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Ultralight amphibious PrandtlPlane: the final design *

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Abstract

The IDINTOS project, co-founded by the Regional Government of Tuscany (Italy), concerns the design of a ultralight amphibious PrandtlPlane and the manufacturing of a flying prototype. A consortium of universities and private companies participated to the project, coordinated by University of Pisa. The paper describes the general design of the aircraft, including aerodynamics, hydrodynamics, structures, propulsion, undercarriages and interior design etc. The aircraft presents a PrandtlPlane wing configuration in order to improve the aerodynamic efficiency and to enhance the safety with respect to stall and manoeuvrability. The control surfaces (ailerons and elevators) are located on both front and rear wing so that the flight mechanics results different with respect to the conventional aircraft. The solution adopted for the propulsion system consists of two ducted propellers that are set laterally on the fuselage. The flap system is made of Fowler flaps in the front wing and plain flaps in the rear one. The interior design of the cabin has been oriented towards a better ergonomic position of the passengers whereas the dispositions of the commands wants to minimize the possibility of any human errors.

1. Nomenclature

α = Angle of attack
β = Angle of sideslip
δ_E = Elevator deflection angle
b = Wingspan of the box-wing system
θ = Pitch angle
C_D = Drag coefficient
C_L = Lift coefficient
C_{L0} = Lift coefficient at $\alpha = 0°$)
C_m = Pitch moment coefficient
C_{m0} = Pitch moment coefficient at $\alpha = 0°$
C_n = Yaw moment coefficient
CG = Center of Gravity
D = Drag force
L = Lift force
mac = Mean aerodynamic chord
$MTOW$ = Maximum Take-Off Weight
Re = Reynolds number
S = Wing area of the box-wing system
SM = Longitudinal stability margin
V = Flight speed
V_C = Cruise speed
V_H = Maximum level flight speed
V_{S0} = Stall speed with full-flaps at $MTOW$
V_{S1} = Stall speed without flaps at $MTOW$
$\overline{x}$ = Optimization variables vector
W = Aircraft Weight

2. Introduction

Figure 1. A 1/10 scaled model of the ultralight amphibious PrandtlPlane (ISIA, Florence)

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*Results shown in this paper have been achieved during the research project "IDINTOS", funded by Tuscany Region (Italy) in 2011

This paper aims to present the final design of a ultralight (ULM) amphibious PrandtlPlane. Such innovative aircraft has been the object of a research project called IDINTOS, co-founded by the Regional Government of Tuscany and coordinated by the Aerospace Section of the Department of Civil and Industrial Engineering of Pisa University, with the main objectives of designing and manufacturing a full-scale prototype.

The PrandtlPlane configuration derives from the "best wing system" concept by Ludwig Prandtl, who in 1924 demonstrated that a box-wing system, under proper conditions, provides the minimum induced drag for given lift and wingspan [1]. As a consequence, most of the potential benefits of the PrandtlPlane configuration can be found in the category of transport aircraft, but nevertheless in the last decade several research programs have been carried out at the University of Pisa (Italy) aiming at applying the PrandtlPlane configuration to small airplanes, such as Light Sport Aircraft (LSA) or Ultralights (ULM).

The reasons behind this choices is the need of developing a technology demonstrator as simple as possible and, less obvious, the additional advantages the PrandtlPlane configuration can provide to small aircraft. In fact, previous studies [3] have shown that the PrandtlPlane architecture applied to small aircraft can increase the flight safety for the following reasons:

- stall occurs on the front wing first and, when this happens, the rear wing introduces a significant negative pitching moment which brings the airplane away from stall conditions. Such "anti-stall" behaviour makes a PrandtlPlane LSA/ULM safer than a conventional one, by making the aircraft more tolerant to stall conditions due to, for example, manoeuvring errors;
- pitch control can be performed by means of two counter-rotating elevators, placed on front and rear wings, which introduce a pitching moment as a pure couple instead as the result of vertical force applied on the tail; this increases manoeuvring precision, improving safety in all the flight conditions in which the aircraft is close to the ground;
- since the two wings are placed at a significant distance from the center of gravity (CG), the pitch damping moment is higher than in a conventional case; as a consequence, the longitudinal stability is improved, with benefits on the safety side, as well as for the flight comfort.

The amphibian here studied, shown in Figure 1, is a side-by-side two-seater and it is provided with a floating fuselage, retractable landing gears, an engine which drives two ducted propellers and two wingtip auxiliary floats. Such aircraft has been designed in order to fulfil the requirements defined by the Italian regulation on sport aircraft [4]. The main technical data of the amphibian, mostly obtained from wind tunnel results, are listed in Table 1.

Table 1
Technical data of the light amphibious PrandtlPlane

Seats	2, side-by-side
Engine Power	100 hp
Propulsion	2 ducted fans
$MTOW$	1091 lbs (495 kg)
Max. Design Weight	1433 lbs (650 kg)
b	26.5 ft (8 m)
S	152 ft^2 (14.1 m^2)
mac	3.3 ft (1 m)
Fuselage/Hull length	21.3 ft (6.5 m)
V_C	124 kn (230 km/h)
V_H	136 kn (252 km/h)
Best gliding speed	65 kn (120 km/h)
V_{S0}	34 kn (63 km/h)
Cruise L/D	10
Max. L/D	18

3. Aerodynamics and Flight Mechanics

3.1. Aerodynamic optimisation

The design of the amphibious PrandtlPlane has started on the aerodynamic and flight mechanic side, by using the optimisation method and algorithm proposed by [5] and detailed for this case in [7]. The optimisation procedure aims to find a wing system which meets the requirements of equilibrium and stability, for both high speed (i.e. cruise) and low speed (i.e. landing) conditions, as well as those coming from regulations.

Assuming that wings have the same wingspan and no twist, whereas taper ratio, sweep angle and dihedral angle are constant, for each wing the design parameters are its longitudinal position, root and tip chords, sweep and dihedral angles, incidence angle (referred to fuselage) and spanwise dimension of movable surfaces (elevators, flaps and ailerons). The position of main components (pilots, engine, fuel tanks, etc.) have also been included in the design parameters set.

The mathematical problem addressed by the optimisation method is shown in Equation 1, in which the cruise drag is the objective function and $\overline{x}$ is the vector of the design parameters, whose upper and lower constraints are introduced through the last expression. The other relations introduce a set of constraint concerning, respectively:

- vertical equilibrium in cruise conditions;

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- limitations on elevator deflections (δ_E), which are applied to guarantee the pitch moment equilibrium for every CG position;
- limitations on longitudinal stability margin (SM),
- $MTOW$ upper limit, according to [4];
- V_{S0} (at $MTOW$) upper limit, according to [4].

$$\begin{cases} \min D(\overline{x})_{\text{cruise}} \\ \\ L = MTOW(\overline{x}) \\ |\delta_E(\overline{x})| \leq \delta_{E_{\max}} \\ SM_{\min} \leq SM(\overline{x}) \leq SM_{\max} \\ MTOW(\overline{x}) \leq 495 \text{ kg} \\ V_{S0}(\overline{x}) \leq 35 \text{ kn} \\ \\ \overline{x}_{\min} \leq \overline{x} \leq \overline{x}_{\max} \end{cases} \tag{1}$$

The wing system found by means of such optimisation procedure is shown in Figure 2, which represents the Vortex-Lattice Method (VLM) model used to evaluate aerodynamic and flight mechanic characteristics.

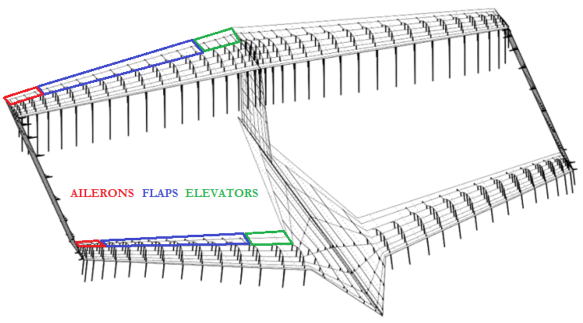

Figure 2. VLM model of the optimised configuration with control surfaces

After the optimisation phase, VLM results have been checked by means of the CFD code StarCCM+ by CD-Adapco, for both cruise and landing conditions

3.2. CFD analysis of cruise condition

Figure 3 shows that the VLM prediction of α-derivatives is quite accurate (errors $< 5\%$), whereas C_{L0} and C_{m0} estimations are quite far form the CFD ones. Therefore, CFD analyses for the aircraft in cruise conditions have been required in order to assess the trim capabilities of the elevator system, which is composed of two counter-rotating surfaces placed on both wings (Figure 2, bottom).

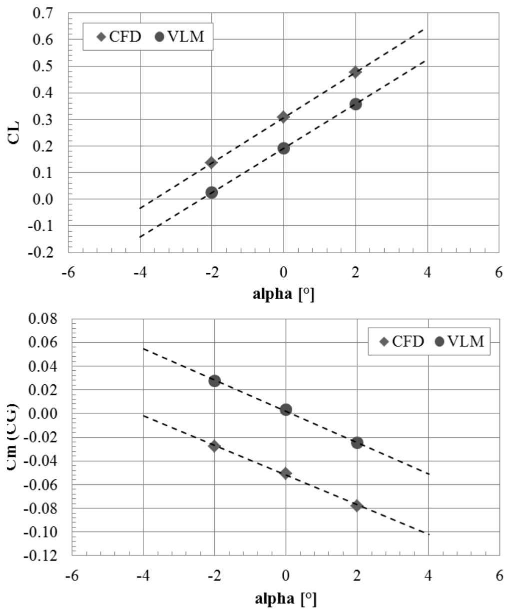

Figure 3. VLM and CFD data comparison on $C_L - \alpha$ and $C_m - \alpha$ curves

As detailed in [11], such analyses have been carried on a model provided with fences, introduced to limit the interference between flaps and other movable surfaces, and adding some of the effects of ducted propellers by means of additional boundary conditions on duct sections.

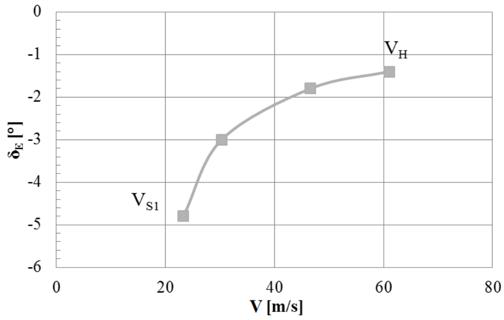

Figure 4. $\delta_E - V$ diagram for level flight with undeflected flaps (CFD results)

Figure 4 shows how, according to the CFD results, it is possible to trim the aircraft with limited δ_E values, for the speed range between stall condition with flaps undeflected (V_{S1}) and the maximum level flight speed (V_H), calculated assuming to use a 100 hp engine at maximum continuous power level.

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3.3. CFD analysis of landing condition

According to Italian regulation [4], ultralight aircraft must have a minimum stall speed with flap deflected (V_{S0}) not higher than 35 kn (18 m/s) at $MTOW$. This requirement has been introduced in the aerodynamic optimisation by means of the VLM code, which has been used to find the lift distribution and, then, the section which undergoes the maximum local lift coefficient. As Figure 5 shows, the critical section is located on front wing, where the maximum local value for the lift coefficient is about 2.5, whereas rear wing experiences lower lift coefficient local values.

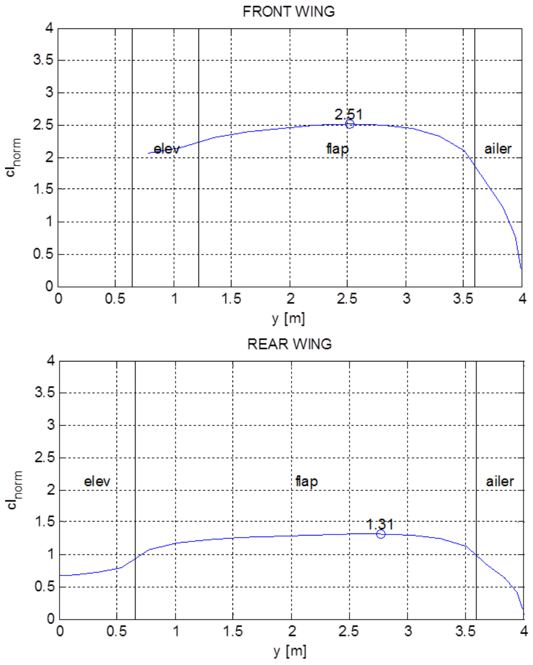

Figure 5. Lift distributions at landing, calculated with the VLM

This behaviour has led to the choice of a flap system composed of Fowler flaps on the front wing and plain flaps on the rear one. The design of such a system have been carried out by means of CFD analyses, which have been also used to verify trim, stability and manoeuvring capability of the aircraft in full-flap configuration.

As described in [9], the Fowler flap design has been carried out by means of bi-dimensional CFD analyses aiming to find the maximum 2D lift coefficient by varying the parameters d_x, d_z and δ_F shown in Figure 6. The solution found has been adopted to create a 3D model of the flapped wing and to simulate the whole aircraft in landing conditions.

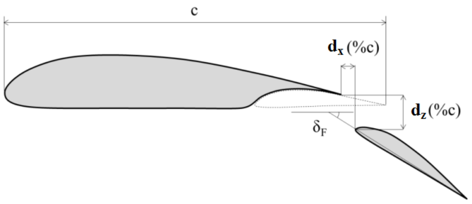

Figure 6. Definition of the airfoil + flap system (2D)

Considering the aircraft data listed in Table 1 and the regulations requirement on V_{S0} [4], the maximum C_L value the amphibian here considered must be able to provide without occurring into stall is 1.73.

As Figure 7 (top) shows, stall occurs at a C_L value close to 2, which meets the above mentioned requirement. In addition, Figure 7 (bottom) shows that before stall a higher pitching moment is introduced, providing an increase of the longitudinal stability and producing a natural “anti-stall” behaviour.

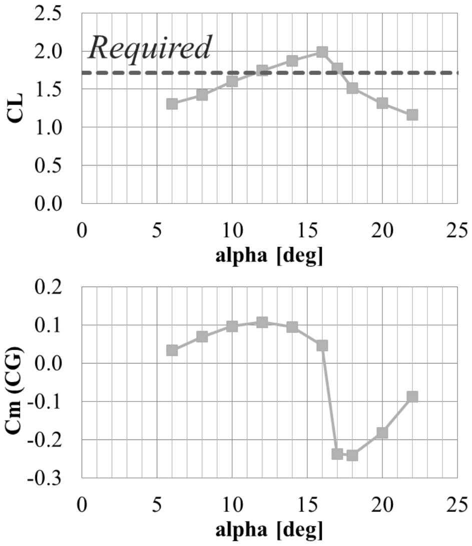

Figure 7. $C_L - \alpha$ and $C_m - \alpha$ curves of the aircraft in full-flap conditions (CFD)

3.4. Wind tunnel tests

Wind tunnel tests have been performed at Politecnico di Milano on a 1/4 scaled model provided with flaps, ailerons, elevators, rudder and removable fences at flaps' sides (Figure 8). As detailed in [18], the following main results have been achieved:

- the vertical wings have been removed in order to perform a drag comparison between a box-wing

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Figure 8. Wind tunnel tests at Politecnico di Milano

and a biplane with the same wing area, showing that, for the same C_L values, the presence of the vertical wings can provide a reduction of the total drag between 6% and 10%;

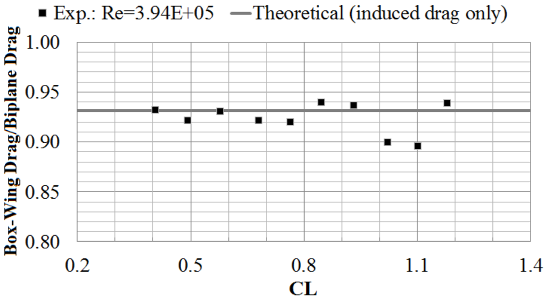

Figure 9. Box-wing drag over biplane drag ratio for different C_L values

- experimental tests on both the clean and the flapped configurations confirm the increase of longitudinal stability before stall (or "anti-stall" behaviour), observed during CFD analyses (Figures 10 and 11);
- several Fowler flap positions and deflections have been tested in order to find the best stall performance, finding small differences with the CFD estimations and confirming the possibility to meet the V_S0 requirement (Figure 11);
- as shown in Figure 10, the aircraft in clean configuration shows an extremely smooth post-stall behaviour, since the maximum C_L value is reached at $\alpha = 15°$ and it remains constant up to 24° (limit value of the test rig);
- the full-flap configuration shows a less smooth post-stall behaviour, characterized by a sudden C_L reduction of about 12.5%, followed by a plateau which extends up to 19° (Figure 11).

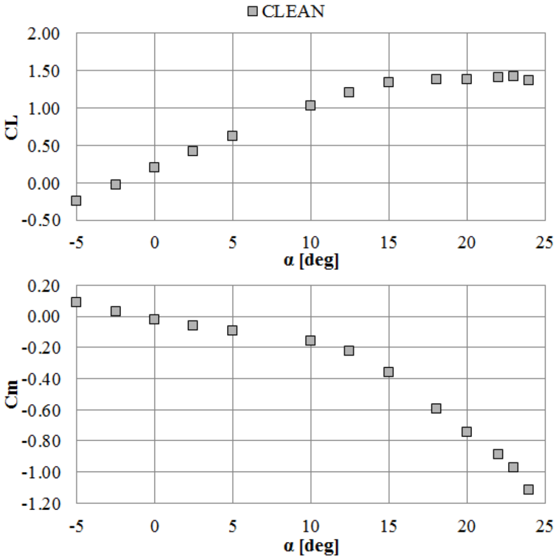

Figure 10. Wind tunnel results for the clean configuration

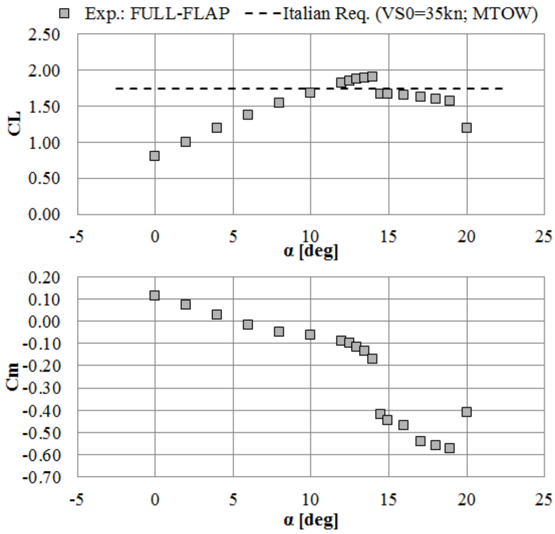

Figure 11. Wind tunnel results for the flapped configuration

4. Hydrodynamics

The hydrodynamic design of the aircraft has been carried out by means of CFD calculation and towing tank tests, which have also been used to calibrate the CFD tool for further analysis.

CFD analyses have been performed in order to study

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the effects of hull design parameters on take-off performance. As described in [6] and [8], the dynamics of several hull shapes has been simulated using a model which has been used to simulate the dynamics of take-off manoeuvre, from rest to lift-off. The hull has been modelled in Star-CCM+ to calculate forces and moments applied by both air and water on it, whereas external forces due to wing system and propellers have been introduced by means of functions, depending on speed and pitch angle.

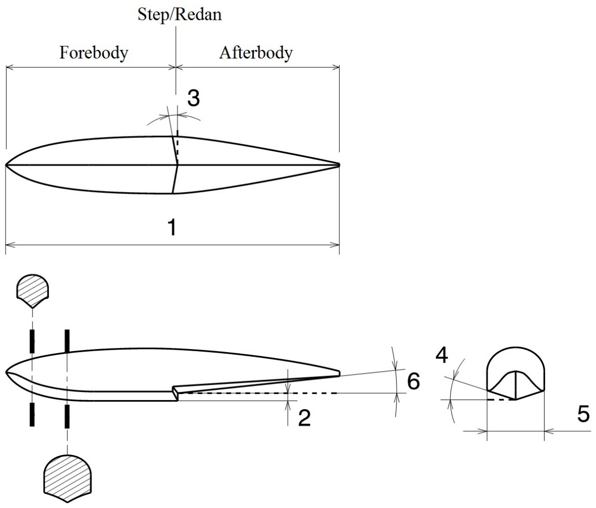

Figure 12. Design parameters: hull length (1), step height (2), step planform angle (3), dead-rise angle (4), maximum beam (5), angle of afterbody keel (6), forebody length (7)

The effects of the design parameters shown in Figure 12 have been investigated and two solutions, illustrated in Figure 13, have been selected as good compromises between performance (i.e.: take-off run length, stability, etc.) and pilots visibility, which is affected by pitch angle. These solutions, different for the forebody length, have been then tested at the towing tank facility of CNR-INSEAN in Rome.

As described in [13] and [15], towing tank tests have been carried out on a 1/3 scaled model which has been connected to the towing carriage through a test rig, provided with actuators, springs and dampers to introduce forces and moments generated by the wing system (Figure 14).

Results achieved, collected in [16] and [17], show that the “T700” version has lower resistance but is unstable for a wide set of applied moment/pitch angle/speed combinations. Therefore, the short forebody hull “T400” has been chosen and a possible stable take-off manoeuvre has been defined (Figure 15).

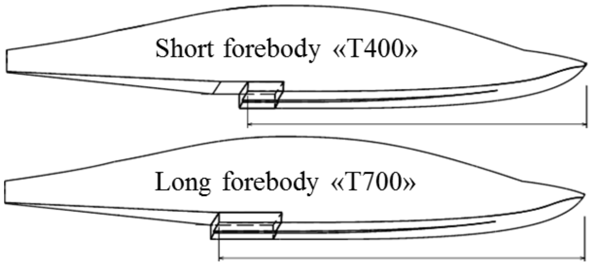

Figure 13. The hull shapes selected for towing tank tests

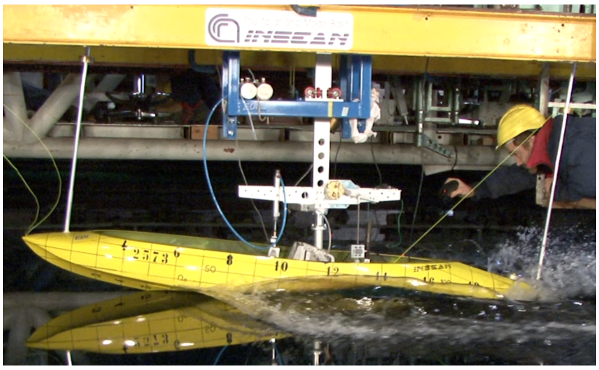

Figure 14. Stability test at the at the towing tank facility of CNR-INSEAN in Rome

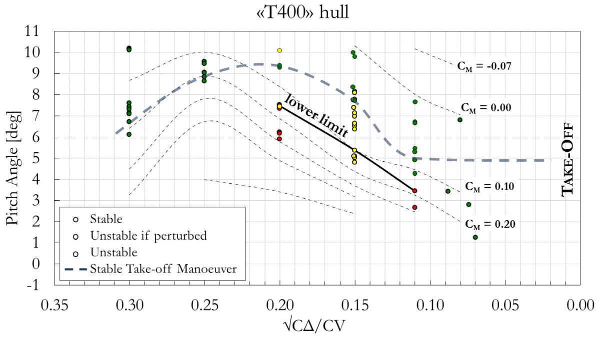

Figure 15. A possible stable take-off manoeuvre

5. Structures

In [12], a preliminary structural analysis has been carried out to evaluate the efficiency of different solutions for the main structures of the wing system, i.e. spars and ribs. Considering wood as base material, it has been observed that the main design parameters

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are the number of spars (1 or 2), the number of fins (1 or 2) connecting rear wing to fuselage and number of carbon fibre layers on spars (Figure 16).

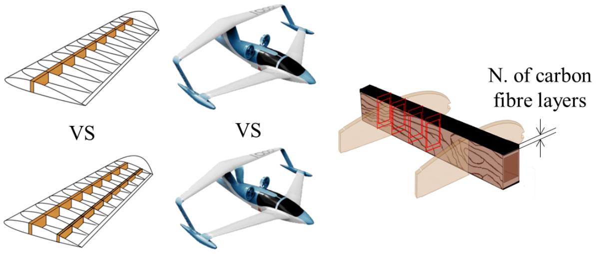

Figure 16. Design parameters taken into account in the preliminary structural analysis

By using the Force Method, the different solutions have been compared finding that the main contribution to energy of deformation is given by torsion; then, for a given weight, the stiffest solution is the double spar one with the single fin connection. In addition, this solution does not require any carbon fibre reinforcement, resulting more simple to manufacture and less expensive.

Such solution, usually adopted by light aircraft manufactures, has been chosen for the detail design, which has been defined after finite elements analyses on both wings and fuselage [14]. Figure 17 shows some FEM analyses and the front wing manufacturing.

6. Propulsion

The amphibian has two shrouded 3-bladed variable pitch propellers, connected to a 100 hp engine by means of synchronous belts and located forward of the step section and above the fuselage in order to have a protection from water sprays.

A preliminary sizing of propellers have been carried out in [20] by using a method based on the Blade Element Theory which takes the mutual interaction between shroud and propeller into account. According to such model, it has been evaluated that, given the same available power and propeller diameter, a proper shroud design allows to obtain an additional 20% static thrust.

As a result, the blade geometry, as well as the shroud shape and position, have been defined in order to provide both a high propeller efficiency in cruise flight and the thrust required for take-off. Figure 18 shows both the propellers and the transmission design.

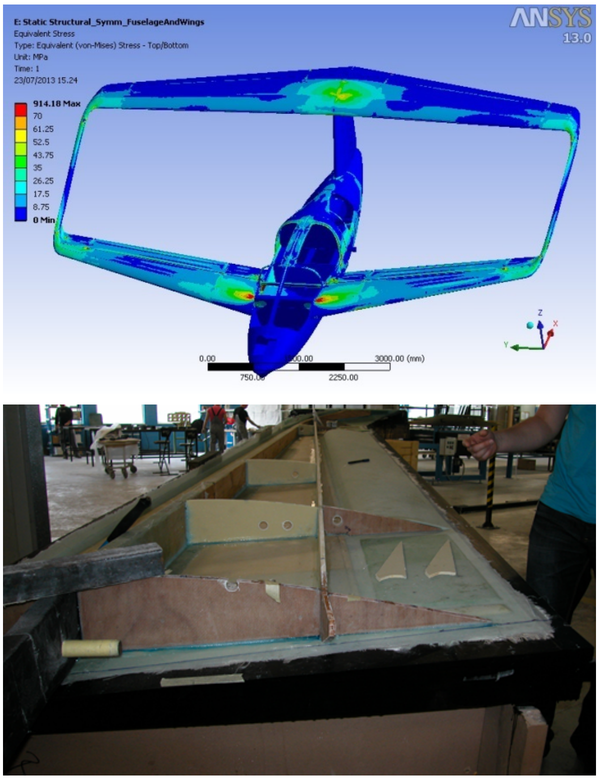

Figure 17. FEM analysis and front wing manufacturing

The problem of one propeller out, due for example to the failure of one of the two belts, has been considered for cruise and take-off conditions, in order to verify the capability of the aircraft to face both the thrust reduction and the yaw moment increase.

Concerning cruise conditions, the performance model defined in [20] has shown that varying the pitch and the number of revolutions per minute, the thrust provided by a single propeller can be even higher than twice the nominal value, which allows to solve the problem of thrust reduction.

The problem of the yaw moment increase, instead, can be faced by using the rudder, whose performance have been evaluated during wind tunnel tests. Figure 19 shows that in the case of a failure of one propeller at the maximum level flight speed condition (V_H), which is the most thrust demanding for cruise flight, different β-δ_R combinations allow to achieve the yaw moment equilibrium.

During the take-off manoeuvre from water, instead, the most critical scenario is the failure of one propeller at take-off speed, when the aircraft is out of the water and maximum thrust is needed for climb. In such a case, the pilot has to perform an emergency water landing, by reducing the power suddenly and deflecting the rudder. Figure 20 shows an example, based on wind tunnel tests data, of yaw moment equilibrium, under the conservative assumption of a 25% thrust re-

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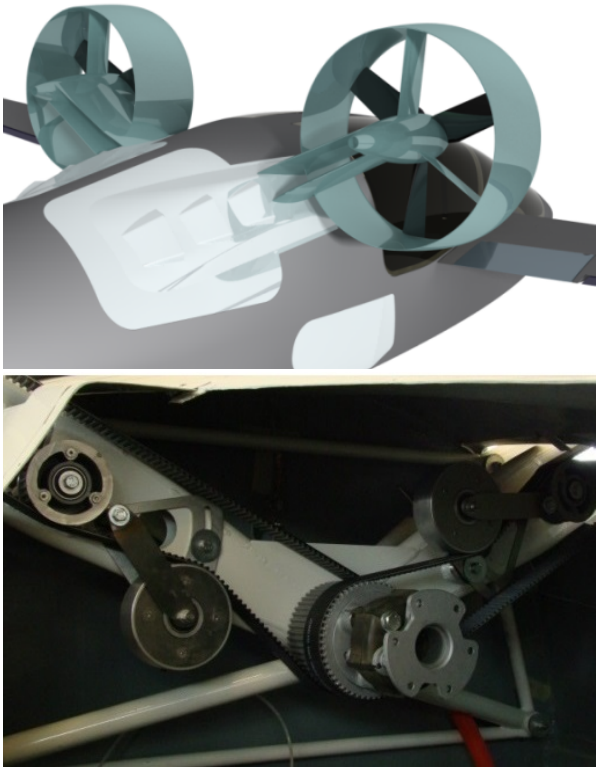

Figure 18. Shrouded propellers and transmission [13]

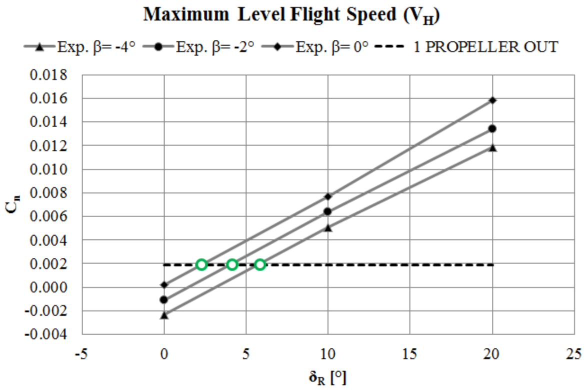

Figure 19. Possible yaw moment equilibrium points in case of a propeller failure at V_H

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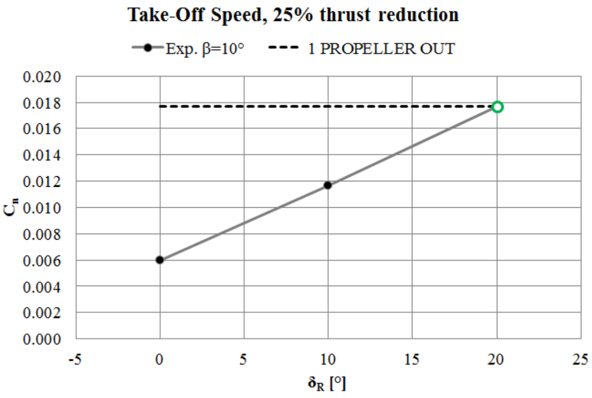

Figure 20. Example of yaw moment equilibrium in case of a propeller failure at take-off speed

7. Undercarriages

The amphibian is provided with a retractable landing gear and a nose wheel. Whereas this latter has a conventional design, the solution found for the main landing gear is innovative, as described in [10], and a patent request has been submitted by University of Pisa.

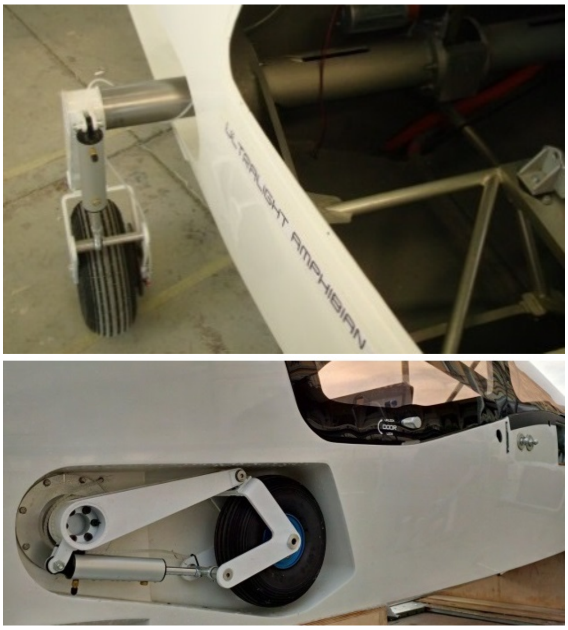

Figure 21. Retractable landing gear of the amphibian

Such solution, shown in Figure 21, consists in a movable pipe connected to a concentric fixed one by means of a pivot which follows a trajectory defined by a shaped guide. This latter allows the movable pipe, at which the wheel group is connected, to extract and rotate without hitting the fuselage.

The advantages of this solution are the following:

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- the housing needs a small internal volume and does not interrupt the fuselage stringers,
- in retracted position, the continuity of fuselage surface is restored and hydrodynamic effects on step section are reduced,
- the system can be actuated both electrically and manually.

8. Interior design

The interior design of the PrandtlPlane here presented has been focused on:

- containment shell design (cockpit floor and side),
- ergonomic design (controls layout, seating, usability of controls),
- project of seats and components for habitability,
- project of the components for safety and crashworthiness (handles, emergency equipment, materials, safety cell, visibility, labelling),
- dashboard and instrumentation design.

Concerning ergonomics, the project is oriented to identify the best posture of the pilot and passenger, the most rational and logical distribution of commands and tools, ease of access to the space pilot, are key parameters for defining the facility, comfort and safety of use of an airplane. In this regard, a preliminary project dedicated to the shell containing seats and commands has been developed, in order to act both as a bulk for bilge water and a safety cell. As shown in Figure 22, the shell also houses the pedals, which are adjustable in flight.

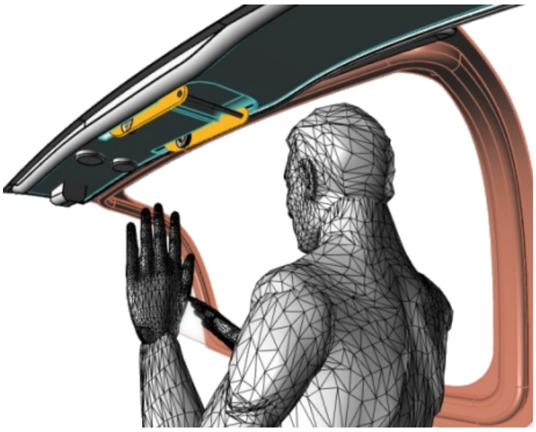

Figure 22. Ergonomic analysis

For instrumentation, the attention has been focused on the integration of systems, carried out by defining a single digital environment for interaction and proposing a redesign of the graphic with the readability of the traditional instruments of flight, such as altimeters, airspeed indicators and varios. Components and devices for the management of the aircraft and navigation, now reliable and economical, have been used with hardware configurations obtained by integrating large TFT display and input systems derived from simulation, videogaming and telephony.

Figure 23. Instrument panel and cabin interiors of the amphibious PrandtlPlane

As Figure 23 shows, the design of the dashboard and the design of the instruments have been created in a dedicated and original configuration. The instrument panel consists of two 8” TFT, a PDF (primary flight display) on the left and the Engine Data on the right. At the centre-bottom, a 4.3” TFT can show safety instructions (state of the landing gear, safety check, etc.) and images of a camera positioned in the front of the plane. Above the 4.3” TFT, a multifunction back-up instrument, equipped with a battery with 3 hours of autonomy, displays altitude (QNH driven by GPS), airspeed and climb/descent rate with a built-in GPS receiver which allows the determination of ground track, present position and ground speed. On sides, near each sidestick, two monochrome LCD monitors

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displays the settings of the trim, the frequency of the radio and the transponder codes. Under the dashboard, the tunnel has been fitted with a 7" tablet with GPS and specific functionality like a check list wizard, made through the use of RFID sensors placed inside and outside of the aircraft, monitorable through the NFC reader of the same tablet. The dashboard/tunnel is provided with a ELT (Emergency Locator Transmitter) system, the ballistic parachute handle, a magnetic compass (backup), flap and landing gear levers, fuel selector and the group of throttle and choke levers. Finally, the armrest contains the screw jack for landing gear emergency opening and the parking brake switch.

Seats have been designed in compliance with the requirements of lightness, strength and ergonomics. They are partially folding (for access to the rear luggage compartment) and have two grommets for the Y-shaped belts (3 points), fixed to the rib of the fire wall. The materials, in addition to responding to aesthetic, have been chosen for comfort, water resistance, ease of cleaning, perspiration. The piloting posture, provided with sidestick and armrests, is designed to increase comfort and reduce effort.

The ceiling of the canopy has a longitudinal structural spar (Figure 22), which acts as a roll-bar and holds the hinges of the access doors with gull-wing opening. The hinges themselves can be removed through a handle, partially embedded in the spar, able to unhook the doors in case of emergency (e.g.: rollover in ditching).

9. Conclusions

Figure 24. Full-scale prototype of the light amphibious PrandtlPlane

The IDINTOS project has started in 2011 with the main purposes of designing and manufacturing a prototype of ultralight amphibious PrandtlPlane. Such objectives have been successfully achieved and the assembly of the aircraft is finished, with the only exception of propellers' shrouds, as shown in Figure 24.

Among the several on-going research activities, the flight tests of a radio controlled 1/4 scaled model, whose maiden flight has been performed on July 2014, are worth of notice for both the additional data provided and the evaluation of the unmanned applications of the PrandtlPlane configuration.

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