out-of-plane load as it is out of the manoeuvring plane (Leong et al., 2016; Mackay, 2004). This is commonly referred to as 'stern dipping', and should be compensated for by the appropriate movement of the aft control surfaces during a turn.

The last remaining lateral point of interest is the Centre of Lateral Resistance (CLR), which is the position along the vehicle hull where a transverse force will result in sway velocity, but no yaw velocity. The location of the CLR is approximately one-third aft of the bow. However, at low speeds and when moving astern, the CLR can move towards midship. This is one aspect that dictates the location of the rudders. Locating them at the stern of the vehicle, further away from the CLR, enables better yaw motion control.

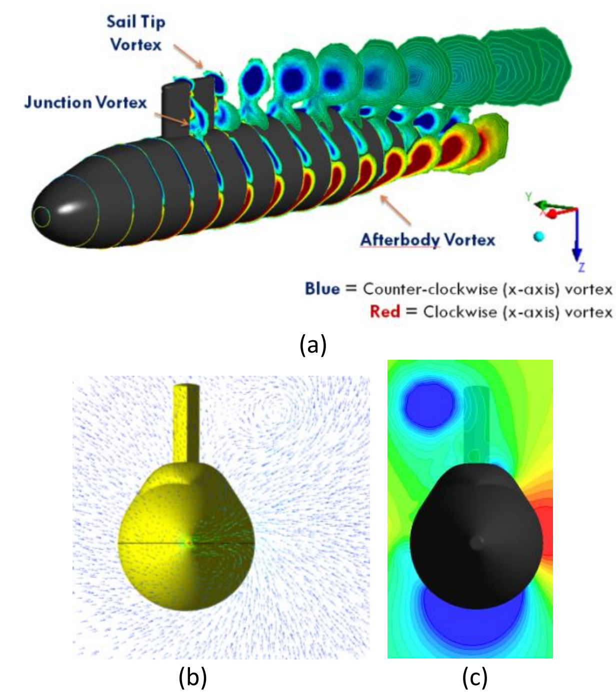

Figure 4. Wake structure from the sail and hull at an angle of yaw: (a) interaction of sail and hull vortices, (b) flow vectors aft of sail, (c) resulting pressure variation, with red and blue representing high and low pressures respectively.

III. VERTICAL MANOEUVRING AFFECTS

In vertical plane manoeuvres there are two important locations: the Neutral and Critical Points (Renilson, 2015). The former is the position where a vertical force applied will cause a change in depth of the vehicle without affecting its pitch angle. The position of the Neutral Point is generally fixed around one-third aft of the bow at higher forward speeds. This provides designers with the option of placing forward control surfaces (if present) at or near the Neutral Point, thus enabling the vehicle to change its depth, while having little effect on its trim.

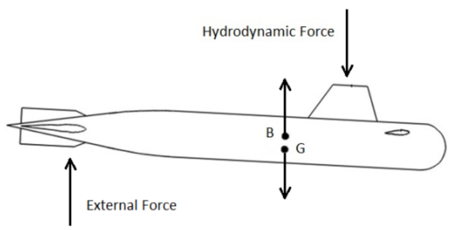

Figure 5. Force balance when an external force is applied at the Critical Point.

The Critical Point is the position along the vehicle where a vertical force applied will cause a change in pitch angle, but will not affect the vehicle's depth. This occurs when the hydrostatic and hydrodynamic components are both in balance, thus no net force is present to move the vehicle in the vertical direction (see Figure 5)

The position of the Critical Point varies with the vehicle's speed; located aft of the Neutral Point (and possibly midship) at moderate to high forward speeds. Thus, a force applied at the aft control surfaces will cause it to trim due to the lever arm from the Neutral Points as well as giving rise to vertical motion. However, at low speeds the Critical Point will move on or close to the aft control surfaces. Thus, when a force is applied to the aft control surface, this will yield a pitching moment (due to the lever arm to the Neutral Point). However, the vertical forces will now be in balance, giving no vertical motion. This can be overcome by the use of the forward planes (if present). The situation can be exacerbated when moving astern as the Critical Point may move aft of the aft control surfaces, causing the vehicle to move in the opposite direction. Hence, the designers should consider the design and location of the forward and aft control surfaces at a range of operational speeds to ensure the required control at all speeds and directions. Renilson (2015) gives a detailed explanation on the location and design of these surfaces.

In addition to the affects mentioned above, the vehicle operation will be affected when operating close to the free surface. This is especially so for the vertical motion as the vertical forces and moments will changes as a function of the vehicle's speed, sea state, and submergence. Figure 6 shows the difference in pressure acting on the hull (and thus the surface suction) for a vehicle operating near the surface and deeply submerged. This effect is further exacerbated if the vehicle has large appendages, such as a sail, fins, or sensors; especially if they are located close to the free surface. Thus, the vehicle has to compensate for this by either taking on extra ballast and/or by use of its control surfaces.

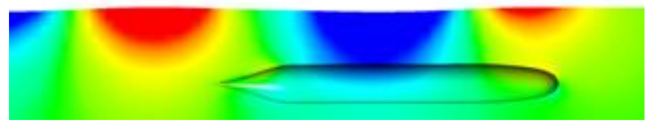

Figure 6. Difference in pressure on the hull between near surface and deep operations, red and blue representing high and low pressures differences respectively.

IV. RESISTANCE AND PROPLUSION

Most underwater bodies are designed to minimise resistance in order to increase speed (or conversely reduce installed power), increase range (for conventionally powered vehicles), and reduce noise signatures caused by hydrodynamic flow noise and machinery noise. Thus, flow separation on the hull and appendages at low angle of incidence is usually avoided to reduce resistance and noise.

The total resistance of a marine craft consist of skin friction and residuary resistance. In surface vessels, residuary is mainly wave making, while for underwater vehicles it is friction form, and induced and viscous form pressure resistance. However, when operating near the surface or on the surface, underwater vehicles can have a significant wave making component. The relevant resistance components are defined below (Renilson, 2015):

- skin friction - resistance of a flat plate with the same surface area and length;
- frictional form resistance - additional frictional resistance due to the shape;
- viscous pressure resistance - resultant of fluid pressures on the body; and
- wave making resistance - resultant of pressures due to the generation of surface wave patterns.

All except the wave making resistance are Reynolds number ($Re = VL/\nu$) dependent, while the latter is Froude number ($Fr = V/\sqrt{(gL)}$) dependent. Note: V is the velocity, L is the length, ν is the kinematic viscosity, and g is gravity. Usually the total form resistance is less that 10% to 20% of the skin friction resistance for an underwater vehicle as seen in Figure 7.

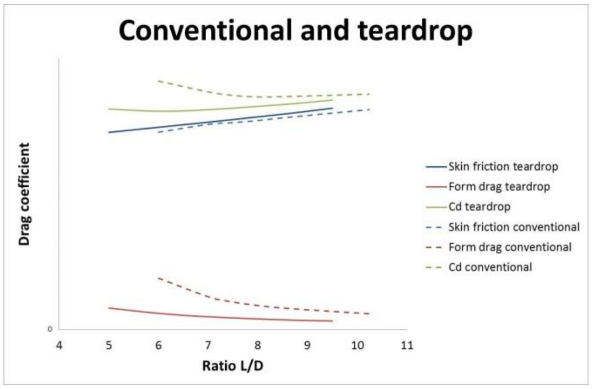

Figure 7. Drag coefficient of underwater hull shapes, including decomposing for conventional (parallel mid-body) and optimum teardrop hull shapes

It is generally accepted that the optimum bare hull form is an axisymmetric body having a longitudinal section similar to a teardrop, with the fullest section approximately 30% to 40% aft of bow. The optimum length-to-diameter ratio and the prismatic coefficient are around 6.6 and 0.61 respectively. However, due to payload and manufacturing requirements, it is difficult to design a vehicle close to the optimum shape. Many have significant parallel mid-body sections that adversely affect the resistance (see Figure 7). Although it is not always possible to optimise the hull shape, designers must attempt to minimise the resistance within design constraints. Although empirical methods are present to calculate resistance, the use of modern computational tools and complementary experimental tools have grown exponentially thus influencing the calculation process (Leong, 2014).

When operating near or on the surface the viscous component dominates at low speed, whereas wave making resistance will take over as the speed increases. The submerged body will generate waves when it is in close proximity to the water free surface that diminish as the depth of submergence increases. Wave making is generated on the water surface due to the pressure field acting around the submerged body as it is in motion.

The bow will produce a wave pattern similar to Kelvin's moving pressure point, while the stern will produce a trough wave pattern (Renilson, 2015). At most speeds, there is some interaction between the bow and stern wave patterns. When the bow and stern wave patterns are in phase it results in an increased wave height and thus resistance due to the greater wave energy content. If the bow and stern wave patterns happen to cancel each other out, the energy content and the wave making portion of resistance is then reduced.

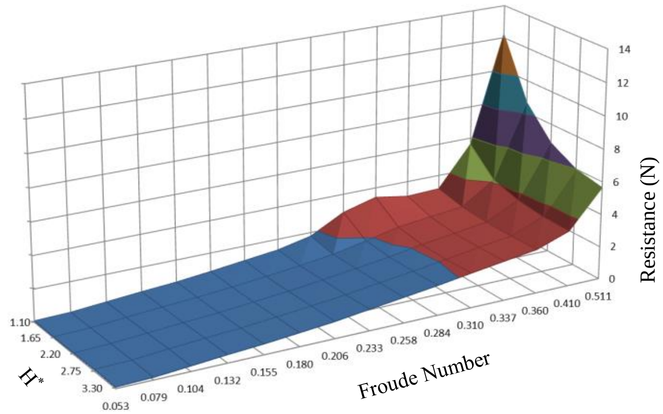

Figure 8. Resistance of the SUBOFF geometry based on non-dimensional depth (H^* = submergence depth to centreline divided by diameter) and Froude number (Fr).

Figure 8 shows the series of humps and hollows of wave making resistance as the Froude number is increased (a similar profile is obtained for the pitching moment). Depending on the Froude number, the percentage increase in drag on a vehicle travelling close to the surface, compared to one operating deeply submerged, can be significant. Generally increasing the L/D ratio (to a point) appears to reduce the effect of the free surface on the power required when operating close to the surface. The optimum L/D value for a vehicle designed to frequently operate close to the surface may be higher than the value for that designed only to operate well below the surface, where wave making does not have an influence.

V. APPENDAGES

Although an unappended body is optimum from a resistance perspective, for stability, manoeuvring, and operational requirements underwater vehicles are fitted with a significant number of appendages. These can be up to 10% to 15% of the bare hull wetted surface, increasing resistance by around 20% to 40%. These appendages include forward control surfaces, aft control surfaces, sail, sonars, sensors, masts, etc. The appendages usually have a lower chord, and hence lower Reynolds Number. In addition, they may be at an angle to the local flow and change the flow over the hull and sensors. Scaling the influence of appendages is difficult, e.g. when using model tests. Appendages should be designed for expected angles of flow, with Renilson (2015) providing some empirical approaches to this. Modern computational techniques can then be used to improve and optimise the design (Seil and Anderson, 2012). Root fairing geometry is important where sections are decreasing.

Most streamlined hull forms are driven by a single, large diameter, slow rotating propeller for efficiency. The propeller diameter however will depend on the vehicle diameter, propulsion motor, and its aft end. Depending on the vehicle, the propellers may be wake adopted, thus enabling them to work efficiently and quietly as possible within the wake generated at the aft end under most operating conditions. Some modern streamlined vehicles also use forms of pumpjets for greater thrust and efficiency.

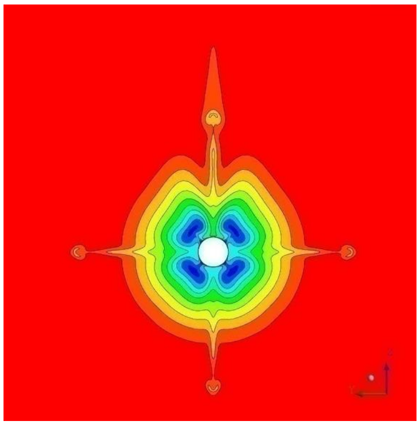

Figure 9. Axial velocity into the propeller plane of an underwater vehicle (SUBOFF), with red and blue representing high and low velocities respectively.

The wake from the vehicle hull form can be quite turbulent due to the boundary layer and the appendages. The flow generating from the bow, sail, forward planes, and aft control surfaces will result in a non-uniform wake entering the propeller plane, as shown for the SUBOFF generic submarine geometry in Figure 9. This results in the propeller operating in an unsteady wake field resulting in blade vibration. Thus, issues such as performance degradation, cavitation, flow noise, etc. will affect the operation of the vehicle. It is seen in Figure 9 that the mixing associated with vortices reduces the wake deficit downstream of the aft control surfaces adjacent to the hull due to the horse shoe vortices created around them, and even more at the top control surfaces due to the addition of those from the sail. In other areas, the growth of the boundary layer is visible, with slower axial flow behind the control surfaces. Depending on the vehicle's operation, efforts are made to reduce the unsteady nature of the flow and adapting the propeller to the wake of that vehicle. The blade numbers should avoid harmonics, with the larger number of skewed blades giving the best performance (Renilson, 2015).

Cavitation may occur on the blade surfaces or surrounding flow when the local absolute pressure is less than local vapour pressure of the fluid. The Cavitation Number is defined as, $\sigma = 2(p - p_{vap})/\rho V_a^2$, where p is the pressure and V_a is the propeller speed of advance. Cavitation on a propeller can occur at the suction-side, pressure-side, tip-vortex, and hub-vortex. Vortices will lead to cavitation, especially in near surface operations, due to the low pressure within the vortex.

VI. SIMULATIONS AND EXPERIMENTS

Although there are a number of methods for predicting the motion of underwater vehicles (Fossen, 2011), the rapid development of computer power has provided designers with accurate and complex high-fidelity computer based simulations to predict and analyse the behaviour of underwater vehicles. Together with empirical methods to provide an initial analysis and complementary experimental work, simulations enable designers and operators to investigate the behaviour of the vehicles under different configurations and conditions in order to optimise their design.

A tried and tested simulation method is the use of the standard equations of motion used in coefficient-based simulation models (Feldman, 1979; Gertler and Hagen, 1967; Ridley, 2003). The models are extremely versatile, enabling the incorporation of additions and changes to represent different platforms and modifications. The required coefficients are usually obtained from experimental work, which includes captive model testing in tow tanks, model test basins, and wind tunnels using static force balances that provides loads at different angles of incidence (Groves, 1989) as well as using planar motion mechanisms to analyse dynamic motions (Kim et al., 2015, Roddy, 1990). Similar results are obtained from rotating arm facilities where the vehicle travels at selected radii and speeds (Renilson, 2015). Figure 10 shows a horizontal planar motion mechanism in a towing tank that enables the calculation of lateral forces and moment coefficients, with the vertical coefficients obtained by 'flipping' the model on its side. Renilson (2015) provides a comprehensive explanation on the equations, coefficients, and their derivation from experimental programs.

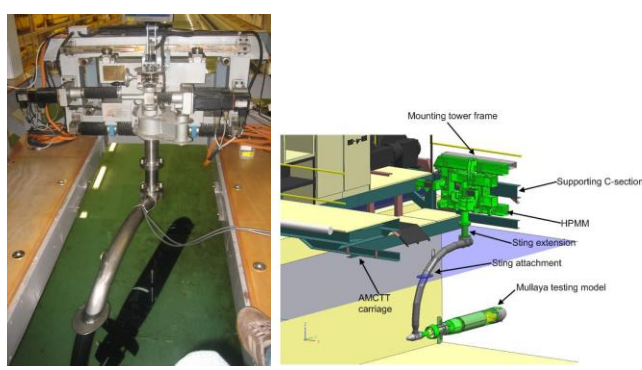

Figure 10. Horizontal Planar Motion Mechanism in the AMC towing tank testing an underwater vehicle.

An alternative to the experimental derivation of the coefficients is the use of Computational Fluid Dynamics (CFD); an option that is gaining popularity as computing capability increases. It is thus possible to conduct 'numerical' experiments similar to those explained above. However, it is essential that the simulations are verified and validated against experimental data. Once validated they provide the option of simulating configurations and conditions that cannot be replicated in captive model experiments. In addition, the ability to simulate at full scale eliminates the scaling effects encountered with scaled model work. Figure 11 shows the CFD simulation of an underwater vehicle undergoing horizontal planar motion, with examples given in Kim et al., 2015 and Phillips et al., 2007.

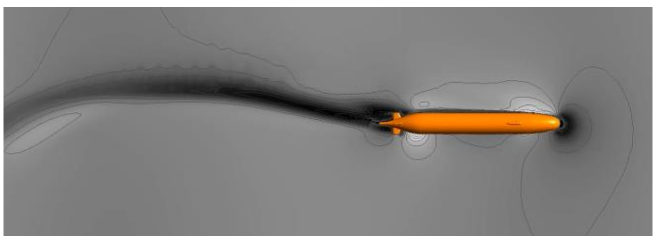

Figure 11. Virtual Horizontal Planar Motion Mechanism of the fully appended SUBOFF geometry.

Recent developments in CFD and associated hardware now allow free swimming simulations that enable designers to assess the manoeuvring characteristics of the vehicle, develop control algorithms and standard operating procedures (SoP), and obtain data for system identification techniques and validation. They replicate physical free swimming models that are carried out using semi-autonomous vehicles that are tested within test basins or suitable lake facilities.

There are many techniques available to model free swimming vehicles, including the ability to incorporate command and auto-pilots, movement of control surfaces, and a number of methods of modelling the propeller thrust such as a rotating propeller or a momentum disk. Figure 12 shows a CFD mesh with a rotating propeller for an appended generic submarine model, while Figure 13 shows the comparison between the CFD simulation of that model and the physical free swimming model results (Kim, 2016).

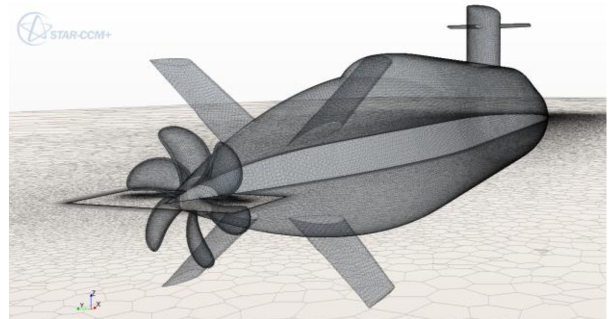

Figure 12. CFD free swimming model mesh with rotating propeller for the BB2 generic submarine geometry.

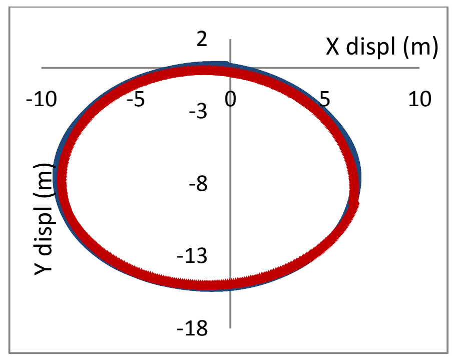

Figure 13. BB2 generic submarine turning circle manoeuvre (15deg, 1.2m/s), blue experimental and red CFD results, with rotating propeller and moving control surfaces.

VII. SUMMARY

This paper describes the principal hydrodynamic characteristics of an underwater vehicle undergoing horizontal and vertical manoeuvres, including the effects on the vehicle during a turn and when operating in close proximity to the free surface. The paper also describes the numerical and experimental methods to characterise the vehicle and predict its behaviour.

It is important that the hull geometry of the underwater vehicles is designed with due consideration to the operational requirements, such as payload and sensor fit, and the vehicle's hydrodynamic characteristics. The design and location of the appendages play a pivotal part, not only in the operational performance of the vehicle, but also on its safety. Thus, it is important that the designer is aware of the hydrodynamics characteristics of the vehicle under different manoeuvring conditions and the variations due to changes to the vehicle configuration.

ACKNOWLEDGEMENT

The authors wish to acknowledge the support and contributions by a number of AMC staff and students (especially Howan Kim and Chris Polis) involved in underwater vehicle research through related CFD and experimental work.

REFERENCES

Feldman, J., (1979), DTNSRDC Revised Standard Submarine Equations of Motion. DTNSRDC Report SPD-0393-09.

Fossen, T. I., (2011), Handbook of marine craft hydrodynamics and motion control John Wiley & Sons.

Gertler, H. & Hagen, G., (1967), Standard Equations of Motion for Submarine Simulation. Naval Ship Research and Development Center Report 2510.

Groves, N., Huang, T., & Chang, M., (1989), Geometric Characteristics of DARPA SUBOFF Models. (DTRC Models Nos. 5470 and 5471), David Taylor Research Centre, Maryland.

Kim, H., Leong, Z. Q., Ranmuthugala, D. & Forrest, A., (2015). Simulation and Validation of an AUV in Variable Accelerations. International Journal of Offshore and Polar Engineering, 25, 35-44

Kim, H., Leong, Z., Ranmuthugala D., Chin C., & Forrest A., (2016 under review), Numerical simulation of an Autonomous Underwater Vehicle undergoing a straight-line and turning circle manoeuvring.

Leong, Z.Q., Ranmuthugala, D., Penesis, I. & Nguyen, H.D., (2014). RANS-based CFD Prediction of the Hydrodynamic Coefficients of DARPA SUBOFF Geometry in Straight-Line and Rotating Arm Manoeuvres, RINA International Journal of Maritime Engineering, 157, 41-51, 2015.

Leong Z.Q, Piccolin, S., Desjuzeur, M., Ranmuthugala, D. & Renilson, M., (2016, under review), Evaluation of the Out-of-Plane Loads on a Submarine Undergoing a Steady Turn.

Mackay, M., (2004), A Review of Submarine Out-of-Plane Normal Force and Pitching Moment. Defence R&D Canada-Atlantic.

Phillips, A.B., Furlong, M., & Turnock, S.R., (2007), Virtual Planar Motion Mechanism Tests of the Autonomous Underwater Vehicle Autosub. STG-Conference/ Lecture day "CFD in Ship Design", Hamburg University of Technology.

Renilson, M., Submarine Hydrodynamics, (2015). London, Springer, ISSN: 2191-530X, ISBN: 978-3-319-16183-9.

Ridley, P., Fontan, J., & Corke, P., (2003), Submarine Dynamic Modelling, Proceedings of the 2003 Australasian Conference on Robotics & Automation, Brisbane.

Roddy, R.F., (1990), Investigation of the Stability and Control Characteristics of Several Configurations of the DARPA SUBOFF Model (DTRC Model 5470) from Captive-Model Experiments, David Taylor Research Centre, Maryland.

Seil, G.J. & Anderson, B., (2012), A Comparison of Submarine Fin Geometry on the Performance of a Generic Submarine. Pacific 2012 International Maritime Conference, Sydney.