

The Potential of Seaplanes as Future Large Airliners

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Abstract

Ever stricter environmental pollution and noise constraints are posing a barrier to the expansion of many already constrained major airports. This paper proposes that seaplanes can be used for long range airline operations, moving low level flightpaths of large aircraft offshore. A novel configuration aimed at alleviating the various drawbacks seen in past seaplane designs is presented and discussed. A complete design framework for the design of modern seaplanes is presented, concentrating on novel methods developed for the design of seaplanes to a takeoff distance constraint. A family of sample aircraft designed to transport between 200 and 2000 passengers is presented and common performance characteristics observed are discussed.

Nomenclature

$\mathcal{R}$	wing aspect ratio
ASK	air seat kilometre
B	beam width
BPR	turbofan bypass ratio
C_{D_o}	zero-lift drag coefficient
C_L	lift coefficient
$C_{L_{max}}$	maximum lift coefficient
C_V	velocity coefficient
C_Δ	beam loading
e	Oswald efficiency factor
g	acceleration of gravity
dh/dt	climb/descent rate
h_{OBS}	obstacle height
L/B	hull length to beam ratio

L_f/B	hull forebody length to beam ratio
L/D	lift to drag ratio
N_e	number of engines
q_∞	freestream dynamic head
T/W	thrust to weight ratio
$\bar{T}/W$	mean takeoff thrust to weight ratio
V_∞	freestream velocity
V_{appr}	design approach speed
V_R	takeoff rotation speed
W/S	wing loading
W_L/W_o	landing to takeoff weight fraction
β	hull deadrise angle
Δ	aircraft load on water
ρ	density of air
ρ_w	density of water
σ	atmospheric density ratio

1 Introduction

Aviation business forecasts continue to predict a substantial increase in global air traffic, while the aviation industry is under ever increasing pressure to reduce noise and emissions. In fact concerns about noise and atmospheric pollution in areas surrounding major airports are already affecting the capacity and expansion potential of existing airports, at a time when many major hubs are already operating at maximum capacity.

One approach to reducing the impact of aviation on populated areas is moving major airports offshore, thus also moving takeoff and approach paths over water. Such concerns, combined with limited land being available for the expansion of some aerodromes near large cities, have led to the construction of offshore airports such as Kansai International and Hong Kong International and the proposal for an airport in the Thames Estuary. Land reclamation however, combined with the need for new termi-

nal buildings and runways to be constructed, is extremely expensive with all three of these projects costing or expected to cost in excess of \$20 billion.

A radical alternative that would negate the need for such extreme infrastructure expenditure would see the use of waterborne aircraft for long haul flights. This transition could be possible if seaplanes are used for hub-to-hub traffic with connecting journeys to smaller inland airports on amphibian or conventional design regional aircraft. Figure 1 illustrates that 16 of the 32 major worldwide airline hubs are already situated in a coastal area, while another 8 are within 50 miles of the coast facilitating passenger transit, making such a move feasible.

Another potential advantage of not operating from paved runways is that seaplanes operating between major seaports could be designed and optimised for much higher passenger capacities than currently possible, reducing the number of trips required to carry a given number of passengers. Furthermore should demand for any particular destination increase, the airport will not be constrained by the number of available paved runways reducing the cost of expansion.

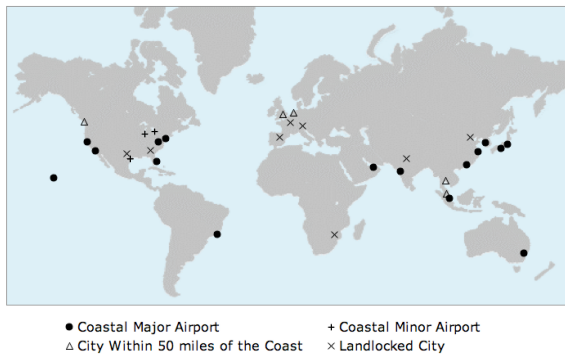


Figure 1: Proximity of major airline hubs to the coast

The major obstacle to the adoption of waterborne aircraft however is the efficiency penalty that has historically been associated with operating from water. The work presented in this paper therefore aimed at investigating the viability of seaplanes as a 21st century mode of transport by developing a design framework to allow their rapid sizing and performance prediction. A novel aircraft configuration aimed at addressing past seaplane shortfalls is presented

followed by novel methodologies developed for the initial sizing of water-borne aircraft. The overall design framework is briefly presented, followed by a discussion of the predicted performance of a family of sample aircraft.

2 Formulation of a Future Seaplane Concept

In order for the use of water-borne aircraft to be viable, levels of fuel efficiency comparable to those of current or future generation aircraft should be achievable. This is achieved by selecting a configuration that maximises lift to drag ratio (L/D), minimises structural weight and features more fuel efficient engines, while allowing the aircraft to operate from water and exhibit both good seaworthiness and airworthiness characteristics.

Seaplanes of conventional design suffer from increased drag and structural weight due to the need for the fuselage to be shaped and reinforced for water-borne operations. A V-shaped hull is necessary to provide good running characteristics on water, while reducing the significant impact loads encountered when landing. Non-circular hulls with sharp edges however lead to a substantial increase in fuselage drag, both as a result of increased surface area and interference drag. The fuselage pressure drag is further increased by the use of steps, vertical discontinuities on the hull surface aimed at negating hydrodynamic suction at high speeds and allowing the aircraft to plane. Stinton [1] indicates that using a V-shaped underside results in a 9-10% increase in fuselage drag, while the addition of a normal step further increases drag by 20-38%. Another design characteristic unique to seaplanes is the need for tip floats, used to ensure the aircraft is laterally stable on the water surface, which add further structural weight and increase the aircraft's drag.

These unwanted side effects of designing aircraft capable of operating from water can be alleviated by opting for a Blended Wing Body (BWB) configuration. Blending the hull with the aircraft's centre section does not severely affect the centre-body's streamlined design, thus improving the aircraft's aerodynamic efficiency by reducing both wetted area and interference drag. To reduce the level of drag

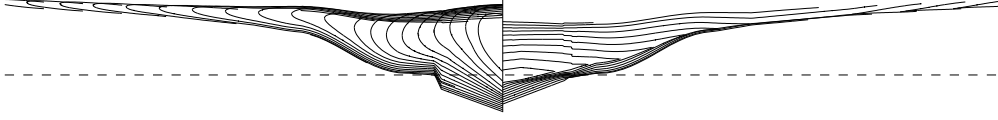


Figure 3: Hull lines of the baseline aircraft

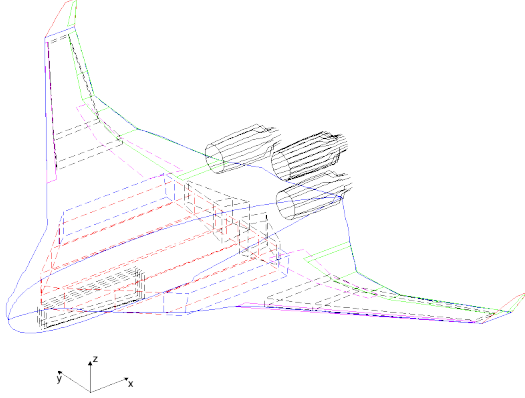


Figure 2: Isometric view of the baseline aircraft showing the placement of major systems. Passenger cabin shown as dashed red, cargo bays as dashed blue and fuel tanks as dashed black lines

resulting from flow separating at the step during flight a 9:1 straight fairing will be used, as wind tunnel tests [2] have shown it can reduce the drag contribution of the step by up to 80% at high Reynolds numbers. Despite these improvements however, the underside of the airfoil sections used for the centre-body, as seen in Fig. 4, must be altered substantially to incorporate the hull step (or its fairing) and afterbody geometry, resulting in a moderate amount of negative camber. Further improvements relative to seaplanes of conventional design, should arise from the reduced structural weight of the aircraft exhibited by past BWB design studies.

The section of the wing just outboard of the hull will be clear of the water at maximum draught, thus not adversely affecting the aircraft's resistance when on water. As seen in previous designs such as the Vultee Skate and the Beriev Be-103 this section will further act as a sponson, improving lateral stability on the water and eliminating the need for tip floats. Figure 2 illustrates the general layout of the baseline aircraft, indicating that passengers and/or payload will be housed above hull and

in this first outboard wing section, the span of which is determined by both volume and water-borne stability requirements. In order for the wing further outboard to be optimised for cruise and its structural weight to be minimised it will be kept clear of water at all times by using varying levels of dihedral, as seen in Fig. 3. In cases where the centre section thickness is not large enough, this may result in a gull wing design. The high position of the wing is also advantageous in allowing emergency exits to be placed not only along the leading edge but also along the side of the aircraft, addressing a longstanding issue with BWB designs. This heavy dihedral, combined with the use of tip fins and the aft sweep of the aircraft, aimed at allowing efficient cruising in the transonic regime, should further act to improve the aircraft's lateral stability characteristics in flight, negating the need for a vertical stabiliser.

Unlike most past seaplane designs, this aircraft is expected to fly at transonic speed and therefore high bypass ratio turbofans or propfans will be used as they operate optimally in those conditions, minimizing the powerplant's specific fuel consumption and therefore improving overall flight efficiency. The engines will be mounted on top of the aircraft centre section, close to the trailing edge, thus shielding them

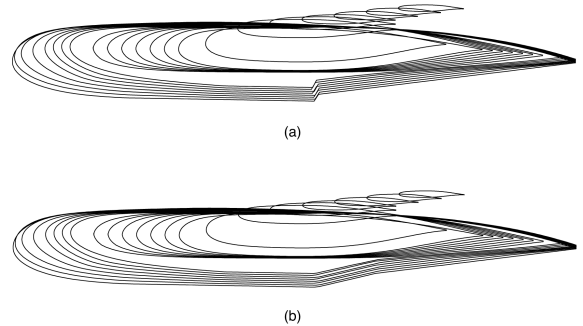


Figure 4: Spanwise variation of airfoil sections (a) with and (b) without fairing

from spay and attenuating the level of noise reaching the surface during take off or landing. Due to the lack of a horizontal stabiliser, only leading edge high lift devices (slats) will be utilised, providing a moderate increase in stall angle of attack and maximum lift coefficient during takeoff and landing. To effectively control a tailless aircraft in pitch elevators must cover much of the trailing edge, while elevons/drag rudders situated near the wing tips are used to control the aircraft in roll and yaw.

3 Sizing to Constraints

The aircraft wing and powerplant are the first to be sized in the design process, considering the performance objectives that the aircraft must meet. As with the sizing of conventional aircraft, thrust matching constraints are set for the various cruise segments, as well as the the desired maximum airspeed and ceiling. Equation (1) is also used to ensure that the critical flight phase minimum climb gradient requirements detailed in FAR-25 are met, where extension of the step fairing explained in section 2 is considered equivalent to retracting the undercarriage.

$$\frac{T}{W} = \frac{dh/dt}{V_\infty} + \frac{q_\infty C_{D0}}{W/S} + \frac{W/S}{q_\infty \pi Re} \quad (1)$$

Ensuring that the aircraft can takeoff or land within a given distance may not seem relevant to the design of seaplanes, as the constraint of a paved runway no longer exists. That may indeed be the case if operating from open water but coastal areas are often congested and it is fair to assume that seaplanes will be operating from some predefined area, kept off limits to maritime traffic in the interest of safety. Moreover, even if the use of takeoff distance constraints is not considered necessary, takeoffs from a rough surface could be uncomfortable for passengers and therefore setting a maximum time to liftoff can serve to limit that discomfort.

No further consideration is given to the landing distance constraint as in the case of seaplanes, the high levels of hydrodynamic resis-

tance ensure that landing distances are almost always lower than the takeoff distance required.

For conventional aircraft operating from hard or soft surfaces, the takeoff distance has been empirically found to be a linear function of the takeoff Parameter (TOP), given by

$$S_{TO} = A \cdot TOP = A \cdot \frac{W/S}{\sigma C_{L_{max}}(T/W)} \quad (2)$$

where A is determined from analysis of past aircraft designs. This approach is widely used in the initial sizing stage to determine field length constraints, however the takeoff distance is simply related to the aircraft stall speed and the amount of power available while all other contributing parameters such as aerodynamic drag and rolling friction are averaged across all types of aircraft. A more detailed approach to implementing the takeoff distance to obstacle height constraint is given by Torenbeek [3] as the sum of the ground and airborne takeoff distances:

$$S_{TO} = \frac{9.34 \times 10^{-4} W/S}{\rho [C_{L_{max}}(\bar{T}/W - \mu) - 0.72 C_{D_o}]} + \frac{h_{OBS}}{\tan |0.9 \bar{T}/W - 0.3/\sqrt{Re}|} \quad (3)$$

where the average thrust produced by a turbofan engine during takeoff is empirically given as:

$$\bar{T}/W = 0.75 \left(\frac{5 + BPR}{4 + BPR} \right) \left(\frac{T}{W} \right)_o \quad (4)$$

This method was found to produce reasonable results if a value of the rolling resistance (μ), or in this case a measure of the mean hydrodynamic resistance to weight ratio, in the range of 0.15-0.25 was used. There is however no consistent way of relating the value of μ to be used to the hull's major hydrodynamic design characteristics. Consequently a new method for rapidly predicting the takeoff distance of seaplanes during initial sizing, based on the aircraft's aerodynamic, propulsive and hydrodynamic characteristics, is needed.

In the absence of consistent data for the takeoff performance of existing seaplane designs or a large enough sample size, takeoff simulations were carried out utilising hydrodynamic resistance and trim data originating from towing tank tests of 78 distinct hull shapes reported

by NACA. Based on the method presented by Torenbeek [3], the takeoff distance with All Engines Operating (AEO) is given as the sum of the ground roll, rotation and climb segments. The analysis for the rotation and climb segments is unchanged in the case of seaplanes. The distance travelled on the water surface to accelerate to the rotation speed (V_R) is given by:

$$S_{TOW} = \frac{1}{2g} \int_0^{V_R} \frac{dV^2}{a/g}. \quad (5)$$

Considering the sum of forces acting on the body, the instantaneous acceleration at a velocity V is given by

$$\frac{a}{g} = \frac{T}{W} - \frac{R}{\Delta} - \frac{\rho V^2}{2} \left(\frac{C_{D_o} + \frac{C_L^2}{\pi \mathcal{R} e} - C_L \frac{R}{\Delta}}{W/S} \right) \quad (6)$$

where R/Δ is the hull's resistance to load ratio, as determined for a velocity V and hull load $\Delta = W - 0.5\rho V^2 C_L S$.

To account for the effects of the aircraft's size and its aerodynamic and propulsive characteristics, 250 distinct, random aircraft were generated for each hull shape. The aircraft maximum lift coefficient ($C_{L_{max}}$), zero lift drag coefficient (C_{D_o}), Oswald efficiency (e) and aspect ratio ($\mathcal{R}$) were chosen at random from the range of values seen in Table 1. Similarly the number of engines (N_e) and mean aircraft thrust to weight ratio ($\bar{T}/W$) were randomly set, with the available thrust assumed constant and equal to this mean value throughout the takeoff manoeuvre. The choice of hull size, typically expressed in terms of the hull maximum width or beam (B), wing loading and takeoff weight was constrained by the availability of tank test data.

Hydrodynamic test results are commonly presented as plots of resistance (R) at the equilibrium trim angle versus velocity coefficient (C_V) for a range of aircraft beam loading coefficients (C_Δ), similar to Fig. 5. The use of non dimensional variables to relate the resistance to velocity, weight and hull size is necessary so that both geometric and dynamic similarity are maintained when using scale model data to predict the behaviour of a full size hull. The

	Range			Units
$C_{L_{max}}$	1.8	-	2.8	
$\bar{T}/S$	400	-	7800	Nm^{-2}
$\bar{T}/W$	0.2	-	0.6	
ρ	1.10	-	1.27	$kg \cdot m^{-3}$
C_{D_o}	0.01	-	0.03	
$\mathcal{R}$	5.0	-	12.0	
e	0.75	-	0.85	
N_{eng}	2	-	6	
C_{Δ_o}	0.3	-	1.3	
β	10	-	30	deg.
L/B	4.5	-	10.8	
L_f/B	2.3	-	5.8	

Table 1: Range of values used for aircraft characteristics in takeoff analysis

beam loading, given by

$$C_\Delta = \frac{\Delta}{g\rho_w B^3} = \frac{W - 0.5\rho V^2 C_L S}{g\rho_w B^3}, \quad (7)$$

gives the ratio of the hull load to its size. It is a good measure of the draught of the aircraft and therefore the frictional resistance experienced in the displacement regime (low speeds), while also indicating the level of hydrodynamic lift produced and therefore lift induced resistance in the planing regime (higher speeds). The velocity coefficient, given by

$$C_V = \frac{V}{\sqrt{gB}} \quad (8)$$

is a variation of the Froude number, a dimensionless number used to represent the ratio of inertial to gravitation forces, which also ensures similarity for the wave making characteristics of a hull. Due to the size of the models and the need to maintain C_V and C_Δ constant across scales, the Reynolds number could not be kept constant, possibly leading to an over prediction of the frictional components of hydrodynamic resistance.

Based on the range of C_Δ and C_V for which resistance data were available for each hull, a value for the aircraft beam loading at rest (C_{Δ_o}) is chosen. A second point at a non-zero speed coefficient and lower C_Δ is then chosen to represent the point of rotation and a mean value for the aircraft lift coefficient ($\bar{C}_L$), such

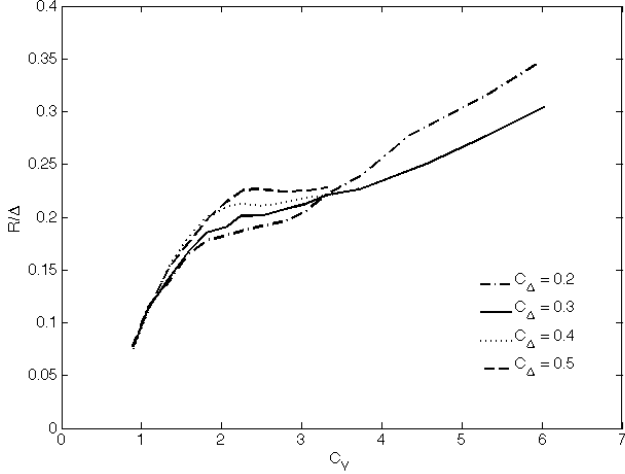


Figure 5: Trimmed Resistance to Weight (R/Δ) ratio of the NACA 47 hull [4] for varying speed (C_V) and loads (C_Δ)

that

$$C_\Delta = C_{\Delta_o} \left(1 - \frac{\rho g B C_{V_R}^2 \overline{C_L}}{2W/S} \right) \quad (9)$$

$$C_{V_R} = \frac{V_R}{\sqrt{gB}} \quad (10)$$

where V_R is the velocity at which the aircraft rotates for takeoff. This is determined based on the assumed aircraft $C_{L_{max}}$ and wing loading by analysing the rotation and climb segments of the takeoff manoeuvre using the methods given by Perry [5]. The aircraft beam and mean lift coefficient can then be calculated using equations (9) and (10).

Using a mean value for the lift coefficient is not strictly accurate, as the actual aircraft trim angle and therefore C_L will vary with velocity when taking off from water, with the aircraft operating at substantially higher angles when transitioning from the displacement to the planing regime. This simplification however is necessary as the majority of datasets available assume a constant value of C_L . Moreover the equilibrium trim angles given ignore the effects of the moments imparted by the aircraft's aerodynamic surfaces and propulsive units and are therefore somewhat higher than would ultimately be observed.

The simulation results were statistically analysed to determine the hull shape parameters that most affected the takeoff performance

of the aircraft. In addition to the beam loading at rest, the hull deadrise angle (β), representing how deep the hull V-shape is, and hull length to beam ratio were found to best correlate with the simulation results. Based on these observations, a simple takeoff run distance prediction model (11) was produced, the coefficients for which can be found in table 2. The total takeoff distance to a given obstacle height can be found by combining (11) with (12).

$$\frac{W/S}{S_{TOW}} = \rho C_{L_{max}} \left[a_1 \frac{\overline{T}}{W} + a_2 \left(\frac{\overline{T}}{W} \right)^2 + a_3 \frac{L_f}{B} + \frac{a_4}{\cos \beta} + a_5 C_{\Delta_o} + a_6 \right] + a_7 \rho C_{D_o} + a_8 \quad (11)$$

$$S_{TO} = S_{TOW} + \frac{h_{OBS}}{\tan \left| 0.9 \frac{\overline{T}}{W} - \frac{0.3}{\sqrt{R}} \right|} \quad (12)$$

a_1	12.54183	a_5	-0.10521
a_2	-6.77017	a_6	-1.42082
a_3	0.08270	a_7	-3.73432
a_4	-0.90283	a_8	0.28393

Table 2: Constants for estimation of water borne takeoff distance using eq. (11)

The simplified model behaves in a similar way to (3) but the mean resistance has been substituted by hull design parameters. The model agrees with past experience from tank tests, showing that a reduction in deadrise and beam loading or an increase in body fineness, represented by the ratio of the length of the body forward of the step (L_f) to the beam, will reduce hydrodynamic resistance and therefore the takeoff run. A more unusual behaviour is the quadratic nature of the thrust term, showing that at high Thrust to Weight ratios, increasing the available thrust has a diminishing impact on the takeoff distance.

From existing airworthiness directives it is not clear if the accelerate/stop distance sizing requirement applies to water borne aircraft, however to account for cases where the seaplane landing area has hard boundaries, such as wave breakers, the balanced field length (BFL) of a

seaplane was also determined. This was done in the same way as for the AEO takeoff distance, however at some velocity below the rotation speed a single engine failure was assumed. The velocity at which failure occurred was then varied until the distance required for the aircraft to come to a full stop and that required for it to clear a 35ft obstacle were equal. For a worst case scenario to be designed for, the use of thrust reversal, spoilers and hydrodynamic braking systems is not considered.

$$\frac{W/S}{BFL} = \rho \left\{ C_{L_{max}} \left[b_1 \frac{\bar{T}}{W} + b_2 \left(\frac{\bar{T}}{W} \right)^2 + b_3 \frac{\bar{T}}{W} \frac{N_e - 1}{N_e} + b_4 \frac{N_e - 1}{N_e} + b_5 \frac{L}{B} + \frac{b_6}{\cos \beta} + b_7 \frac{N_e - 1}{N_e C_{\Delta o}} + b_8 \right] + b_9 C_{D_o} \right\} + b_{10} C_{\Delta o} + b_{11} \quad (13)$$

b_1	7.15099	b_7	0.10283
b_2	-5.49267	b_8	-0.85773
b_3	3.07740	b_9	-3.088908
b_4	0.07182	b_{10}	0.76658
b_5	-0.04534	b_{11}	-0.083248
b_6	-0.74138		

Table 3: Constants for estimation of takeoff Balanced Field Length using eq. (13)

The BFL model (13) shows a reliance on the common aerodynamic or propulsive design parameters similar to the surface distance relation for normal takeoffs derived previously. The number of engines however now combines with the available thrust to penalise the BFL for the thrust lost following an engine failure. The effect of the hydrodynamic design of the hull shows some differences to the AEO takeoff distance. The deadrise angle has the same effect as for AEO but the beam loading and hull fineness, in this case best represented by the length to beam ratio (L/B), show the reverse effect. This is attributed to the assumption that the hull hydrodynamic resistance is the only decelerating force applied to the aircraft in case of an aborted takeoff and therefore the higher L/B and the lower $C_{\Delta o}$ are, the lower the hydrodynamic resistance will be,

substantially increasing the stop distance.

To validate the accuracy of the methods presented, the reported takeoff performance of existing seaplanes was compared to that predicted by equation (12). The geometric, propulsive and aerodynamic characteristics of the sample aircraft were approximated as closely as possible based on reported specifications, drawings and rough calculations. As seen in table 4, equation (12) can predict the takeoff distances to within $\pm 12\%$, a reasonable margin of error for an initial sizing methodology.

Validating the BFL model from a large number of sample aircraft was not possible, however the accelerate/stop distance for the Canadair CL-215 was estimated to be 1860 m, compared to a quoted distance of 1920 m [6], an underestimation of 3%.

The final constraint is the aircraft approach speed and consequently its stall speed in the landing configuration. For conventional airliners the approach speed is usually around 130-140 kts to ensure the aircraft is travelling slow enough for the pilot to have adequate control and time to react during this critical flight phase, thus setting a maximum wing loading constraint.

$$\left(\frac{W}{S} \right)_{max} = \frac{\rho V_{appr}^2 C_{L_{max}}}{3.38 (W_L/W_o)_{max}} \quad (14)$$

The design point is typically chosen such that the above constraints are met, while minimising thrust to weight ratio and maximising wing loading, such that empty weight and drag can be minimised. In the case of water-borne aircraft however, the takeoff and landing impact load factors that the fuselage must be designed to meet are proportional to the stall speed squared, as per FAR-25.523 to 25.537. Therefore the hull structural weight penalty, assuming the maximum lift coefficient remains constant, is inversely proportional to the wing loading. This implies that when designing seaplanes, the maximum allowable stall speed should be treated as an optimisation parameter, constrained by impact loading and controllability considerations, and chosen such that the overall aircraft weight is minimised.

Aircraft	Reported Distance (m)		Predicted Distance (m)	
	Run	To $h_{OBS} = 50$ ft	Run	From $h_{OBS} = 50$ ft
Beriev Be-103	-	850	641	753
Canadair CL-215	-	808	761	855
Canadair CL-415MP	-	814	832	909
Gevers Genesis	305	-	343	437

Table 4: Comparison of predicted and reported takeoff distance for existing seaplane designs.

4 Preliminary Design Process

The complete aircraft sizing is carried out within an automated design environment, the layout of which is seen in Fig. 6. The aircraft maximum takeoff weight is obtained based on a user defined mission profile using the weight fraction method. The wing and engines are subsequently sized using the methods detailed in section 3. A thermodynamic cycle analysis is carried out to design the engines and obtain their off-design performance.

The underside of the aircraft is generated based on user inputs for the hull shape and seawing width and the aircraft centreline length is estimated such that the submerged hull provides 105% of the required buoyancy, keeping the remaining wing section clear of the water surface. The passenger compartments are placed above the static waterline and are sized to accommodate the desired number of passengers in a single class configuration, while cargo bays can be situated underneath or outboard of the passenger cabin. The cabin dimensions and layout are dictated by the desired aircraft aerodynamic shape, however may be automatically modified, along with the predefined hull side height, beam loading and length to beam ratio values if excessively thick airfoil sections have been generated in order to maintain a high enough sectional critical Mach number along the body and delay the onset of wave drag. Once miscellaneous components such as fins, engines, fuel tanks and control surfaces have been placed on the aircraft, the weight and balance characteristics of the aircraft are estimated using the empirical methodologies detailed by Roskam [7], modified to account for the penalties of operating from water.

The planform and varied cross sectional shapes encountered along the BWB’s span dictate the use of computational methods to pre-

dict the aircraft’s pressure loading. The Vortex Lattice Method is used as it offers a good level of accuracy at a low computational expense. Two dimensional airfoil characteristics used for stall and some drag predictions are obtained from wind tunnel test data where possible or a combination of empirical and 2D panel methods using viscous-inviscid matching. The potential flow results are used to ensure the static margin lies within a user defined bound, by moving the outer wing section, and to check that the aircraft is laterally statically stable. The aircraft’s behaviour on the water when at rest is also checked by ensuring a sufficient hydrostatic righting moment is generated when the aircraft is perturbed. Due to the range of hull length to beam ratios used, the longitudinal stability of the hull at rest is always satisfactory, while the seawing width and dihedral angles are varied to ensure the aircraft equilibrium roll (or loll) angle is below a maximum value set for passenger comfort and the outer wing section remains clear of water in rough seas.

The maximum takeoff weight and maximum lift coefficient are major design drivers, both affecting the size of the wing and therefore the aircraft. The entire sizing process is therefore repeated until both values have converged, basing the inputs for each initial sizing run on the results of the previous iteration. Following convergence, the aircraft’s performance and handling qualities are evaluated based on the previously obtained aerodynamic and propulsive characteristics. Water takeoff and landing distances are evaluated using the simulation procedure detailed in section 3, without the previously stated assumptions regarding constant lift coefficient and thrust. The onset of porpoising, a dynamic pitch-heave oscillation occurring in the planning regime, is also checked

using empirical methods derived from a large collection of tank tests.

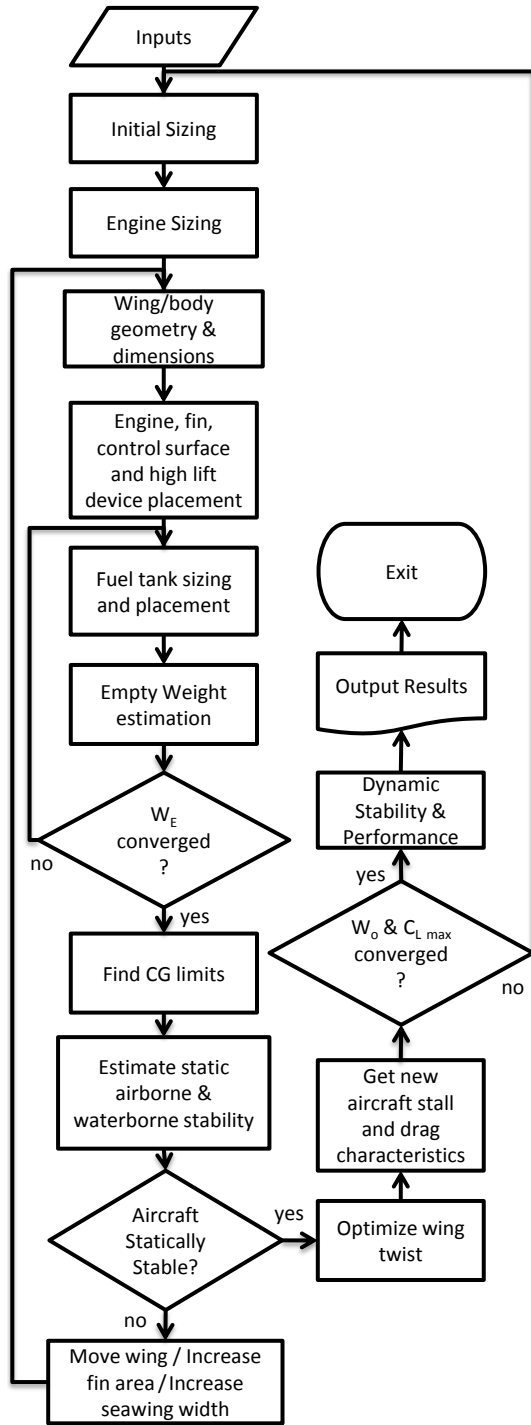


Figure 6: Layout of the design framework used for sizing BWB seaplanes

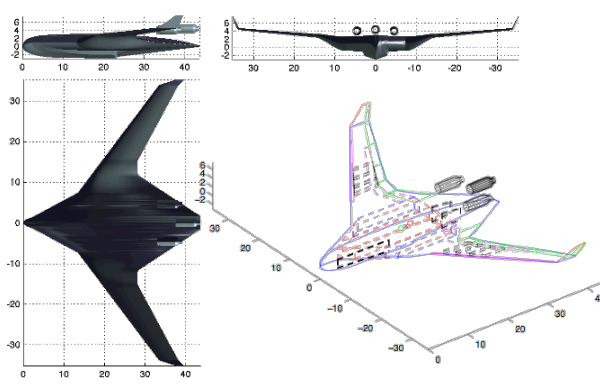
5 Observations from Sample Designs

The computational design framework described in section 4 has been used to generate a number of sample aircraft, presented in

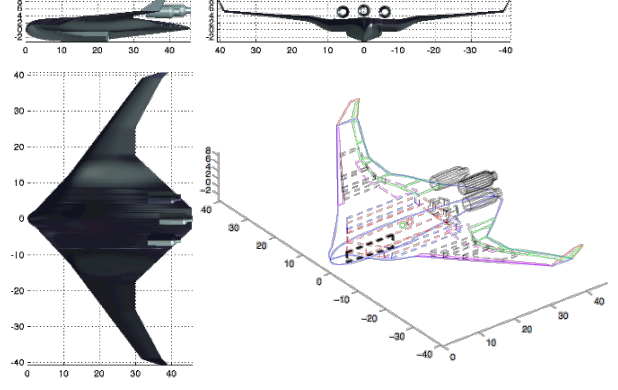
table 5 and Fig. 7. These designs, intended for various passenger numbers and cruise ranges, have been roughly optimised by varying the wing planform, aspect ratio and length to beam ratio. They demonstrate the flexibility and scalability of the design framework and allow for certain observations on the potential of seaplanes for airline operations to be made, although the performance of aircraft resulting from a more thorough optimisation is expected to be superior to that seen here. All aircraft have a design cruise speed of Mach 0.8 at 35,000 ft and feature a 35 degree swept outer wing section and turbofan engines of bypass ratio 8.

For all studies the minimum number of engines was constrained to three in order for the thrust to weight ratio necessary to meet the BFL requirements, set at 2500m for the two smaller aircraft and 3500m for the rest, to be minimised. The resulting thrust to weight ratios varied between 0.32 and 0.37 and the takeoff distance was determined to be the major sizing constraint resulting on average in a 5% excess in thrust to weight ratio relative to the remaining cruise and climb constraints. All aircraft were found to be airworthy, exhibiting good handling characteristics in both the longitudinal and lateral modes. Takeoff and landing distance constraints were consistently met and porpoising instabilities were not encountered.

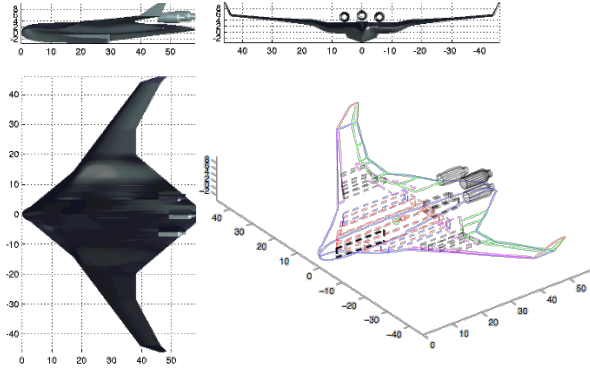
The results indicate that the hull length to beam ratio has a major impact on the design of the aircraft, affecting not only its running characteristics on water but also the centreline thickness to chord ratio and therefore drag rise Mach number. For smaller aircraft, higher hull length to beam ratios were found to perform best. For larger, long range aircraft hull fineness ratios in the range of 5 to 6.5 appear to blend very well with the rest of the aircraft. The exact value is largely dependent on the wing planform and the minimum centre section thickness required, as dictated by cabin and cargo packaging constraints. For example, when a second floor is added for the 850 passenger case, seen in Fig. 7(d), the optimum hull length to beam ratio increases so that the wing



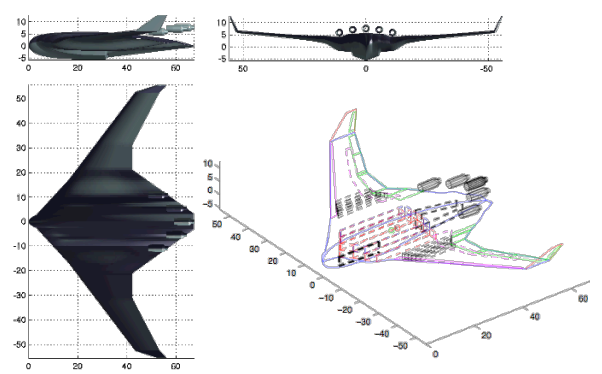
(a) 200 passengers, 5600 km range



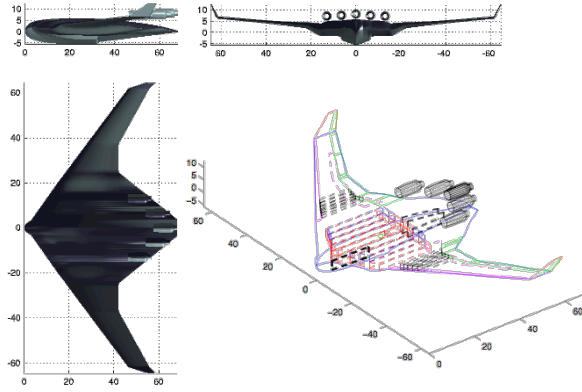
(b) 350 passengers, 13000 km range



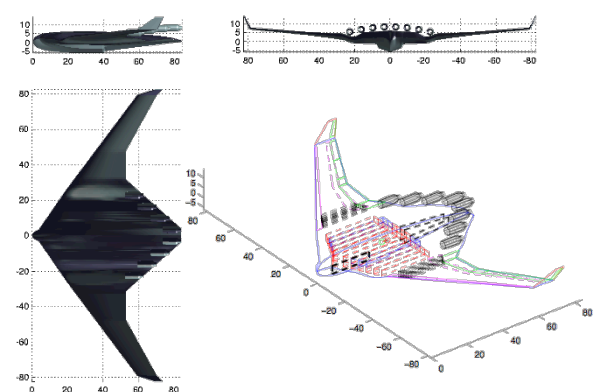
(c) 550 passengers, 13000 km range



(d) 850 passengers, 15000 km range



(e) 1200 passengers, 15000 km range



(f) 2000 passengers, 15000 km range

Figure 7: Three-views of and isometric wireframe view illustrating the packaging of sample aircraft.

Number of Passengers	Range (km)	Length to Beam ratio L/B	Max takeoff weight (N)	$(L/D)_{max}$	Energy consumption (MJ/ASK)
200	5600	8.0	1,256,000	22.5	1.657
350	13000	5.0	2,910,000	23	1.363
550	13000	6.0	4,142,000	21.5	1.149
850	15000	6.5	6,426,000	21	1.239
1200	15000	5.5	7,965,000	24	1.094
2000	15000	6.5	12,624,000	24	0.946

Table 5: Summary of design specifications and performance characteristics of sample aircraft

thickness to chord ratio remains less than 16%.

The fuel efficiency of the sample aircraft, given in table 5 as energy consumed per available seat kilometre (ASK), is found to be proportional to the aircraft size, in line with expectations. The estimated fuel efficiency of the smaller sample aircraft is found to fall somewhat short of the fuel consumption figures given for modern long range airliners by Peeters et al [8]. The ultra high capacity aircraft however seem to meet or exceed current energy efficiency levels of 1 - 1.1 MJ/ASK.

Although these results are not for optimised aircraft, the fuel efficiency observed is hampered by a combination of persistent aerodynamic and weight related issues encountered. All sample aircraft show that the aerodynamic penalty of shaping the hull for water-borne operations is minimised and that maximum lift to drag ratios between 21 and 24 are possible. However the lower maximum wing loading achievable by BWB aircraft means that at a cruise altitude of 35,000 ft, the maximum L/D was typically observed at Mach 0.5. Furthermore, due to the elevon deflection required to trim the aircraft and counter the nose-down pitching moments imparted by the high thrust line, the trimmed cruise L/D for most cases was found to be in the range of 11 to 15.

A number of steps may be taken to improve the aerodynamic performance of the aircraft. The use of a V-tail or canard would allow the use of high lift devices, increasing the maximum wing loading possible. Lowering the thrust line by using boundary layer ingesting engines, combined with the effects of a stabiliser, should also result in a substantial reduction in trim drag. A reduction of the design cruise speed or increase of the cruise altitude

should also serve to improve the aerodynamic performance. Operating at a lower Mach number would have the added benefit of allowing contra-rotating open rotors to operate at near maximum efficiency, typically found between Mach 0.7 and 0.8.

Another contributing factor to the relatively reduced efficiency of the the sample aircraft is the overall structural weight of the aircraft. Due to the lack of more accurate means of predicting the weight penalty resulting from water impact loads, a rather conservative 60% weight penalty was applied to the hull, following suggestions by Raymer [9], undoubtedly resulting in a large overestimation of the maximum takeoff weight and therefore also fuel weight. Further work would see the incorporation of a structural design module into the design synthesis to not only more accurately predict the weight of the hull but also allow for the hull deadrise angle and aircraft approach speed to be optimised.

Reviewing the system packaging drawings shown in Fig. 7, as aircraft size increases, the volume available for storing fuel is found to be increasing far in excess of that required. This unexpected feature of the proposed design suggests that larger BWB seaplanes may prove ideal for the use of hydrogen as a fuel, as this large excess volume may be used to accommodate large volumes of hydrogen fuel stored at relatively low pressures. The aircraft could therefore benefit from the reduction in emissions possible with the use of hydrogen without substantial weight penalties for its storage.

Overall these sample results show that the

proposed configuration as studied cannot yet compete with the latest generation of airliners. However, it clearly has the potential to achieve that target, since substantial improvements in fuel efficiency should be attainable with minor modifications to the aircraft design and mission profile and following a broader optimisation study, as suggested above. The resulting aircraft performance characteristics were nevertheless found to be far better than those of past seaplane designs, suggesting that the proposed configuration could be easily used for niche missions requiring water-borne operations, such as water bombing or strategic airlift.

6 Conclusions

A radical approach to freeing large aircraft from ever more stringent noise constraints at airports was presented, suggesting that seaplanes could be a viable alternative for long range passenger flights. A novel blended wing body flying boat design intended to alleviate many of the aerodynamic and weight penalties associated with operating from the water surface, while maintaining good airworthiness and seaworthiness characteristics, was presented. A design framework intended for the rapid design and evaluation of such aircraft has been produced and is briefly described. The initial sizing process for seaplanes was further discussed and novel methods for the prediction of water-borne takeoff distances, using parameters available in the initial design stage, were presented. A family of sample aircraft designs were obtained and their performance was analysed, showing that despite not currently being capable of achieving fuel efficiency levels on par with current generation airliners, the proposed

design presents a clear improvement over past seaplane designs and with the suggested modifications it clearly has the potential to set another paradigm for future long-range travel.

References

1. Stinton D. Aero-marine design and flying qualities of floatplanes and flying-boats, *Aeronaut J*, March 1987, pp. 97-127
2. Smith, A. G. and Allen, J. E. Water and air performance of seaplane hulls as affected by fairing and fineness ratio, *ARC R&M 2896*, 1954
3. Torenbeek E. *Synthesis of Subsonic Airplane Design*, Delft University Press, 1982
4. Ward K. E. Hydrodynamic tests in the N.A.C.A tank of a model of the Short Calcutta flying boat, *NACA TN 590*, 1937
5. Perry D. H. An analysis of some major factors involved in normal take-off performance, *ARC Current Paper 1034*, 1969
6. Canadair Ltd. *Canadair CL-215 airplane flight manual*, Canadair Limited, 1986
7. Roskam, J. *Airplane Design: Part V - Component Weight Estimation*, DARcomporation, 2003
8. Peeters, P. M., Middel, J. and Hoolhorst, A. Fuel efficiency of commercial aircraft: an overview of historical and future trends, *National Aerospace Laboratory NLR-CR-205-669*, 2005
9. Raymer, D. P. *Aircraft Design: A Conceptual Approach*, AIAA, 1999