COMBINED FLIGHT DYNAMICS OF SEAPLANES WITH HYDROFOIL LANDING GEAR

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Abstract

Sailboats for professional races and a growing number of water-sports devices are using hydrodynamically active surfaces (Hydrofoils) to create lift and reduce drag. Seaplanes and amphibious aircrafts can use a system of Hydrofoils, functioning as hydrodynamic landing gear, to remove the need for additional floating devices or a boat shaped fuselage of the aircraft. This leads to new design and configuration options for seaplanes and amphibious aircrafts – something which has not really changed since the beginning of flying. In the following, the preliminary design process of using hydrofoils as landing-gear on aircraft is specified, focusing on forces and momentum during take-off.

1. INTRODUCTION / BACKGROUND:

The currently used seaplanes are based on floats or on boat-like fuselages which can be used to take-off and land in water (Figure 1).

Figure 1: DHC-6 Twin Otter[1] (top); Flywhale[2] (bottom)

As Investigated by *Parkinson* [1] seaplanes have limited abilities in wavy water, since waves strike against the hull and cause large impacts, forces and moments on the structure. During take-off and landing, the seaplane can be subjected to strong and uncontrolled wave motions and winds which greatly affects aerodynamics on the wing and the overall drag, which is undesirable in these critical phases [2]. Overall drag can be up to 65% higher with waves than without waves [3]. In addition, splashing water leads to considerable losses in aerodynamic performance [4] and changes in the pressure distribution [5] and momentum [6]. Other effects of spray water on aerodynamic surfaces are summarized in [7]. Waves hitting the floats can cause high, irregular forces and moments which have to be compensated by the aircrafts control surfaces, even at low speeds. Hitting waves at high speed induces very high structural loads which requires strong, and therefore heavy, designs of the floats. According to *FAA*[3] rules each float must create 80 percent more buoyancy than what required theoretically to support the seaplane's weight while not moving[4]. This means the bigger and heavier the aircraft, the bigger and heavier the floats need to be – hence increasing empty weight and hydrodynamic/aerodynamic drag dramatically. This significantly limits the aircraft size which is

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[1] www.jetphotos.net AHK707

[2] Flywhale Aircraft GmbH&Co.KG

[3] Federal Aviation Administration

[4] Paragraph CS 23.751 Main floats buoyancy

physically and economically reasonable. The design of amphibious aircrafts (aircrafts able to take-off and land either on land or in water) is tending towards integrated bodies combining boat hulls and aircraft fuselages (see the new *Avic AG600*[5] or *Flywhale*). This design provides static buoyancy and limited hydrodynamic lift while cruising. The whole fuselage needs to be capable to withstand high water loads at high speeds and impacts of waves, resulting in high structural masses and difficult design parameters [8] for cruising stability and forces as described by *Dala* in "*Dynamic Stability of a Seaplane in Takeoff*" [9]. On top of this, the outcome is a rather poor aerodynamic design of the fuselage.

As shown in [10] seaplanes and amphibious aircraft have a significant market potential, especially in Asia. *Castelluccio*, *Maritano*, *Amoroso* and *Migliore* describe in [11] a notable market potential at the mid-sea. To reach full market capabilities both essays see the need for the technical optimization of seaplanes. The use of hydrofoils as landing gear is an effective option to address many of the technical and economic issues specified in [10] and [11] which limits the commercial success of water based aircrafts.

The most promising approach to solving these problems is to use a controllable hydrofoil system as a landing gear on seaplanes. The hydrodynamic lift generated by the hydrofoils while driving through the water lifts the fuselage above the water surface. Such systems are increasingly used in professional sailing and other water sports equipment (Figure 2).

Figure 2: Ineos Mule[6] *(top) Nacra 17*[7] *(bottom)*

Hydrofoils are hydrodynamic effective surfaces shaped with a special cross section – like airfoils of aircrafts – which are connected with a mast to the underside of the fuselage. The underwater flow around the surface generates a lifting force while cruising in the water. This force is capable of lifting significant parts of the fuselage out of the water resulting in considerably less drag. *Thomas William Moy* 1861 used a boat with underwater planes as a test vehicle for aerodynamic investigations of lift and drag. Also this was not intended it was the birth hour of hydrofoils [12]. After further theoretical investigations of *Prof. Enrico Forlanini* [12], the first aircraft to take off from water[8] in 1910 already employed airfoil shaped floats creating a hydrodynamic lifting force [13]. Nevertheless, hydrofoils as landing gear on seaplanes has not prevailed, and no major innovations have been made since. This is illustrated by comparing the *Dornier DO J Wal* from 1922 and the *Albatros* from 1913 (Figure 3) with the *Flywhale* from 2017 and the *DHC-6* from the 2000s (Figure 1).

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[5] China Aviation Industry General Aircraft

[6] www.Ineosteamuk.com

[7] www.britishsailingteam.uk

[8] *Hydravion*, Henri Fabre (France)

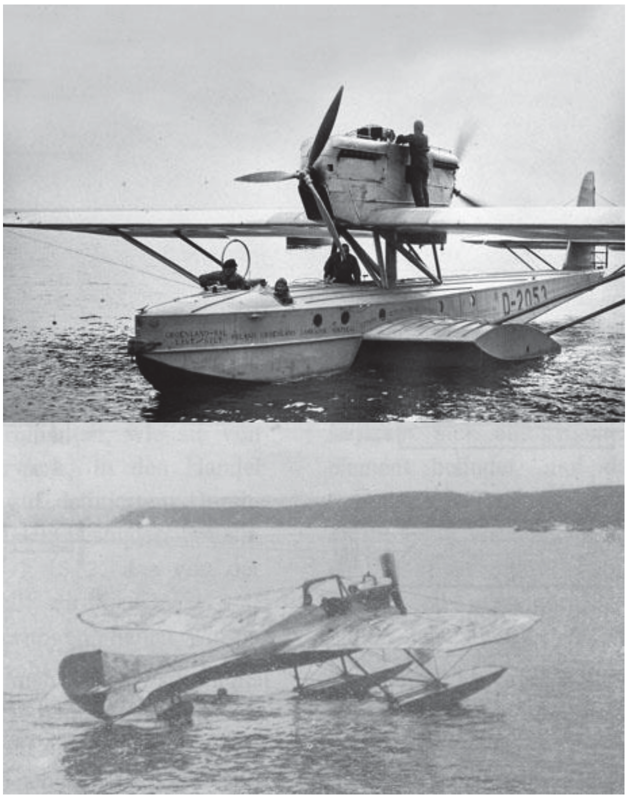

Figure 3: DO J Wal[9] (top); Albatros[10] (bottom)

The *Akoya* by *Lisa Airplanes*[11] is currently the only waterborne aircraft with an innovative landing gear concept. Two rigid, non-controllable and non-retractable hydrofoils, which pierce the water surface, and the fuselage itself are used as landing gear. The fuselage and the overall configuration of the *Akoya* are thus much better suited to the requirements of an efficient aircraft in comparison to traditional seaplanes. The potential to initiate the rotation to lift-off, compensate for wave movements and significantly reduce the power requirement to reach the lift-off speed, which is quite possible with controllable hydrofoils, cannot be exhausted with the *Akoya's* rigid hydrofoils. However in [11], solutions for these problems are required in order to achieve a larger market volume with seaplanes. In terms of speed, drag, and seaworthiness, the hydrofoil system of *America's Cup* 2017 catamarans set the reference which shall be achieved. Completely submerged L- and T-shaped hydrofoils are used whose angle of attack and trailing edge flaps can be individually controlled.

FLIGHT DYNAMICS WITH HYDROFOIL LANDING GEAR:

The ride on hydrofoils is described by sailors and water sports enthusiasts like flying over the water surface. Indeed there are many similarities between sailing using hydrofoils and flying an airplane. Bigger boats have one or more hydrofoils in the vicinity of the centre of gravity (CG) to generate the main lifting force and one or more hydrofoils at the back or front to control the flight height and angle of attack like an empennage. Other possibilities of hydrofoil configuration are also explained in [13]. The dynamic lift generated at the hydrofoils can be calculated like the aerodynamic lift at an aircraft's wing, however other effects like cavitation have to be taken into account for accurate lift computations and CFD simulations [14] [15].

The cruise until lift-off can be described as a flight-flight coupling. At a certain speed, the hydrofoils of the landing gear lift the aircraft above the water surface, leaving them the only remaining structure in the water. This speed is much lower than the necessary aerodynamic lift-off speed. As speed increases during the take-off cruise, aerodynamic forces increase until the aerodynamic lift becomes slightly higher than the aircrafts weight at lift-off speed. Relevant aerodynamic forces and moments from the main wing (index MW) and empennage (index Emp) and the hydrodynamic forces on the hydrofoils of the landing gear are shown in Figure 3.

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[9] www.dorniermuseum.de

[10] Bodensee Wasserflugzeug Wettbewerb

[11] www.lisa-airplanes.com/en/

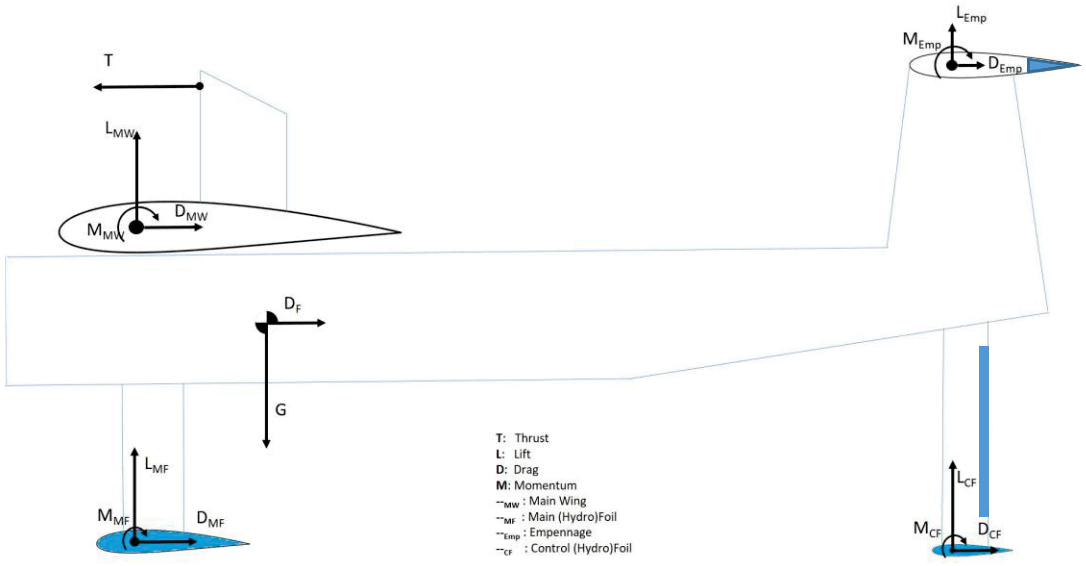

Figure 3: Forces and moments on seaplanes with hydrofoil landing gear

During take-off and landing, each aerodynamically and hydrodynamically effective surface brings a lift force, a drag force and a momentum into the system. The hydrofoil-landing gear system consists of a *Main Hydrofoil* (index MF) and a *Control Hydrofoil* (index CF). The Main Hydrofoil acts like the main wing of an aircraft; it generates lift capable of carrying the whole aircraft at a certain speed. The Control Hydrofoil acts like the empennage of an aircraft, and is fitted with a rudder and elevators to control the flight in the water.

The hydrodynamic forces on a hydrofoil landing gear, which is capable of matching the performance of modern regatta ships, are significantly greater than the aerodynamic forces on the aircraft wings during take-off and landing. This is because the wing area of the Main Hydrofoil is designed to fly the aircraft above the water surface at fairly lower speeds than the Main Wing is designed to do. Furthermore, the higher density of water compared to air determines the lift force directly. Nevertheless, due to the higher density of water the hydrofoils are also much more sensitive to angle of attack changes and flow disturbances.

The aerodynamic lift and drag on the aircraft's wing increases with increasing speed, until the take-off speed of the aircraft is reached. This results in a complex system of forces and moments, which must be mastered by a suitable design and control concept of the hydrofoil landing gear. Furthermore, the landing gear should also affect the performance of the aircraft while cruising in the air as little as possible, hence its integration into an overall aircraft concept must be considered early. The variety of dependencies from different engineering disciplines (aerodynamics, hydrodynamics, structural dynamics, aircraft design) and physical limits (cavitation, for example), as well as the novelty of the controllable hydrofoil landing gear on seaplanes, makes it a difficult design task.

A major difficulty is controlling the flight-flight coupling at high speeds during the take-off. The low flight altitude, which is less than the length of the hydrofoils mast, and significant influence from the aerodynamic surfaces have to be considered. Moreover, cavitation tends to start with higher speeds at the hydrofoils, which disturbs the flow and therefore the lift and performance.

1.1 Aero-/ hydrodynamic centre

The aerodynamic and hydrodynamic centres are points where the moment around the transverse axis (pitch) is approximately constant when the angle of attack is varied. Each lifting surface has its own aero-/hydrodynamic centre as well as the combination of the Main Wing and empennage and the Main Foil and Control Foil. Moreover such a point can be calculated for the whole aircraft consisting of the hydrofoil landing gear, wing and empennage. The locations of these points are important in terms of cruising stability and manoeuvrability. For a relaxed stability during cruising, the position of the aerodynamic centre of the wing-empennage combination needs to be behind the centre of gravity, following the aircrafts longitudinal axis. During take-off the aircraft is influenced by aerodynamic and hydrodynamic forces.

Relaxed stability during cruise is a requirement, and therefore sets the location of the centre of gravity in the design phase of the aircraft. The configuration and position of the landing gear must be adapted so that the hydrodynamic centre suits the location of the centre of gravity. The conclusion of studying the behaviour of the hydrodynamic centre with an analytical calculation script is that it is important not to neglect the higher tail volume of the Control Foil (in comparison to average aircraft tail volumes) and a smaller lever arm between the Main Foil and the Control Foil (in comparison to the distance of the main wing to the empennage). In the study, the ¼ chord line of the main wing and the Main Foil are located at the same position. The diagram below (Figure 4) shows the distance Δx from this ¼ chord line to the location of the hydrodynamic centre of the Main Foil – Control Foil combination while varying the tail volume and lever arm of the Control Foil (CF).

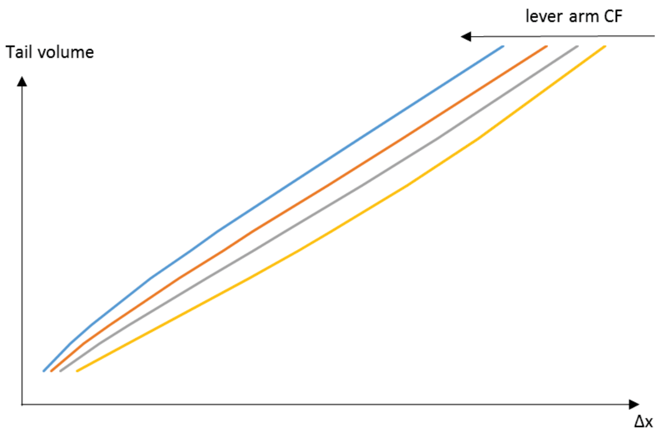

Figure 4: Distance from ¼ chord line to the location of the hydrodynamic centre

The outcome can be used to find the optimum position and size of the CF to match the aerodynamic centre of the main wing and empennage combination as close as possible (which defines the location of the CG of the aircraft). Furthermore, the calculation shows that the location of the combined aero-/hydrodynamic centre which is determined by solving the forces and moments of the main wing -empennage – Main Foil and Control Foil combination is highly affected by the hydrodynamic centre. The Δx of the combined centre is almost equal to the hydrodynamic centre; thus it is even more important to locate and size the hydrofoil landing gear correctly (i.e. using the aerodynamic centre of the main wing and empennage combination).

1.2 Take-off

An analytical calculation script was used to determine the theoretical lift forces and lift coefficients for each surface for the take-off. For a reference aircraft the required hydrodynamic lift of the Main Foil (L_{MF}) is shown in blue, and the aerodynamic lift of the aircrafts main wing (L_{MW}) is shown in red (Figure 5 top). Up to the take-off speed of the aircraft at 35 m/s, the sum of the two lift forces shall not exceed 90% of the weight of the aircraft, so that the hydrofoil-landing gear always remains a certain distance under the water surface. To achieve this, the lift on the Main Foil must continuously decrease as speed increases during the take-off cruise. The theoretical lift coefficient (CA_{MF}) which is necessary to reduce the hydrodynamic lift on the Main Foil is determined and shown in Figure 5 (bottom). For the lift coefficient of the main wing (CA_{MW}) assumptions has been made.

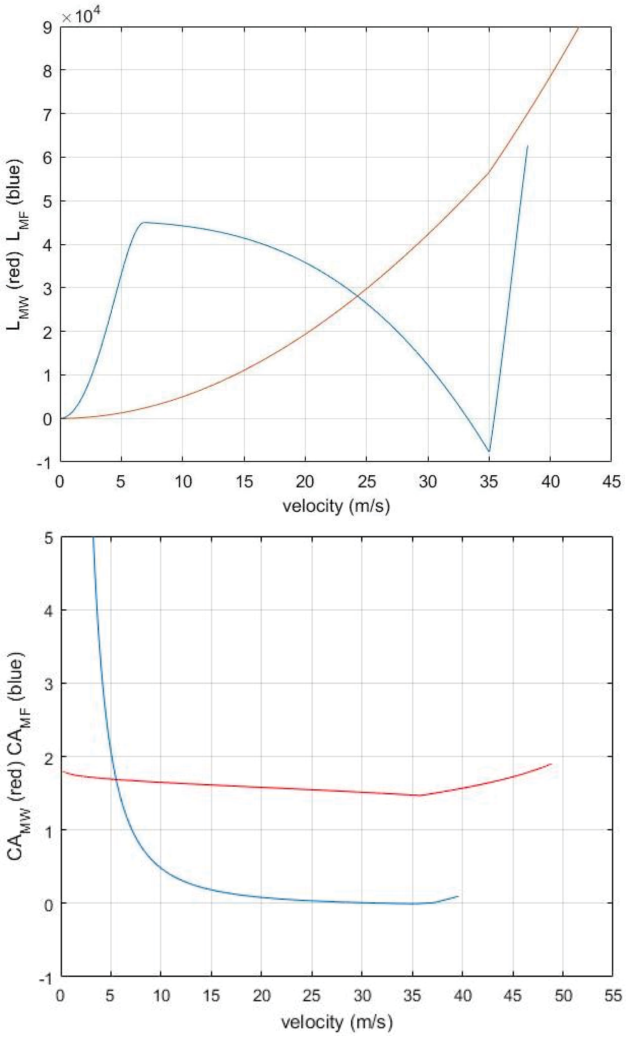

Figure 5: Lift and lift coefficient at the main wing and Main Foil during take-off

With flaps and a high angle of attack at the beginning of the take-off cruise, a lift coefficient of 1.9 is assumed for the main wing. This lift coefficient decreases during the take-off cruise since the angle of attack of the aircraft needs to be reduced to meet the requirements of the landing gears angle of attack. A linear decrease was assumed in the determination script. Due to the increasing speed the lift at the main wing still increases during the take-off cruise. To maintain the sum of the aerodynamic and hydrodynamic lift forces at 90% of the aircrafts weight, the CA_{MF} has to decrease to almost zero. Only when reaching the take-off speed, the rotation is initiated by an increase in lift on the hydrofoil landing gear, which lifts the aircraft completely off the water surface.

The Control Foil, which has a symmetrical airfoil and variable pitch or trailing edge flaps, is used like an empennage to stabilize and control the pitch angle of the aircraft during cruising in the water. When reaching the lift-off speed, the Control Foil pulls the aircraft into a rotation which leads to a C_A increase at the Main Foil and the main wing. The C_A increase at the Main Foil results in a major lift increase which can be seen, for the reference aircraft, at 35m/s in Figure 5. In this case, the Main Foil is designed to lift the aircraft above the water surface at already 7m/s to decrease drag and the maximum engine power needed. For the speed at lift-off, the Main Foil is rather oversized, which leads to the rapid increase of the lifting force, but this helps with leaving the water very quickly for take-off.

1.3 Landing

For landing the hydrofoil landing gear is extended to reduce the landing shock. The glide angle and angle of attack of the aircraft needs to be rather small, otherwise the landing gear generates too much lift once in the water, and the aircraft will be catapulted back in the air. Furthermore, the Control Foil needs to compensate for the high nose-down moment resulting from the hydrofoils drag when the Main Foil dives into the water.

1.4 Requirements for the Control System

To maintain the aircraft in a stable cruise during take-off and landing a fully automated control system for the hydrofoil landing gear is necessary, because in this phases the pilots' workload is already large enough. Furthermore, the hydrodynamic forces are so dominant that it would be nearly impossible to steering the vehicle manually. During the take-off cruise, the angle of attack of the Main Foil needs to be reduced continuously to almost zero (depending on the airfoil used). While this is desirable, as the small angle of attack leads to less drag on the Main Foil, it makes it difficult to keep the system stable regarding disturbances from waves and gusts. One can imagine hydrofoiling on the aircraft's landing gear as flying very close to the ground (0.5 – 1m, depending on the length of the hydrofoils mast) at high speed with an oversized wing and lots of disturbances. If there is a disturbance, for example a wave causing a negative angle of attack, a negative lift coefficient will prevail and pull the aircraft with a massive force back to the water's surface. For example, at 35 m/s in Figure 5, a small change of the lift coefficient significantly changes the lift on the hydrofoil. An Inertial Measurement Unit (IMU) can help derive the absolute flight altitude above the water surface, so that the hydrofoils do not get too close to the water surface where they are more easily influenced by waves and other disturbances. Moreover, an IMU can capture the angular velocities and accelerations very precisely. The control algorithm of the control system needs to keep the angular velocities as small as possible and within a certain range in order to maintain a stable hydrofoil flight. For a continuous calibration of the IMU and further accuracy, a distance sensor for measuring the actual distance of the water surface could also be used, which would continuously calibrate the IMU. However, this is quite challenging, since the water surface is never flat and the frequencies of the measuring methods needed to record the distance to water are rather slow. Because of the massive change of lift due to a small CA change at high speeds (as we can see in Figure 5), the actuation system needs to be very quick, precise and stiff - which is another challenge yet to solve.

2. CURRENT STATUS OF THE PROJECT

As an extension to the literature review and discussion of the prior state of the art, two simple remote-controlled models have been built. The first one has two catamaran hulls, a rigid non-controllable hydrofoil landing gear and a propulsion system (Figure 6 top). The configuration (e.g. angle and position of the hydrofoil landing gear) can be changed slightly prior to each test run, thereby developing a further understanding of the interrelated forces and moments. The second model (Figure 6 middle) on the other hand is a test bed for the control system. It does not have its own propulsion system, and it must be towed by a boat (Figure 6 bottom). This test bed allows several different configurations (size, position, planform, water depth) of the Main Foil and the Control Foil to be tested. Moreover, the Control Foil is equipped with a control mechanism to rotate the left and right surfaces independently to achieve pitch and roll control, while a rudder allows yaw control.

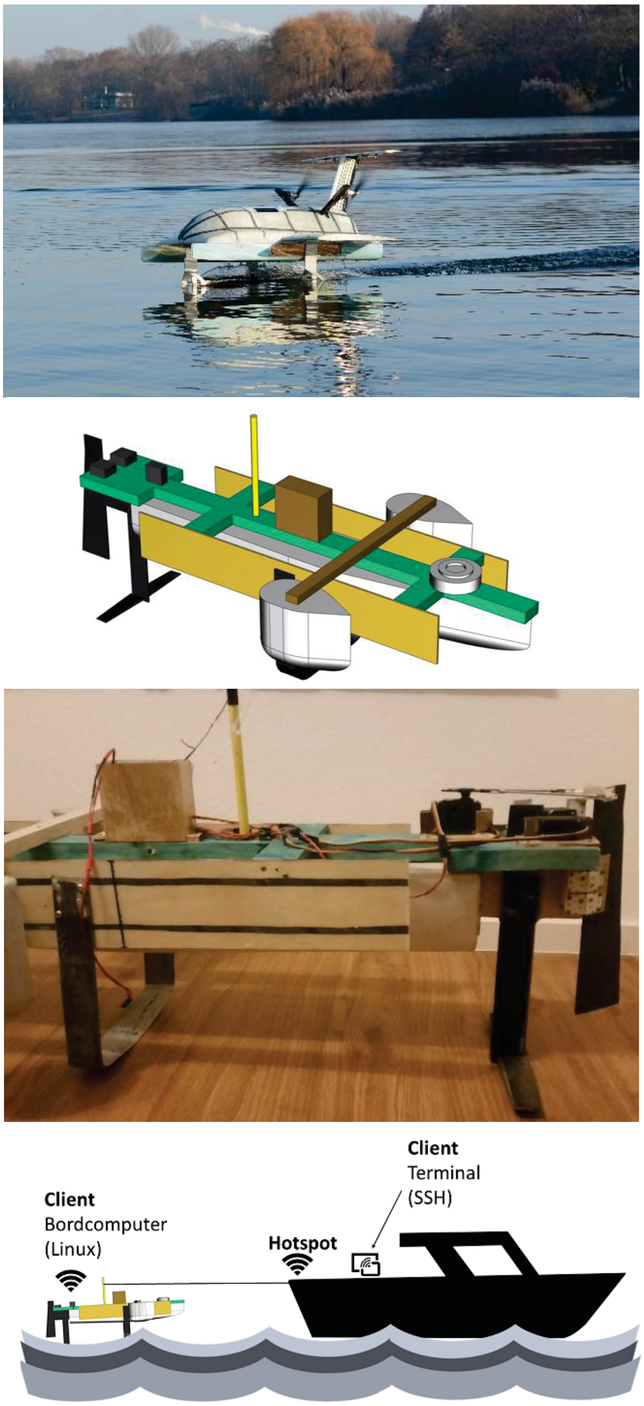

Figure 6: RC- models to investigate different hydrofoil landing gear configuration and control systems

Furthermore, computational flow simulations of the hydrofoils in the water have been carried out to investigate the mutual influence of the foils (Figure 7). The turbulence of the water of the leading hydrofoil influences the flow around the aft foil. Based on the findings of these simulations, it is possible to deduce the required horizontal and vertical distance of the arrangement of the hydrofoils and is therefore useful for studies on the configuration of the hydrofoil landing gear.

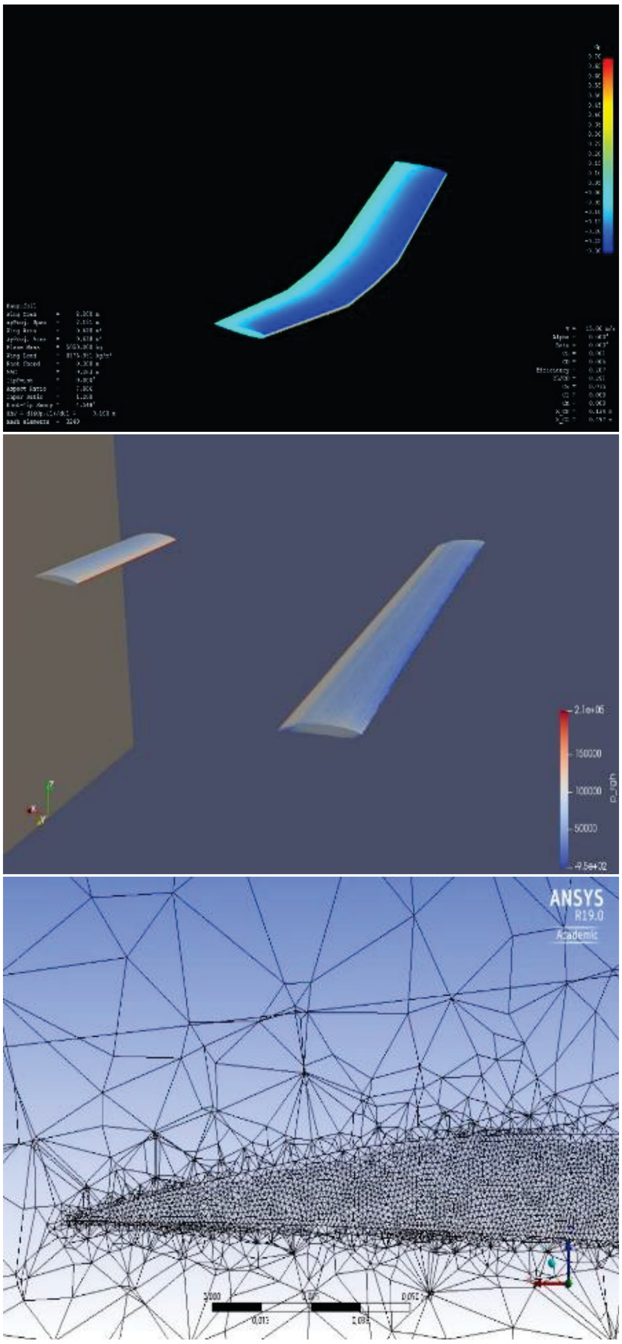

Figure 7: Computational flow simulations of hydrofoils in the water for evaluation of the mutual influence of the forward and aft foils

3. CONCLUSION

The current progress in hydrofoil development for sailboats and water sport devices makes the use of hydrofoil landing gear system in seaplanes promising. Moreover hydrofoiling has a lot more in common with aircraft than boats, which makes it an interesting task for aerospace engineers and aircraft designers, as outlined in the *SegelReporter* [16]. A hydrofoil landing gear would be a radical new design that would influence seaplanes in several ways; therefore, the aerodynamic, structure, design and configuration of the whole aircraft needs to be taken into account when designing the landing gear. Computational Fluid Dynamic (CFD) simulations need to be optimized to handle cavitation more accurately in order to find a suitable airfoil and planform for the hydrofoils. The manufacturing process of carbon fibre reinforced plastics, which is the main material hydrofoils are made of, already allow complex geometries and tailored mechanic and dynamic abilities to cope with the requirements of a hydrofoil landing gear. Smart control systems and potentially software with artificial intelligence can handle the difficulties stabilizing the complete system while cruising in the water and reduce the mental strain on pilots. Further investigation with the help of CFD will determine the optimum distance of the Main Foil and Control Foil and the overall setup of the landing gear. Testing will be done to verify and optimize the simulation data. After that, an integrated design process of a hydrofoil landing gear for seaplanes will be developed. The iterative process of mass estimation during the preliminary design process and stability margin calculations will be modified for seaplanes with a hydrofoil landing gear. Finally, an overall aircraft concept with an integrated design will be developed.

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