Conceptual design of a Cargo Seaplane

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A Dissertation

Submitted to the department of Engineering

University of South Wales

27th March 2025

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1.0 Introduction

The aim of this paper is to come up with a conceptual design of a cargo seaplane and to validate its flight characteristics and ability to carry out its mission. The seaplane design is a rare design due to the trend towards fuel efficiency and the large number of paved airports, but the seaplane has the unique ability to land without a runway.

1.1 Background

Seaplane designs were popular in the early days of aviation for several reasons, but paved runways were uncommon and rarely long enough to support large designs of aircraft. Using seaplanes allowed the new aircraft technology to integrate with the already well-established nautical infrastructure such as ports to allow for the logistics side of aviation to take place. Aircraft at the time commonly used fixed pitch propellors which were optimized for cruise and didn't provide full power during takeoff, resulting in a longer takeoff distance. This meant that for

some designs, using the existing waterways was the only option as longer runways were a rarity until after World War 2.

A major prewar part of seaplane design is the Schneider Trophy. During the 1920s, Air Racing became a sport, and the Schneider trophy quickly became the most famous air race and a huge driver of seaplane designs from both military and civilian teams. The trophy required the race to be won 3 times by the same club in five years and was eventually won in 1931 by Supermarine Aircraft, the same that manufactured the Spitfire. During the 1913 to 1931 period that the race ran, the aircraft increased from 45 mph to 380 mph. Due to engine problems in 1931, the Macchi MC.72 did not participate but it did go on to set a new speed record that still stands, averaging a max speed of 440mph. This record stood for all propellor aircraft for five years and still stands as the fastest seaplane design of all time. (Schneider Trophy, n.d.)



Figure 1 Macchi MC.72 (ASME. n.d.)

Seaplanes played a number of roles during WW2, including but not limited to anti-submarine warfare, reconnaissance, transport and search and rescue. All the major powers designed and developed a variety of their own seaplane designs to be employed where runways were not feasible. The Pacific and Atlantic theatre made seaplanes a highly versatile design with vast amounts of ocean needing to be covered. Designs such as the PBY Catalina, BV138 and Kawanishi H8K all played crucial roles in rescuing airmen and sailors alike.

Despite the large historical significance, seaplanes are not common in modern aviation due to several factors.

During WW2, land-based designs proved to be easier to operate so a large number of paved runways and airports were created to house these aircraft, and this significantly reduced the need for water-based aircraft.

Additionally, Aviation is tending towards fuel efficient designs utilizing large turbofan engines and the large frontal area of a seaplane due to the hull design is not fuel efficient.

There are a lot of challenges with operating seaplanes such as saltwater causing corrosion, water conditions and currents, sea debris and environmental concerns which will all need to be considered in my design to make it a feasible concept.

The requirements for a modern seaplane have evolved massively from the early days of aviation and they now focus more on transportation of goods and pleasure flights to experience a flying boat. This design fits into the transportation of goods as it is a cargo seaplane design and aims to fill the gap in the market that gets resources to and from small ports to larger cargo hubs like airports or seaports. Generally, when something is ordered to a place from far away, the shipping may take weeks to arrive due to the cargo having to utilize large, slow cargo ships. If you are in a remote location where port infrastructure is not developed or with shallow waters, these large ships cannot directly deliver cargo. This is where the design for the seaplane comes into play. It may not have the capacity of a multi-million-ton cargo ship, but it does present the ability to deliver straight from ports or airports to these locations without the need for runways or deeper waterways. It also removes the need for a middleman in having to get a smaller boat to deliver the cargo which in turn saves money and time as the seaplane can fly directly to from the large port to the small port without stopping.

1.2 Aims and Objectives

The aim of this paper is to conceptualize a seaplane design that is capable of delivering cargo from cargo hubs to smaller, more remote locations. The aircraft should be able to fly 9500km as outlined in Section 4.2 and carry a cargo greater than 20 tons (Section 4.1).

2.0 Market

2.1 Geographical Demand

Seaplanes are crucial to areas with no terrain suitable for aircraft or other transport means. An example of this is the Canadian artic region where 60% of indigenous communities do not have year-round road access (Sheppard and White, 2017). Seaplanes provide a lifeline to these places by providing food medicine and construction materials. According to Smith 2021, 500+ tons of cargo are transported annually to Nunavut, Canada to circumvent ice road closures by Air Tindi's fleet of seaplanes.

Similarly, Fiji's Pacific Island Air moves 30% of the inter-island perishable goods via seaplanes Canada faces similar problems with 60% of shops in remote areas selling out of date perishable good.

To add to this, 79% of artic airfields show damage to the surface which if left unrepaired would deem the airfield to be unusable. (Johnson, 2023) and by 2030, the thawing permafrost would deem 40% of gravel runways to be unusable.

2.2 Economic Advantages

Seaplanes cut costs by removing the dependency on runways

According to the Asian Development Bank, building a 1500m runway costs up to $30 million whilst a seaplane compatible floating dock costs only $500,000. Alaska's Lake Hood Seaplane

Base handles 190 daily cargo flights, saving $12 million annually in runway upkeep (Alaska DOT, 2022). Additionally, not using a runway saves on runway landing costs and overall reduces the cost of transporting cargo on some routes.

2.3 Extended applications

The design of the seaplane also acknowledges the other, less common, usages of the type such as firefighting aircraft, military transport and disaster relief.

After Hurricane Dorian (2019), Bahamas Air Sea Rescue delivered 50 tons of aid via seaplanes to islands with destroyed airports and evacuated 900+ people. (Tropic Ocean Airways, 2019) This shows that even with commercially available seaplanes, there is a use for them in this sector

Firefighting is another possible purpose of this aircraft. Many cargo aircraft such as 747s and the DC10 have been repurposed to fight fires but the CL415 and other seaplane-based fire bombers hold the distinct advantage of being able to collect water directly from water sources which increases the number of missions the aircraft can carry out and in turn reduces the spread of the fires. A modular design is discussed in section 11.3 which could incorporate the water tanks needed for firefighting duties.

Another possible role of the seaplane is military transport. Aircraft such as the A400 and C130 commonly practice short field landings in the amphibious assault role on areas such as beaches and dirt runways but lack the capability to land in areas like fjords or areas without suitable landing areas. The seaplane can also be used for ship resupply and maritime surveillance as well as covert troop insertions or any other specialist role. Section 11.3 covers modular designs so it is feasible that the aircraft could also be used as medical evacuation or fitted with a module with seats as a troop carrier.

3.0 Mission

3.1 Primary Role

This sea plane design intends to add a quicker way to transport cargo between cargo hubs and additionally, smaller, more remote locations such as islands or less developed countries. The design of the seaplane allows it to land in much shallower waters than commercial shipping can which provides the ability to bring a large amount of cargo to previously accessed areas whilst bypassing unnecessary cargo hubs.

The modern seaplane is often attributed to firefighting designs, so it is worthwhile considering this in the design process as only select aircraft types are suitable for firefighting roles. It is also worth considering other possible uses for a seaplane such as military transport or disaster relief.

3.2 Design features

The design will be a flying boat design instead of a floatplane design. The floatation of the design will come from the hull (fuselage) of the aircraft instead of the use of additional floats (or pontoons) external to the aircraft. It will also include the addition of retractable wingtip floats to keep the aircraft from rolling over in the water whilst also providing a way to reduce flight drag.

The design should also feature the use of suitable new materials such as carbon fiber composites and other materials that are known to be aviation grade but water resistant. The aim is to keep maintenance costs as low as possible.

The design should carry a reasonable amount of cargo whilst keeping in mind CG limits and the need to takeoff from water where drag and hydrodynamics are a much larger factor in the takeoff roll.

3.3 Validation

The design will be validated by the Merlin MP521 Engineering flight simulator where the key flight characteristics of the design can be analyzed. The data should match the calculated characteristics of the aircraft where possible, but it is noted that the accuracy of the flight simulator may be limited.

4.0 Specifications

4.1 Payload

The design incorporates the use of 20 AKH cargo containers, a common lightweight cargo container that is often found in the Airbus A320 family but is also fitted in larger aircraft such as the A380 and Boeing 777 and 787. This specific container can carry up to 1134kg of cargo per container and is a relatively small design at 2.44 x 1.53 x 1.14m, allowing for easy positioning of the containers around the aircraft to affect the CG of the aircraft as required and makes for easier loading and unloading where space is limited. (ANA Cargo, n.d).

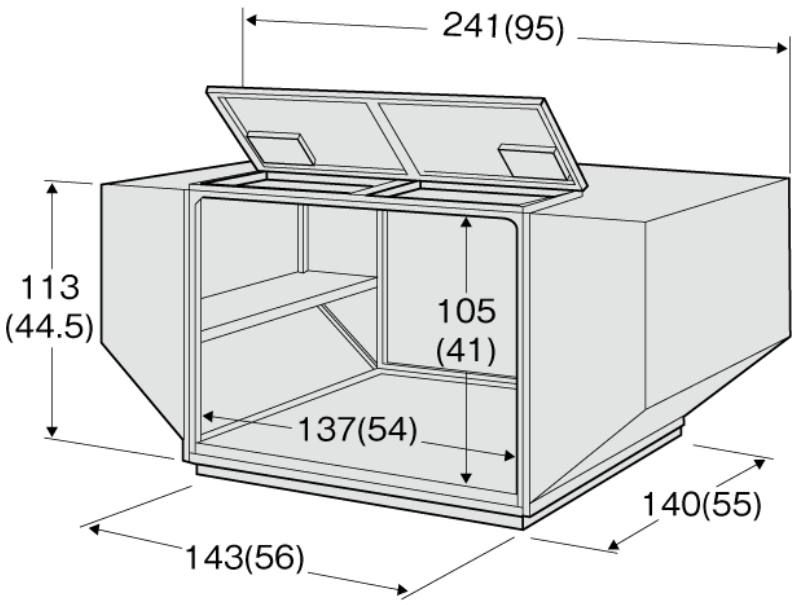


Figure 2, AKH Cargo container with dimension (ANA Cargo n.d)

The payload calculations accounted for the inclusion of 4 crew members, allowing for multiple pilots to be in rotation during longer flights.

4.2 Range

The desired range was set up to be 9500 km. According to the World Shipping Council, the top 10 busiest port include Shanghai at number one and Rotterdam at number 10, a distance of roughly 9000km (World Shipping Council, n.d.). These two ports were specifically chosen from the list as they are the two with the greatest distance between them in the top 10. An extra 500 km of extra range was included as fuel in case of emergency and to extend the range of the aircraft to reach further destinations. This distance is sufficient to align with the mission goals, for example the range is large enough to connect artic Canada to multiple large cargo hubs across Northern America and Europe

4.3 Performance

The aircraft is designed to meet strict criteria which enable seaplanes to operate in tight environments where high climb rate designs are desirable. The aircraft was built with the ability to climb at a rate of 3000ft/min in mind to be able to clear obstacles such as trees on climb outs from areas where terrain is a factor. The climb rate is dependent on a multitude of factors such as airport elevation, ambient temperature and aircraft weight but is defined to be a 6.7% climbs rate by the EASA (EASA,2023). This is later calculated after finding the W_TO (Section 6.3) to be equal to 831.4 ft/min climb rate at takeoff speed but this requirement is a minimum.

The aircraft was also designed to reach a cruising altitude of 35,000 ft and be able to sustain Mach 0.8 at this altitude which allows it to use high altitude airways common to airlines and air freight.

4.4 Water Operation

Operation on water is a key part of seaplane design. The design of the “hull” of the aircraft must be so that there is not excess spray which could lead to the pilot’s vision being impaired. This is especially critical in seaplanes where the runways are often public domain, and boats may unknowingly impede seaplane operations.

The visibility from the cockpit must be high due to both the above-mentioned runway incursions but also the challenge of having still water. When water is still, it has a glassy reflective surface which makes it incredibly hard to see the surface and judge altitude when landing but higher visibility helps to mitigate this.

The aircraft must also not enter an uncontrollable state of porpoising or swinging, which may lead to parts of the aircraft that are not designed to be in contact with water being submerged, as well as being generally dangerous.

The aircraft should feature low speed control devices such as water rudders to provide adequate maneuverability at low speed

4.5 Desired performance table

Payload	22680 kg
Range	9500 km
Altitude	35000 ft
Cruise Speed	M 0.8
Climb Speed	3000 ft/min

5.0 Design choices

A major part of the design of the seaplane is reducing the amount of seawater that is on the surfaces whilst still providing an effective and stable aircraft to fly.

5.1 Wing

The design of the seaplane incorporates a high wing anhedral wing design similar to the C17 and A400M and incorporates the use of a NACA 2412 wing profile to generate lift at slow speeds.

The High wing anhedral design provides the engines with the clearance they need from the water to not ingest harmful seawater in most operations. The anhedral design sweeps the wings vertically downwards so that the tip is lower than the root which provides less inherent stability but provides with maneuverability and prevents overstabilization. It also helps to reduce the height of the CG which provides more stability on the water, but this is later discussed in (Section 9.2). The anhedral design does make the aircraft less stable on the roll axis but this is a worth tradeoff for the extra maneuverability gained by the aircraft.

The improved maneuverability is highly desired when taking off due to the wingtip floats rising out of the water and no longer providing stability as air speed increases. The downwards angle also means that the wingtip floats can be mounted further out on the wing as there is less distance between the wingtip and the water.

This wing design also provides low wingtip vortices which is necessary with the wingtip floats as the aerodynamic performance of the wingtip floats aerodynamically is not known and outside of the scope of the study. Generally, low wingtip vortices are a desirable trait as they reduce drag and therefore fuel consumption.

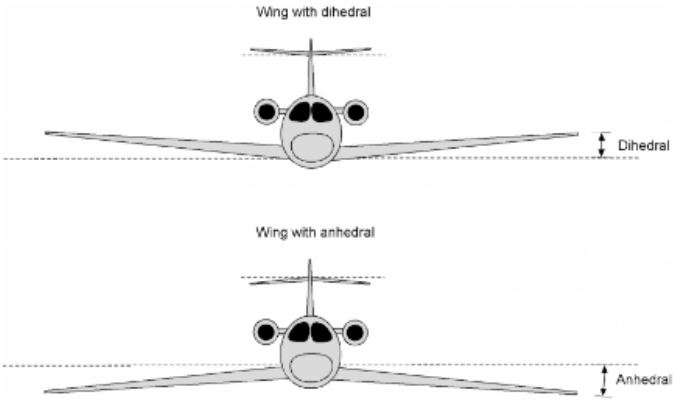


Figure 3, Illustrated difference between anhedral and dihedral wings, (Green, M.D. 2023)

The NACA 2412 profile was chosen for the wing due to its great performance with high lift coefficients at low angles of attack and its gradual stalling characteristics making it predictable and functional. This wing is perfect for short field water operations for these reasons.

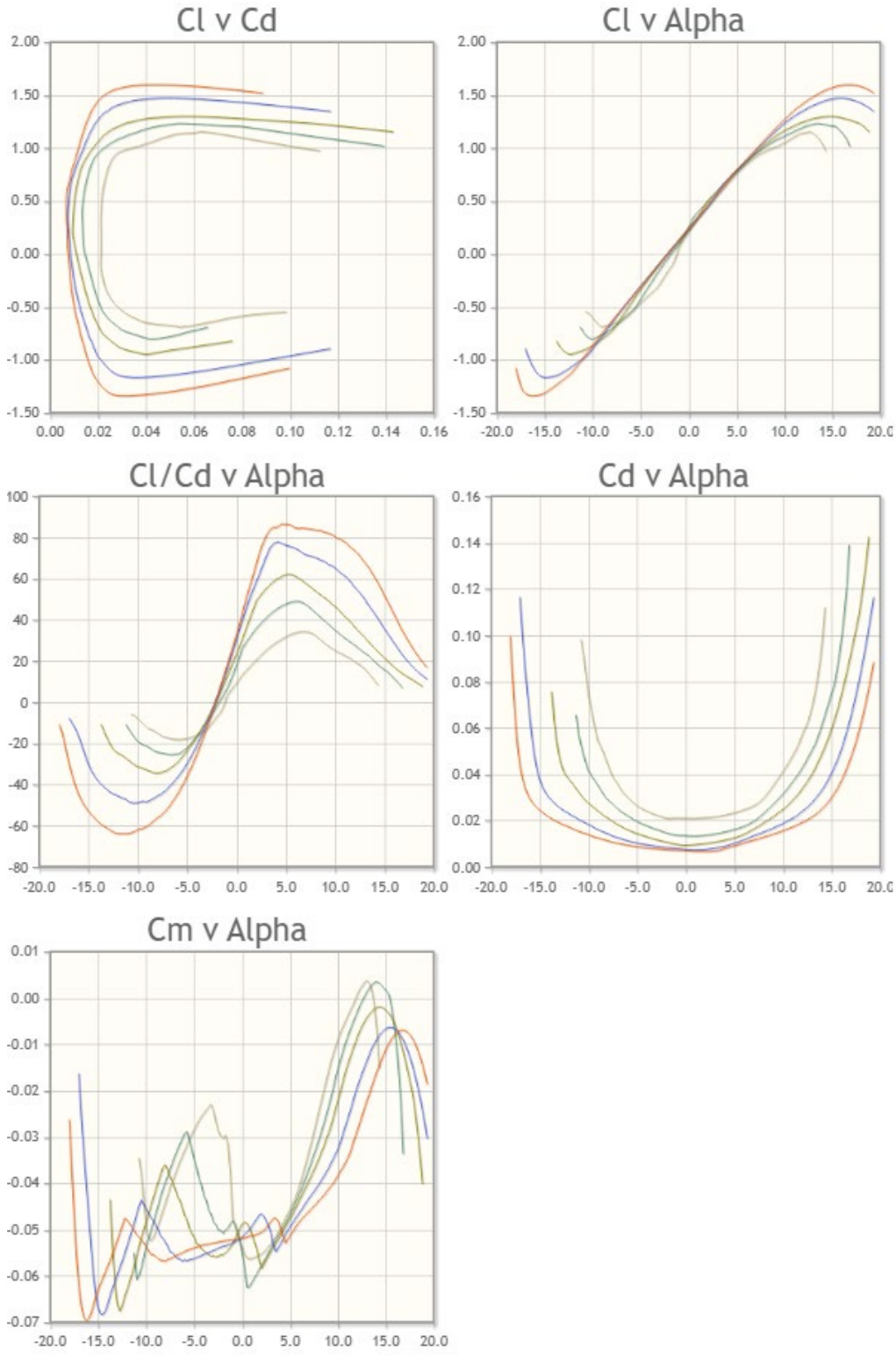


Figure 4, Plots of NACA 2412 at varying Reynolds numbers with a N_Crit of 5, showing the wing characteristics (Airfoil Tools n.d.)

5.2 Engines

The BR 715 C1-30 is a joint development engine between BMW and Rolls Royce, it was chosen due to its adaptability into seaplane operations as well as high thrust with low maintenance

needed. The engine needed to be a low bypass turbofan to provide the power needed but whilst also fitting into the wing structure so the BR715 fits this role perfectly with a fan diameter of only 1.42m whilst providing 93kN of thrust per engine at sea level (General Electric, 2017).

This engine powered over 150 Boeing 717 aircraft which were known for their short field performance. The C1-30 variant of the engine was specifically designed for high gross weight versions of the 717 so it already fits to the mission profile of the cargo seaplane. Additional uses of the BR715 include adaptation into the new B52J models being produced. This engine has also previously been used in the BAE Nimrod that also featured an in-wing engine design proving that this engine is suitable for that sort of construction. The BR715 specifically was chosen due to its high thrust at sea level.

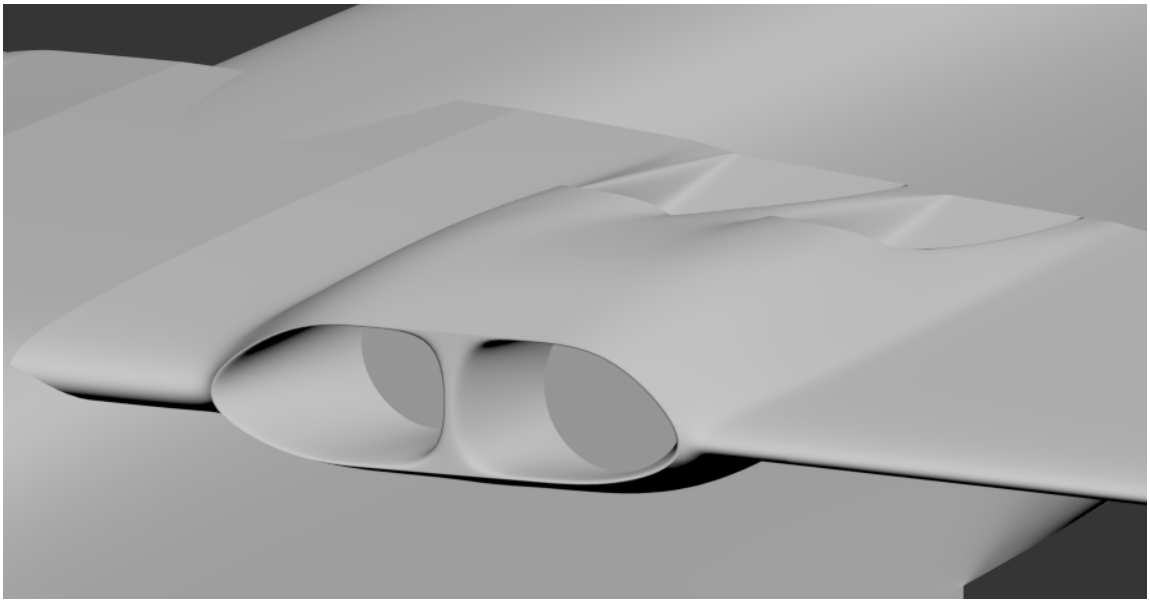


Figure 5, Engine placement in wing root in conceptual model

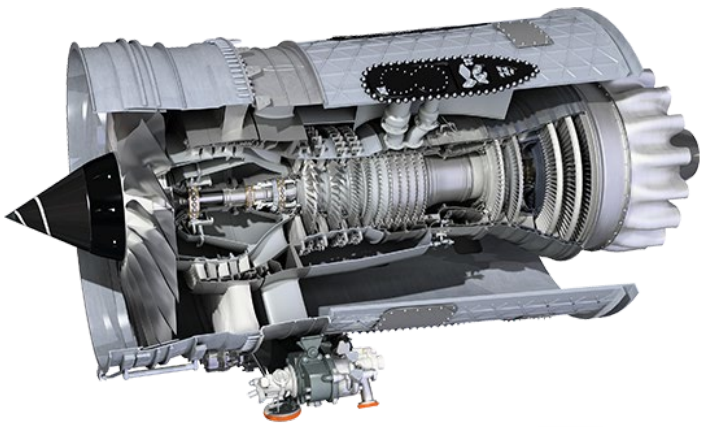


Figure 6, BR715 Engine illustration (Rolls-Royce, n.d.)

5.3 Fuselage

Much of the fuselage design came when designing the hull elements, but this is discussed in (Section 9.3). The key part of the fuselage design was the loading door to board the cargo. The design of this should be so that the aircraft can be unloaded easily in remote locations without massive infrastructure. The aircraft features a cargo door on the port side that is centered around the CG. This is necessary as loading an aircraft on water from extreme ends may cause the trim angle to change and elevate the loading door above or below the loading area. The aircraft may feature either ramps or inbuilt jib cranes to account for the change in height when loading. The placement of the door is also at the center of buoyancy, making ramps a viable option. The loading process is discussed further in (Section 11)

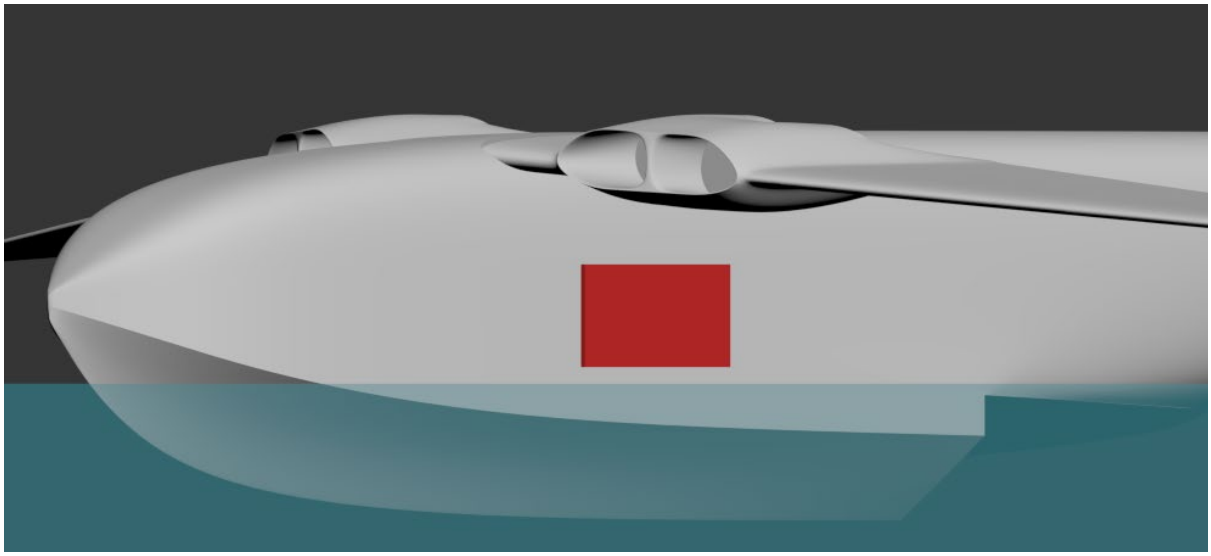


Figure 7, Cargo door placement on conceptual model, illustrated by the red rectangle. This is at full MTOW

In regard to controlling the spray, the fuselage should be fitted with spray rails and sister keelsons to rigidify the structure and to add directional stability.

5.4 Tail

A T tail design is used to prevent the spray from the engines from being directed towards the control surfaces that are susceptible to corrosion and to elevate them out of the jetwash of the engines. It was previously found that damage was caused to a P6M seaplane that had the same sort of design with the T tail was due to the thrust from the engine causing structural damage to the tail section of the aircraft, resulting in a structural failure in the tail section (GlobalSecurity.org, n.d).

5.5 Materials

The evolution of technology has introduced new viable materials for aircraft to use, some of which are corrosion resistant.

The hull primarily uses a carbon fiber reinforced polymer (CFRP). This gives the hull a high strength to weight ratio and an exceptional corrosion resistance, much greater than conventional and historical aluminum alloys (Composites UK, n.d.). This is critical as this part is constantly exposed to corrosive sea water and it is crucial to keep the degradation low to maintain longevity and low maintenance costs. Areas of high impact, such as the keel, should

employ a titanium alloy such as Ti-6Al-4V due to its resistance to corrosion but its much stronger fatigue strength (Litvin & Smith, 2009).

The wing skin should be formed from a fiberglass reinforced polymer to resist spray induced erosion. The exposed hinges, such as that of the elevator or retractable wing floats should be formed of corrosion resistant stainless steel such as Grade 316 Stainless steel which has better resistance to corrosion than other grades. (Stainless UK, n.d.).

The engine itself is placed high up on the wing to minimize ingestion of salt water but should be fitted with corrosion resistant metals throughout the engine and should be washed regularly.

Sacrificial anodes should also be fitted to the aircraft to direct corrosion away from important parts of the airframe.

All of the material choices are aimed at longevity and reducing the amount of maintenance required, especially when the aircraft is commonly operating out of areas with little infrastructure.

6.0 Initial Calculations

6.1 Preliminary Calculations

The first step in designing an aircraft is making preliminary calculations to find the desired weight of the aircraft to know how much lift will need to be produced. In this case, the Martin P6M was used as a baseline to the design specifications as it too features 4 overwing turbojet engines.

The first step to find the likely takeoff weight for the aircraft. The takeoff weight of the P6M is 83,558kg so it was assumed that the concept aircraft should have an estimated takeoff weight of 85000kg for the sake of simplicity. The Payload Weight which is known to be 22680kg from the desired specifications. The weight of the crew is assumed to be 98kg per each of the four crew members to include their own personal cargo for overnight stays.

6.2 Fuel Weight Fractions

The fuel weight fractions are a series of equations used to describe the fuel usage at different stages of flight and are key to finding how much fuel is needed accurately. The equation for the final fuel weight is below

$$\frac{W_{fuel}}{W_0} = 1.05 * (1 - \frac{W7}{W_0})$$

Eq1

To account for trapped fuel and other fluids like oils, an additional 5% is added to the total fuel weight. The fuel weight fraction values for cruise and loiter need to be calculated in order to find W7/W0.

$$Cruise = \frac{W_3}{W_2} = \exp \frac{-R * C}{V(\frac{L}{D} * 0.866)}$$

Eq2

=0.8079

Where R is range, C is specific fuel consumption and V is cruise speed. The L/D value is given as an estimate of 15 from Roskam's table for flying boats. L/D for cruise is known to be approximately 86.6% of L/D Max

$$Loiter = \frac{W_5}{W_4} = \exp(\frac{-E * C}{\frac{L}{D}_{Max}})$$

Eq3

=0.9950

Where endurance is known to be 30 mins, and the L/D is equal to L/D Max.

The diversion stage is also calculated. This assumes an additional range of 350km at a height of 20,000ft and a speed of Mach 0.5

$$Divert = \frac{W_6}{W_5} = exp\frac{-R \times SFC}{v\left(\frac{L}{D_{Max}} \times 0 \cdot 866\right)}$$

Eq4

=0.9881

The equation to find the W7/W0 can now be formed and calculated as

$$\frac{W7}{W0} = 0.9506 * \frac{W6}{W5} * \frac{W5}{W4} * \frac{W3}{W2}$$

Eq5

Where the 0.9506 is the other stages of flight multiplied together from Roskam's table.

$$M_{FF} = 1.05 * (1 - \frac{w_7}{w_0})$$

Eq6

The Mission Fuel fraction can then be calculated and was found to be 0.2542 W0 can then be solved iteratively using the formula. The total mission fuel incorporates an additional 5% margin (Raymer, 2018)

$$W0 = \frac{W_{crew} + W_{payload}}{1 - \left(\frac{W_f}{W_0}\right) - (\frac{W_e}{W_0})}$$

Eq7

Resulting in a final value for Takeoff Gross Weight, W0 as 78521kg.

The next step is to calculate the Takeoff Weight. This is done with the equation

$$\log_{10}(W_{TO}) = A + B(C \times W_{TO} - D)$$

Eq8

The constants for A, B, C and D are as follows
A = 0.1703 (taken from Roskam's regression line table (2.15))

B = 1.0083 (taken from Roskam's regression line table (2.15))

C = 1-(1-$\frac{W7}{W0}$ - W_{tfo})

D = W_{PL}+W_{Crew}

This equation was solved iteratively in MATLAB resulting in a W_{TO} of 83,897kg

The fuel weight of the aircraft is determined by multiplying M_{FF} by W_{TO} resulting in a fuel weight of 21,326kg. This value seems correct as an airbus A320 carries about 15,000kg of fuel for 7000km and the Martin P6M carried about 20,000kg of fuel for a range of 4830km with inefficient engines.

6.3 Weight Results

Takeoff Weight	83897 kg
Operating Empty Weight	39610 kg
Empty Weight	39218 kg
Fuel Weight	21326 kg

7.0 Wing loading

With the Takeoff weight calculated, it is necessary to find the wing loading and thrust to weight ratio of the aircraft to calculate climb rates, stall speeds, geometry and other important performance analytics. The C_{LMaxL} of 3.4 was based on Roskam's tables for flying boats. The density of air was set to 1.225kg/m^3 for air at sea level. W/S is the ratio of weight to wing area so given that we know the weight, the wing area can be found. The first step is to calculate the wing loading.

$$\left(\frac{w}{s}\right)_{Landing} = \frac{(s_L - s_a) \times c_{LMax}}{80}$$

Eq9

= 48.8 lbs/ft^2

The highest value of wing loading will occur during the climb out stage, but the landing stage is used to estimate the wing sizing due to the dependance on the wings during the landing stage. The climb out stage will have a higher wing loading but this is due to having a high fuel weight, it is a less important stage for the wings as the climb performance is more dependent on thrust to weight ratio. The landing distance was estimated based on similar aircraft types to be around 2500ft or 770m (Airforce Technology, n.d.)

The final wing loading can then be used to calculate the wing area. $\left(\frac{w}{s}\right)_{Landing}$ is multiplied by 4.8824 to get it into metric form. You can then divide the W_{TO} by $\left(\frac{w}{s}\right)_{Landing}$ to find the wing area which gives a result of 352.1m^2

8.0 Sizing

8.1 Wings

The wing area is found by dividing the takeoff weight by the landing wing loading, resulting in a wing area of 352 m^2. This can then be used to find the wingspan using the aspect ratio of 5.4 which was taken from the P6M resulting in a total wingspan of 43.73m.

$$Wing\ Length = \sqrt{AR \times S}$$

Eq10

The wing's taper ratio was initially set to 0.25 but later refined to be 0.375 for stylistic purposes, resulting in improved aileron efficiency and improved stall characteristics, making it more suited to slow speed operations in confined spaces such as lakes, as well as looking better.

With this knowledge, the wing root and tip can be calculated

$$C_{Root} = \frac{2S}{b(1+\lambda)}$$

Eq11

$$C_{Tip} = C_{Root} \times \lambda$$

Eq12

The above equations give a root chord of 11.71m and a tip chord of 4.39m

The MAC (Mean Aerodynamic Chord) of the wing can also be calculated at this stage. This is an important calculation for aerodynamic stability relating to cargo loading and weight/balance calculations.

$$\bar{C} = \frac{2}{3} C_{Root} \frac{1+\lambda+\lambda^2}{1+\lambda}$$

Eq13

= 8.61 m

8.2 Fuselage

The fuselage length can be calculated using the formula

$$Length = aW_0^c$$

Eq14

Where a and c are given by Raymer's conceptual aircraft design table 6.3. a = 0.44 and c = 0.41. This gives a fuselage length of 44.60m which is a reasonable value as it is close to the A400M length of 45.1m

8.3 Tail section

The dimensions of the horizontal and vertical tail can be calculated from the wing dimensions

$$s_{vt} = \frac{c_{vt \times b \times S}}{L_{vt}}$$

Eq15

$$S_{Ht} = \frac{C_{Ht} \times \bar{C} \times S}{L_{vt}}$$

Eq16

For the Vertical tail

$$v_T L = \sqrt{A \times S}$$

Eq17

$$c_{Root} Vt = \frac{2 \times S_{vt}}{L_{vt} + (1 + \lambda)}$$

Eq18

$$c_{Tip} Vt = c_{Root} Vt * \lambda$$

Eq19

For the horizontal tail

$$H_T L = \sqrt{A \times S}$$

Eq20

$$c_{Root} Ht = \frac{2 \times S_{vt}}{H_{vt} + (1 + \lambda)}$$

Eq21

$$c_{Tip} Ht = c_{Root} Ht * \lambda$$

Eq22

The tail section features a T tail design to elevate the elevators out of the turbulent air from the engines and above any possible spray from the water. The vertical height of the tail is 7.33m tall and supports a horizontal stabilizer with a total width of 16.89m. Both of the tail surfaces have a taper ratio of 0.5 which is suggested from Raymer's book. L_{vt} is the defined as half the fuselage length and dictates the position of the tail section from the ¼ chord of the wing to the ¼ chord of the tail. Below is a list of the constants used in the calculations, all taken from Raymer's book

C_VT (Vertical tail volume coefficient)	0.06
C_HT (Horizontal tail volume coefficient)	0.7
L_VT (1/4 chord tail distance)	22.30m
A_VT (Vertical tail aspect ratio)	1.3
A_HT (Horizontal tail aspect ratio)	3
λ (Tail Sweep)	0.5

9.0 Hydrodynamics

The Hydrodynamics of a seaplane is crucial to its operation, dictating the buoyancy, stability and drag. Whilst CFD was outside of the scope of this paper, the following section aims to justify the design choices of geometry for stability and efficiency.

9.1 Buoyancy

The hull of the aircraft must displace the weight of the aircraft. According to FAA §23.751, The aircraft must be able to support 80% more weight than the maximum weight. Using Archimedes principle:

$$F_B = \rho_{water} \times g \times v = 1.8 \times W_{To}$$

Eq23

Were

ρ_{water} = 1025 kg/m^3 (seawater density)

g = 9.81 (gravity)

v = to be found (displacement volume)

This gives a resultant volume of 146m^3 of displacement at full loading. From this we can see that the waterline of the aircraft is 2.65m from the bottom of the aircraft. This submerged section has a cross-sectional area of 9.32m^2 and a length of 15.75m

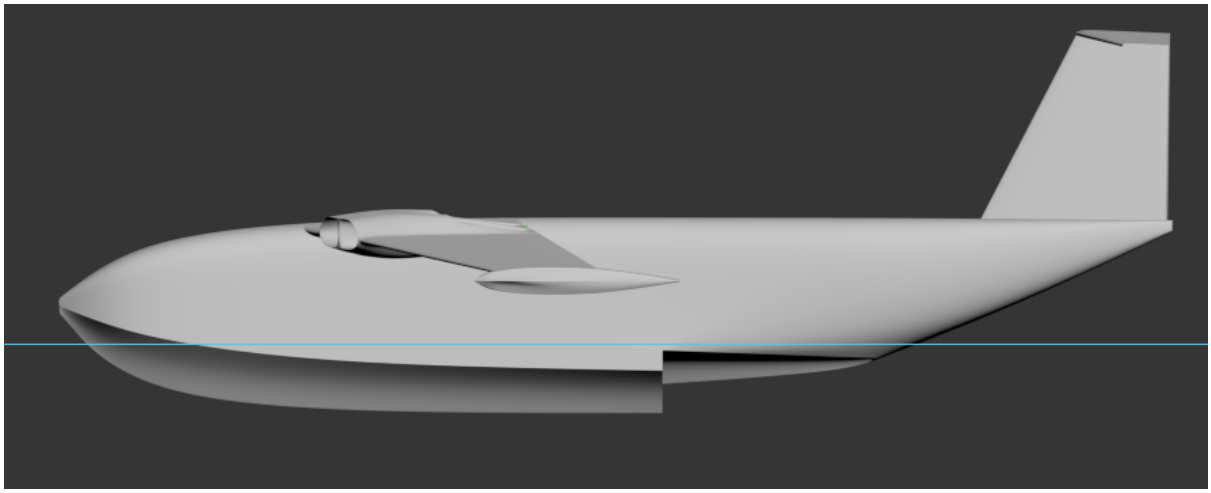


Figure 8, Waterline of the aircraft indicated by the blue line

9.2 Hydrostatic Stability

The center of buoyancy can be found by finding the centroid of the submerged area, displayed on Figure 8 as the red circle.

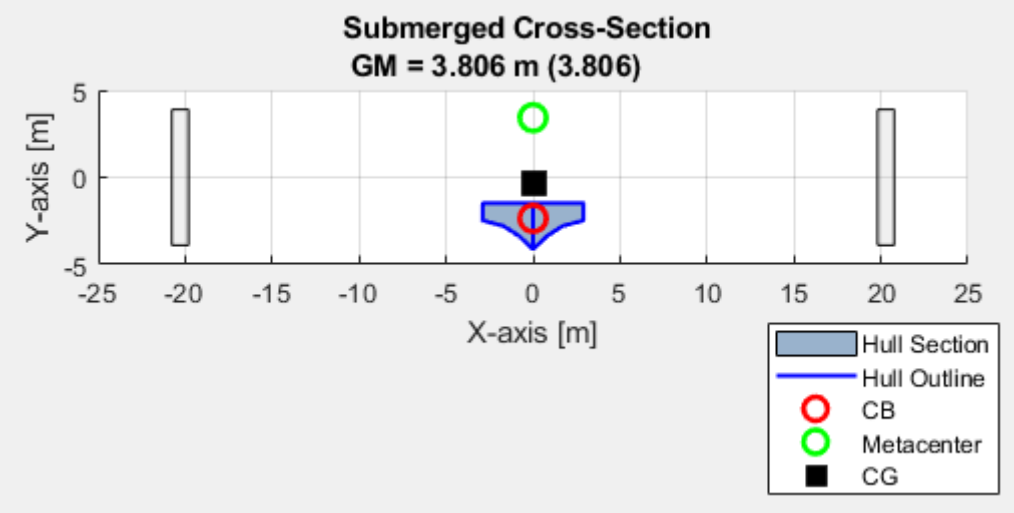


Figure 9, Metacenter and Center of Buoyancy plot

The metacenter of the hull is fundamental to naval designs, determining a object's stability and resistance to capsizing. It serves as a predictor of stability when the body is subjected to heeling (tilting) forces, such as waves, wind, or uneven loading by mathematically predicting the Center of Buoyancy's path as the body rotates.

$$GM = BM - BG$$

Eq24

BM = $\frac{1}{v}$ = Metacentric Radius (Distance between CB and Metacenter)

BG = Vertical distance between CB and CG

I = Second moment of area

v = Volume of water displaced

Where a positive GM value gives a positive, self-righting stability.

The hull itself is an inherently unstable design due to the high center of gravity from the high mounted wings and the engines in the wing. The GM value was calculated in MATLAB and found to be -1.11m which would have a rolling over tendency. This is counteracted by the wingtip floats that act to stabilize this force. They provide a stabilizing force that raises the metacenter by 5.78m which results in a positive GM of 3.8m

9.3 Hybrid Hull Design

The Hull itself is designed with stability in mind featuring a hybrid of hull designs to remain stable both when on "The step" and at low speeds. During the takeoff roll, the aircraft is

designed to lift itself out of the water to reduce the drag caused by the water and transiting into flight. During this stage, the deadrise angle and flaring play an important role in keeping the aircraft stable and away from porpoising tendencies. This design features a hybrid between a flared base and a flat base to maximize this stability. The front of the design is flared to cut through the water which benefits low speed operations such as taxiing and initial take-off roll. This front design also greatly affects spray characteristics and greatly improves visibility and reduces water ingress into the engines (Savitsky,1964). The transition to a non-flared base towards the rear helps to reduce the drag caused by the water whilst offering high secondary stability and good rough sea performance (Savitsky, Brown, 1976)

10.0 Cargo

The ability to efficiently load and unload cargo is crucial to the seaplane's mission. This section will outline the procedures and the details of the design that allow it to operate as intended as defined in Section 2

10.1 Floating cargo dock concept

The main intention of the seaplane is to be able to load and unload without leaving the water. This was conceptualized to be possible by the use of a floating pontoon system which sits to one side of the aircraft. This is both an eco-friendly and cheap option which should be possible to incorporate into developing port systems. The pontoon system is also modular, meaning that it can be disassembled and transported by the seaplane itself which means that the idea is rapidly deployable. An example is shown below



Figure 10, Modular floating dock system (Gulfstream Docks, n.d.)

This would give a large area for ground crew to work around the aircraft as well as space for the cargo to be staged before loading or unloading. This additionally makes it easier to get the cargo from the port infrastructure to the aircraft without needing to bring the aircraft into busy waterways as the cargo can be taken to the aircraft via tugboat.

The Martin aircraft company who designed the P6M which is commonly referenced in this report also conceptualized a cargo variant of the aircraft known as the sea mistress. They also concluded that a floating docking system would be the most feasible option. The figure below shows concept art for their idea.

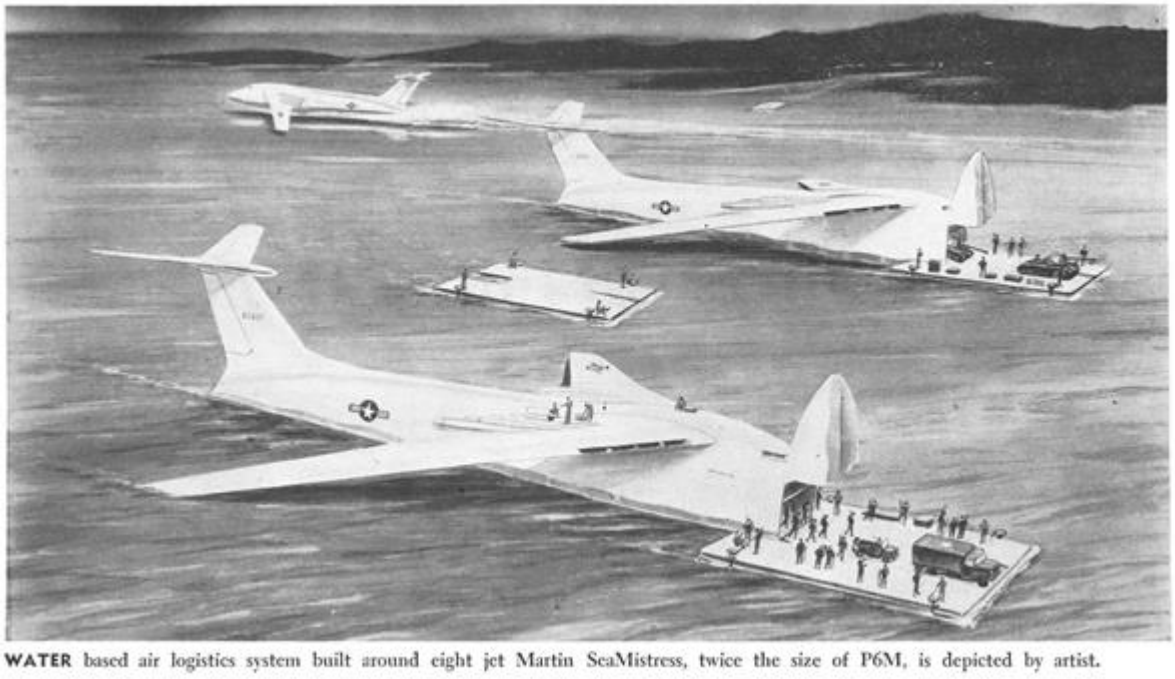


Figure 11, Martin Sea Mistress concept art (Secret Projects Forum, 2011)

Their design features an opening nose design which would allow for easier loading, but I believe the seals around that door would be susceptible to water ingress although there is no evidence to support this. For this reason, it was chosen to mount the doors above the waterline which means that a failure in a door locking system would not be as catastrophic.

The general unloading process would involve floating the platform out to a quieter area where it will not disturb other traffic, having the aircraft dock with the platform then tying the aircraft to the platform. Then work can commence, either using a tugboat to position the platform and aircraft elsewhere or unloading can begin via forklift or other industrial equipment. The cargo door will open on the side and onboard ramps can be deployed to get the forklift onto and off of the aircraft.

It is theorized that a pontoon of size 20x8m is suitable for the seaplane design. This pontoon should be able to hold up to 82,000kg of cargo which is more than enough for cargo plus the weight of forklifts and crew. This is calculated with

$$1025 \times (20 \times 8 \times 0.5) = 82000$$

Where 1025 kg/m^3 is the density of seawater and the volume is 80m^3

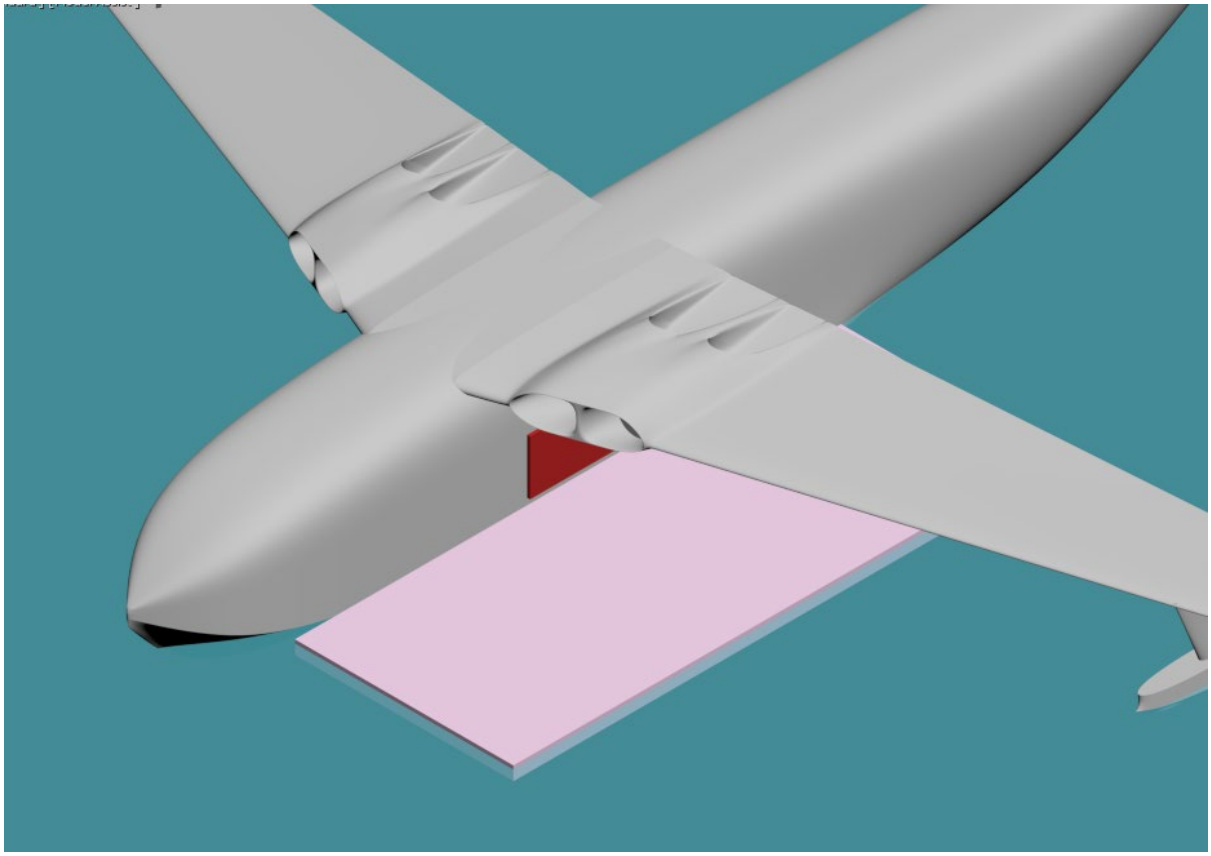


Figure 12, Concept model seaplane moored to pontoon section in pink

10.2 CG Management

The CG of the aircraft is an important factor to be considered when loading the aircraft regarding the stability and controllability of the aircraft. The Mean Aerodynamic Chord (MAC) of the aircraft is used for this calculation which has previously been calculated in Section 8.1. It is defined with the following equation

$$CG_{\%MAC} = \frac{CG_{actual} - CG_{forward\ limit}}{MAC\ Length} \times 100$$

In this case the CG envelope of the aircraft is defined to be 15-35% MAC, meaning that the aircraft will be stable when within 15-35% of the length of the MAC. The forwards limit ranges from 17% MAC at the empty weight and decreases to 9% MAC at MTOW which accounts for the additional elevator authority needed at higher weights. From this calculation, the CG envelope can be formed which is a visual way of seeing if the CG of the aircraft is in a stable location. The aft limit also changes during flight, which accounts for fuel burn compensation.

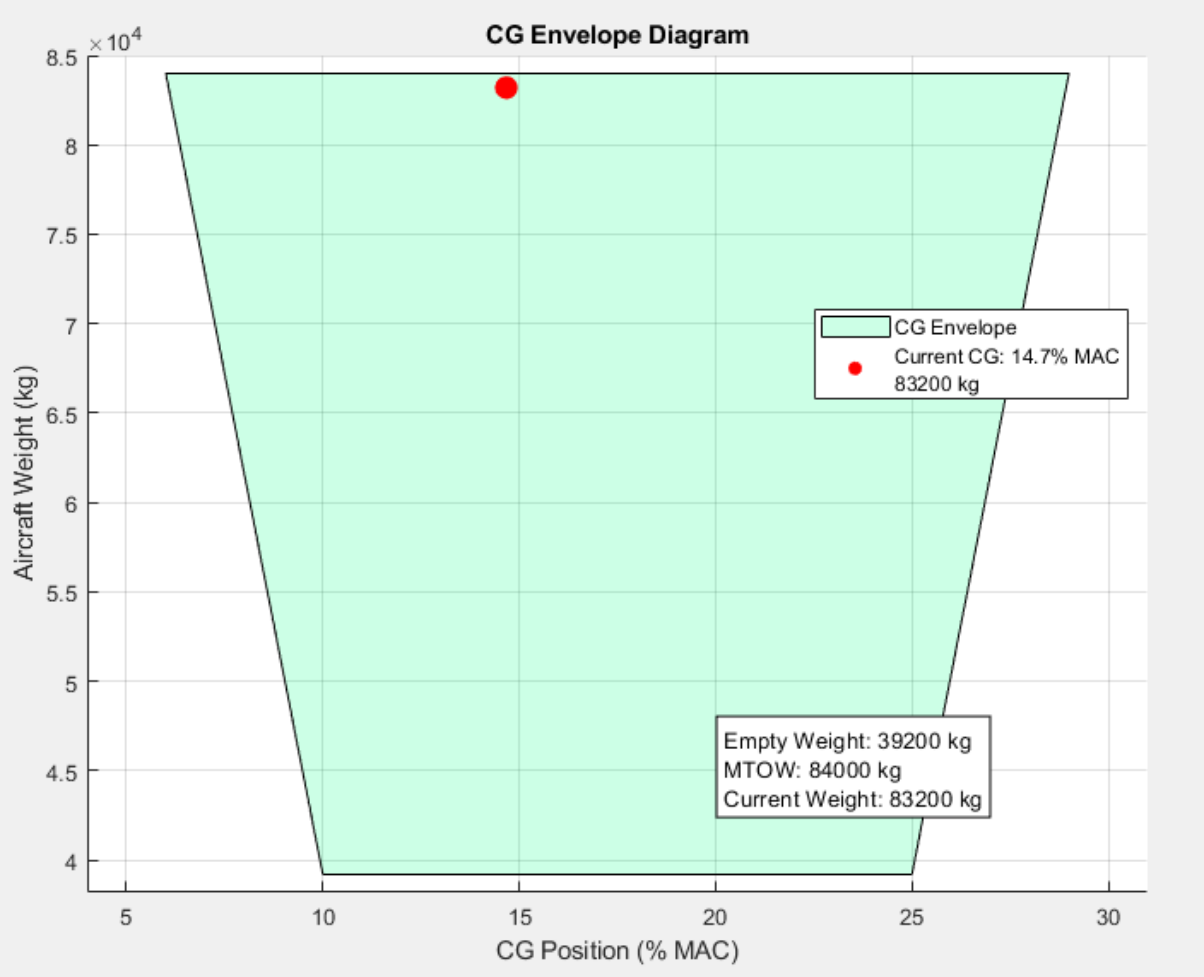


Figure 13, CG Envelope graph showing max payload max fuel

When loading, care should be taken to load the heaviest objects closest to the CG to mitigate instability. The forwards and aft limits give approximately 3m of play between the forwards and back limits. In some configurations, such as full fuel no cargo, the aircraft will be outside of CG limits (31.5% in this case) so ballast tanks should be used in order to keep the aircraft in trim. In most cases where there is cargo on the aircraft, it can be positioned in a way that there is not a need for ballast.

Flight simulator tests show that it is stable at MTOW, as shown in Section 11

The CG of the aircraft was worked out by using the location of the different components and their weight to calculate the overall CG. The majority of the weight came from the aircrafts fuselage due to the size of it, but this also includes rough estimates for the onboard systems and plumbing required to make the aircraft fly. From these values the CG could be calculated.

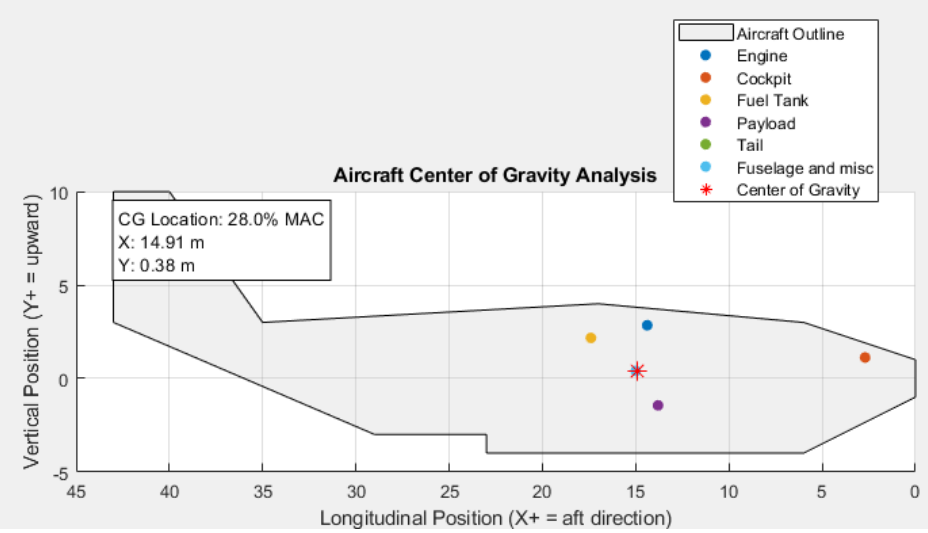


Figure 14, Rough aircraft drawing showing weight approximation

10.3 Additional considerations

The design of the cargo was such that the seaplane could be used in remote locations where not much infrastructure was available. For this reason, a sliding crane system was conceptualized which was intended to allow for loading and unloading to smaller boats or areas where the floating dock system was not feasible. These would be an option with purchase and be mounted inside the aircraft's door so they could lift cargo from the CG and use an extending arm to get the cargo outside of the aircraft. This provides alternatives to areas like disaster areas to use what little they have to unload the aircraft without need for any infrastructure at all.

Consideration was also taken for larger cargo containers as an option by making the cargo door 2x4m, which is larger than needed. This allows for a variety of air cargo containers to be loaded if needed but the idea behind using smaller AKH containers was to allow smaller infrastructure to be able to handle the cargo, where larger containers are less easily maneuvered and loaded.

It was also conceptualized that a modular type of system could be implemented with a cargo bay of this size. This would allow for more practical uses such as the implementation of a modular medical station or water tanks for firefighting. It was also conceptualized that the aircraft could be temperature regulated to allow for the storage of perishable goods such as fresh fish, but it may be more practical to refrigerate only a section with a refrigerated module.

11.0 Flight Testing

The design of the aircraft was validated using a Merlin MP521 Engineering Flight simulator. By inputting data such as wing section aero centers and weight values, the characteristics of the aircraft and its stability can be assessed.

11.1 MP521 Flight Simulator

The Merlin MP521 Engineering Flight Simulator is a versatile tool that takes the basic geometric data inputted by the user and transforms it into an aerodynamic simulation. The Excalibur editor is used for this, A simple graphical interface that allows known data to be inputted and further

allows for various aircraft types, including piston, turboprop, jet, turbofan, gliders, V/STOL, rotary-wing, aerostats, and low Earth orbit vehicles, without needing to write code. The editor will allow for nonlinear, transonic simulations in 6 DOF (Degrees of Freedom) making it a robust platform for testing aircraft designs and concepts. The simulator allows data to be exported to produce analytical data on the aircrafts stability.

The flight simulator features a capsule with all of the necessary flight controls and an instructor station where the Excalibur editor can be changed, and data can be logged and exported. The instructors station also features a rudimentary flight control system which is enough to control the aircraft without having to enter the capsule.



Figure 15,Flight simulator instructor station



Figure 16, Flight simulator capsule

11.2 Excalibur Editor

The Excalibur Editor is the key to the merlin flight simulator's success in rapid prototyping due to its sophisticated but easy to use user interface. The Excalibur software supports nonlinear, transonic, real-time six-degrees-of-freedom simulation by inputting basic parameters such as geometry of the aircraft, mass properties and aero centers which can all be found simply with calculations.

Aerodynamic data such as wings and vertical stabilizers are entered into the software as V and H Panels, using simple data such as aspect ratio and span to generate a wing and positioning it with the aerodynamic center. Controls surfaces could be added to these H and V panels using the TED (Trailing Edge Device) section which allowed for aircraft to be controlled with ailerons and elevators. The wing section for this design is split into 3 sections, Inner, Middle and Outer. The inner section features the engines, so it has no TEDs. The middle section features the flaps which are a split flap design, and the outer section features the ailerons. The horizontal stabilizer of the tail section was also entered as a H Panel. The only V Panel in the aircraft was the vertical stabilizer which works in an identical way to the H panels. The H and V panels also require an aerodynamic profile to be input, for this design NACA 2412 was chosen due to its good performance and high lift capabilities, outlined in Section 5.1

The CG of the aircraft was calculated from a combination of the aero centers and the input value for the empty weight and payload weight. The diagnostics section of the editor provided information to cross reference between the design and flight simulator such as the thrust to weight ratio and the wing loading. The CG of the aircraft could be controlled but this was not utilized during testing

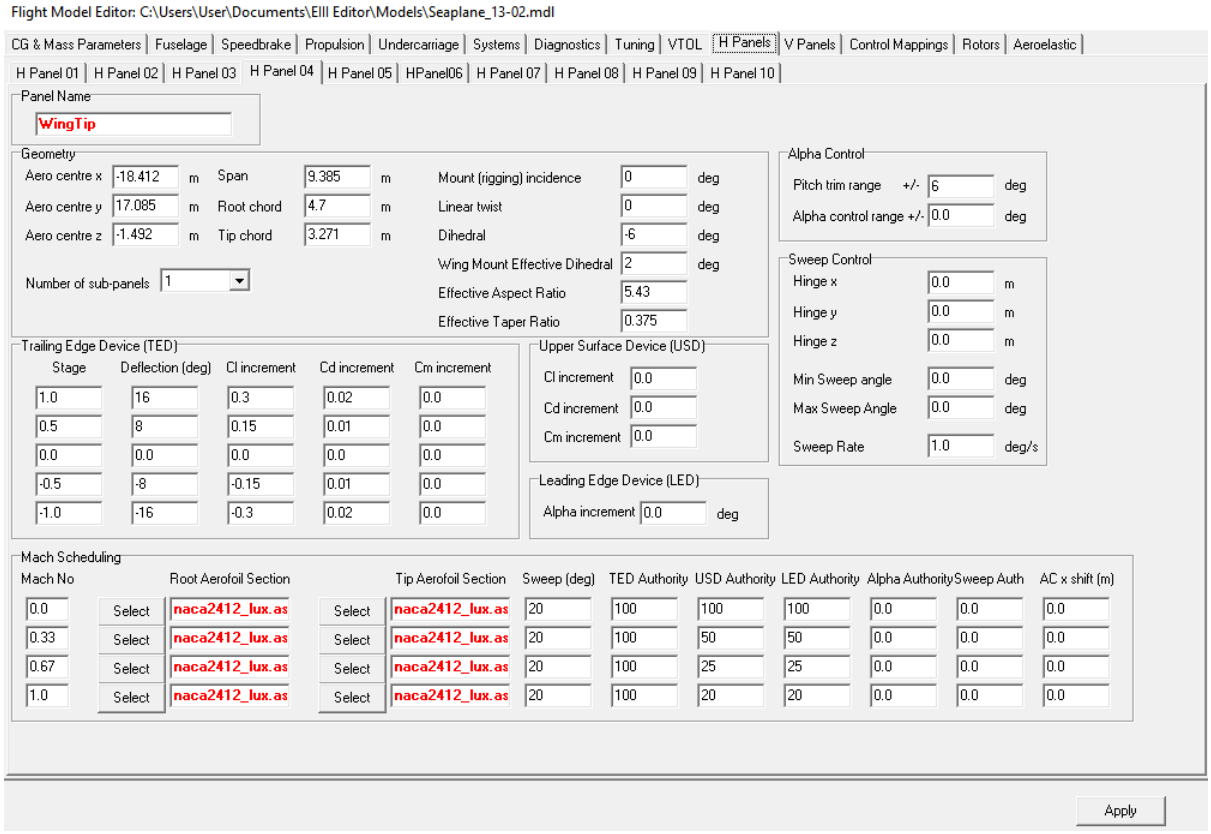


Figure 17, Excalibur editor showing the H panel data for the wingtip section

11.3 Results

11.3.1 Climb rate fully loaded

The fully loaded rate of climb was tested in the simulator. This simulates departure and validates that the climb rate is above the mandated 800 ft/min as set by EASA. The best rate of climb was found through practical evaluation for both flaps full and clean configuration. The best ROC for flaps full was 165kt IAS, at a rate of 5000ft/min at a 20 degree climb angle. The aircraft achieved 4800ft/min in the clean configuration at 17.5 degrees climb angle. This greatly exceeds the desired value of 3000ft/min.

11.3.2 Stalling

Stall speed was then tested. The stall speed was desired to be 130kts or better in a full flaps configuration. The aircraft achieved a stall speed of 132kts with MTOW in a full flaps configuration which is 1.54% greater than the desired value but still passable as a result. With 0 flaps at the same weight the aircraft achieved a stall speed of 152kts which is a satisfactory value.

The tests for stall speed were re conducted with 50% fuel and 0 payload. The stall speed for clean configuration was 122kts and 144kts for full flaps configuration.

Whilst testing the stall speed, low speed characteristics were observed. The aircraft had a very predictable and gentle stall when stalling. The aircraft was tested with turning stalls and it remained mostly coordinated without the tendency to “drop a wing”. The aircraft performed very well at low speed, showcasing good maneuverability and roll rate which are needed in seaplane operations in tight spaces such as mountains and lakes.

11.3.3 Engine out operation

The critical speed was also evaluated. This test consisted of reducing the air speed to near stalls and then cutting the throttle to two of the engines on one side to cause an instability in the yawing moment. The critical speed is defined to be the speed at which this change causes the aircraft to be uncontrollable. This speed was found to be lower than the 0-payload clean stall speed of 122kts, so the aircraft is deemed to be stable in all normal cases. Additional and more thorough testing is needed to find this speed and any sort of lateral instability.

The climb rate of engine out operations was tested as well. It was found that the aircraft could climb with full flaps on a single engine at 500ft/min but in this event, a triple engine failure would have occurred which is highly uncommon. Due to the proximity of the two engines, double engine out operations were also analyzed, and it was found with full flaps, the aircraft could climb at 195kts at a rate of 2600ft/min.

11.4 Validity

The validity of the results is worth discussing in this case. The simulator is designed for rapid prototyping work and massively simplifies most aspects of flight. The simulator lacks any sort of actual CFD or fluid dynamics and instead works off of a series of pre-determined Cl and Cd values which greatly limits the authenticity of the results. Future work should include the use of CFD or wind tunnels to validate simulator and calculated data.

The simulator works well to test different CG loadings and how payload affects flight characteristics and provides a quick and easy way to verify if an aircraft could fly.

12.0 Discussion

This cargo seaplane combines historic techniques of seaplane design with modern materials and modern objectives to form a versatile multirole transport plane.

The choice of a high wing anhedral and the wing profile NACA2412 provides a aircraft with stable slow speed characteristics which are crucial for seaplane aircraft that can commonly be used in tight environments. The anhedral design both drops CG to improve waterborne stability and trades roll stability for instantaneous maneuverability. The design incorporates retractable wingtip floats, inspired by the PBY Catalina, this gives a reduced drag in cruise and stabilizes the aircraft giving the aircraft a positive hydrodynamic stability. The design also incorporates the use of modern materials such as Carbon Fiber Reinforced Polymers and titanium which are less susceptible to corrosion than historical materials, increasing longevity and allowing for frequent operations in remote areas.

The flight simulator's results verify that the aircraft has an exceptional climb rate of 4800-5000 ft/min (Section 11.3) which greatly exceeds the EASA mandated 800ft/min, allowing for rapid obstacle clearance which is necessary in areas such as fjords and lakes where the aircraft could be operating. The stall speed of 132kts is marginally higher than the expected value of 130kts, highlighting the potential for optimization in low lift device design.

The BR715 engines, selected for their high thrust output and short field performance, align well with the missions goals and provide enough thrust for a thrust to weight ratio of 0.45, enabling the high climb rates previously discussed. The engines placement close to the wing root provides great stability in engine out operations but limits low speed water maneuverability using differential thrust.

The hull design incorporates a low spray hull with instabilities with a medium spray but extremely stable hull design to provide a low spray, stable hull design with high efficiency. The design relies on wingtip floats but the low-speed aerodynamics of the aircraft quickly mitigates the need for these when accelerating for takeoff.

It is noted that the design has its limitations. One such limitation is rough sea conditions may cause the aircraft to be grounded until conditions improve but this is a drawback will all seaplane-based aircraft. This design specifically may be more susceptible to large waves due to the anhedral wing bringing the wingtips down and closer to the water. The wingtip floats were designed with this in mind and have been spaced as far apart as possible to prevent capsize.

The floating dock system offers practical and rapidly deployable solutions remote logistics. This solution does however overlook the logistical challenges of tugboat availability and training in situations such as disaster relief. The proposed crane idea in section 10.3 mitigates this but needs further investigation and analysis for its weight, complexity and usefulness.

The reliance on the Merlin MP521 simulator highlights possible future work. The simulator utilizes maths-based equations for flight dynamics which provides a good platform for rapid prototyping but limits the accuracy of the results. Future work should include CFD for both

hydrodynamics and aerodynamics which would allow for spray simulations and in-depth hydrodynamic stability and aerodynamic analysis.



Figure 18, Seaplane design render over Artic islands

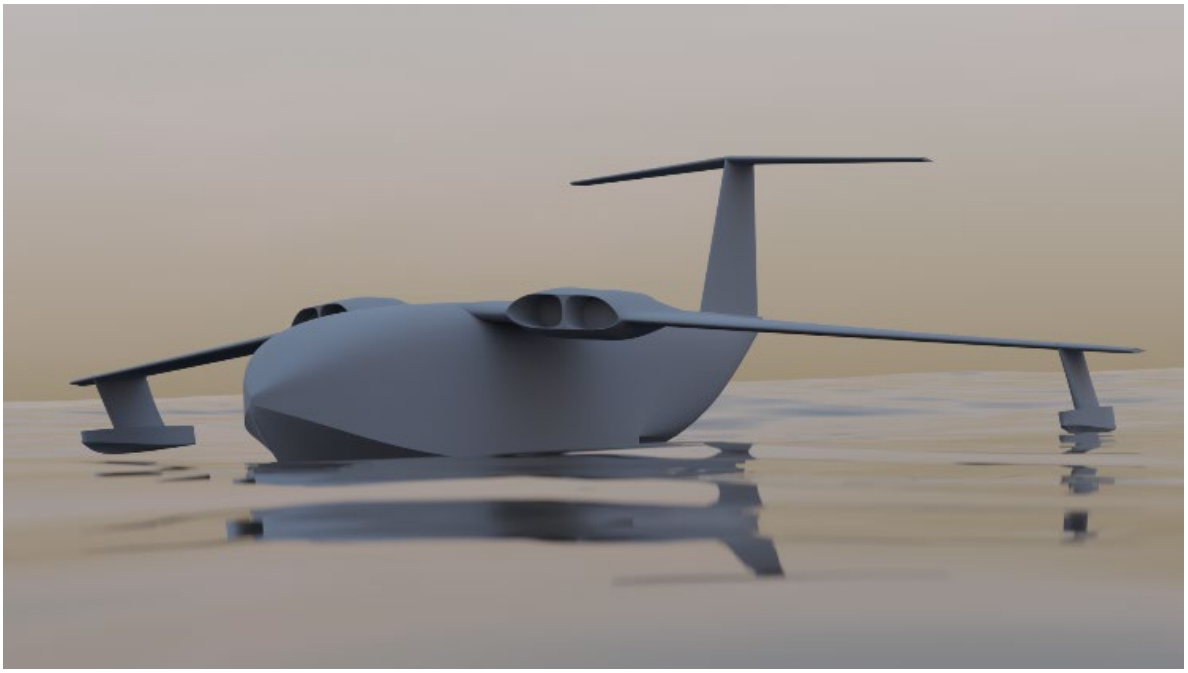


Figure 19, Seaplane design on water with wingtip floats extended

13.0 Conclusion

The seaplane design of this dissertation addresses a crucial gap in a growing market for faster global logistics. The quick transportation of global cargo to infrastructure limited communities is an untapped market which could benefit millions of people. This study highlights the feasibility of a seaplane that's capable of bridging the gap in logistics between cargo hubs and communities.

This dissertation achieved the goal of making a conceptual cargo seaplane and demonstrated its practical use in places such as the Artic and Pacific islands. The aircraft can carry up to 22 AKH cargo containers or 22 tons of cargo and meets all safety requirements such as minimum climb rate and buoyancy, this is further validated by simulator data and testing. The aircraft provides a stable but agile base platform to transport cargo and also a solution to loading and unloading in remote locations where infrastructure is not common. The hull design incorporates a hybrid design, giving the pilot a high visibility, low spray but stable aircraft on water. The use of floating docks reduces the costs for all parties involved and saves costly runway maintenance and fees.

In the future, it would be beneficial to run the aircraft through CFD to validate the aerodynamics and hydrodynamics of the design. This could be evolved into real world testing with models such as RC models or practical models to test against seawater corrosion. It would also be beneficial to model the aircraft in a more complex simulator environment where phenomenon like P factor exist. The MP521 is great for rapid prototyping but lacks in depth simulation.

In conclusion, this study revitalizes the seaplane as a viable option in modern logistics by combining historical lessons with current technologies and safety standards. The report addresses both technical and operational challenges and paves the way for a new era of sea plane designs and development.

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