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Frediani, A., Cipolla, V., Oliviero, F. IDINTOS: the first prototype of an amphibious PrandtlPlane-shaped aircraft. Aerotec. Missili Spaz. 94, 195â209 (2015). `https://doi.org/10.1007/BF03404701`

IDINTOS: the first prototype of an amphibious PrandtlPlane-shaped aircraft [*]

A. Frediani[a], V. Cipolla [a], F. Oliviero [a]

[a]University of Pisa, Department of Civil and Industrial Engineering

Abstract

This paper summarizes the main activities conducted to design, optimize and build a prototype of an innovative light amphibian. This aircraft is a "PrandtlPlane", a particular box-wing configuration which introduces relevant advantages as increased aerodynamic efficiency and safety of flight; the research project, called IDINTOS, has been co-funded by the Regional Government of Tuscany (Italy), coordinated by the University of Pisa and carried out in 30 months by a consortium of public bodies and small private firms, starting from 2011. In this contribution an overview is given also on several aspects concerning the design, as the aerodynamic optimization, the construction and tests of three scaled models for towing tank wind tunnel and, flight tests, respectively.

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} = Min. stall speed (full-flaps)
V_{S1} = Min. stall speed (no flaps)
$\overline{x}$ = Optimization variables vector
W = Aircraft Weight

2. Introduction

The aviation community of western countries has recently identified the requirements necessary to the production of greener, quieter and safer airplanes of the next generation. In Europe, the guidelines for the innovation in aircraft industry (defined in the document [**?**], updated in 2010 with [**?**]) indicate the improvement of safety of flight, the reduction of ground operations and, mainly, a cut of atmospheric pollution as the goals of the civil aviation of the future. In the last years, an increasing attention has been devoted to new aerodynamic configurations as the solution to be adopted to satisfy the new requirements. Among the proposed solutions, the most promising are the Blended Wing Body, the Truss Braced Wing and the PrandtlPlane (Figure **??**).

Figure 1. Blended Wing Body, Truss Braced Wing and PrandtlPlane configurations

In the Blended Wing Body configuration the parasite drag is reduced by shaping the fuselage (body) as a wing section in order to minimize the non-lifting surfaces. In the Truss Braced Wing configuration, the induced drag is reduced by the increase of the Aspect

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

Ratio, made possible by the introduction of trusses which increase the wing stiffness. The PrandtlPlane configuration is based on the minimization of the induced drag by the adoption of a box-wing system ([?]).

All the configurations present advantages and disadvantages. In the case of the Blended Wing Body, a reduction of about 11% of the empty weight and a fuel burn saving of 32% are claimed in the reference case of 480 passengers aircraft with 9000 NM ([?]) when compared to an equivalent conventional aircraft; on the other side, some problems exist as, for example engine integration, low speed stability of flight and control, lateral stability, quality of flight, emergency evacuation. Several Truss Braced Wing configurations have been studied and an exhaustive analysis of all these activities are summarized in [?]; many open problems are on the table, especially regarding aeroelastic effects and slender structures under compression.

The PrandtlPlane configuration is the result of the application of the "best wing system" concept, due to L. Prandtl ([?]), to civil aircraft; it can be adopted to design different airplanes, from small to extra-large ones and with different propulsion systems; for example, Figure **??** provides an artistic view applied to a freighter and a 250 seats with a Liquid Hydrogen propulsion; contrary to conventional layouts, PrandtlPlane configuration allows to extend transport aircraft to more than 1400 passengers ([?]).

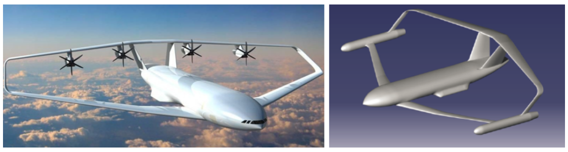

Figure 2. Artistic views of PrandtlPlane solutions (from [?])

The Prandtl's results on the Best Wing System were considered a pure academic solution without no practical applications ([?]) to Aeronautics for about half a century. In the middle of the 80's, some fundamental papers (e.g. [?], [?], [?]) promoted research on the application of the Prandtl's Best Wing System to civil transport aircraft (and also military [?]) but, in spite of a high potential reduction of the induced drag, the box wing structural solutions were proved to be critical as far as aeroelastic effects were concerned and, in particular, the weight design against flutter proved to be unacceptable. It is clear today that the introduction of new aircraft configurations is a challenge to be faced by taking all the aspect of the design into account: Aerodynamics, Flight Mechanics and Controls, Structural design, Aeroelasticity, architectural aspects and ground operations, engine integration, etc. The PrandtlPlane configuration is a proposal of aircraft design which takes all these aspects, together, into account and, accordingly, the design procedure is fully integrated and totally different from conventional aircraft.

According to Prandtl, the multiplane that provides the minimum induced drag for given lift and wingspan is a box-wing system, in which the induced velocities on the horizontal wings are constant along the wingspan and null on vertical wings. After a research dedicated to determine the exact solution of the Prandtl problem, see [?] and [?], a lot of fundamental activities were conducted, especially in the last decade, with a significant contribution from Italian researchers. Relevant results were achieved on theoretical aerodynamics of multiple wings, leading to a generalization of the Prandtl results (e.g.: [?], [?], [?], [?]) on structural optimization of box shaped wings (e.g. [?], [?], [?], [?]), on aeroelasticity and flutter (e.g.: [?], [?], [?], [?]), on flight mechanics and engine integration (e.g. [?], [?], [?], [?]), on new green fuel propulsion ([?]). A deep and complete overview of the research activities conducted mainly in the last two decades can be found in the already cited paper [?].

Although most of the potential benefits of the PrandtlPlane configuration concern the category of transport aircraft, several research programs have been carried out recently at the University of Pisa (Italy) aiming to apply the configuration to small airplanes, such as Light Sport Aircraft (LSA) or Ultralights (ULM).

The first reason behind this choice was the need of developing a technology demonstrator of the PrandtlPlane solution; this challenge became feasible after the approval of the IDINTOS project by the Regional Government of Tuscany (Italy), with the goal of building a prototype of PrandtlPlane aircraft.

The second reason was the possibility of showing which additional advantages the PrandtlPlane configuration could provide to small aircraft category.

The third reason was the attempt to create the industrial production of a new attractive aircraft as a the one at hand.

Previous studies have shown that the PrandtlPlane architecture applied to small aircraft can increase the flight safety, the manoeuvring precision and the flight quality. The increase of the flight safety is a consequence of the longitudinal stability of the aircraft in which stall occurs on the front wing first and the rear wing introduces a 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. The increase of ma-

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noeuvring precision is a consequence of the pitch control performed by means of two counter-rotating elevators, placed on front and rear wing roots; pitching moment as a pure couple can then achieved without modifying (contrary to conventional one) the lift of the aircraft; this improves also safety in all the flight conditions, especially when flying close to the ground. Finally, the flight quality is enhanced since the two wings are placed at a significant distance from the centre of gravity and, thus, the pitch damping moment is higher compared to conventional cases.

In the rest of this paper, the analysis will be limited to a PrandtlPlane configuration applied to a small aircraft, designed with the adoption the same tools used for large capacity PrandtlPlanes.

3. The IDINTOS project

IDINTOS is a research project with the main objective of designing and manufacturing a full-scale two-seater amphibian prototype under the responsibility of an University Institution; the Italian acronym is the equivalent of Tuscan Innovative Seaplane. The former Department of Aerospace Engineering of Pisa University (DIA) was the coordinator of the project, responsible of the overall architectural design and of the overall management; other public entities involved in the project were DESTEC(Department of Energy and Systems, Pisa University), ISIA (Institute for Industrial Design in Florence) and six private small companies (EDI, MBVision, Humanware, Dielectrick, Daxo, CGS). The project was proposed by DIA in the context of a regional competition and, after the approval, it was concluded in 30 months; several graduate students in Aerospace Engineering at Pisa University participated in the different fields of the research activities. The decision of producing an amphibian aircraft is based on commercial and technical aspects. The commercial aspects are: the production of small hydroplanes is growing in the last times and their selling price is relatively high; the technical aspects are: the configuration is particularly efficient during flight and during take-off run on water and it is also stable as far as porposing conditions are concerned.

The technical data of the aircraft are listed in Table **??**; they are the result of preliminary choices and the consequence of an optimization procedure of the aerodynamic configuration ([**?**]).

The amphibian, whose 1/10 scaled model is shown in Figure **??**, is provided with a floating fuselage, retractable landing gears and a thermal engine inside the fuselage which drives two ducted propellers by means of belts; the aircraft has been designed according to Italian regulations on leisure and sport aircraft ([**?**]).

The project has been developed through the following phases: optimization-based preliminary design, theoretical and CFD analyses, towing tank tests, wind tunnel tests, flying tests on a scaled model and final manufacturing of a prototype ready to fly. The present paper goes through such phases, describing the activities carried out and the most relevant results.

Figure 3. 1/10 scaled model of IDINTOS

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

4. Optimization-based preliminary design

The preliminary design of the wing system has been carried out by means of an optimization procedure, performed using an in-house developed code, proposed in [**?**] and detailed for this application in [**?**]. The procedure allows us to obtain a configuration with the maximum aerodynamic efficiency which satisfies the requirements of equilibrium and stability of flight, for both high speed (i.e. cruise) and low speed (i.e. landing) conditions, taking also the following constraints

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into account: aircraft weight, CG envelope, control surfaces (elevators, flaps and ailerons).

For manufacturing reasons, some simplifications have been assumed for the geometry of the wing system ,e.g., wingspan is the same for both wings, twist angles are null, taper ratio, sweep angle and dihedral angle are constant along the wingspan of each wing. As a result, the wing system design parameters are: wingspan, longitudinal position of each wing, root and tip chords, sweep and dihedral angles, incidence angle (referred to fuselage) and spanwise dimension of control surfaces. Such design parameters, together with the positions of main internal masses (pilots, engine, fuel tanks, etc.), compose the optimization variables vector x.

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

The mathematical problem of optimization is shown in ??, in which the objective function is the aerodynamic efficiency in cruise conditions; MTOW indicates the maximum take-off weight, δ_E is angle of front and rear elevators and the inequality refers to the pitch moment equilibrium constraint; SM(x) is the margin of stability, limited inside the extreme positions of CG, V_{Sreq} is stall speed prescribed by the Requirements; the last expression defines the boundaries of the optimization variables domain. The first three constraints are valid for both cruise flight condition, and landing conditions (i.e. max angle of attack).

The optimization procedure is based on the following items:

- An accurate estimation of the parasite drag is obtained from the polar curves of the profiles; we use a modified version of the Vortex-Lattice Method (VLM) AVL, with 12-points on the airfoil polar curves.
- An empty weight model is used, in which fuselage and wings weights are estimated by assuming constant surface densities (from statistics or existing LSA/ULM airplanes).
- The stall speed is predicted by means of a proper procedure, which has to be initialized with a small value of α:
  - for a given α, the lift distribution Cl(y) is calculated for both wings with the VLM;
  - the local Cl(y) is compared with the maximum lift coefficient of the associated airfoil Cl max (y), (known from experimental or analytical data), in order to detect possible flow separations.
  - if Cl(y) ¡ Cl max (y) (i.e. 2D stall conditions do not occur in any of the wing sections), α is increased; otherwise, the associated C_L value is used to calculate the stall C_L as proposed for swept wings in [?].

Figure ?? shows some examples of optimized solutions which satisfy all the constraints listed above; the last one is the configuration adopted for IDINTOS. The solutions indicated by the optimization software do not take into account some important features as the visibility of the pilots, the empty weight, and, in particular the aspect of beauty.

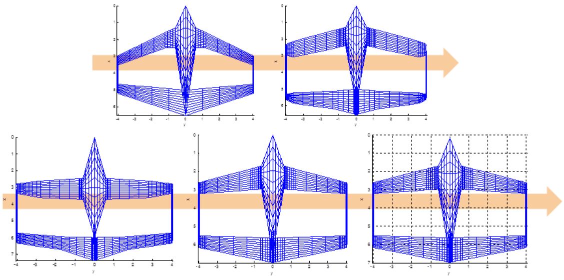

Figure 4. VLM models of the optimized configuration

The final solution is shown in Figure ??.

5. CFD Analyses

CFD analyses have been performed for different cases and with different purposes; some examples of applications are given in the following.

- The water take-off manoeuvre has been simulated at the beginning of the project ([?], [?], [?]); several different hull configurations were taken into account (the parameters defining the hull are listed below in Figure ??) and a set of optimal hulls have been defined; two of them have been chosen for further experimental investigations conducted on scaled models by the water towing tank of CNR-INSEAN in Rome. After the experimental activity, the test conditions were simulated again with a CFD tool in order to validate the CFD models [?].
- The high speed flight conditions (cruise) have been studied with CFD both for verifying VLM

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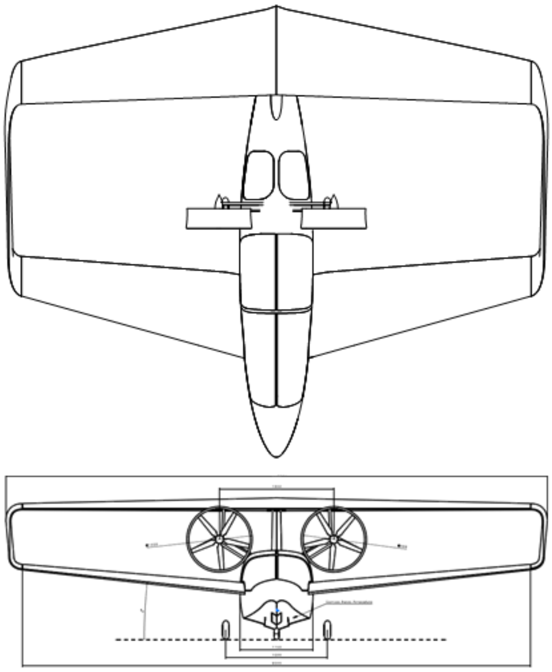

Figure 5. Final configuration of IDINTOS

results and estimating aircraft performances and, then, to validate results against wind tunnel data.

- Low speed flight (landing) has been simulated in order to design the flap system and verify the fulfilment of stall requirements.

- More details on all these aspects can be found in the next sections of this paper.

5.1. Water take-off CFD analysis

Analysis of water take-off manoeuvre has been performed using Star-CCM+ software, in order to study the effects of hull design parameters, as shown in Figure **??**.

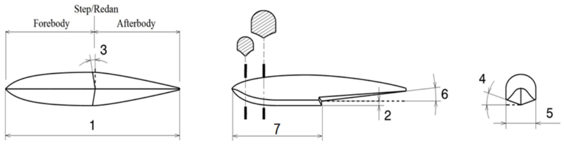

Figure 6. Hull design parameters: hull length (1), step height (2), step planform angle (3), dead-rise angle (4), maximum beam (5), angle of afterbody keel (6), forebody length (7)

As mentioned before, several hull shapes have been studied by varying these design parameters. Each simulation was performed by modelling the hull as a rigid body in the presence of the following degree of freedom: pitch rotation, vertical displacement and horizontal displacement. During these analyses, the wing system was modelled in order to reduce the computational cost, but lift, pitch moment and pitch damping were introduced as external forces (calculated previously by the CFD code, for given values of speed and α). For this purpose, rigid body equations have been implemented, using the VLM predictions for the aerodynamic derivatives.

A significant effect introduced by the wing system is the pitch damping moment, C_{mq}, in which q is related to pitch angular velocity θ; another important external force acting on the hull is the thrust provided by propellers, evaluated through the actuator disk model ([**?**]).

The multiphase flow, made of water and air, has been simulated with the VOF (Volume Of Fluid) model, recommended for free surface problems. The incompressible RANS equation solver was used, with the Realizable Two-Layer $\kappa-\varepsilon$ turbulence model and the Two Layer All y+ wall treatment for boundary layer modelling.

Twelve hull variants, including 10 conventional and 2 planing-tail configurations, have been simulated and, as a result, two conventional hulls have been selected (Figure **??**) as good compromises between performance (short take-off run), pilot visibility (limited pitch angle values) and comfort (small pitch oscillations) and, thus, were chosen for the towing tank tests.

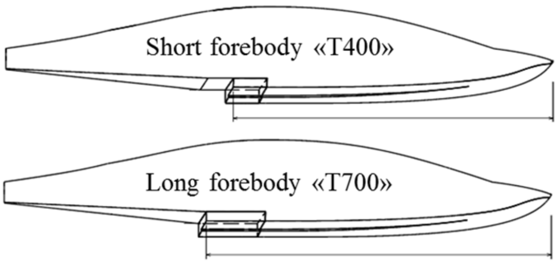

Figure 7. Hull shapes selected for towing tank tests

Towing tank data have been used to provide data for validation of the CFD approach; results of CFD simulation carried out to assess further modification of hull shapes or design of new hulls gained an higher level of confidence. Typical example of comparison between CFD and experimental results are depicted in Figure **??**. The figure on top shows that (i) some differences

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occur only before the critical speed, (ii) the critical speed (the speed corresponding to the loss of resistance following the jump on the step) is exactly the same even though CFD underestimates the reduction of resistance, (iii) the pitch angles during the take-off run correlate perfectly.

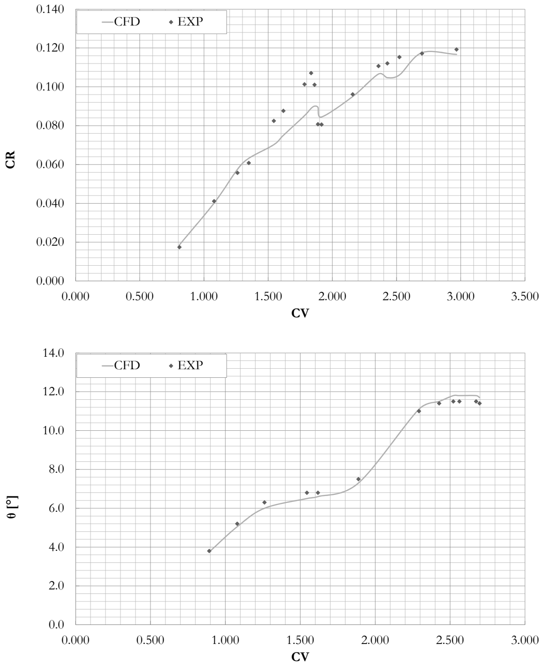

Figure 8. Comparison between CFD and experimental results on the hull resistance and pitch angle

5.2. "High speed" aerodynamic CFD analysis

Cruise, or "high speed", conditions have been simulated in Star-CCM+ and all the aerodynamic derivatives have been assessed; in particular $C_L - \alpha$ and $C_m - \alpha$ curves have been compared with the relative ones obtained with the VLM, showing good accuracy on α-derivatives (error ¡5%), whereas the differences on CL0 and Cm0 values were more significant. For such reason, as detailed in [?] and [?], a trim correction has been performed by taking the main effects of ducted propellers into account by means of additional boundary conditions on duct sections (Figure **??**).

The effects of the two lateral propellers have been considered with different levels of completeness in order to evaluate the effects of the propellers on the lift distributions between front and rear wings and the effects on the lateral stability of the aircraft. An example of computation can be found in Figure **??**.

The CFD analysis has allowed us, also, to define the aerodynamic properties of the aircraft in the hypothesis of attached stream and linear aerodynamics. A typical result in shown in Figure **??**, i.e. the prediction of elevator angle deflections for flight speed ranging from the stall condition with undeflected flaps (VS1) to the maximum continuous power speed (VH), considering 100 hp of available power.

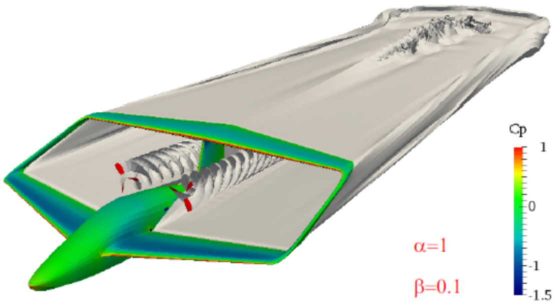

Figure 9. Domain boundaries on ducted propellers ([?])

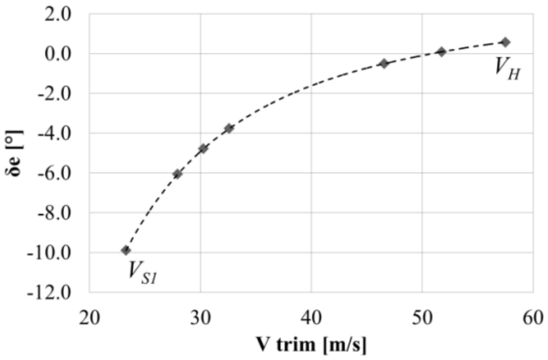

Figure 10. $\delta E - V$ diagram for level flight with undeflected flaps at cruise altitude (CFD)

5.3. "Low speed" aerodynamic CFD analysis

According to Italian regulation on ULM, the minimum stall speed with flap deflected VS0 must not exceed 35 kn (65 km/h). In order to fulfil such requirement, 2D and 3D CFD analyses have been performed to design a flap system composed of Fowler flaps (FF) on front wing and plain flaps (PF) on the rear one ([?]). This complex solution is unusual in the case of small aircraft but it is unavoidable to comply with Italian Regulations.

The Fowler flap design has started by comparing the $C_L - \alpha$ curves of different airfoil + flap two-dimensional

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systems, defined through the 3 parameters in Figure **??**, namely: the horizontal distance between airfoil and flap (x_{FF}), the vertical distance (z_{FF}) and the angle of deflection (δ_{FF}).

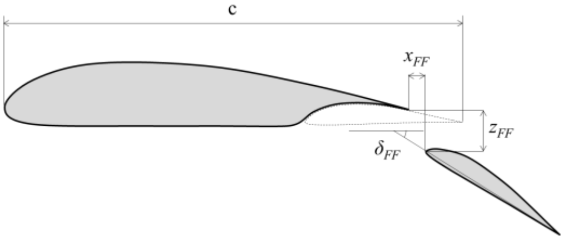

Figure 11. Definition of the airfoil + flap 2D system

In accordance with the literature, CFD results have shown that the best performance are achieved for $x_{FF} = 0$, while the optimal vertical distance (z_{FF}) depends on the section adopted, since it has a strong influence on maximum C_L; Figure **??** is a typical result of this CFD analysis. The chosen 2D solution has been adopted to create a 3D model of the flapped wing and to study the whole aircraft in landing conditions. As the $C_L - \alpha$ curves suggests, stall occurs at C_L values higher than the required one and, when it happens, a significant negative pitching moment is introduced, confirming the anti-stall behaviour of the system.

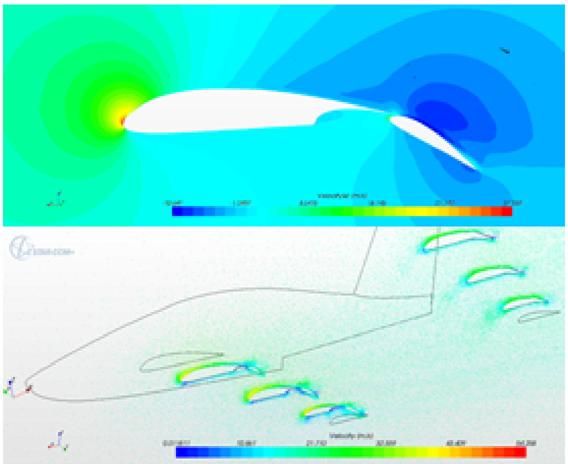

Figure 12. 2D and 3D aerodynamic fields

As done for "high speed" conditions, CFD analyses have been carried out in order to study δE effects on trim. Results shown in Figure **??** confirm that a proper design of the counter-rotating elevators allows to obtain a small influence of δE on C_L providing a nearly pure couple pitch control.

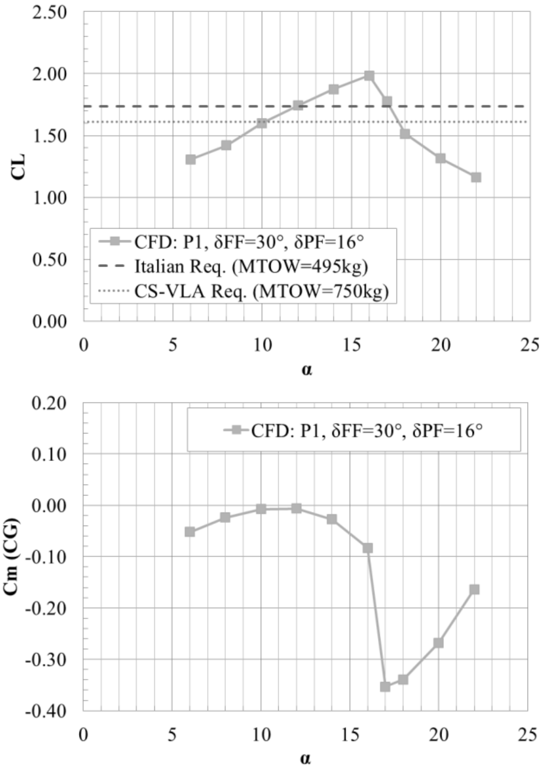

Figure 13. C_L and C_m vs α curves for level flight with flaps deflected at sea level (CFD)

6. Towing tank tests

The towing tank tests have been carried out at the CNR-INSEAN facility in Rome (Italy), with the aim of studying the take-off dynamics of the candidates hull shapes "T400" and "T700" presented before. As described in [**?**], a 1/3 scaled model of the hull has been mounted on a test rig, provided with actuators, springs and dampers in order to introduce forces and moments generated by the wing system (Figure **??**).

The scaled model is provided with scaled values of total weight, position of the CG, scaled components of the Inertia tensor (verified experimentally with a pendulum). The system is provided with a lift alleviation (proportional to the run speed on water to take-off), linear springs to simulate the stiffness (e.g., of $C_{m\alpha}$, $C_{L\alpha}$, etc.), damping (C_{mq}), actuators (propellers); all the parameters were registered by means of load cells. Hundreds of runs have been carried out; we distinguish them in three classes.

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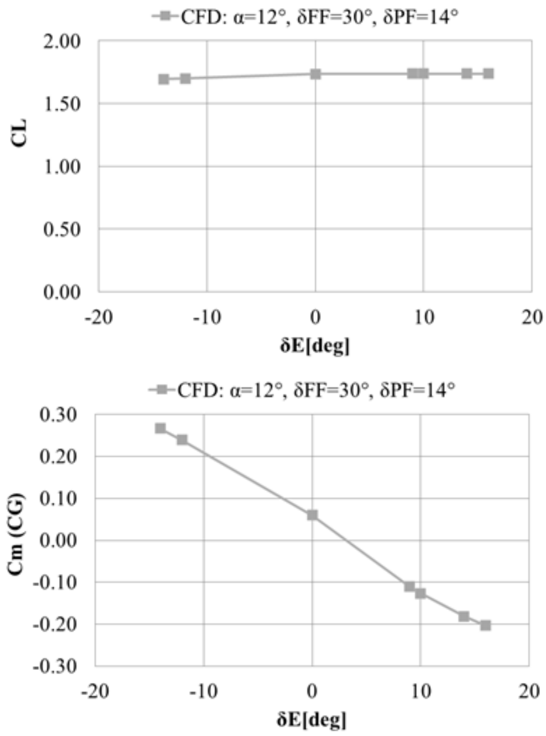

Figure 14. $C_L - \delta E$ and $C_m - \delta E$ curves for level flight with flaps deflected at sea level (CFD).

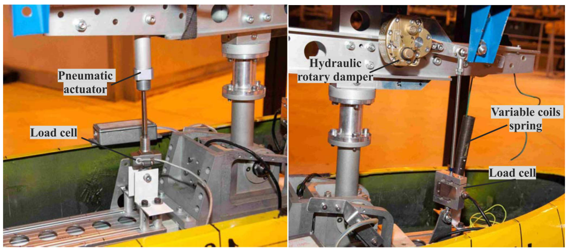

Figure 15. Some rigs used in the towing tank tests at CNR INSEAN in Rome

Figure 16. Stability test at the towing tank facility of CNR-INSEAN in Rome (this photo was the winner of photographic competition in Italy to celebrate the 90 years from the foundation of CNR)

- “Low speed tests”: the objective was to study the displacement phase, up to the transition to the planning phase (“hump”); each run is performed at constant speed, providing the model with vertical translation and pitch rotation (θ) as degrees of freedom; no wing system effect on the hull model is introduced.
- “High speed tests”: the objective was to measure the water resistance in planning phase considering wing system effects; each run has been performed at constant speed and pitch angle, providing the model with vertical translation and introducing lift effect (unloading).
- “Stability tests”: the objective was to study the dynamic behaviour of the hull in planning conditions, considering the wing system effects, in order to exclude the instability phenomenon called “porpoising”; each run has been performed at constant speed, providing the model with vertical translation and pitch rotation as degrees of freedom and introducing lift and pitch moment components (C_{m0}, $C_{m\alpha}$ and C_{mq}). Figure **??** shows a typical stability test.

A typical outcome of the test is given in Figure **??**, the condition $\sqrt{C\Delta}/CV = 0$ indicates that lift equals weight, i.e. take-off conditions are reached. Therefore, the black dashed line represents a complete stable take-off manoeuvre, for which each “step” (green dot) is associated to the applied pitch moment required to have stability of motion.

It is worth noting that, as also observed during preliminary CFD take-off analyses, the effect of the pitch damping moment (Cmq) is significant for the stability of the hull dynamics during take-off run. By means of a comparison carried out with the VLM code, it has been observed that the Cmq value of the here considered PrandtlPlane is about 3 times the Cmq of a conventional wing-tail ULM/LSA. By using a variable hydraulic damper, stability tests at different Cmq values have been performed, showing a significant increase in stability for the PrandtlPlane case.

7. Wind tunnel tests

Wind tunnel tests have been performed at Politecnico di Milano facility, a closed circuit with a 4 m wide and 3.8 m high section, in which it is possible to reach the maximum speed of 55 m/s. A 1/4 scaled model has been used (Figure **??**) to perform the experimental

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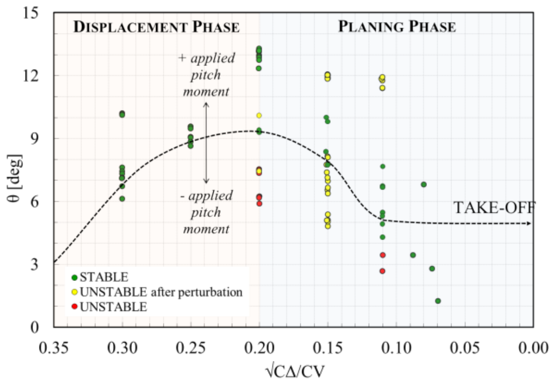

Figure 17. Results of the towing tank stability analysis for the T400 hull

campaign summarized in Table ??.

Figure 18. Wind tunnel tests at Politecnico di Milano

Table 2
Wind tunnel tests campaign

Flight Condition	Objectives
Cruise	α and β derivatives, stall
Cruise	δ_A derivatives
Cruise	δ_E derivatives
Cruise	δ_R derivatives
Cruise	Strut interference
T.O./Land.	α and β derivatives, stall
T.O./Land.	δ_A derivatives
T.O./Land.	δ_E derivatives
T.O./Land.	δ_R derivatives
T.O./Land.	Fences effects
T.O./Land.	Winglet effects

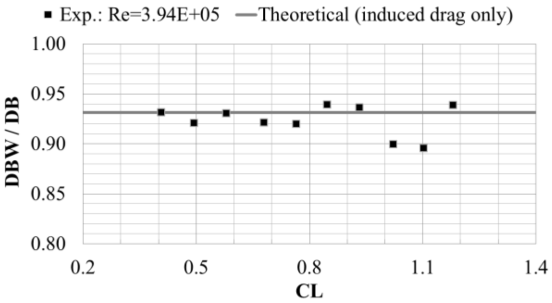

Figure 19. Effect of the lateral wings removal on the drag reduction

The scaled model has been provided with flaps, ailerons, elevators, rudder and removable fences at flaps' sides. The fuselage has been connected to a 6 components balance through a steel structure, which also allows to mount the model upside-down in order to evaluate the aerodynamic interference of the strut.

In this paper, it is not possible to examine all the results obtained during the campaign (see [47]), however, the most relevant achievements are here outlined.

- The investigation on winglets effects have been carried out in order to compare the biplane drag (DB) (obtained by removing the lateral wings) with the box-wing drag (DBW); the result is that, for a given C_L, the total drag reduction provided by the aerodynamic effects due to winglets ranges, from 6% to 10% (Figure ??), in good agreement with the theoretical prediction.
- Experimental results for the clean configuration confirm the anti-stall behaviour of the PrandtlPlane, which can be observed considering both the $C_L - \alpha$ and the $C_m - \alpha$ curves (Figure ??). As α increases above the value of about 10°, a flow separation develops on the front wing, causing an increase of the negative pitch moment, which opposes to stall occurrence. For $10^\circ < \alpha < 15^\circ$, $C_L - \alpha$ decreases and becomes null when maximum C_L is reached; such values remains constant for α values up to 24° (maximum feasible value for the test model), showing a very smooth stall behaviour.
- Concerning the pitch control performed with counter-rotating elevators, wind tunnel tests have shown a linear relationship between the pitching moment (C_m) and the elevators deflection angle (δE) in the range $-5^\circ < \alpha < 15^\circ$. A good agreement with CFD data has been found, confirming that the elevators deflection have small influence on lift (mean value of $C_{L\delta E}$ $= 7 \times 10^{-4}$ deg^{-}1).
- Studies on the flap system have been carried out

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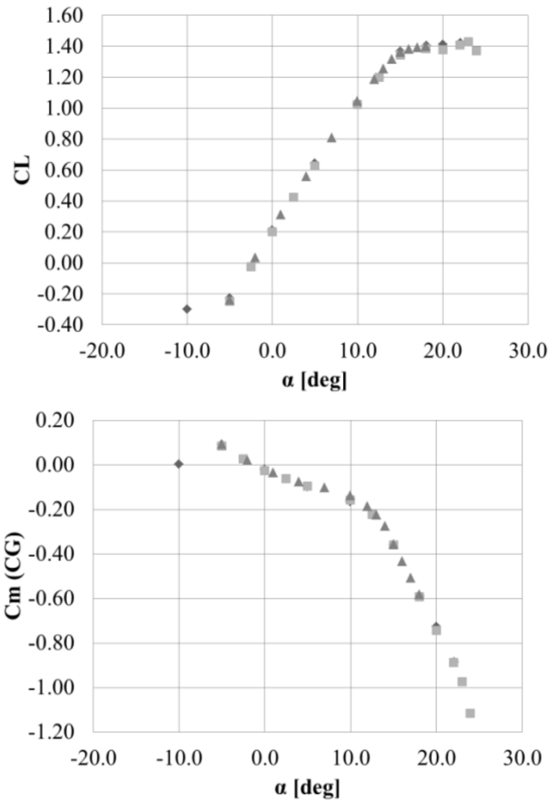

Figure 20. Wind tunnel results for clean configuration. Because of the contact between the model and the strut, it has not been possible to increase α beyond the value of 24°

in order to define the optimal position of the Fowler flap (see x_{FF} and z_{FF}, Figure **??**) and the deflection angles, in order to fulfil the stall requirement. Figure **??** shows the fulfilment of such requirement according to preliminary CFD results, related to a slight different flap system, and experimental data. Concerning experimental data, it is worth of notice that after the stall (α¿14°), the $C_L - \alpha$ curve shows a large plateau which denotes a very smooth stall behaviour also for the flapped configuration.

- A general remark is that the CFD predictions have been fully confirmed by the experiments in the linear range but some discrepancies emerged out of linearity (e.g. the stall onset in Figure **??**). In particular it emerged the need of improving the lateral stability; the model was modified by increasing the rudder surface and introducing two fences on the rear wing; new tests were conducted and the two solutions were studied separately both computationally and experimentally.

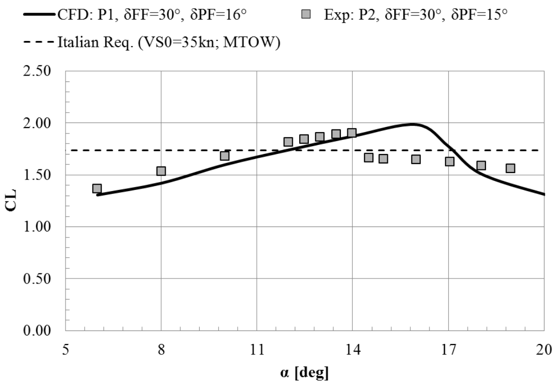

Figure 21. Comparison of experimental and preliminary CFD analysis on the fulfilment of stall requirement. CFD and experimental data are referred to slight different flap systems

Before concluding the wind tunnel analysis section, we show some pictures of the scaled model in Figure **??**: the CAD model, some details of the wing, the interface with the balance and the final model with the flaps extended

Figure 22. Some details on the manufacturing of the 1/4 scaled model for the wind tunnel tests

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8. Flight tests on a scaled model

A radio controlled 1/4 scaled model has been built with the main goal of investigating the dynamic behaviour of the airplane, with particular attention to low speed and stall conditions. For such reasons, the dynamic scaling criteria described in [**?**] have been applied, aiming at satisfying the following relations:

- Linear dimension ratio: n (4)
- Mass ratio: n^3 (64)
- Moment of inertia ratio: n^5 (1024)
- Linear velocity ratio: $n^{0.5}$ (2)
- Angular velocity ratio: $n^{-0.5}$ (0.5)
- Time ratio: $n^{0.5}$ (2)
- Reynolds number ratio: $n^{1.5}$ (32)

The model, shown in Figure **??** during tests at the Remotely Piloted Aircraft System test centre of Capannori Airport (Lucca, Italy), has the following properties:

- Wingspan = 2 m
- Wing area = 0.88 m^2
- Motors = n.2 Brushless, 1100W
- Propellers = 13”x10” (2-blades)
- Empty weight = 9 kg
- Test weight = 10 kg

Stall tests with flap retracted have been performed and, a minimum speed of 17.3 kn (32 km/h) has been measured.

By means of the aforementioned dynamic scaling criteria, such results have been used to estimate the stall behaviour of the full-scale airplane. It is worth of notice that considering the test weight of the model (10 kg), the corresponding value for the full-scale airplane is 640 kg.

Figure 23. Flight tests on a radio controlled 1/4 scaled model at Capannori Airport (Lucca, Italy).

9. The prototype

Figure **??** shows the presentation of IDINTOS prototype at the AERO2014 Fair in Friedrichshafen (Germany), whereas Figure **??** shows some steps of the construction of the prototype.

Some details about the prototype components are described in the following.

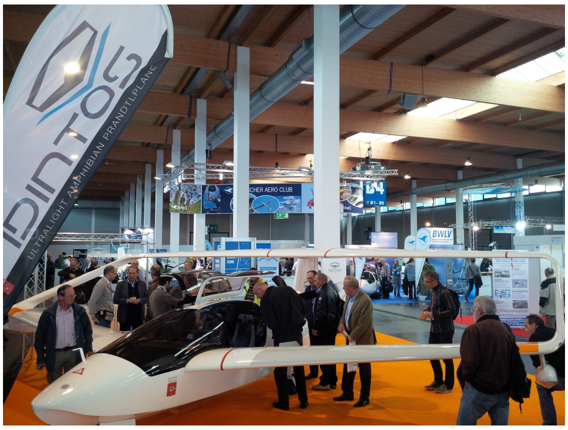

Figure 24. IDINTOS prototype presented at AERO2014 Fair in Friedrichshafen (Germany)

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Figure 25. Full scale prototype of the light amphibious PrandtlPlane: rear wing manufacturing and preliminary assembly

9.1. Cabin

A preliminary mock-up of the cabin was built by ISIA in order to check the visibility of the pilots and the final configuration of the cabin was designed by ISIA and MB Vision (Figure **??**). Cabin interiors, dashboard and instruments have an innovative design; the instruments are based on digital devices. CAD models have been used to take ergonomic, seats and components habitability, safety and crashworthiness into account

9.2. Structures

Wings' structural components have been designed by means of a preliminary tool, based on the Force Method ([**?**]) and then verified through FEM analyses. Preliminary analyses has been carried out to evaluate the efficiency of different solutions to be adopted for the main structures of the wing system, i.e. spars and ribs.

Figure 26. IDINTOS maquette and cabin

Considering wood as base material, it has been observed that the main design parameters are the number of spars (1 or 2), the number of fins connecting rear wing to fuselage (1 or 2) and the number of carbon fibre layers on spars; different solutions have been compared finding that the main contribution to energy of deformation is given by torsion. Thus, for a given weight, the stiffest solution is the double spar one with a single fin connecting rear wing and fuselage. In addition, this solution does not require any carbon fibre reinforcement, leading to a simpler and less expensive manufacturing. Such conventional solution has been modelled in detail and analysed with Finite Elements ([**?**], [**?**]).

Structures are mostly made of fiberglass and epoxy resins, with few parts made of wood (spars), carbon fibre (cabin firewall) and metal (reinforcements).

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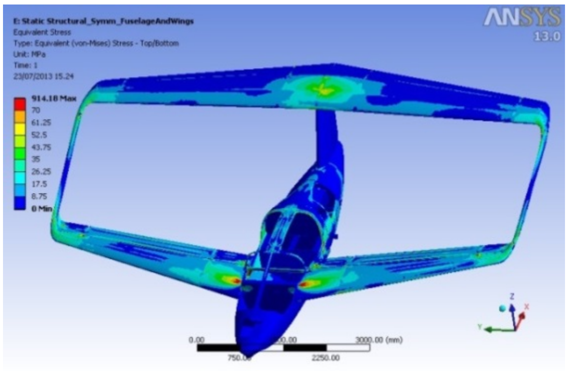

Figure 27. FEM analysis of the entire structural model

9.3. Propulsion

Ducted propellers have been chosen as propulsion system of the amphibious PrandtlPlane, in order to: protect blades from water sprays, protect users from propellers, reduce the negative pitching moment due to thrust, (to avoid instability during planning phase), reduce the width of the assembled fuselage (required for transportation and hangaring purposes), increase propeller efficiency and take-off thrust.

The shrouded propellers have been designed by using an in-house method based on the Blade Element Theory, which optimize the mutual interaction between duct and propeller ([?]). Figure **??** shows the 0.90 m diameter ducted propellers laterally on the amphibian; the shape of the blade, results, from the optimization in-house code, totally unconventional, with low taper and aspect ratio. The duct allows to increase the take-off thrust of about +20%, and, thus, the estimated total thrust provided by the two ducted propellers equals the value of a conventional 1.70 m diameter, 2-bladed propeller. Figure **??** shows one of the manufactured 3-bladed variable pitch propellers and the internal structure which connects them to a 100 hp engine by means of synchronous belts.

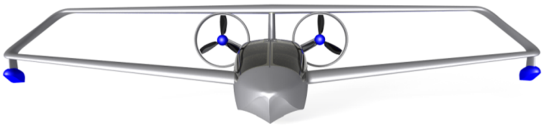

Figure 28. CAD model of the amphibian with ducted propellers

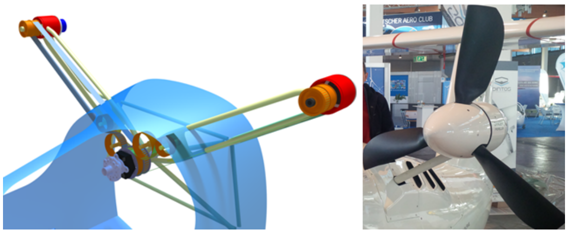

Figure 29. Propellers (shroud missing), transmission and internal structures

9.4. Undercarriages

The amphibian is provided with retractable landing gear and nose wheel. This latter has a conventional design, whereas the solution adopted for the main landing gear is innovative, as described in [?] and a patent request has been submitted by University of Pisa ([?]). Such solution, shown in Figure **??**, is based on a fixed pipe which connects the lateral walls of the fuselage (and reinforce it) and a movable pipe inside the fixed one , with the wheel groups connected at the tips; the two pipes are connected each other by means of a pivot which moves along a proper trajectory.

10. Conclusions

The research project "IDINTOS" has started in 2011 with the aim of manufacturing a prototype of ultralight amphibious PrandtlPlane, the first made in Italy. Such objectives have been successfully achieved: towing tank, wind tunnel and flying tests have been performed in order to define the final design; the assembly of the aircraft has been completed and the aircraft was presented at Friedrichshafen in 2014.

The first conclusion concerns the increase of aerodynamic efficiency, observed through the wind tunnel comparison between the box-wing and the biplane configurations. As shown in this paper, given a C_L value, C_D can be reduced from 6% to 10%, even though the friction drag increases, in quite good accordance with the theoretical predictions on the induced drag efficiency. Such results experimentally confirm that the theoretical estimation of the induced drag reduction of the box-wing respect to the monoplane (being for the present layout as, in the order of about 30%). The second conclusion is about the stall of the PrandtlPlane. CFD analyses and wind tunnel data have shown that the box-wing system is stable at high angles of attack, and that the stall behaviour is very smooth. Such characteristics can increase the flight safety especially for ULMs and LSAs, for which stall is the cause of 30% of accidents.

The third conclusion relates to pitch control performed by means of counter-rotating elevators: as pre-

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Figure 30. Main undercarriage of the amphibian (external shield missing)

dicted by CFD analysis and then verified during wind tunnel tests, a proper elevators design allows a pitch control without transient lift variations and, therefore, pitch variations can be obtained applying a pure couple, which can increase the manoeuvring precision, improving safety in all the flight conditions in which the aircraft is close to the ground.

The forth conclusion concerns the pitch damping moment, which for a PrandtlPlane is about 3 times higher than a conventional wing-tail airplane. The beneficial effect of this characteristic on longitudinal stability has been observed during towing tank tests, in which the higher damping moment has allowed to avoid the "porpoising" instability. Such improvement in stability can have benefits on cruise flight conditions as well, increasing both safety and flight comfort.

The fifth conclusion is that even a small University Department can face the challenge of designing, optimizing and producing a prototype together with the help of small firms, when a financial support is made available and the level of students in Aerospace Engineering is high; many students conducted their graduating thesis in aerospace engineering working enthusiastically on the IDINTOS project.

11. Acknowledgments

The authors gratefully acknowledge the fundamental contribution of Mr. Mauro Romagnoli, of Dr. Riccardo Rossi (EDI) and of the students (it is impossible to name all them) in Aerospace Engineering of Pisa University.

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