SIMULATING FLOOD RECOVERY MANOEUVRES USING A FREE-RUNNING SUBMARINE MODEL

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SUMMARY

Managing submarine safety, effectively, requires an understanding of many areas of platform performance, including its ability to manoeuvre. QinetiQ's free-running submarine model (FRM) capability, the second generation Submarine Research Model (SRMII), forms a key part of the UK's predictive manoeuvring capability that supports the MoD's ability to conduct hydrodynamic assessment of the manoeuvring and control performance of the Royal Navy's current and future submarines. Uniquely for an FRM, the SRMII has a large and capable ballast system. This is able to emulate a flooding incident within a submarine compartment and the subsequent emergency recovery procedures, which may include blowing the submarine's main ballast tanks. This paper discusses how the SRMII's ballast system was used to generate model-scale trajectories, which are not obtainable with many other FRMs. The experimental data were used to successfully validate the mathematical model, which predicts the maximum pitch angle response of a full-scale submarine to a compartment flood, to within an average accuracy of 1% at model-scale. However, the range of the non-dimensional flow angles the FRM exhibited was shown to be within that for a full-scale flood trajectory. Therefore, further tests have been proposed to increase the extent of the data in the future.

NOMENCLATURE

CFD	Computational Fluid Dynamics
CoG	Centre of Gravity
COTS	Commercial-Off-The-Shelf
FAZ	Flood Avoid Zone
FRM	Free-Running Model
GRP	Glass Reinforced Plastic
HP	High Pressure
MBT	Main Ballast Tank
MLD	Manoeuvring Limitation Diagram
SOE	Safe Operating Envelope
SRMII	Submarine Research Model II
UK MoD	United Kingdom Ministry of Defence

1. INTRODUCTION

Today's military submarine can typically only operate in a very restricted portion of the world's ocean depths, for example the typical collapse depths of submarines from World War II were around 280m (Gabler, 1986). Although submarine design has changed since then, maximum operating depths remain far less than the average depth of The World's Oceans (3,688m). To provide assurance that a submarine design would be capable of operating safely within these rather tight boundaries means quantifying the manoeuvring characteristics early on in the design process. This is crucial in reducing the risks of producing designs that are unsuitable for the environment in which they are expected to operate.

The focus of manoeuvring and control studies is towards understanding the performance of a submarine operating in deep water, see Ray *et al* (2008) for example, and a number of approaches both numerical and experimental, reflecting the state-of-the-art at the time, can be applied throughout the design process. QinetiQ has an active role in assuring submarine safety using an approach, based on complementary numerical and experimental techniques that have been developed from their knowledge of hydrodynamics gained over a number of years, to provide a validated understanding of the manoeuvring and control performance of a submarine design, (Crossland *et al*, 2012). Irrespective of the operational requirements of a new design, a submerged submarine will be required to manoeuvre safely in the vertical and horizontal planes, which can be translated, in generic terms, to be able to accurately evaluate the performance of a particular hullform and appendage configuration at the design stage to:

- determine measures of directional stability;
- establish the size and power requirements of any control surfaces;
- design suitable motion control systems;
- determine that standard manoeuvres meet international maritime regulations or national design guidelines; and
- demonstrate that the submarine can safely recover, within the boundaries of operational requirements, from the consequence of credible system level failure.

Therefore, a requirement for any nation that operates submarines (and that has due regard for safety), is the ability to model and predict when operating conditions could occur that could put the safety of the platform (and hence crew) in danger. To conduct such analysis requires access to validated modelling and simulation tools and techniques. Such tools underpin the ability of the design and operating authorities to provide timely safety advice, for both normal and emergency operating conditions.

One area where these tools are commonly used is for the calculation of Safe Operating Envelopes (SOEs), these are discussed further is Section 2.

This paper describes one aspect of mathematical model validation, with regard to free-running model tests. This particularly focuses on modelling flood events and the subsequent recovery of the submarine. The outcome of this research will provide both design guidance and a validated evaluation toolset, for the benefit of:

- Future projects groups investigating submarine design at a concept level;
- Acquisition design groups carrying out more detailed project definition assessments; and
- In-service support to set safety and operational constraints for the submarine fleet.

2. HAZARD MITIGATION AND SAFE OPERATOR GUIDANCE

Because of wider present-day awareness of safety of personnel, hazard mitigation modelling and the provision of Safe Operating Envelopes (SOEs) to submarine command is now considered as best practice by top-tier navies worldwide. Assuring the safety of submarines is paramount to the work that QinetiQ undertakes by considering the key elements that contribute to safety assurance. This includes design optimisation, provision of validated safety guidance and the development of robust emergency procedures for implementation by trained operators. This enduring support through the life of the submarine underpins the operational safety case that helps ensure that if an incident were to occur, the submarine would be able to recover safely and return to port.

The provision of this safety advice is based on two major incidents from which operators of submarines must be able to safely recover: a control surface jam at high speed and a flooding incident at low speed. The provision of safety guidance that mitigates the risk to the submarine following such incidents requires a detailed understanding of the behaviour of the submarine, a fully validated prediction capability, an understanding of the submarine systems that are crucial to safe recovery and the presentation of data in a way that is useful, unambiguous and easily understandable.

Figure 1 provides an example of a Safe Operating Envelope (SOE) in the format of what is known as a Manoeuvring Limitation Diagram (MLD) in the UK, to provide guidance to Submarine Command, see Haynes *et al* (2002). This example provides boundaries of safe operation in terms of speed and depth. The slow speed boundaries (Flood Avoid Zone or FAZ) are present as a consequence of a flood and at higher speeds the restrictions are limited to mitigate against the risk of a plane jam (jam lines). In order to generate such a robust set of curves it is crucial that the response of the submarine following such emergency scenarios is known. The only practicable means of doing that is to have a reliable mathematical model of a manoeuvring submarine.

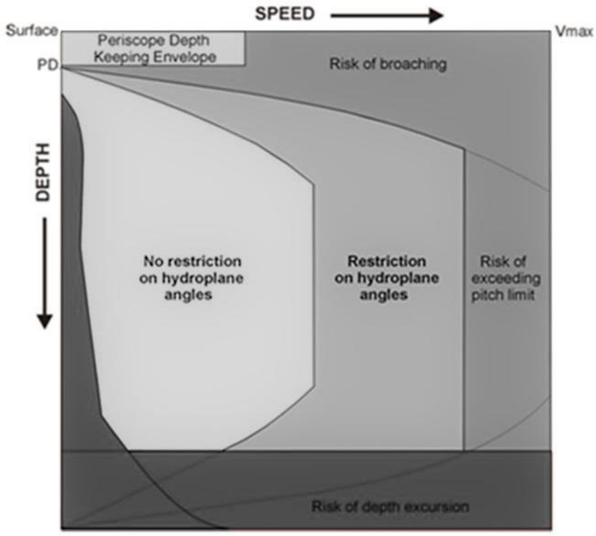


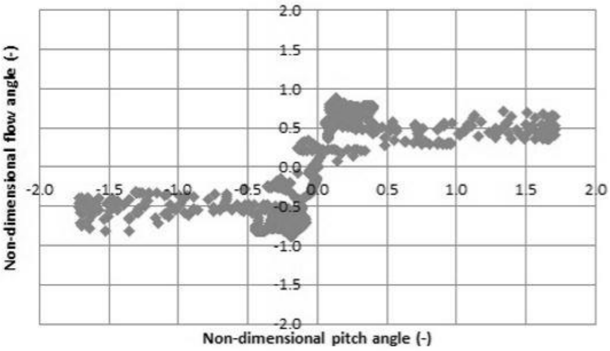
Figure 1: Example of a Safe Operating Envelope (Haynes *et al*, 2002)

The trajectory of a submarine at any instant in time is described in Bishop & Parkinson (1970), in some detail but the assumptions and simplifications result in a set of 6 simultaneous non-linear equations for small disturbances and slowly varying motion, which are to be solved for the 6 unknown translational and rotational accelerations. Provided the forces and moments on the submarine are known, the accelerations can be found. The time integrations can be then undertaken to determine the translational velocity and rotational rates, and subsequently position and attitude. The key technical challenge is determining the hydrodynamic, and other non-hydrodynamic related, forces and moments on the submarine, at each time step.

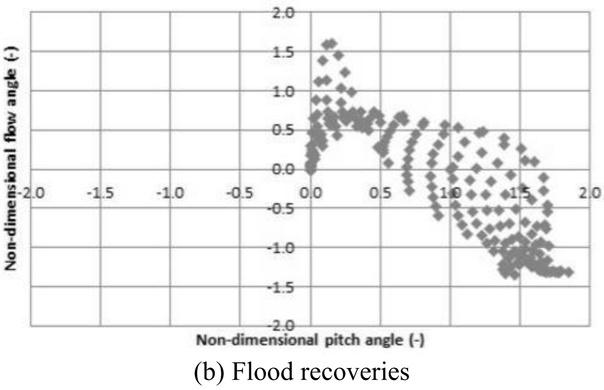
The essence of the mathematical model of submarine manoeuvring is the determination of the hydrodynamic forces and moments that are acting on the geometry. One mathematical approach assumes that the motion of the submarine is slowly varying (Haynes *et al*, 2002), and that these quasi-steady state forces and moments on a manoeuvring submarine can be described by a series of empirical equations as described in Gertler and Hagen (1967) for example. The approach is then based on establishing a set of hydrodynamic coefficients that relate the state variables of the motion to the three forces and three moments acting on the submarine. Current approaches include physical model tests using a constrained model, numerical methods or a combination of both, see Renilson (2018) for an expanded explanation of the generic approach and Crossland *et al* (2012) for this process applied to a particular submarine design. Whether from physical model tests, Computational Fluid Dynamics (CFD) or a combination of both, once the hydrodynamic coefficient set has been obtained, the form of the mathematical model is known and can be used to develop a simulation capability for design studies including investigating the resultant SOE.

Once the mathematical model is available, it is prudent for the accuracy of its results to be validated. If the full-scale submarine exists and is operational, then full-scale manoeuvring trials can be conducted for some scenarios. However, for submarine designs that are still under construction, or for scenarios that are potentially too damaging to the platform, then this is not possible. Therefore, a credible alternative to this is Free-Running Model (FRM) tests. This allows validation of both the jam and the flood recovery trajectories within the SOE.

It is more traditional to focus validation activities on the jam lines. In this scenario, the submarine has high forward speed compared to its rate of change of depth. This is shown by the plots in Figure 2, which show how the calculated non-dimensional flow angle (or hydrodynamic angle of attack) varies with non-dimensional pitch angle for a number of hydroplane jams and floods. Note that the data have been non-dimensionalised due to the sensitivity of the precise data.



(a) Jam recoveries



(b) Flood recoveries

Figure 2: Pitch angle vs flow angle during jams and floods

Notes relating to the above figure:

- The pitch and flow angle have been non-dimensionalised against the maximum value for pitch/flow angle that is typically achieved in constrained physical model tests.
- Each plot contains a number of sets of data for jam (a) or flood (b) trajectories, with data points taken at a constant time interval.

Examples are shown in Figure 2a, which demonstrate how the calculated flow angles vary with pitch angle for hydroplane jams to rise and dive for a range of different initial speeds and jam angles. For a jam to rise, starting at (0,0), the pitch angle increases to the maximum positive pitch angle (≈1.5 times the reference pitch angle) rapidly, with flow angles increasing to a positive value that is ≈0.5 times the reference flow angle. As the pitch angle reduces from the maximum (following the initiation of the recovery actions), the flow angle stays approximately constant. However, as a steady recovery speed and pitch angle are developed, the flow angle increases to just less than 1.0 times the reference flow angle and the pitch angle increases again to less than 0.5 times the reference pitch angle. For jams to dive it can be seen that the relationship is similar, but with negative flow angles and pitch angles. Hence, the maximum flow angle does not tend to exceed a non-dimensional pitch angle of ±1.0 in the example shown in Figure 2a.

When a submarine encounters a flooding incident, the floodwater creates an out-of-trim condition which is then countered by increasing the speed of the submarine and if necessary blowing the Main Ballast Tanks (MBTs). These flood recovery manoeuvres can result in more significant flow angles on the submarine because of the low forward speed compared with the rate of change of depth. It is likely that when the submarine is operating in an area that is adjacent to the FAZ boundary the flow angles experienced during a flood recovery could exceed those typically measured during the captive model tests.

Examples are shown in Figure 2b, which demonstrate how the calculated flow angles vary with pitch angle for a number of flood recovery manoeuvres for a range of different initial speeds, depths and flooding incidents. At the start of the incident the submarine is at (0,0). However, as the floodwater increases the weight of the submarine, it causes it to sink and to generate a pitch moment. This results in a rapid increase in the flow angle (in the positive direction) in excess of 1.5 times the reference angle. As the submarine speeds up and gains hydrodynamic control over the flood mass, the flow angle reduces. However, as the MBTs are blown to create buoyancy to counteract the flood mass, the submarine begins ascending to the surface. This results in the flow angle becoming negative up to 1.5 times the reference flow angle.

This implies that to validate the entire SOE boundary, the mathematical model needs to be compared against measured responses that are typical of those around the jam lines and the FAZ. Furthermore, mathematical algorithms describing the flooding of water into the submarine and the subsequent blowing air from the high pressure air bottles into the MBTs, and how this manifests itself as buoyancy, are required in addition to the hydrodynamics model described earlier.

3. MODELLING FLOODING

Modelling floodwater entering a submerged submarine through a failed pressure hull penetration can be quantified with an adaptation of the Bernoulli equation for the velocity of fluid flow through a small orifice. The flow velocity through the hole is a function of the pressure inside the submarine, the hydrostatic pressure external to the submarine, the cross sectional area of the hole and a discharge coefficient.

If the total volume of floodwater in the submarine compartment is significantly less than the total compartment volume, the pressure inside the submarine can be assumed to remain at atmospheric pressure. However, in some cases (where there is significant watertight/airtight subdivision of the submarine, such that the compartment volume is small, but the potential flood hole diameter is large), it is more appropriate to take account of the rise in air pressure within the submarine.

The value of the discharge coefficient depends upon the type of flooding incident. For a direct penetration in the submarine pressure hull, a discharge coefficient of approximately 0.6 might be suitable, (Franz & Melching, 1997) to reflect the contraction of the flow through the flood hole. This is appropriate for floods on a small diameter seawater system that is open to the sea, where the pressure hull fitting has failed. For systems that require larger pressure hull penetrations, it is normal to include some ability to secure the flood (through hull-mounted valves) should a failure occur. Therefore, for these types of securable systems, it is likely that any failure is going to be within the pipework rather than the pressure hull penetration itself. In this case, a discharge coefficient of 0.6 may not be suitable and the actual value may be somewhat less than 0.6 due to losses in the flow velocities due to the pipework system that the floodwater has to pass through.

Once the rate at which floodwater enters the submarine is known, the impact of that floodwater on the submarine response is required. The successful recovery of a submarine is sensitive to pitch angle, so the dynamic effect of the longitudinal centre of gravity of the flood mass may have a significant effect on the response of the submarine following a flood. Modelling this effect, taking account of the highly non-linear sloshing behaviour of the floodwater in the compartment would require complex CFD calculations to be coupled with a submarine manoeuvring simulation. This is not currently considered to be a practicable approach due to the significant computational cost associated with calculating the large number of manoeuvring trajectories required to define the FAZ. Therefore, it is considered appropriate to apply a quasi-steady state assumption for the floodwater by taking the compartment geometry, and calculating the flood mass and its centroid for the instantaneous pitch angle.

It should be noted that the formation of the manoeuvring equations are based on a simplification of Newton's equation where it assumed that the mass is constant:

$$F = ma$$

where F is the force on the body of mass m with acceleration a. In the case of a manoeuvre that includes flooding in a submarine, the mass is not constant. So, to be correct the equations of motion should be extended to:

$$F = ma + v\dot{m}$$

Where the body has velocity v and rate of change of mass $\dot{m}$.

However, because floodwater typically accounts for less than 0.5% of the submerged displacement, the $v\dot{m}$ term has traditionally been ignored when accounting for floodwater in submarine hydrodynamics. Instead, the floodwater appears as an additional external force on the LHS of the equation. This approach has been justified by simulating the trajectory of a submarine, at the defined form volume and mass, and comparing the responses with the form volume and mass increased by 0.5%. Note that both need to be increased to maintain the hydrostatic equilibrium, as clearly an out of trim of this magnitude, would have a significant effect on the submarine. Comparing these two trajectories shows minimal differences indicating that the dynamic influence of a change in mass of the body can be neglected.

Likewise, previous, unreported, sensitivity studies have shown that a change in inertia (due to floodwater), of the submarine, greater than 30% would be required to have a significant impact on the resultant trajectories.

4. MODELLING HIGH PRESSURE AIR BLOWING

Blowing high pressure air into MBTs for flood recovery can be divided into three parts: the flow of air from high pressure bottles, water flow out of from the ballast tank and the evolution of the pressure in the ballast tank, (Font *et al*, 2010).

To model the flow of air from the bottle into the tank through a valve (that acts as a nozzle), (Font *et al*, 2010) neglected pressure losses and heat transfer in the pipework that connected the bottle to the tank. A method was derived by (Font *et al*, 2010) using a theory based on one dimensional steady flow of an ideal compressible gas. Since this method does not account for any pipework pressure losses, these algorithms are most suited to cases where the emergency bottle group is located adjacent to the blow nozzle in the MBT as any connecting pipework will be short. This would probably be the case where the HP air system has been designed to have a dedicated emergency blow bottle group, external to the pressure hull, which is independent from any normal HP air system, internal to the submarine, Figure 3. An alternative configuration is possible with the air from the emergency bottle group being supplemented with air from the normal HP air system. To allow this arrangement to function, the pipework system is significantly more complex because the bottle groups supplying the main HP air system bottles also have to supplement the emergency system, which has its own set of bottles, when required – see Figure 4. The other point to note is that the simplistic model is based on the assumption that the gas behaves as an ideal gas. Marchant *et al* (2014) suggested that more sophisticated engineering software simulations methods coupled with the assumption that air behaves as a real gas would be better suited to model the complexities of an HP air blow that includes the normal HP air system. A number of commercial engineering simulation codes are available to model pneumatic systems. Two such examples are AMESim by Siemens, or FloMASTER by Mentor Graphics Corporation. QinetiQ have developed AMESim real gas models of representative HP air systems for modelling blowing in submarines.

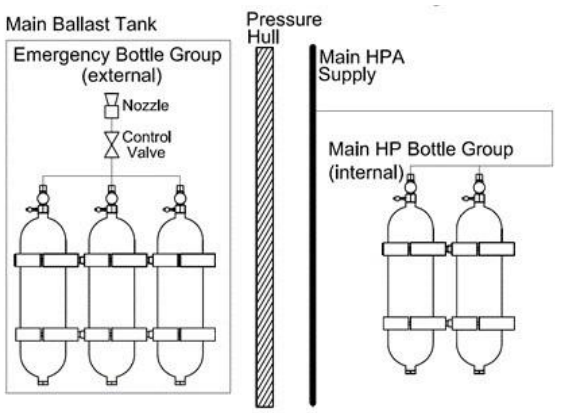


Figure 3: Possible arrangement for separate emergency HP air system

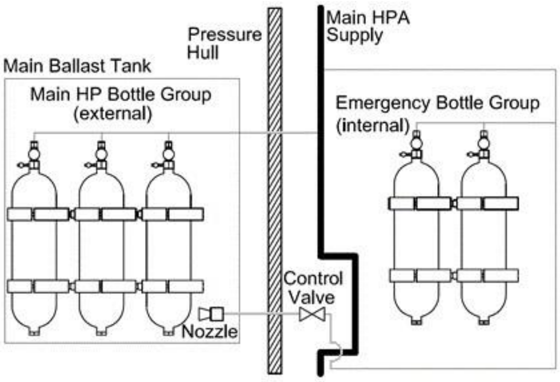


Figure 4: Alternative arrangement with Normal and Emergency bottle groups

Using either the simplified blow model or the complex AMESim model the mass flow rate of air at the nozzle can be determined, from which the pressure at the tank nozzle is also known. It is the difference between the pressure in the tank and external water pressure that results in water being forced from the ballast tank through the flood grillages at the bottom of the MBT. Font *et al* (2010) applied the Bernoulli equation at the ballast tank flood grillages to determine the volumetric flow of the water.

Once the flow of air to the ballast tank nozzle and the flow of water from the ballast tank are understood, the next step in the process is to understand how the air blown into the tank manifests itself as buoyancy. According to Font *et al* (2010), the air is blown at high velocity, rapidly mixing with the water in the tank promoting good heat transfer from water to air (which will cause the air to expand); this process is considered isothermal and the ideal gas law can be used to determine the volume of the air in the tank. As the hydrostatic pressure decreases when the submarine drives towards the surface, the air volume within the MBT will expand. This results in an adiabatic process that decreases the air temperature in the MBT.

There is also an additional physical phenomenon to take into account during a flood recovery. During a recovery the submarine will adopt a positive pitch angle, which means that the forward MBTs are at a lower hydrostatic pressure than the aft ones. This phenomenon is considered to be significant when considering flood recoveries; whilst all MBTs may have equal masses of air blown into them, the air in the forward MBTs will have expanded to create a larger buoyant volume than the air in the aft ones. The impact of this is an additional pitch moment due to the differential expansion of air within the MBTs; this effect becomes more significant as the submarine approaches the surface.

Again, it should be pointed out that the equations of motion do not take account of any change in mass of the submarine, in this case due to the blowing of the MBTs. The resulted buoyancy due to air in the MBTs and the reduction in seawater is accounted for as an additional force on the LHS of the force equation.

The volume of water in the MBTs typically accounts for between 10-15% of the submerged displacement of the submarine. However, the MBTs are only fully proven, due to the exponential expansion of air at reduced hydrostatic pressures, just prior to surfacing. As such, for the majority of the flood recovery scenario, the change in submarine mass due to the blow would be significantly less than the 10-15%. Extending the studies to that described for the flood mass, have shown that expanding the range of mass change (from 0.5%) due to blowing also has minimal impact on the dynamics of the trajectory. Therefore, for blowing the constant mass assumption used in the equations of motion is considered to be valid.

As discussed with the flood case, a change in inertia, due to the change in condition of the MBTs, for the submarine of greater than 30% is normally required to have a significant impact on the mathematical model.

5. FREE-RUNNING SUBMARINE MODELS

A free-running model is a geosim of a full-scale submarine; it is used as a tool during the design and operation phases to gather data relating to the hydrodynamic manoeuvring and control performance of a submarine design. As part of the process for modelling the manoeuvring performance of a submarine, there are a number of reasons for undertaking FRM tests that include:

- validation of the mathematical model;
- manoeuvres suitable for the application of System Identification techniques, leading to improvements in the mathematical model predictions;
- to explore different control strategies;
- to investigate and validate the boundaries of the SOE
- design of suitable motion control systems.

The Submarine Research Model (SRM) capability has been employed in all the above areas, but is chiefly used for exploring the extremes of the manoeuvring envelope (Haynes *et al*, 2002).

The SRM capability was first developed in the 1980's, consisting of an aluminium pressure hull that is 4.5m long with a diameter of 0.6m. Glass Reinforced Plastic (GRP) cladding is attached to this pressure hull to make it conform to the external shape of a range of submarine geometries with L/D ratios typical of SSNs or small SSKs, see Crossland *et al* (2015). The SRM is best suited to investigate hydroplane jams and subsequent recovery strategies, which are, by their nature, typically conducted at higher speeds. This first-generation design does not have active ballast control so is not particularly suited to slow speed operations, such as those required to investigate flood recovery scenarios.

In support of studies to develop a replacement for the Vanguard Class SSBNs, this capability was upgraded (Crossland *et al,* 2015), to the Submarine Research Model II (SRMII) Figure 5 partially clad as the platform considered in this paper. More detail about the design and operation of the SRMII can be found in Crossland *et al* (2015) and Crossland *et al* (2014), whilst the history of the development of FRM technology is discussed in Marchant & Kimber (2015).

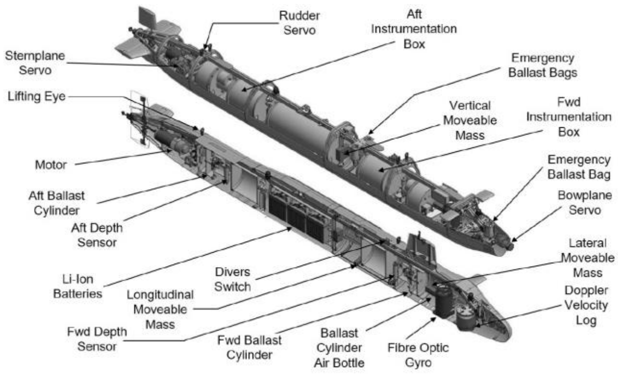


Figure 5: SRMII Free-Running Model

The application of free-running models within the overall test and evaluation of a submarine's manoeuvring and control performance is detailed in Marchant & Kimber (2014), with further details as to why physical model experimentation of this type is still relevant explained in Marchant & Kimber (2017). One of the most significant improvements in the SRMII design was the inclusion of an automated ballast and trim system that is described in the next section. This hugely capable system provides the means to investigate flood recoveries in submarines to inform on the validation of the entire SOE.

5.1 BALLAST AND TRIM SYSTEM OVERVIEW

The ballast system in the SRMII consists of two open ended cylinders, each containing an internal piston. The position of this piston is controlled by a stepper motor, which changes the size of the 'dry' volume contained behind the piston. The capacity of each cylinder is just over 10 litres. The innovative approach to minimising the power requirement of the stepper motor was to keep the dry side (inside the cylinder) pressurised to offset the external hydrostatic pressure. The air is supplied from a small diver's air bottle inside the model. A regulator on the air supply line to the ballast cylinder ensures that the pressure behind the piston is maintained only slightly higher than the ambient hydrostatic pressure.

The benefit of this approach is that the piston can be rapidly moved to change the ballast of the SRMII. The stepper motor is capable of moving the piston at 50mm/s in air. However, in water a practical limit of ≈20mm/s has been established. This is more than sufficient to model equivalent floods and blows to full-scale submarines on the model.

The ballast cylinders are located at either end of the model and can be operated independently to provide a wide range of mass and moment changes. The components, assembly and locations within the model are shown in Figure 6.

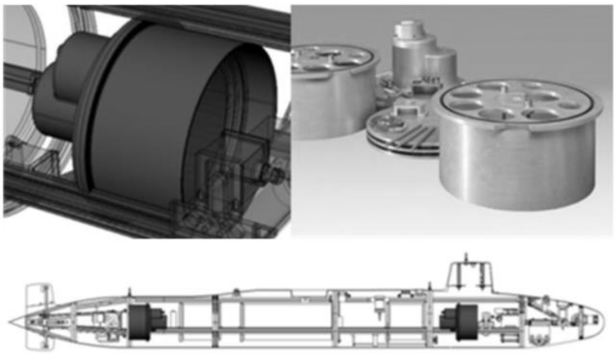


Figure 6: Ballast system components in SRMII

The design also incorporates a static trim system, consisting of three movable masses, each fixed to a lead screw, and driven by stepper motors. These align with the principal axes of the model such that the longitudinal mass can generate pitch moment, the transverse mass can generate roll moment, and the vertical mass changes the height of the centre of gravity (CoG) of the model. As a combined ballast and trim system the model can be either programmed with predetermined changes to the ballast and trim condition, or for the on-board software to order changes autonomously as required.

In the context of modelling flood recoveries, the ballast and trim system can replicate the change in mass and moment imparted on the submarine for a range of significant flood scenarios. This can be done in a number of ways, potentially by embedding the mathematical representation of the flood and blow algorithms in the on-board software as a closed loop system responding to the instantaneous depth and pitch of the model. Alternatively, the scenario can be treated as "open loop", imparting a known change in mass and moment on the model. The approach adopted in the experiments discussed for the remainder of the paper aims to provide the particular validation evidence for the hydrodynamic models in a flow regime that is typical of flood recoveries. The most appropriate approach in this case is to treat the scenario as open loop and use simulation to generate, a priori, time histories of changes in mass and moment that are representative of a flood recovery. These suitably scaled mass and moment changes are then replicated in the SRMII as part of a run. This approach is described in more detail within the next section.

6. EXPERIMENT RESULTS

This section describes the results from an experiment conducted with the SRMII free-running model in QinetiQ Ocean Basin. The model geometry, partially illustrated in Figure 5, was a traditional cruciform design. Unfortunately, the results shown in this section have had to have the axes removed from the plots, or be non-dimensionalised, due to the sensitivity of the precise data.

6.1 FLOOD AND BLOW TRAJECTORIES

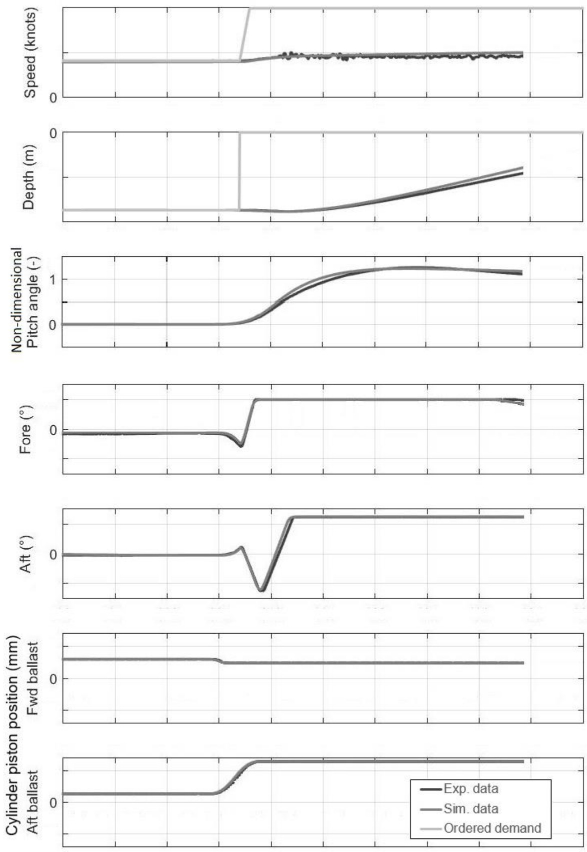
The ballast and trim system was used to provide systematic changes in mass and moment that are representative of different flood and blow scenarios. The aim was to achieve a wide range of incident flow angles (both positive and negative) to validate the mathematical model. The scenarios replicated floods (of increasing severity) at a typical aft engine room location, where the size and complexity of seawater systems are more likely to result in a significant flooding incident should a breach to the watertight integrity occur. For the blow scenarios, the ballast and trim system was used to represent blowing of HP air into a forward MBT that made the model buoyant and created a bow up pitch.

For each flood scenario, the aft ballast cylinder was used to increase the mass of the model, whilst the forward cylinder was adjusted to ensure a representative longitudinal moment for the flood mass was applied. It should be noted that the ballast cylinders apply the additional mass about the axis line of the submarine, whereas a flood on a full-scale submarine would have an impact upon the vertical centre of gravity of the submarine, increasing the distance between the centre of buoyancy (B) and gravity (G).

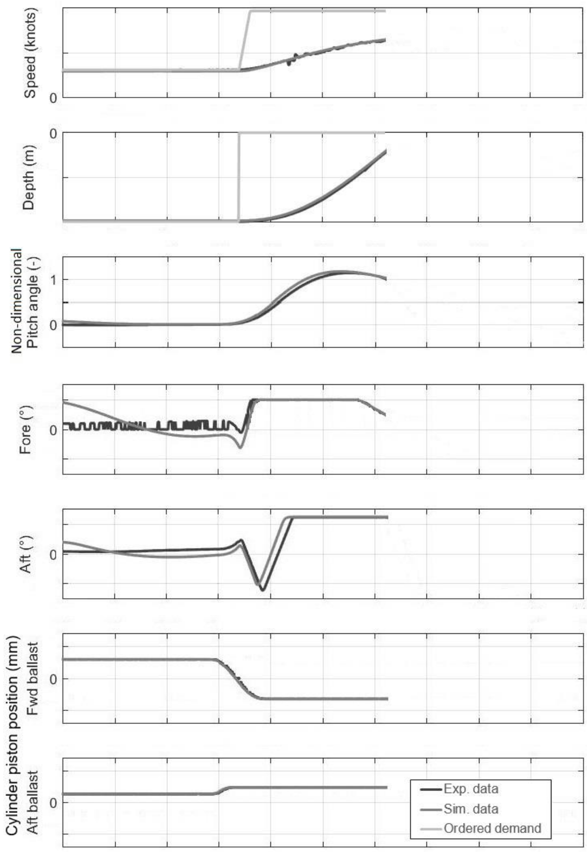
Once the flood had been represented, there was a short delay to replicate the time taken for the crew to react and execute their emergency recovery procedures. It should be noted that time was scaled from full-scale to model-scale assuming Froude scaling of 1/√scale factor. Following this time delay, the appropriate propulsor response was applied and the model was driven to the surface using a specifically designed autopilot that controlled pitch during the ascent. Any increase in speed of the model would enable the hydroplanes to partially counter the flood mass and moment and control pitch angle to an acceptable level.

All of the flood scenarios were initiated whilst the model was at low forward speed, and therefore the change in mass and longitudinal moment created by the flood induced a significant pitch angle. By varying the initial speed of the model and the recovery RPM, a range of peak pitch angles (the point at which the hydroplanes were able to reduce pitch) were obtained.

For each blow scenario, the forward ballast cylinder was used to make the model light, whilst the aft cylinder was adjusted to ensure a representative longitudinal moment for the blow (in conjunction with a potential flood mass) was applied. It should be noted that the ballast cylinders apply the reduction in mass about the axis line of the submarine, whereas a blow on a full-scale submarine would have an impact upon the vertical centre of gravity of the submarine, increasing the distance between the centre of buoyancy (B) and gravity (G).

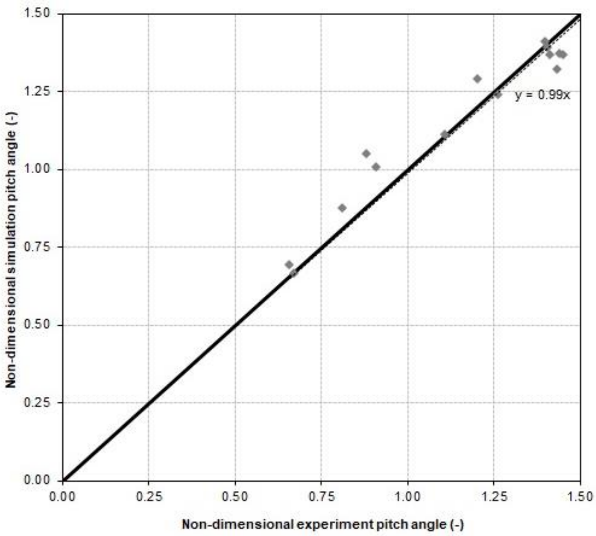


(a) Flood

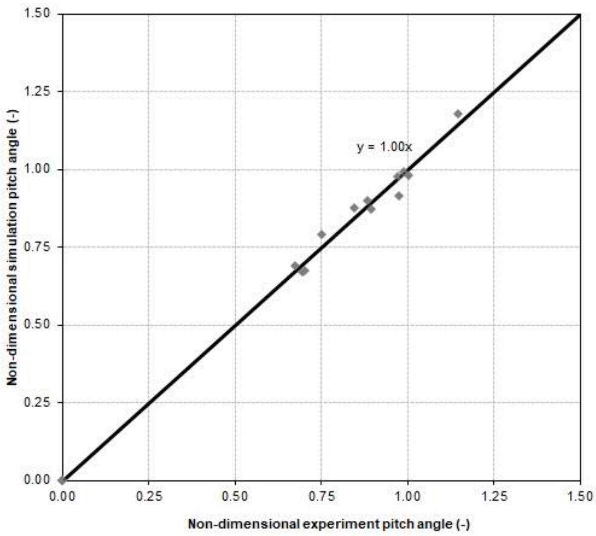


(b) Blow

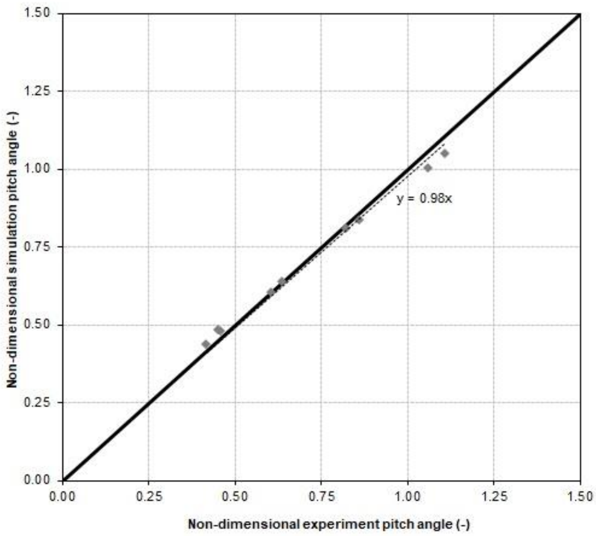
Figure 7: Trajectories of flooding and blowing



(a) Flood



(b) Blow



(c) Jams

Figure 8: Correlation of simulated peak pitch angles with measurements

Once the change in trim condition of the model had been achieved, the response of the model (in terms of appropriate propulsor response and autopilot actions) was the same as the floods. Again, by varying the initial speed and the recovery RPM, a range of peak pitch angles could be obtained. Varying the initial conditions also enabled the model to undergo a range of hydrodynamic angles of attack (both positive and negative).

In this analysis, separate floods runs and blows runs from the free-running model were analysed. Although it was possible to conduct floods followed by a blow in a single run, the depth constraints of the Ocean Basin and the size of the model meant that there was insufficient time within the trajectory for the full effect of the flood, followed by the blow to occur, before the submarine surfaced.

Comparing the simulation results with the experimental trajectories allows a greater level of assessment of the validity of the mathematical model for these type of manoeuvres.

Figure 7 provides example measurements of flood and blow responses of the model compared with simulation. In both cases, the predictions of the initial response in depth and pitch compare well with measurements, as do the ascent parts of the trajectory as the model drives to the surface.

Initial exploratory tests were conducted in QinetiQ's Ocean Basin at Haslar, where the water depth is around one model length. To allow the recovery trajectories to fully develop for the more extreme flood and blow cases, a deeper initial depth is required, so similar tests are planned in the future using a deep-water facility.

6.2 SIMULATION CORRELATION

To provide an overall view of the quality of the simulations when compared with the experiments, a correlation of the simulated peak pitch angles from the flood and blow trajectories with the measurements is shown in Figure 8. This is a similar concept to that used when assessing simulation of peak pitch angles during hydroplane jam recoveries.

The results of the correlation show that predictions of maximum pitch angle for both (a) flood and (b) blow scenarios correlate very well with the measured pitch angle. However, also shown is a similar correlation plot for jam scenarios (c) which shows slightly less scatter in the data compared with plots (a) and (b). Either this suggests some limitations in the mathematical model, or an illustration of the increased level of uncertainty in conducting these types of experiments compared with hydroplane jam recovery manoeuvres. Due to time constraints, a full uncertainty analysis has not been conducted on these data but this may be performed at some time in the future.

To illustrate the extent to which the mathematical model has been validated, in the context of the FAZ, the combinations of the measured flow and pitch angles for the flood and blow scenarios generated during the experiment are shown in Figure 9. Also shown, for comparison, is the area indicated within Figure 2(b) as the flow and pitch angle combinations that are generated when calculating a FAZ boundary.

Figure 9 shows that the extremes of flow angle that are predicted to occur during a full-scale flood were not sufficiently represented during the free-running model experiments. This is because the serial data for floods and blows is within the range of the captive model tests. This is largely due to the inability to test the necessary combinations of floods and blows in the limited depth of the Ocean Basin. It is possible that it is these extreme flow angles where the accuracy of the mathematical model may be called into question.

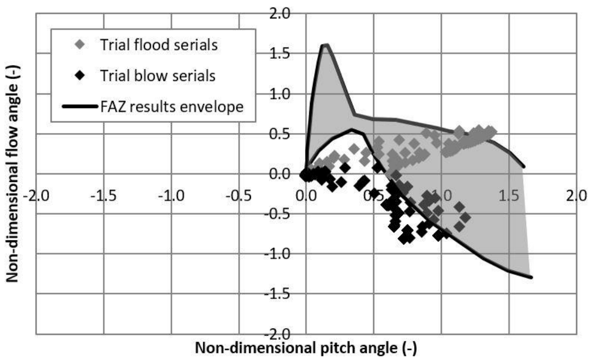


Figure 9: Hydrodynamic angle of attack vs pitch angle compared to FAZ

Once the more extreme tests of combinations of flood and blows have been undertaken, then the full validation of the mathematical model can be performed. If the model requires improvements then this could be done by including higher order terms in the Gertler & Hagen (1967) mathematical expressions such as Park *et al* (2017), who augmented the force and moment equations with up to fifth order terms derived from wind tunnel experiments on a captive model. However, the example data shown in Park *et al* (2017) indicates that this approach does not take into account stall effects. In reality, high flow angles at low speeds are likely to result in stall and this may require a different approach. One alternative approach for capturing the non-linear effects due to high angles of incidence may be to introduce look-up tables that are derived from captive models tests. These look-up tables would be accessed at each time step of the simulation to provide a force and moment rather than through the coefficient based approach. One disadvantage of this approach is that the lookup table must capture the range of data required for simulation, as typically look-up tables cannot be used for extrapolation, whereas the coefficient based approach can extrapolate (with due caution) for scenarios outside of the fitted range of data.

7. CONCLUSIONS

This paper has discussed one specific application of a free-running submarine model capability, which was the validation of predicted responses that are typical of a submarine recovering from a flood or responding to a blow. The experiments successfully proved the methodology for conduct and analysis of validating trajectories for flood recoveries using QinetiQ's free-running model capability.

The correlation that has been undertaken with the current data has shown that the predicted peak pitch angles compare well with those measured during the experiment; predictions to within an accuracy of 1% has been found at model scale. However, as a consequence of some of the limitations with this experiment, the flow angles achieved were not as extreme as those predicted to occur during flood scenarios around the FAZ boundary and moreover, were within the range over which a captive model would be tested (from which the hydrodynamic coefficients are derived). Therefore, to some extent the correlation was expected to be good.

Further tests will be planned using a deep-water test facility (reservoir) to provide the additional water space that would allow tests to be conducted at deeper initial depths. These conditions would generate more significant flow angles on the model thus providing validation data in these extreme but still pertinent, areas.

These tests provide confidence that these validated tools are providing an understanding of the behaviour of a deeply submerged submarine that is subjected to a major flood because of a failure in a pressure hull penetration. This capability underpins the provision of safe operating envelopes of current and future underwater platforms during normal operations and emergency conditions which is a key requirement for any nation that operates submarines with due governance regarding safety.

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