Aerodynamically Alleviated Marine Vehicles (AAMV): a review of the main challenges and hydrodynamic aspects

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Several new high speed marine vehicle configurations have been developed during the last two decades, due to an increasing demand for such vehicles for civil and military transportation. At the upper end of the speed range, a vessel can be equipped with aerodynamic lifting surfaces in order to alleviate the weight of the vehicle, leading to a lower effective displacement, with lower hydrodynamic drag and required power.

A general review of the latest research on wing-in-ground effect (WIG) vehicles has been undertaken, highlighting some of the main technological challenges. From the earliest stages of development longitudinal stability has been one of the main challenges to be resolved. Additionally, the promise of increased aerodynamic efficiencies demonstrated at the theoretical level has not been easily achieved, often due to matters of stability, hydrodynamics, structural design and operational practicalities. Hydrodynamically, overcoming hump drag has proven problematic, often requiring significantly higher power during the take-off phase than at any other time in the operational profile. Whilst several general methods have evolved to address this issue, the limitations imposed by various configurations remain impediments to more efficient and effective designs.

The present work includes specific considerations for the preliminary design of a hullform with more favourable waterborne characteristics than existing WIGs. Initial tank testing was carried out to assess resistance performance for a representative operational profile during a take-off phase.

1 INTRODUCTION

1.1 Context

Various high speed marine vehicle configurations have been developed during the last several decades, due to an increasing demand for such vehicles in civil and military marine transportation (Clark et al. 2004). Yong (Yong et al. 2005), has recently updated a study initially conducted by Von Karman and Gabrielli (Gabrielli & Von Karman 1950), showing the relative speed and transport efficiency of current modes of transportation. Marine vehicles have maintained a permanent place in the global economy for several reasons, such as their efficiency in transporting a high volume of goods over large distances, and their effectiveness and efficiency in smaller and more localised routes and applications.

There are a number of options in the field of high speed marine vehicles, most notably planing monohulls, slender hulled catamarans and trimarans, hydrofoils, surface effect ships, air cushion vehicles and wing in ground effect (WIG) craft. Although WIG craft employ aerodynamic surfaces to bodily rise free of the water surface, this category of vehicle is internationally recognised as a marine vessel first and foremost. One of the reasons for this classification is that operation is necessarily near the water surface in order to exploit the favourable ground effect. Vehicles that can operate both in and out of ground effect are possible, although once a critical operational altitude is reached further civil aviation regulations are applied (Rozhdestvensky 2006).

Therefore, there seems to be a clear case to maximise the potential of a near surface marine vehicle, able to achieve speeds typical of aircraft whilst exploiting aerodynamic, regulatory and ultimately cost efficiencies to operate in a similar manner to traditional marine vehicles (Paek, 2006). This paper will document some of the primary technical impediments to WIG development, and to the realisation of a true hybrid marine craft.

Historically, WIG have physically resembled low flying aircraft, with their associated geometrical features. However, these characteristics have often proved unfavourable in a marine environment. Attention is now focussed on the development of a hybrid class of vessel, able to comfortably operate on the water surface yet still deliver the speed of aircraft during an airborne cruise mode. This has been termed an Aerodynamically Alleviated Marine Vehicle (AAMV), as it employs aerodynamic lifting surfaces to counteract the gravitational weight of the vehicle, resulting in a lower effective displacement, wetted surface, and ultimately resistance for a given speed. The resulting increase in transport efficiency using this type of configuration promises the ability to move people and cargo over water with much greater comfort, speed and efficiency than is currently achievable by any other method.

The AAMV can operate successfully in a number of modes: low speed displacement and so-called semi-displacement waterborne modes; a transient condition defined by hydrodynamic and aerodynamic forces of the same order of magnitude (Collu, 2008); and finally completely free of the water surface for high speed transit, fully airborne although not beyond the influence of the ground effect zone.

2 MAIN CHALLENGES

2.1 Stability & control

Longitudinal pitch stability has been identified as one of the key design parameters that are critical for success of WIG craft. The necessary proximity of the ground plane that offers the promise of increased aerodynamic efficiencies at flying heights not more than 10% of the wing chord, measured from the horizontal ground to the trailing edge of the foil, demands sufficient stability and control to avoid unintended physical contact with the ground surface (Korolyov, 1998).

This proximity also complicates the equilibrium states necessary for stable operation, introducing the concept of an aerodynamic centre in height in addition to the more recognised and understood aerodynamic centre in pitch.

The mathematical approach for the determination of pitch and height stability for ground effect wings was begun by Kumar (1967) in his research at Cranfield College of Aeronautics, where the basic problem was framed and investigated. Independently, Irodov in U.S.S.R. and Staufenbiel and Kleinedam in Germany (Irodov 1974; Staufenbiel 1980) further developed the mathematical framework to investigate the longitudinal stability of WIG vehicles. It was shown that there is a change of pitching moment about the vessel centre of gravity with a change of height above ground, and what is termed a change in the position of the aerodynamic centre with height above ground.

Figure 1 shows a graphical representation of the necessary positions of the aerodynamic centres in pitch and height, and body centre of gravity for airborne stability near the ground. The implications of these relationships permeate every aspect of the WIG craft and must be thoroughly understood before any meaningful progress can be made toward its development.

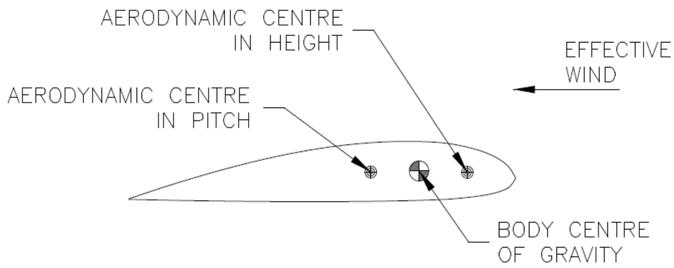

Figure 1: Critical positional relationship of aerodynamic and weight centres

Aerodynamic stability is clearly fundamental to the success of such a vehicle but is not limited to a singular ‘cruise-only’ design condition. Although aerodynamic forces may be negligible at lower, conventional marine craft speeds, analysis of the transitional regimes leading to and from the airborne condition indicate hydrodynamic forces are of the same order of magnitude as aerodynamic forces.

Collu, et al (2009) investigated the longitudinal stability of a generic AAMV configuration in a combined aero-hydro regime, and documented the third neutral point for this condition, called the hydrodynamic centre in heave, that should be considered in AAMV design. In order to have a static stability condition, this position should be downstream of the aerodynamic centre in height.

2.2 Aerodynamic efficiency

WIG craft aim to exploit the enhanced lift and reduced drag due to the ground effect, having the potential to be more efficient than an equivalent aircraft configuration flying out of ground effect, and at speed much higher than high speed marine vehicles.. However, the WIG craft designed to date have not been able to fully exploit this theoretical advantage, with reduced efficiencies often due to the inclusion of additional lifting and/or control surfaces and other required design compromises (Halloran and O’Meara, 1999; Rozhdestvensky, 2006).

Alternative configurations have been investigated to address the loss of aerodynamic efficiency, trying to utilise an overall configuration closer to the wing-body approach. A multihull superstructure can be shaped as an aerodynamic profile, in order to exploit the large area available between the hulls and increase the ground effect due to the hulls acting as end plates. Such approach was introduced with the 'Ekranocat' concept (Doctors 1997), where the effect of having aerodynamic lift sustaining a fraction of the vehicle weight was defined as 'aerodynamic alleviation'. Matveev and Dubrovsky (2007) presented a hybrid 1000t trimaran that comprises three wave-piercing planing hulls and a wing-shaped superstructure: based on numerical simulations and aerodynamic experimental data, this configuration seemed to be characterised by a high overall efficiency and good seaworthiness, at speeds about twice those of contemporary fast ferries and combat ships.

It is well known that aerodynamic performance characteristics are strongly influenced by the wing profile, aspect ratio, and the presence of other surfaces and geometric features. Increasing the aspect ratio is known to increase aerodynamic efficiency, although there are various factors limiting wing span in practice. Certain manoeuvres applicable to all WIGs, such as roll or banking in a turn, are limited by wing span and height above surface. Additionally some types of WIG rely on a dynamic air cushion under the main wing, where a more compact platform has been shown to be more effective (Yun et al. 2010). Furthermore, the span of the wing is also limited by the port facilities where the vehicle is intended to operate. Nevertheless, Kolyzaev et al (2000) maintain that aspect ratio demonstrates more influence upon aerodynamic characteristics than other geometric parameters.

Due to the stability requirements (section 2.1), many WIG configurations use a large horizontal surface as tail, and this additional element decreases the overall aerodynamic efficiency of the vehicle. In order to minimise the size of the tail, S-shaped profile families have been designed (e.g. DHMTU) specifically for WIG configurations. Another solution is to adopt a reverse delta configuration for the wing (Lippisch configuration). Despite the fact that an S-shaped aerodynamic profile and a reverse-delta wing plan area have a lower efficiency than a clean profile and plan area, they allow a substantial reduction of the tail horizontal area required, leading to an increased overall vehicle aerodynamic efficiency.

Another relatively unexplored area of research is the effect of a non-planar ground surface, with possibly lower lift forces generated and the resultant loss in aerodynamic efficiency (Rozhdestvensky 2006). Taking into account the occurrence of waves, any prospective AAMV should anticipate the periodic variation of lift generation.

2.3 Waterborne performance

As all marine WIG vessels operate directly from the water surface, and certainly cannot attain flight without lifting off from this surface, hydrodynamic performance characteristics play a critical role for overall vehicle success.

The high power required for take-off has proven to be one of the greatest impediments to the development of this type of vehicle (Rozdestvensky, 2006) as hydrodynamic resistance is the largest contributor to overall vessel drag during the transitional phases. This limits operation in increasing sea states and has often led to installed power in excess of cruise mode requirements.

High power requirements and peaks in the resistance curve as a vessel attempts to climb out of the water are not new phenomena, as naval architects have been successfully designing to overcome this 'hump speed' for more than half a century.

There have been a number of configurations particular to WIG craft that have originated with the intent of reducing hump drag. Examples include vessels with stepped planing hulls incorporated into the underside of their fuselage, hydrofoil appendages, power augmented ram (PAR) employing forward mounted thruster engines that direct their exhaust under the main wing, and dynamic air cushion (DAC) that use similar techniques as conventional surface effect ships to encapsulate the oncoming air and maintain a high pressure zone on the underside of a lifting surface as the vessel moves forward.

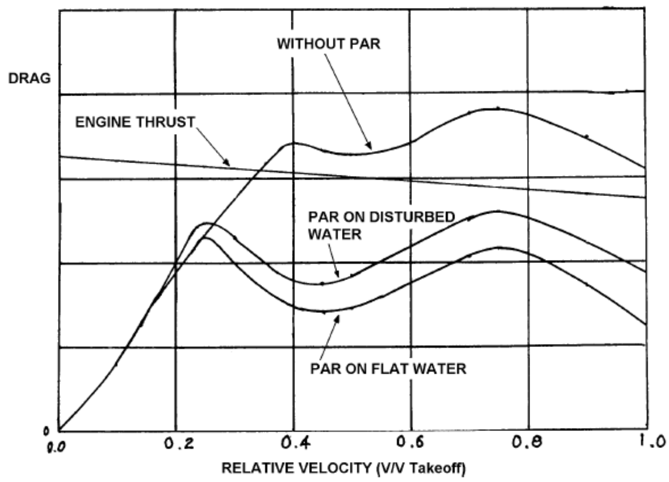

Figure 2. Ekranoplan-type WIG typical resistance curve with and without PAR (from Halloran & O'Meara, 1999)

The most prolific WIG test programme to date, organised in the former Soviet Union beginning in the 1960s, typically favoured the PARWIG design. The iconic images of the Caspian Sea Monster (KM), amongst others, clearly displays the 'bow thrusters' mounted far forward, just abaft the cockpit. These thrusters were throttled back to idle during airborne cruise as they were only required during the take-off phase.

Figure 2 shows representative resistance curves for aeroplane-derivative WIG designs, and the effective drag reduction when using the PAR technique. This data was compiled from recorded experiences with the Russian Navy. In spite of the disadvantages of installing these booster engines for the relatively short time spent in the take-off phase, the characteristic bow thrusters remained a hallmark of this type throughout their development (Komissarov and Gordon, 2010).

The exact differences between PARWIG and DACWIG remain opaque at times, but the fundamental concept of dynamic air injection is shared by both types. DAC is often understood to be more suitable for very small craft due to their ability to operate proportionately closer to the water surface. Derivatives of this type include craft that generate a static air cushion that permit hovering above the surface at a zero speed condition.

Hydrofoil assisted take-off has been tried a number of times but appears to have inherent limitations such as the onset of cavitation on the upper surface, additional mechanical complexity, and safety concerns at low altitude and negative angles of attack, rendering the technique less than ideal.

The majority of existing WIG designs utilise planing surfaces to reach the speeds required to initiate aerodynamic lift. Whilst this may be the simplest arrangement to incorporate into a prospective design, it has contributed to the difficulty of take-off in waves, often exacerbated by unfavourable running trim (see also section 3.2). The transitional phases of take-off and landing are frequently categorised as the most difficult part of WIG design, with sea state and environmental conditions given as primary factors (Yun et al, 2010); therefore performance improvements in this area would be of foremost importance for a new design concept.

2.4 Summary

There are clearly technical challenges to be resolved in order to utilise the aerodynamic forces generated by very high speed vessel operation. Longitudinal instability has often proved problematic in this speed regime, but there remains a promise to harness these forces to safely sustain the weight of the craft.

By equipping a vessel with aerodynamic lifting surfaces in order to alleviate its weight, a lower effective displacement can be achieved. This concept has been proven to function successfully, although there has been little mainstream interest in these craft.

There are several main families of WIG configurations, although none have shown themselves to be particularly suitable for operation as a full-time marine vehicle. Practically all of the WIGs to date have employed aircraft style wing and fuselage configurations and geometries, with varying degrees of success, but have inevitably not found favour as marine vehicles.

3 NOVEL HULLFORM CONCEPT FOR ENHANCED WATERBORNE PERFORMANCE

3.1 AAMV, a different WIG concept

Existing WIG marine vehicles are typically fixed-wing aeroplane derivative craft that utilise the water surface simply for the take-off and landing phases, as such they tend to possess no particular seakeeping ability or load carrying capacity beyond a few seated passengers. This is fundamentally opposed to the concept of the AAMV, which aims to deliver typical marine vehicle capability, in addition to extreme waterborne speeds characterised by $Fn_L > 2$.

The hybrid AAMV concept offers unique capabilities in a variety of applications ranging from commercial or military transport vessels to fast ferries and yachts. An application that has shown immediate potential is that of fast crew transport vessel for offshore windfarms or oil and gas platforms, as a lower cost, higher payload alternative to the helicopters presently used.

The water surface has historically been an obvious place to launch aircraft, eliminating the need to build runways, providing a flat surface (when calm) with few obstructions. An entire class of fixed-wing aircraft known as seaplanes, including floatplanes and flying boats, evolved and thrived with the need to travel and land in austere ports, until around the post-war period of the last century.

Therefore, seaplane floats were an initial source of investigation. Unfortunately, there are a number of drawbacks and design considerations not applicable to the AAMV design, such that their usefulness would be quite limited for this application. Typically floats could be positioned wherever dictated by other parameters laid down during the aerodynamic design of an aircraft, possibly even retrofitted or included as an afterthought. Floats simply need to allow the craft to achieve speeds and rotation angles necessary for take-off and landing, once the basic hydrostatic criteria have been satisfied. Manoeuvrability is generally quite limited on the surface, and any level of seaworthiness beyond the taxiing phase is often not required. Fuel efficient operation at lower speeds would be quite poor, primarily due to the high drag of chines, transverse and steps tapered aft sections (Faltinsen, 2005).

3.2 Rationale behind the novel hullform

The attainment of sufficiently high speeds for waterborne take-off has typically been achieved through the use of recognisably standard hard-chine, hydrodynamically planing hullforms faired into the underside of the main fuselage. There are several significant disadvantages of this method, briefly described as follows.

- The overall dimensions of the planing surface must conform to the vessel geometry, most notably the longitudinal aspect ratio (length over breadth) must lie within the constraints of the fuselage dimensions, which may be sized according to other criteria of the design envelope, e.g. minimisation of aerodynamic parasitic drag.
- The longitudinal centre of mass (LCG) must be precisely located for stable WIG operation, although that position is typically much further forward than the location most suitable for planing craft. This could result in excessively high hydrodynamic resistance as the vessel fails to adopt the attitude required to achieve planing efficiencies realised by marine-only vessels.
- Hydrodynamic resistance of beamier geometries can be very high prior to reaching the planing condition, often requiring higher powering configurations to be installed than would be necessary during an efficient cruise condition or any other point of the operational profile. This power is needed to overcome the so-called 'hump drag'.
- Extreme accelerations resulting from slamming and wave impact of the planing hull has been well documented. This has led to structural failures, increase of scantling and structural weights, debilitating injuries to personnel and chronic fatigue to operators and crew. Increase of deadrise is the standard method of reducing these slam-induced pressures, although at the cost of reduced efficiency.
- The planing hullform is also very inefficient at lower speeds of the displacement and semi-displacement regimes, with resultant powering requirements far in excess of specifically designed vessels operating at similar speeds.

In addition to resistance penalties, a coupled longitudinal-transverse instability phenomenon has been reported for planing hullforms with unusually far forward centres of gravity. The vessel may attain stable equilibrium on-plane in a normal manner, before experiencing a sudden decrease in the running trim angle, whereby the fullness of the bow sections tend to initiate a roll and/or yaw response. This is not presently a well understood problem (Savitsky, 1985).

These factors indicate an alternative hullform would be desirable, one that could accommodate a centre of gravity further forward than typically found, but also one that allows that vessel to achieve the required waterborne speeds. Therefore, a design brief with the following characteristics was laid out:

1. Must be able to carry a centre of mass (and therefore centre of buoyancy) around amidships, defined as LCG/LOA = 0.5.
2. Must be suitably shaped to allow high speed operation without excessive powering or undesirable behavioural characteristics, e.g. submarining, yaw instability, excessive slamming, etc.
3. Would ideally offer low speed resistance, as defined by $Fn_L < 1.0$, similar to conventional efficient semi-displacement hullforms.

Additionally, the hull would have to retain its desirable characteristics at various drafts, as the vessel will experience vertical translation (heave) as the aerodynamic lift forces generated by the wing increase.

In contrast to conventional planing hulls, where it is common practice to maintain the longitudinal sections straight and flat throughout the after part, significant rocker was introduced along the entire length of the keel. It was thought that a bow up trimming moment caused by hydrodynamic pressures aft may well be advantageous aerodynamically to increase angle of attack on the wing and initiate the weight unloading process, albeit at the risk of inducing downward hydrodynamic suction force.

Once a trim angle of approximately 3° is reached with the bow clear of the water, the buttock lines become effectively flat. Instead of the deeply veed forward sections of conventional planing hulls, the enclosed volumes are inverted, i.e. somewhat flat-bottomed with finer angles topside on the reverse stem, with cutaway forefoot and foredeck in profile. Figure 3 shows a representative lines plan for a hull with these characteristics.

The LCB was situated at 0.5 LWL for the static design draft condition, with the transverse sections configured so this centroid moves forward gradually as the vessels rises bodily. As the location of the centre of mass is not expected to shift significantly during take-off or landing phases, this misalignment of longitudinal centres should increase the bow-up trimming moment, likely to be favourable for the aerodynamic configuration.

Design ratios such as length over volume and length to beam ratio were selected to be representative of suitable values, without particular optimisation for a specific design or other criteria.

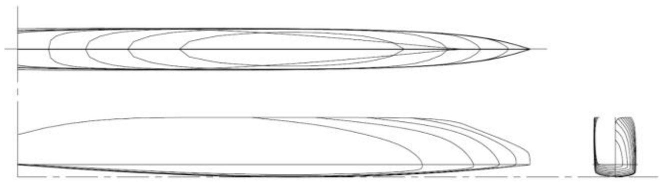

Figure 3: Representative lines plan showing plan, profile and body plan views

3.3 Experimental test

3.3.1 Rationale

In 2006, a research program aiming at investigating AAMV configurations was initiated at Cranfield University, focusing on the estimation of the loads and the vehicle dynamics during the high speed waterborne phases, when hydrodynamic and aerodynamic forces of the same order of magnitude can occur (Collu, 2008). Among the results, a concept configuration characterised by very high lift-to-drag ratios has been defined (Williams et al. 2010), and a model of dynamics specific for this configuration has been developed, deriving a novel static stability criteria (Collu et al. 2009).

The model of dynamics consists of two parts: a system of equations of equilibrium, used to estimate the equilibrium attitude of the AAMV configuration, and a system of equations of motion, used to estimate the dynamic response (modes of oscillation) of the vehicle.

As regards the equilibrium model, the aerodynamic forces are calculated estimating the angle of attack and distance from the ground of the aerodynamic surface, then interpolating the values of the provided aerodynamic coefficient database to obtain the lift, drag and pitching moment at that angle of attack and height above surface.

Hydrostatic and hydrodynamic forces are obtained using a Savitsky approach for a prismatic planing surface (Savitsky 1964), modified to take into account the influence of the aerodynamic forces and moments on the equilibrium (Collu 2008). Due to the limitations of the Savitsky approach, it would be difficult to estimate the hydrodynamic forces for the present configuration, therefore it was decided to determine the required coefficients experimentally.

The net forces can be estimated by calculating the alleviated displacement (equal to the vehicle displacement minus the aerodynamic lift) and the trim angle, and then interpolating between the measured hydrodynamic resistance and moment coefficients for a particular equilibrium state.

For a given hull, it is then necessary to build a database of drag and moment coefficients, having as input the alleviated displacement and the trim angle, in function of the Froude number. This approach is similar to the one adopted by NACA (now NASA) to experimentally test seaplane hulls (Parkinson and House, 1938).

The present experiment was carried out to obtain this data for the particular hullform considered.

3.3.2 *Experimental protocol*

A model of 3 m LOA was constructed in the Ocean Laboratory workshop of glass reinforced plastic (GRP) over a CNC milled foam core; hand laid, vacuum bagged, and resin infused. The laminate schedule consisted of 2-4 plies (dependent on location) of 300 gsm E-glass in a 2/2 twill weave. Before lamination, a mounting plate was recessed into the deck amidships, bonded in and glassed over. The surface was finished to an approximate average roughness of 0.4 micron (240 grit sandpaper) and finished with a high gloss enamel coating.

For the initial tests it was decided to use a fully constrained towed rig, with the model positioned precisely to replicate specific displacement and trim combinations. The resulting forces and moments imposed on the model were measured to a calibrated accuracy of 0.75 N and 0.05 Nm respectively, using a six-axis force/torque transducer. Test runs were carried out in calm water at carriage speeds ranging from 1 m/s to 12 m/s.

The testing programme matrix included four displacement conditions (with corresponding heights above datum) and three trim angles: 0°, 3°, 6° bow up. Multiple speed runs were carried out to assess the conditions most likely to be seen by each of the combinations. Ten unique configurations were tested in total. The model was designed to be suitable for scale factors between 5 and 10. Depending on the scale selected, the corresponding maximum full-size speeds tested would be between 52 kt and 74 kt.

For this paper, the results of the trimmed conditions have no particular importance as these would not be natural angles developed without the interaction of the aerodynamic wing. The actual attitude, or running trim, of the completed vehicle would be a function of wing size, orientation and location, in addition to the hydrodynamic components.

The tests were undertaken in April 2014 in the towing tank in Qinetiq-Haslar, as this facility features one of the highest towing carriage speeds currently available. The tank dimensions are 271 m long, 12.2 m wide and 5.5 m deep. The sampling frequency of 100 Hz allowed sufficient data to be collected at the maximum towing velocity and permissible acceleration/deceleration.

Prediction of total free body resistance for the model configuration in the tested speed regimes was estimated prior to testing to be used as a form of comparative benchmark. The estimate was based upon slender body theory, characterised as a first principles potential flow approach to predict the far-field wave pattern. The contribution of viscous effects was estimated using a form factor multiplier on the frictional resistance of the static wetted surface area, as documented in the ITTC 1957 method. Although this form factor can be shown to vary with increasing speed, careful selection of a single average value for the entire range was expected to have a maximum error of +/-5% (Molland et al, 1994).

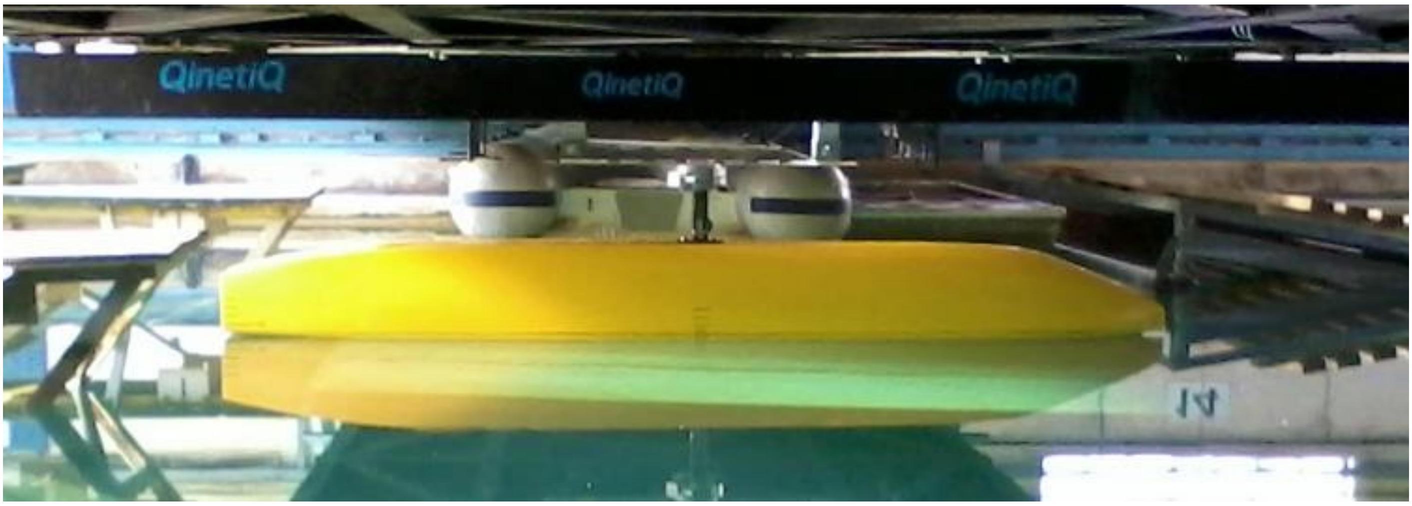

Figure 4. Model in the towing tank in preparation for testing

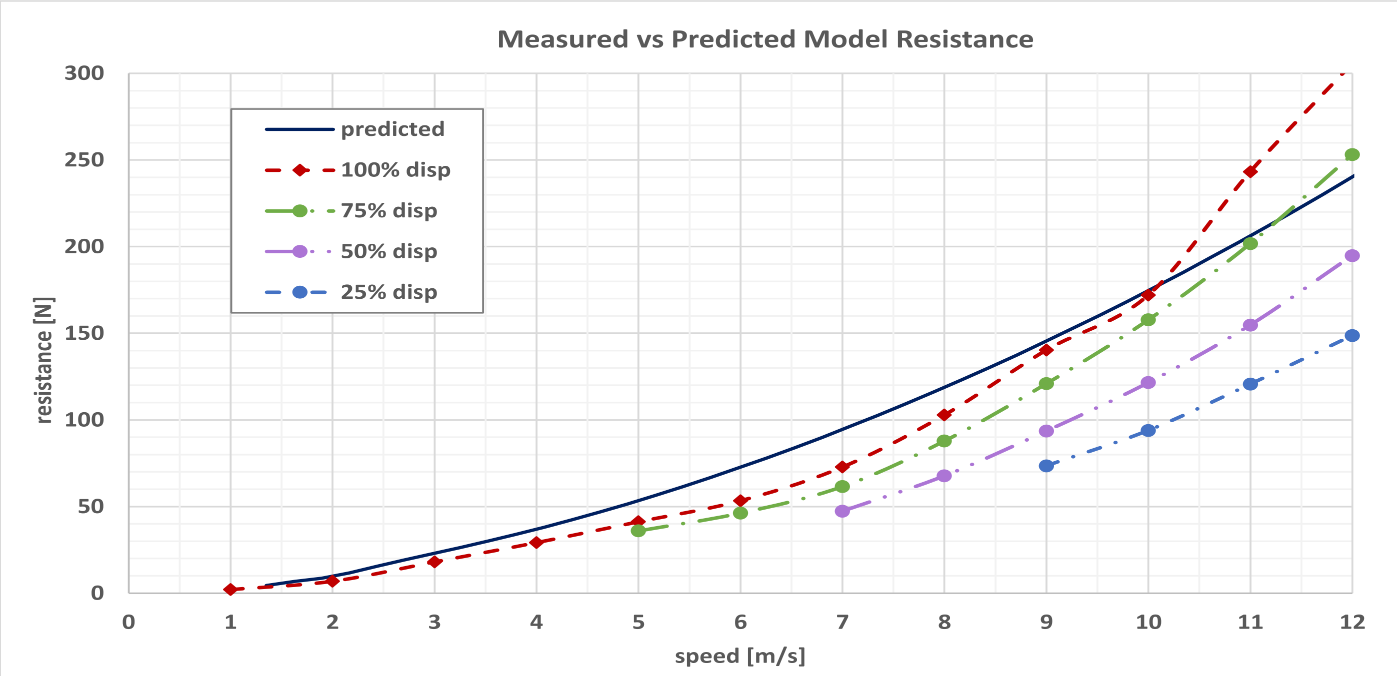

Figure 5. Preliminary results of the even keel performance at four displacements

3.4 Discussion

Preliminary results of the level trim resistance tests is shown in figure 5, along with the nominal prediction line for the full displacement condition. The model appears to perform slightly better than expected at lower speeds before a rapid drag increase around 9 m/s, however as the bodily sinkage was fully constrained it is likely a free body test would demonstrate a heavier effective displacement and higher drag values.

There was no attempt to install spray rails or any other method for the reduction of side wetting. Images and video from the tests show considerable rise of the bow wave up the topsides at many of the higher speeds. The control of the side wetting in future test would be expected to reduce skin friction drag and provide additional lift.

The curves represent the four tested displacement conditions, in order to represent stages of weight unloading experienced during a take-off procedure. The lower part of the speed range is where the vessel would be entirely hydrostatically and then hydrodynamically supported. As forward speed increases, aerodynamic alleviation of the vessel weight would occur, effectively reducing the displacement.

The upper part of the speed range would correspond to conditions where aerodynamic lift is significant, with the result that the predicted drag would effectively skip to the next curve, representative of the newly unloaded condition. For a given power, the ongoing lowering of hydrodynamic resistance should allow the craft to accelerate rapidly, further generating aerodynamic lift until water contact diminishes entirely at lift-off.

As the vessel was constrained in pitch and heave, the results cannot be taken as a definitive representation of the vessel free body performance, but would form the basis of a future testing programme.

4 CONCLUSIONS AND FUTURE WORK

The article has documented some of the main technical challenges still complicating the design and development of WIG marine vehicles, focusing on stability, aerodynamic efficiency, and waterborne performance. The dynamics of an AAMV configuration (and other WIG craft) need further theoretical, numerical and experimental validation, especially for the high speed waterborne phases. Linked to this, the WIG configurations adopted so far have an aerodynamic efficiency substantially lower than the potential one ‘promised’ by the ground effect phenomenon. Furthermore, WIG craft developed to date have typically been fixed-wing aeroplane derivative craft that utilise the water surface simply for the take-off and landing phases; as such they tend to possess no particular seakeeping ability or load carrying capacity beyond a few seated passengers, and they are also characterised by high hydrodynamic drag, especially at take-off speed.

In order to tackle this last challenge, the present work focuses on specific considerations in the design of a suitable hullform for an AAMV configuration. In many current and past WIG craft, aerodynamic aspects have governed the design, centred on the airborne cruise condition, leading to poor resistance and manoeuvrability characteristics during waterborne operation. A true AAMV needs to be fully operational as a marine vehicle, something that existing aero-derivative designs have not been able to achieve.

An experimental hullform has been developed and initially tested for suitability in this challenging environment. A thorough testing programme would be required, including both calm water and in waves, before definite conclusions could be presented about the suitability of this hull shape.

5 ACKNOWLEDGEMENTS

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