The “SeaStryder” Hydroplaning Floatwing Aircraft

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Abstract

The SeaStryder is an entirely new approach to sea plane design by Aquavion Aircraft Ltd. It was designed as a multi-role, tandem wing, amphibious aircraft that has application in the general, commercial and military aviation market segments. This aircraft uses partial submergence of the front wing for static buoyancy and lateral stability while in water displacement mode and when underway, the bottom of the front wing as a dynamic hydroplaning surface. The wing has been shown to behave well hydro-dynamically and during its take-off run it begins to hydroplane quickly. This quick hydroplaning action results in a takeoff run that is typically 1/3 that of contemporary seaplanes, resulting in significant fuel savings for the run-up portion of the flight.

Introduction

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The basic design concept has evolved into a series of “Stryder” designs, the Stryder200, Stryder600 and Stryder6000. The first two are general aviation designs and the latter is designed for commercial transport of passengers or goods in ground-effect mode or at altitude. One general aviation version of the aircraft is the Stryder600RV which is a recreational aircraft with on-board living facilities. It will accommodate 4 people and includes berths, head/shower combo, small galley and stand-up headroom. Once arriving at a water destination, the Stryder600RV converts to a very low drag power boat with a typical water resistance coefficient of 0.002 when hydroplaning. As a result, it consumes considerably less fuel than that of a standard power boat of the same installed horsepower at the same hydroplaning speed.

A full size prototype version of the Stryder200 aircraft is under construction in preparation for evaluation before proceeding to the Stryder600.

Mission Statement and Choice of Configuration

Choice of an aircraft configuration for a preliminary design involves the selection among many possible, at times disparate, choices to achieve the mission statement of the design. Access to highly sophisticated evolutionary algorithms to automatically and optimally make these choices is usually limited to the proprietary files of the major aircraft manufacturers. Without access to these applications, the designer must resort to iterative applications of their experience and current level of knowledge and awareness of past and contemporary technological approaches to aircraft design. The configuration selection journey can be a long and torturous route to final selection but still an exciting one none-the-less.

For the SeaStryder, this amounted to consideration of approximately 50 possible configurations before the present configuration was finally selected. The mission statement of course, preceded the selection process and was specified as follows:

The Stryder600RV aircraft would perform the following **mission**:
Provide a cross-country, amphibious, general aviation aircraft with on-board living accommodations, with 6000lb maximum takeoff weight, with a range of 600 to1200 nm (depending on payload and fuel fraction) and a cruise velocity of at least 200 mph at any altitude up to 10,000 ft maximum operational altitude. The takeoff distance of the craft from water will be less than 1/3 that of contemporary seaplanes under identical weight, wind and wave conditions and the overall aircraft drag coefficient should be at least ½ that of contemporary seaplane designs.

The aircraft would provide the following **functions**:

1. The aircraft will provide both a recreational boating mode and flight mode of operation, with stand-up headroom of 6 ft. 4 in.,
2. In boat mode, the aircraft will provide living accommodations for up to 4 people with 1 week food supplies on board,
3. The aircraft will provide live-aboard utilities including a washroom/shower combo, kitchenette with food preparation counter, refrigerator, air conditioning unit, water filtration, sterilization and desalination plant (boat mode), berths for 4 people and a gas generator capable of supplying all electrical loads combined,
4. In flight mode, passengers will be able to safely walk to and from either the cockpit area or the rear cabin area to the centrally located washroom and kitchenette area without exceeding the cg limits of the aircraft while under manual or autopilot control,
5. In boat mode, the craft will be able to maneuver safely in waves up to 2 ft significant wave height with a continuous, maximum hydroplaning speed of 80 mph wave conditions permitting,
6. In flight mode, at a takeoff speed of 86 mph indicated, the craft will be capable of flying in ground effect indefinitely under autopilot control and then climb to altitude at will (IMO class C ground-effect craft).
7. The craft will incorporate electronic servo fly-by-wire with all-glass cockpit MFD’s both primary and backup for both front seats,
8. The aircraft will be designed to be offered as an experimental kitplane or as a fully certified aircraft.

The focus of the mission statement is on the extended utility of the aircraft particularly when in boat mode. This is what distinguishes the SeaStryder from its competition. No other current seaplane is purpose-built to include the added value of the live-aboard utility to be offered; in particular, the washroom facilities and especially the stand-up headroom in an aircraft in this weight range. To be able to stand up on a long flight to simply stretch or make a sandwich or use the washroom is unheard of in contemporary general aviation (non-military) seaplanes of this size.

To achieve the above mission statement and provide the listed functionality required the usual tradeoffs between utility and performance but in the classic case of a seaplane, there is the not-so- insignificant additional challenge of achieving the necessary water performance without severely compromising the aerodynamic performance.

For the SeaStryder, the objective became one of maximizing internal fuselage volume to allow the sought-for added utility and attempting to remove all the usual trappings of traditional seaplanes that contribute to their overall lack of efficient flight. These “trappings” include the use of outboard wing floats and their associated support structures, under-slung hydroplaning floats with their associated drag-laden support structure as used in standard floatplanes, low aspect ratio “sea wings” used to provide lateral stability on the water which suffer from significant shed-vortex drag and, up-swept rear fuselage drag as found on standard flying boat designs. In addition to these, there are the various forms of drag produced due to the many "chines" and spray dams used on traditional flying boat hulls to keep generated spray away from engines, props and flight control surfaces.

However, one of the most significant sources of drag in traditional seaplanes is that due to the hydrodynamic "steps" that are used to break water surface suction allowing takeoff to occur. In particular, the step employed on the bottom of the hull of a flying boat or on the bottom of the twin floats of a standard floatplane, contributes an additional 20 to 40% (depending on step design) increment in fuselage hull or float drag due to the continuously shed vortex produced by these structural discontinuities while airborne. It became a major objective to eliminate this form of drag in the SeaStryder configuration.

Insight into how to accomplish this came from viewing historic footage of early floatplanes that used the trailing edge of the floats to achieve the function of the traditional "step", the latter innovation being introduced by Glenn Curtis in the early 1900's. This, coupled with the insight gained by noticing how ditching low-wing aircraft would hydroplane on their wing for short periods before usually going nose-over and then rebounding back to the surface into displacement mode prior to sinking, inseminated the idea of using the wing as a hydroplaning surface and the trailing edge of the wing as the "step", and hence, the **Hydroplaning Floatwing** concept was born.

In this way, static displacement buoyancy, lateral hydrodynamic stability, hydroplaning surface and hydrodynamic step functions were embodied in one component only: the wing. The bonus was that the trailing edge of the wing provided a natural step function as well as its intended aerodynamic function and yet no additional shed vortex was produced when airborne; the added drag of the step had been eliminated.

Building on this concept, and aiming for a STOL performance that would reduce takeoff run to 1/3 that of contemporary seaplanes, it was noted that most of the takeoff run of traditional seaplanes involved transitioning from displacement mode to hydroplaning mode before finally achieving the commencement of the acceleration-to-takeoff portion of the run-up. Takeoff run-up distances of 1800 to more than 2000 ft. and run-up times of 30 seconds to minutes are not uncommon depending on aircraft wing and power loading. It was soon determined that the low hydrodynamic L/D ratio of the flying boat hull or floatplane float and the large surface suction and hydrodynamic skin friction drag of the hull or floats during the initial displacement mode though transition to commencement of hydroplaning, were responsible for the protracted time and distance needed for takeoff. The insight obtained here was to achieve a large hydrodynamic lift at low speed to lift the aircraft's fuselage as clear of the water as possible to minimize skin friction drag and surface suction during the transition phase. This would quickly put the aircraft into the hydroplaning phase and begin the acceleration phase to liftoff, very much sooner in the takeoff run. This is the big advantage of the Hydroplaning Floatwing concept employed on the SeaStryder.

At maximum takeoff weight and at rest in the water, the front wing of the SeaStryder sits with an angle of attack relative to the water surface of approximately 11 degrees. The wing is partially submerged with the waterline extending on the top of the wing approximately 2/3 of the way from the trailing edge to the leading edge at the root chord and laterally along the trailing edge to the polyhedral joint on both sides of the front wing (as shown in Fig.1), forming a triangular patch of displacement water. A similar triangular waterline exists on the underside of the wing. A portion of the rear end of the fuselage is also immersed providing counterbalancing moments while at rest. The rest of the fuselage is completely free of the water. At this angle of attack and submersed wing area, a hydrodynamic L/D ratio of about 4 is obtained in a fluid whose density is about 800 times that of air. This submersed portion of the wing amounts to an initial static configuration of an almost hydroplaning hydrofoil, since the limiting case of hydrofoiling is hydroplaning. This results in a large hydrodynamic lift being generated at low forward

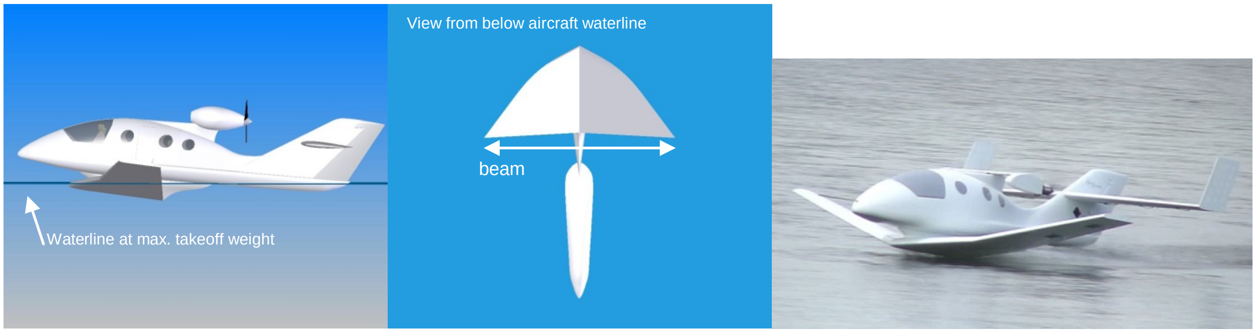

Fig.1 Displacement mode and Hydroplaning mode of Stryder600 aircraft

speed, ultimately lifting the fuselage and its tail end entirely free of the water and thus significantly reducing the transition time to begin the hydroplaning phase of run-up. Once the SeaStryder is hydroplaning, aerodynamic lift begins to build with hydrodynamic lift provided by an ever smaller triangular patch of water until liftoff occurs at which time all the full weight is supported by the wings.
In order to achieve this initial angle of attack while at rest in the water and in order to keep most of the fuselage free of the water during transition, it was decided to mount the front wing on a pylon connecting the bottom of the fuselage to the front wing as shown in Fig.1. This arrangement has several advantages but also a few disadvantages.

The advantages are:
1. The required angle-of-attack (AoA) is obtained for quick transition,
2. The wing does not pass through the fuselage thus maximizing useful payload volume,
3. The wing is easily detached (6 bolts) allowing for aircraft transport on a trailer or storage in a driveway or hangar,
4. The wing is easily replaced if damaged beyond repair,
5. The pylon volume can be used for additional fuel storage.

The disadvantages are:
1. A smaller section modulus of the pylon puts higher bending moment stresses at the fuselage/pylon connection than if the fuselage were connected directly,
2. The merging of two adverse pressure gradients between the upper surface of the wing and the side surface of the pylon whose planform cross section is also an airfoil, may lead to flow separation issues possibly requiring installation of vg's to prevent separation.

Since the advantages far outweighed the disadvantages, the wing pylon feature was retained.

Choice of engine mounting provided additional opportunities to improve the performance and utility of the SeaStryder. Since both twin engine and single engine options were to be offered, and again, to maximize access to the internal volume of the fuselage for utility features, a universal engine mounting pylon was incorporated about midway along and at the top of the fuselage. This allowed for a single pusher prop to swing in the space between the end of the cabin and the beginning of the vertical stabilizer as shown in Fig.1 as well. The single engine will likely be a Pratt & Whitney Canada PT-6A turboprop (with constant speed props) delivering 600HP in the pusher configuration as similarly employed in the Piaggio Avanti aircraft installation.

The twin engine version will consist of a stub wing mounted on the universal engine mount pylon supporting at each end either twin piston engines of 300HP each or twin turboprops with constant speed props (see Fig.2). The added advantage of the twin installation is the increased maneuverability provided on the water where differential pitch control can be used to provide the turning power needed over and above the air rudders at the lower hydroplaning speeds. The twin installation also increases the safety aspect of the aircraft in the case of one engine inoperative situations arising. Because the thrust-lines of both engines in the this configuration are a little more than one propeller diameter distant, operation on one engine should occur right down to touchdown even on the critical engine.

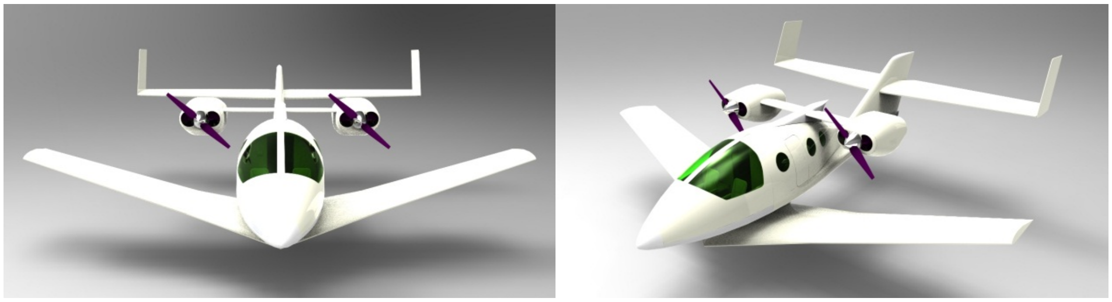

Fig. 2 Twin Engines on Stub Wing

An additional advantage of the twin installation using the stub wing mount is the ability to install the engines below the stub wing thus significantly lowering the thrust-line and putting it closer to the drag-line of the aircraft. This reduces the tendency of the aircraft to nose-over when full power is applied on a go-around landing attempt for example. The front wing of the aircraft acts like a huge spray dam while hydroplaning keeping water spray away from the engines and props and allowing a lower thrust-line installation for the twin option.

Maintenance of the engines is facilitated by the modularity of the single and twin plants through their common connection to the universal engine mounting pylon. Quick disconnect fuel lines and electrical connectors will allow removal of either power module for immediate replacement or overhaul on a separate test bed although the engines may also be serviced while mounted on the aircraft.

Drag Coefficient

At this point in the development of this aircraft, the overall drag coefficient of the plane has not yet been determined other than some initial estimates using standard drag build-up procedures available to the designer. The ¼ scale aircraft is scheduled to be wind tunnel tested in the large University of Ontario Institute of Technology (UOIT) full scale all-climate wind tunnel facility located in Oshawa, Ontario. Flow visualization studies and force balance measurements will be made. Addition of vortex generators and stall strips if required will be implemented based on the wind tunnel results. These results are to be published in a subsequent paper.

Hydrodynamic Performance Data Analysis

In order to determine how the Stryder will perform compared to conventional aircraft; it was benchmarked in three categories. The first category is distance required to take off at full throttle. The lower the take-off distance is, the more operationally flexible an aircraft becomes. A low take off distance allows the aircraft to operate in a greater range of environments such as small lakes and narrow rivers.

The second category for comparison will explore the drag to weight characteristics of the aircraft as it accelerates to take off velocity. The advantage of this comparison is that it provides insight into the hydrodynamic behaviour of the novel Stryder configuration and allows for a direct graphical comparison between the Stryder and flying boats as well as float planes.

Finally a comparison of energy expenditure of the aircraft during take-off will be performed. A large portion of the energy expended by aircraft occurs during the take off stage. This comparison will determine if there are energy savings associated with the new design and if it can be competitive with conventional seaplanes.

Experiments

Testing was performed on a quarter scale model of the Stryder. The model is instrumented with several data acquisition and telemetry systems. On-board there is a global positioning system (GPS) used to measure position, ground speed and altitude. There are also instruments used to measure and record voltage and current applied to the motors in order to calculate power. Recordings are also made of the propeller's rounds per minute (rpm) and a Pitot tube is used to measure airspeed. All these readings are collected by a data acquisition system from Eagle Tree Systems of California.

During the testing four different runs were performed at different power levels. The remote control provides power to the motors from the batteries in proportion to the number of "clicks" that the throttle is moved forward. A click is the smallest step change in power given by the batteries that the remote control can provide. This can also be thought of as the remote control's resolution. One run was performed at 6 clicks, two were performed at 8 clicks and a final run was performed at the maximum of 12 clicks.

In each of these controlled experiments the data acquisition system was turned on as the Stryder sat idle in the water. Then power was applied to the motors driving the propellers using the controller to a fixed number of clicks for the duration of the run. The aircraft was allowed to proceed forward and hydroplane until just before lift-off occurred, at which point power on the throttle was turned off and the aircraft came back down into the water and slowed to a stop, completing the run.

Separate "moving-vehicle wind tunnel" experiments were performed to generate values for static and dynamic thrust characteristics of the propellers. The motor was mounted onto a carbon fibre plate with a strain gage apparatus. Known forces were applied to the apparatus and a relationship between strain gage voltage and force was generated. The thrust generated by the propeller was then determined in both the static and dynamic cases through strain gage voltage readings.

The results of these experiments are values for velocity, strain gage voltage, motor voltage and current, and propeller rpm. From these base values, information about thrust and power output can be determined. This information along with other measured properties of the Stryder such as mass and physical dimensions can be used to describe the characteristic behaviour of the Stryder and compare it against other seaplanes and vehicles.

Data Analysis

Distance to Take-off

To begin, we plotted the velocity of the quarter scale Stryder during the full throttle run up against time. The resulting curve allowed us to identify three distinct regions of acceleration.

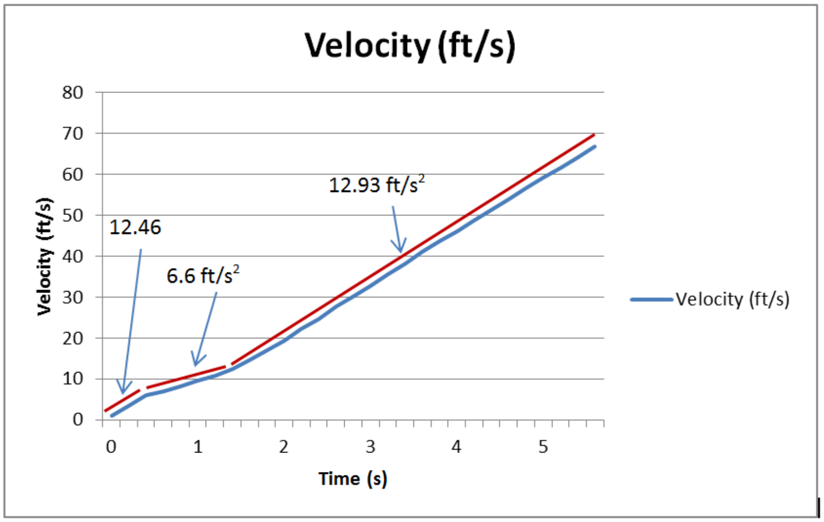

Fig. 3 Velocity vs. Time for Take-off Run

Take off distance of the full scale Stryder was calculated with constant acceleration equations, using the constant acceleration calculated for each of the three stages of the run up and the scaling factor. The equation $\int v\,dt = \int (v_i + a\Delta t)dt$ is used to calculate the distance traveled by the full scale Stryder.

Time, Velocity and Acceleration of the 12 Click Run (Unscaled)				
Time (s)	t_0=0	t_1=0.6	t_2=1.6	t_3=5.6
Velocity (ft/s)	0	7.04	14.67	-
Acceleration (ft/s^2)	0	12.47	6.60	12.93

The time at t_3 is where lift off occurs. To get the appropriate values for the full scale aircraft, the time and velocity are scaled by the scaling factor $\lambda^{1/2}$, while acceleration remains constant when scaling. The full scale Stryder is 4 times larger than the model, so λ is equal to 4.

Time, Velocity and Acceleration of the 12 Click Run (Scaled)				
Time (s)	t_0=0	t_1=1.2	t_2=3.2	t_3=11.2
Velocity (ft/s)	0	14.08	29.34	-
Acceleration (ft/s^2)	0	12.47	6.60	12.93

Using these values and the constant accelerations for each of the three stages of flight, the total distance will be the summation of the three distance calculations:

$$S_{total} = \left[v_0\Delta t + \frac{1}{2}a_1\Delta t^2\right]_{t_0}^{t_1} + \left[v_1\Delta t + \frac{1}{2}a_2\Delta t^2\right]_{t_1}^{t_2} + \left[v_2\Delta t + \frac{1}{2}a_3\Delta t^2\right]_{t_2}^{t_3}$$

$$S_{total} = 8.98 + 41.36 + 648.48 = 698.82ft$$

Drag Behaviour

Knowing that the mass of the Stryder is 89.3lbs we calculated the net force generated at each of the three stages of acceleration using the following equation: $F = m \times a = \frac{F_w}{a_g} \times a$, where F_w is 89.3lbs, a_g is 32.174ft/s^2 and a is the acceleration experienced during each stage of the run up.

The thrust force was determined using a calibration curve that related force to strain gage voltage readings. Power was then applied to the motor with the Stryder held stationary, driving the propeller and generating strain gage voltage readings that could be related to force values. The relationship between power provided to the motors and thrust generated by the propellers during the run up could then be determined.

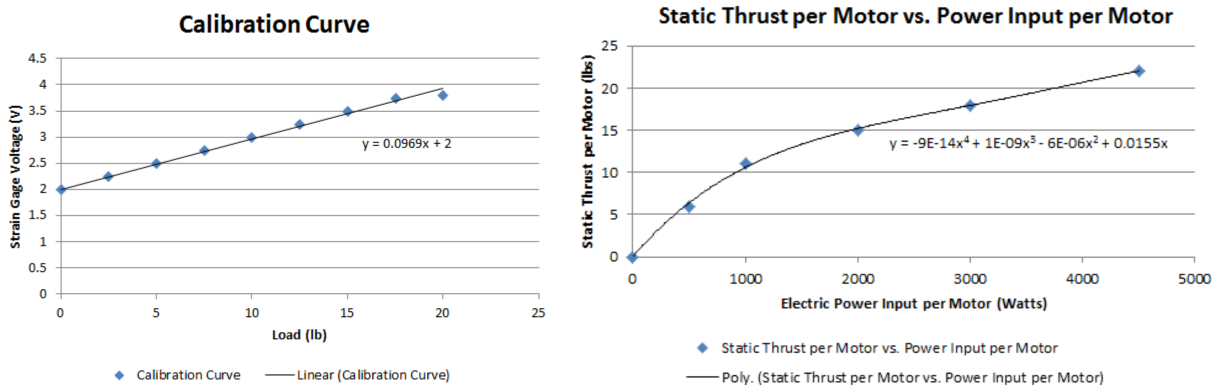

Fig. 4 Curves for Determining Power Input to Thrust Relationship

However, since the Stryder was held stationary it is important to note that a static thrust curve may not be valid in describing behaviour of the aircraft while it is in motion. This is the case when propeller thrust decreases with an increase in aircraft speed. However, many fixed-pitch propellers are designed for high speed flight and operate at increased efficiency at increased speeds. By calculating the thrust coefficient, power coefficient and advance ratio we determined that the efficiency of our propeller increases with an increase in flight speed. This means that our static thrust calculation will not overestimate the thrust generated and is an acceptable calculation method. Data from our moving-vehicle wind tunnel testing confirmed this result and showed almost constant thrust during the run-up phase.

Given values for thrust and net force, the resistance can be calculated as the difference between thrust and net force: $R = T - F$. With values for the resistance force experienced by the Stryder a dimensionless coefficient of resistance can be calculated and used for scaling. However the resistance used in calculating this coefficient can only come from waving making resistance and thus aerodynamic drag must be removed. The aerodynamic drag was calculated using the following equation at each point of the run up: $F_{AD} = \frac{1}{2}v^2 A\rho C_{AD}$. In this equation *v* is velocity at each point, *A* is the projected wing area, 26.8ft, *ρ* is the fluid density, 0.0023769slugs/ft^3, and C_{AD} is the coefficient of aerodynamic drag, 0.03, determined through wind tunnel testing. Once the aerodynamic drag force was removed from the total resistance the coefficient of resistance was calculated using $C_R = \left(\frac{R}{wb^3}\right)$, where *R* is the wave making resistance at each point, *w* is the specific weight of sea water, 64lb/ft^3, and *b* is the beam width at 3.5ft.

Once C_R is calculated it can be rearranged to solve for scaled values of resistance as according to Froude scaling laws C_R remains constant when scaling. Rearranging the equation to solve for R we get: $R = C_R wb^3$ where the value for *b* scales according to $l_F = l_M \times \lambda$. In this equation *F* and *M* represent the full scale and model respectively and the scaling factor, λ, is 4.

The scaled aerodynamic drag can be calculated using the same equation as before: $F_{AD} = \frac{1}{2}v^2 A\rho C_{AD}$. Except substituting velocity and projected wing area values using scaled values through the following two equations: $v_F = v_M \times \lambda^{\frac{1}{2}}$ and $A_F = A_M \times \lambda^2$.

The total drag is then the sum of the scaled waving making resistance R and aerodynamic drag F_{AD}. The drag to weight ratio can then be calculated as $\frac{D}{W} = \frac{R+F_{AD}}{m_F}$ where m_F is the full scale mass equal to: $m_F = m_M \times \lambda^3$. These values can be plotted against the Froude number, determined through: $Fr = \frac{v}{\sqrt{gL}}$ where v is the scaled velocity, g is the force of gravity at 32.174ft/s^2, and L is the scaled beam width. The resulting curve can be seen below alongside the drag to weight characteristics of typical flying boats and aircrafts with floats. Beside that is a comparison that also includes behaviour of round bottom motor boats and speed boats [1].

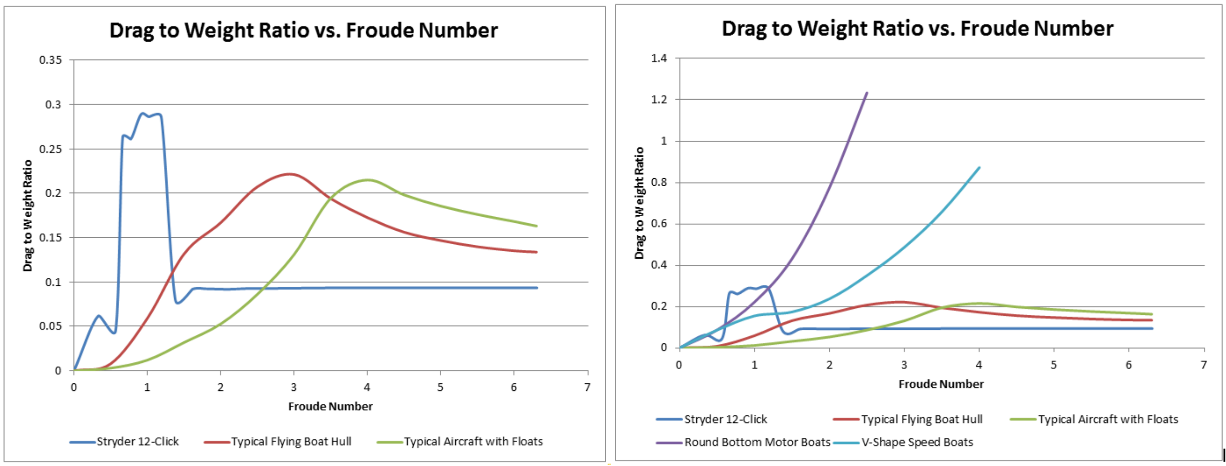

Fig. 5 Drag to Weight Ratio vs. Froude Number for Various Seaplanes and Vehicles

Energy Comparison

In making a comparison of the potential efficiency between the Stryder and conventional aircraft we will use the drag to weight vs. Froude number curves.

The integral of the D/W curve can be expressed as: $\int \frac{D(F)}{W} dF = \frac{1}{W}\int D(F)\,dF$.However, since $F = \frac{v}{\sqrt{gL}}$, the expression can become: $\frac{1}{W}\int D\left(\frac{v}{\sqrt{gL}}\right)\cdot\left(\frac{dv}{\sqrt{gL}}\right)$. This can be rearranged to yield: $\frac{1}{W\sqrt{gL}}\int D\left(\frac{v}{\sqrt{gL}}\right)dv$. Since power can be expressed as $P = Fv = Dv$, where $dP = D(v)\,dv$ then it is clear that integration of the left side of the equation with respect to Froude number is equivalent to integration of all the power differentials over all velocities encountered in the run-up as indicated in the right side of the equation. This will be representative of the total power required by each type of aircraft over all velocities and thus proportional to, but not equal to, total energy consumption during the take-off run.

A summation was performed to find the area under each curve using the following equation: $\sum \frac{F_2 - F_1}{2} \times \frac{\left(\frac{D}{W}\right)_1 + \left(\frac{D}{W}\right)_2}{2}$. A sum of 0.338 was obtained for the Stryder, a sum of 0.438 for a typical flying boat and a sum of 0.368 for a float plane. These values can be represented as figures of merit defined by $FOM = 1 + \frac{\sum_B - \sum_x}{\sum_B}$, where $\sum_B$ is the summation for the baseline aircraft which will be the flying boat in this case and $\sum_x$ is the summation for the aircraft being compared. The value for the typical flying boat being used as the baseline will be 1, the typical float plane has a value of 1.16 and the Stryder has a value of 1.23. This means that the Stryder should be approximately 23% more efficient than the flying boat and 7% more efficient than the floatplane for run-up energy expenditure at all velocities encountered in the run-up.

Discussion

From these results we see a take-off distance of about 700ft for the scaled Stryder. This compared to contemporary seaplanes is a very favourable figure. In comparison the Turbo Beaver and the Be-103 both require a run up distance greater than 1500ft for take-off [2][3]. The advantage of this for the Stryder is the flexibility of operating in more limited aquatic environments than contemporary seaplanes.

The resulting drag to weight (D/W) curves reveal some interesting characteristics. The Stryder has a higher D/W compared to contemporary seaplanes at low Froude numbers however this higher D/W occurs over a short range of Froude numbers between 0 and 1.5. Past this region of high D/W it has a much lower D/W ratio than other seaplanes and this continues until lift off. The rapid reduction in D/W is the stage where the hydroplaning action of the Stryder begins. In other seaplanes there is a more gradual increase of D/W which continues until higher Froude numbers of 3 to 4 after which there is a small reduction and plateau in D/W until lift off.

The quick hydroplaning action of the Stryder at low Froude numbers and the low D/W ratio opens up the interesting possibility of using the structural design choices in boating applications. To this end, a graphical comparison is presented between the D/W behaviour of the seaplanes including the Stryder and the behaviour of round bottomed motor boats and v-shaped bottom speed boats. Both types of boats experience large D/W ratios especially at high Froude numbers, an improvement in this area might be possible through the design of the Stryder.

The energy comparison using FOMs shows a potential reduction in energy expenditure during the run up to lift off compared to contemporary seaplanes. The reduction is mostly likely accounted for in the quick hydroplaning action of the Stryder giving it the advantage over other seaplanes. With a large portion of aircraft operating costs being the cost of fuel, these initial results look promising for the Stryder.

Conclusion

Additional improvements in performance can be made through the use of variable pitched propellers which can be rotated axially to increase the efficiency of the propeller at various speeds. Other improvements include: the addition of winglets, which will reduce wingtip vortices and reduce drag, the use of leading edge slats to reduce stall speed by delaying boundary layer separation, and using ailerons and wing flaps to increase lift generated.

Without these additions the Stryder still compared very favourably to contemporary seaplanes in each of the areas it was benchmarked in. While the tests and analysis performed provided good first estimates further testing is required to confirm these initial results. Aquavion is currently exploring options on gaining further access to wind tunnel testing facilities.

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