THE PRANDTL WING

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1. INTRODUCTION

Passenger and cargo traffic are estimated to grow by a factor of two or three in the next two decades, especially along medium and long range routes worldwide. From the end of the 80s, an increasing interest was devoted towards airplanes bigger than B747, due to the traffic growth together with the limited number of available slots and, also, to the competition pressure on the airliner companies. In the document titled “British Airways Requirements for a new large airliner” (Proceeding of the Royal Aeronautical Society, 1992), it was written that “by the term of the century the B747 will be too small when frequency increases are not possible”. At that time, all the questions connected to the so called sustainable growth were not considered.
After a decade, the scenario changed. The A380 new large airliner is going to enter into service and a new attention has been devoted to the sustainable growth in Aeronautics by the European Community which, in 2002, defined the advanced concepts for future transport aircraft. The second part of the title of the lecture series (Advanced Concepts for Future Civil Transport Aircraft) is examined first in this paper, in order to define the innovative configuration aircraft which satisfy these concepts.

<u>Advanced Concepts for Future Transport Aircraft</u>.
According to P. Busquin [1], “the aeronautical sector needs a long term vision to tackle future challenges”. These challenges were defined by a group of eminent personalities, October 2002, in a document titled “European Aeronautics; a Vision for 2020” [2] .
This document, starting from the present state of the art on transport aviation in Europe, defines the future scenarios in fixed wing transport and indicates the next challenges and goals of the fixed wing air transport in 2020.
Typical requirements for the civil air transport of the future are: more available space and comfort, 10-12% time reduction for boarding and disembarkation of passengers and luggage, more cargo in addition to luggage, possibility of operating from present runways and airports, 30% reduction of Direct Operating Costs, improvement of the operative life, reduction of initial investment and maintenance costs, 0.85 Mach minimum cruise speed, reduced approach and landing separations due to wake vortex turbulence.
The V and VI Framework European Programmes in the field of Aeronautics introduced the concept of “Sustainable Growth” as fundamental for European countries; in this context, the reduction of pollution in the atmosphere and of noise and emissions in the areas around airports are mandatory for future generation aircraft. Cabin noise level and the passenger comfort have also to be enhanced; the level of survivability to accidents in take off and landing is a main requirement for the next generation aircraft; structural design, design against crash and fire, fuel tanks, new materials, evacuation system, etc., are of major importance in this concern.

The reduction of Direct Operative Costs and noise and noxious emissions can be obtained by technology advancements (new materials for structures and engines, reduction of production and maintenance costs, etc). These advancements can produce long term benefits, but a 30% reduction of Direct Operating Costs will be not achieved in the next future. The increase of aircraft capacity is another way of reducing the unit costs but, on short routes, very large aircraft are not used and, on long routes, the biggest possible aircraft compatible with existing airports must be included in an 80x80m horizontal square, in order to be compatible with present airports. Hence, the advantage of increasing dimensions will be no longer possible after the introduction into service of A380 aircraft.
The improvement of the aerodynamic design against drag is essential for meeting the previous requirements and for the commercial success of any transport aircraft programme. The need to improve the aircraft performances is mandatory; according Airbus, a 1% reduction of drag for a large transport aircraft saves 400.000 litres of fuel and, consequently, 5000 Kg of noxious emissions per year [3]. Many national and international authorities underlined the improvement of pollution due to the aircraft’s share in global emissions.
The problems of noise and noxious emissions during take off and landing produce the worst impact on people living in the surrounding areas; therefore, the improvement of the low speed aerodynamic efficiency of aircraft is a great challenge.
In a large transport aircraft during cruise flight, drag is mainly due to friction drag (45-50%) and induced drag (40-45%)
Many ways of reducing friction drag are proposed as, for example: HLF suction, porous surfaces for HLFC, Shock Control, Turbulent flow control, introduction of devices on the outer surface, etc.. The research activities are in progress and, till now, the overall benefits are not yet well understood; however, the overall benefits coming from the investments in this fields regard the basic physics of friction drag and, hence, they will be applicable to any kind of configuration, including the innovative ones.
The induced drag depends on the lift distribution along wing span. The lift distribution of to-day transport aircraft is so optimized that further significant reduction of induced drag cannot be easily obtained.
In conclusion, a possible jump forward in air transport will come from the introduction of completely new, non-conventional, aircraft configurations.

Innovative Aircraft Configurations.

A number of configurations have been proposed and, in particular: Blended Wing Body, C-Wing, Polyplane, Three surfaces, Joined wings. The present proposal is a new transport aircraft configuration in which all new requirements mentioned before have been taken into account comprehensively. The main starting property of this aircraft configuration is a very high reduction of aerodynamic induced drag, based on an intuition of L. Prandtl, at the beginning of the history of aeronautics. According to Prandtl, the lifting system with minimum induced drag is a proper box-like wing (named "Best Wing System"), in which the following conditions are satisfied: same lift distribution and same total lift on each of the horizontal wings and butterfly shaped lift distribution on the vertical tip wings. When these conditions of minimum occur, the velocity induced by the free vortices is constant along the two horizontal wings and identically zero on the vertical side wings (these are the Munk’s conditions for minimum induced drag). The efficiency depends on the gap between the horizontal wings and, in particular, the induced drag decreases for increasing non-dimensional gap (that is: gap-to-span-ratio). The ratio between the induced drag of the Best Wing System and the optimum monoplane with the same lift and total span was calculated before 1920 and in 1924 [4]. In this paper, Prandtl used an approximate procedure (without giving information about the

computation performed); a closed form solution of Prandtl's problem was given in 1999 [5], confirming that Prandtl's results, at least in the range of the wing gaps of interest for applications, were substantially correct. In the Best Wing System, the lift distribution on the horizontal wings results from the superposition of a constant and an elliptical part and, over the vertical wings, is butterfly shaped. Owing to the Munk theorems, the induced drag is independent of sweep angles and, therefore, Prandtl's concept can be applied also to transonic and supersonic aircraft.
In honour of Prandtl, the configuration has been named "PrandtlPlane".
The PrandtlPlane friction drag minimization is still an open problem. The wave drag in the transonic range depends on configuration details. The shape of the aircraft is complex and the number of parameters for a multidisciplinary optimization are much higher than in a conventional configuration. These considerations led to set up fully parametric geometry generators and proper surface meshers for carrying out CFD (Computational Fluid Dynamics) analyses (these subjects are not discussed in this notes).
The PrandtlPlane configuration can be used to design a complete family of aircraft, ranging from small aircraft to wide bodies (even larger than Airbus A380). All the aircraft of the family can be compatible with present airports; in fact, in the case of aircraft larger than e.g. A380, the higher efficiency of the configuration can be used to reduce the wingspan below 80m, without drag penalty (compared to conventional aircraft). The possibility of improving the PrandtlPlane capacities beyond the largest possible conventional aircraft is one of the possible advantages for reducing the unit direct operative costs in the future.
On the opposite side, the PrandtlPlane configuration can be used to design small ultra light aircraft (ULM) or UAVs (Unmanned Aerial Vehicles), including also seaplanes configurations. The PrandtlPlane small aircraft combine a high degree of safety and efficiency with a new appealing design.

2. THE PRANDTL'S BEST WING SYSTEM

The PrandtPlane configuration, as said before, aims to reduce the induced drag.
In case of mono-plane conventional configurations, it is well known that the minimum induced drag occurs when the lift distribution along the span is elliptical and it results $D_m = \frac{L^2}{q\pi b^2}$, where q is the aerodynamic pressure, L is the total lift and b is the wing span.
The induced drag of a biplane, D_b, is the superposition of self induction and mutual induction effects, or:

$$D_b = D_{11} + D_{22} + 2 \cdot D_{12} = \frac{1}{\pi q}\left(\frac{{L_1}^2}{{b_1}^2} + \frac{{L_2}^2}{{b_2}^2} + 2 \cdot \sigma \frac{L_1 L_2}{b_1 b_2}\right).$$

Now, putting $L = L_1 + L_2$ (total lift), $r = b_2/b_1$ ($0 \le r \le 1$), and, $L_2 = Lx$, the condition of minimum occurs when

$$x = \frac{r - \sigma}{r + \frac{1}{r} - 2\sigma},$$

and, consequently:

$$D_{b_{\min}} = \frac{L^2}{\pi q {b_1}^2} \cdot \frac{1 - \sigma^2}{r\left(r + \frac{1}{r} - 2\sigma\right)}.$$

The induced drag of a biplane is minimum when *r* is maximum in the interval [0,1]; this condition occurs when *r=1* and, hence, we obtains *x=1/2* (the minimum occurs when the lift is equal on the two wings). Therefore, the expression for the minimum induced drag of the biplane becomes: $D_{b_{\min}} = \frac{L^2}{\pi q b_1{}^2} \cdot \frac{1+\sigma}{2}$.

The ratio $\kappa = D_b/D_m$, or *efficiency of the biplane* becomes:

$$\frac{D_b}{D_m} = \kappa = \frac{1+\sigma}{2};$$

in the range h/b= 1/15 – 1/4 we have that σ= 1/(1+5.3 h/b) and the function $D_b/D_m = f(h/b)$ is shown in the following figure.

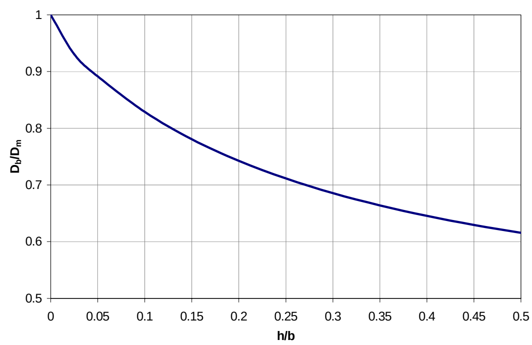

Figure 1. Optimum *Efficiency of biplane* versus h/b.

The induced drag of an optimum biplane is smaller than the equivalent monoplane and, for a given span, it decreases with *h/b.*
The induced drag of an optimum triplane is lower than that of an optimum biplane.
When the number of wings tends to infinity the induced drag tends to a minimum; the configuration corresponding to this minimum is a box wing which, according to Prandtl, is the limit case of multiplane with infinite wings, in which the lift of the internal wings tends to zero and the vertical side wings generate the same tip vortex distribution of the internal wings.
An approximate expression of the *efficiency* of the *Best Wing System* was given in Prandtl's NACA TN 182; the expression of it is the following:

$$\frac{D_{B.W.S.}}{D_m} \cong \frac{1+0.45\,h/b}{1.04+2.81\,h/b}.$$

Figure 2 shows a comparison between the efficiencies of the best wing system by Prandtl and the optimum biplane with the same span and total lift.

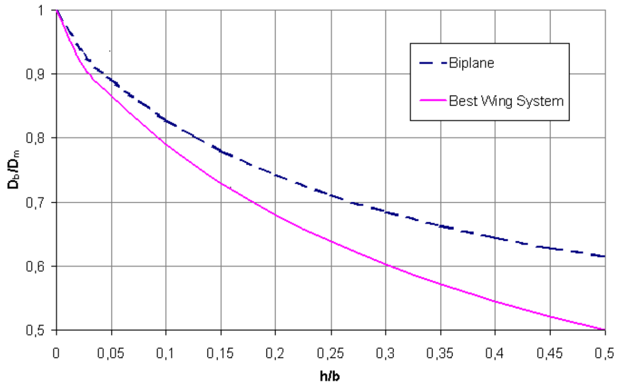

Figure 2: Induced drag of the optimum biplane/optimum monoplane rate vs h/b.

A closed form solution of the Prandtl problem of Best Wing System was given in 1999 ([5]); as shown in figure 3, in the range of applications of h/b (0.1 - 0.2), the results were slightly different from those by Prandtl, (the conclusions by Prandtl were slightly optimistic).

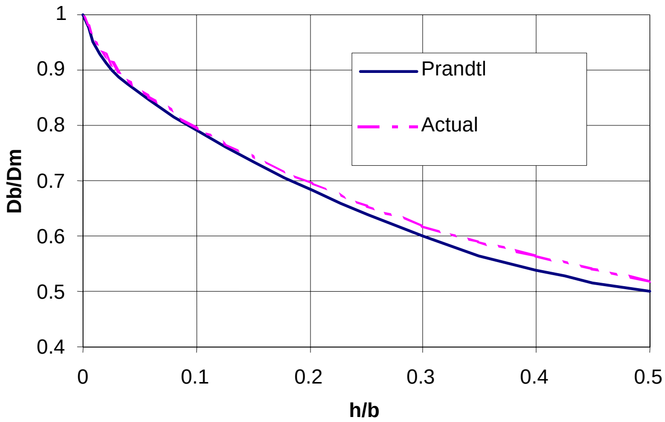

Figure 3: Comparison between the Prandtl’s results and [5].

The differences are larger for higher h/b values and, in particular, when h/b tends to infinity (Prandtl’s curve tends to 0.16; the solution in [5] tends to 0.5, the same of a biplane with infinite gap).
The aerodynamic efficiency of Best Wing System is higher than the optimum biplane and also, of any lifting system with the same span and total lift. The practical interest of the results on the best wing system lays on the fact that, for h/b in the range of practical interest (0.1 – 0.2), the induced drag of the *Best Wing System* reduces from 20% to 30% with respect to the optimum monoplane; in this sense, it is a jump forward.
Along the vertical wings, lift distribution is symmetric and butterfly shaped (lift is directed outwards in the upper part and inwards in the lower part), and induced velocity is identically zero. Along the horizontal wings, the optimum lift distribution is made of a constant part and an elliptical one (Figure 4) and an optimum proportion between them exists; the induced velocity is constant (the value of this constant depends on the total lift).

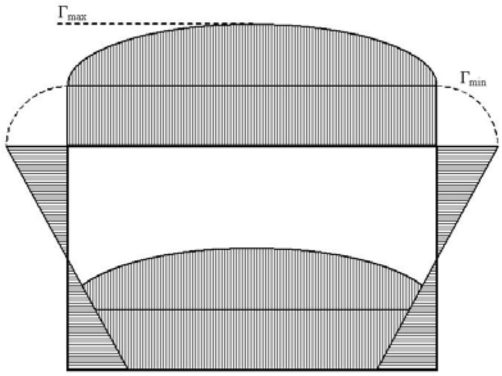

Figure 4. Lift distribution on the Best Wing System.

A condition close to the Best Wing System could be obtained also at low speed, with high lift devices extended; it could be obtained by improving the elliptical parts on both the wings with the same amount (some comments will be given later on in these notes); this remark is the leading criterion for the high lift devices optimisation.
From the structural point of view, the Best Wing System is a box wing in the front view. A box wing, contrary to a cantilevered wing, is an overconstrained system. This property is very interesting and opens new concepts in the structural design of wings as shown in the following examples: (1) the instability to torsional divergence of the negative-swept wing is balanced by the high stability of the positive-swept wing; (2) a hinge can be positioned on one of the two horizontal wings parallel to the roll axis, with the consequence that the bending moment are nil there and a lift transfer occurs from this wing to the other one; (3) the hinge in the example (2) could be a damage and, hence, the box wing is a typical "Damage Tolerance" system (this is an improvement of safety).

3. THE PRANDTLPLANE AIRCRAFT CONCEPT

In this section, the aerodynamic principle of Best Wing System is applied to design an aircraft configuration taking Structures, Flight Mechanics, Controls, Aeroelasticity, etc. into account simultaneously. The aircraft concept, as said before, is named "PrandtlPlane"; hence, PrandtlPlane is the engineering application of the mathematical concept of Best Wing System. The PrandtlPlane concept was first applied to a very large aircraft, with a fuselage similar to A380 (figure 5).

Figure 5: Preliminary application of the Prandtl's concept to transport aircraft ([6], [7]).

The fuselage is a wide body, enlarged vertically, with three decks (two for passengers and one for cargo); the front wing, rearward swept, is connected to the fuselage bottom while the rear wing, forward swept, is attached to the fuselage top (for flutter problems).
This solution proved to be satisfactory from many points of view, with the exception of one. In fact, there exists a disadvantage due to the fact that the rear wing shows a small aerodynamic efficiency in the root region, where the interactions with rear body and fin occur (the presence of shock waves reduces even more the aerodynamical efficiency). Hence, in order to obtain the static stability of flight, the center of pressure of the whole aircraft (coincident with the center of gravity during trimmed flight), needs to be positioned closer to the front wing, with the consequence that this wing is more loaded than the rear one. So, the condition of equal lifts, mentioned before, is violated and the aerodynamic efficiency is reduced. In other words, the static stability of flight and the aerodynamical efficiency are conflicting in the solution in figure 5.
In the period 2000 - 2002, five Italian Universities carried out a national project, financed by the Ministry of University, to develop the PrandtlPlane configuration with application to a 600 passenger aircraft. An important result of the project was the solution of the conflict between aerodynamic efficiency and stability of flight, obtained with the development of a new configuration.
Figure 6 summarizes this research activity; it shows a typical new very large aircraft. In the new solution, the fuselage is enlarged horizontally, with a single deck for passengers and the bottom one for goods and luggage. The rear wing is positioned over the fuselage and connected to it by two fins.
This aircraft is stable in cruise flight, the margin of stability can be controlled and modified by a proper variation of chords and, also, of sweep and twist angles along the span of both the wings. This result is the consequence of the high aerodynamic efficiency of the rear wing (between the two fins), which depends on both the gap and the shape of the top fuselage or, in other words, on the characteristics of the aerodynamical "channel", defined by top fuselage, bottom rear wing and lateral fins.
The main characteristics of this solution will be summarised in the next item, making reference to the main elements of the aircraft.

Fuselage.
The fuselage (contrary to A380) is enlarged horizontally, with a constant width along the longitudinal axis; the fuselage stern is provided with a trailing edge similar to a profile. In the case of a 600 seat aircraft, a typical arrangement provides three corridors and 14 seats abreast with 3 LD1 containers abreast in the cargo compartment.
The front wing crosses the fuselage under the cargo floor and, hence, contrary to conventional aircraft, the cargo compartment is continuous along the whole fuselage, with four doors for loading and, at the same time, unloading containers.
Passengers occupy a single deck and, even for very large aircraft, the fuselage length is lower than an equivalent conventional aircraft (and the flight qualities are enhanced during short period motion and pilot induced pitch manoeuvres). The emergency exits have the same distribution of conventional aircraft (this condition is important for airliner companies), and the number of crew members is reduced for having passengers on a single floor.
The main landing gear is made of four or more legs. The solution adopted is to use many wheels of smaller diameter, positioned along lateral sponsons (in order, as said before, to obtain a cargo bay as long as the whole aircraft); an example of structural solution for the main landing gear sponson is presented in the next section. The cargo capacity of the

PrandtlPlane is enormously higher than a conventional aircraft and, as said before, the time reduction for boarding and disembarkation of passengers and goods and luggage is reduced significantly, as requested in the Vision 2020. In practice, we could say that the PrandtlPlane concept is a mixed passenger-cargo aircraft.

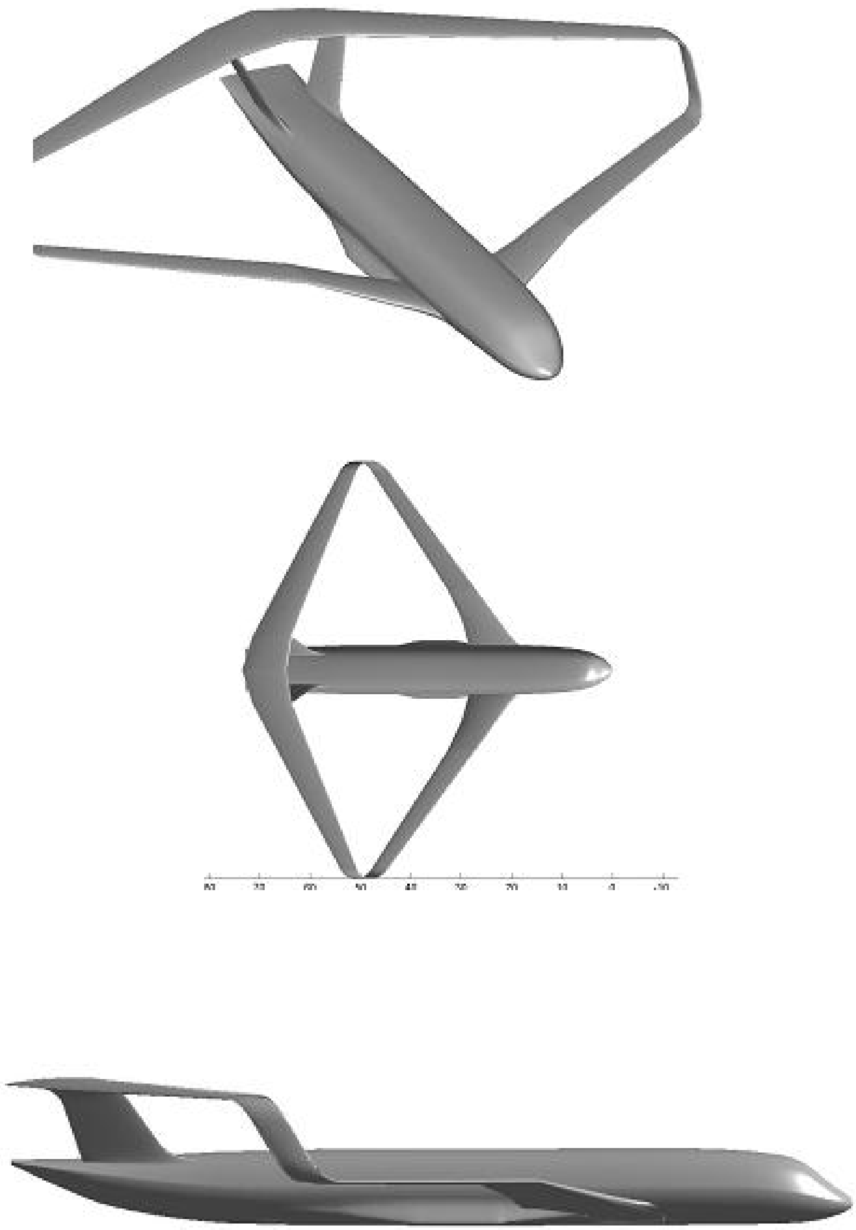

Figure 6: Sketch of a configuration with high aerodynamical efficiency and stability of flight ([8]).

From the structural point of view, the fuselage in flight is equivalent to a doubly supported beam, the supports being the front and rear wing and, then, (contrary to conventional aircraft) bending stresses in the fuselage are nil close to the front and rear wing roots. Bending stresses are maximum between the two wings (it follows that the sponson structures will be designed to improve the fuselage bending stiffness). During touch down, (contrary to conventional aircraft) the fuselage bending moment reduces the stresses in flight. The eigenmodes of the aircraft are completely different from conventional ones; in particular, the lateral bending modes of front conventional fuselages are no longer present. The design against Flutter can influence the fuselage structures. The damping moment and the moment of inertia along the pitch axis are higher than an equivalent conventional aircraft; hence, the flight qualities are considered to be very satisfactory (level I); the main problem is to design properly the pitch control system.

Lifting system.

As said before, the structures of the lifting system are over-constrained to the fuselage. On the other side, the local stiffness along the wing span is lower than conventional aircraft (nearly the half, supposing that the PrandtlPlane wings have the same wetted surface of the correspondent conventional wing plus the stabiliser). A comparison between the two solutions is not simple and depends on the aircraft capacity. Preliminary results show that the maximum static bending deflection of the wing system is lower than conventional aircraft, under the same total lift and wing span. More research is necessary on this subject, taking also aeroelasticity into account.

The lifting system provides an intrinsic structural safety as far as Damage Tolerance is concerned. In fact, a wing can be damaged without producing a global failure, due to the over-constrained solution adopted.

The engine integration is not critical and different strategies exist according to the aircraft capacity. In the case of a very large aircraft with 4 engines, two engines could be positioned under the front wing (or over it, in case of low noise solution) and the other two on the lateral fuselage or under the rear wings (and the moment of inertia along the roll axis is reduced compared to a 4 engine conventional aircraft); in the case of two engines, they could be connected to the rear fuselage (an example will be given later on, where the wings are completely “clean”) or under the front wing.

The primary wing structures could be manufactured in composites, owing to the “clean” wings and the high lift devices small concentrated loads. Fuel is contained in both the wing boxes and is consumed in such a way that no variations of the centre of gravity occur during cruise; hence, one single flight condition is optimised (with positive effects on the aircraft performances). As said before, the moment of inertia along the pitch axis is very large, with consequences on the Short Period and Phugoid response in Flight Mechanics and, also, the need of efficient pitch control. As already said, the static aeroelastic phenomena are completely different from conventional aircraft.

As a final remark, it is easy to observe that the lifting system and the fuselage are part of one single structural system (contrary to conventional aircraft), because the box system connects front and rear fuselage as shown in the sketch in figure 7; usually, the bending stiffness of the lifting system is negligible compared to the fuselage one.

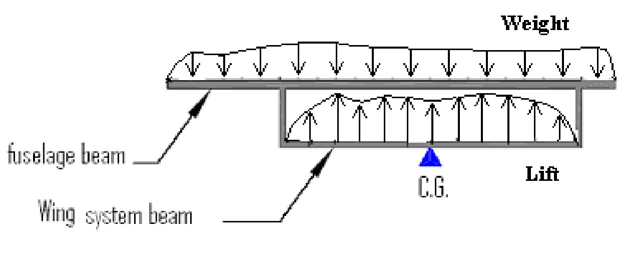

Figure 7: Structural sketch of lifting system and fuselage in a PrandtlPlane configuration.

In figure 7, the lift forces on the wing system (empty weight excluded) equal the weight forces on the fuselage, pitch moment being zero.

Flight Mechanics and Controls.

As said before, a Twin Fin PrandtlPlane aircraft is stable in any flight condition, with a proper margin of stability and with equal lifts on front and rear wings.
As said before, the pitch control could be critical in the case of very large aircraft, due to large moment of inertia along the pitch axis. In order to address pitch motion, the control is made of two elevators, one on the front and the other on the rear wing, moved in phase opposition; this control provides a pure moment in pitch. Other strategies are possible by mixing the canard and pure pitch moment controls. In general, the results obtained so far show that the flight qualities are level I, that the Short Period motion is stable and strongly damped (due to the high value of the derivative M_q) and the Phugoid motion is stable with a lower damping.
In any case, the pure moment pitch control is safer than conventional controls (with negative lift on the elevator).
Results available so far show that the PrandtlPlane configuration is very stable with respect to stall, because the stall angle of the rear wing is much higher than that of front wing (due to downwash).
The design parameters to control the lateral stability are the dihedral angles of the front and, in particular, the rear wing and, also, the vertical tip wings. The lateral control is unconventional due to the double rudder; the vertical wings could be used for lateral control as well. The ailerons could be positioned on the rear wing; they could be used as flaperons so that the high lift devices are positioned along the whole span on both the wings.

High lift devices

With a proper design, the theoretical condition of “Best Wing System” could be obtained with the high lift devices extended, contrary to conventional aircraft. In fact, in the Prandtl best wing system, the lift on the horizontal wings is made of the elliptical and the constant parts. A near-optimum configuration in take off and landing could be obtained by increasing the elliptical part of the same amount on both the wings. In this case, as said before, slats and flaps must be positioned along the whole span of both wings. The design and optimisation of high lift devices is one of the main challenges of the aerodynamic design.
This solution could allow us to reduce noise and noxious emissions in take off and landing according to the above mentioned principle of sustainable growth.

Application as a freighter

The application of Twin-Fin PrandtlPlane configuration as a freighter aircraft is straightforward, due to the fuselage shape. As already said, the main undercarriage is made of multiple legs with small wheels, contained inside lateral sponsons. A cargo deck as long as the whole aircraft length is obtained; the stern and the bow will be moveable and the cargo compartment will be not pressurized.
The very high maximum take off weight of this aircraft needs a very large wing surface. In this configuration it is immediate to obtain a large wing surface without compromising the static stability of flight; on the contrary, in a conventional aircraft, a very large wing surface must be accomplished by a very large tail volume, for flight stability.
The development of the cargo PrandtlPlane configuration is a great challenge of future transport aviation.

Application as a conventional or seaplane cryogenic freighter

The PrandtlPlane configuration is suitable also for a cryogenic aircraft, in which (contrary to other proposal, e,g. [9]), the hydrogen tanks are positioned under the lower cargo deck.
Figure 8 shows a (artistic) section a seaplane cryogenic freighter PrandtlPlane aircraft. The green aircraft is a dream of the future, in the Vision 2020 of Europe. The proposed solution can be also designed according to the Low Noise Aircraft in order to fly 24 hours per day all weather.

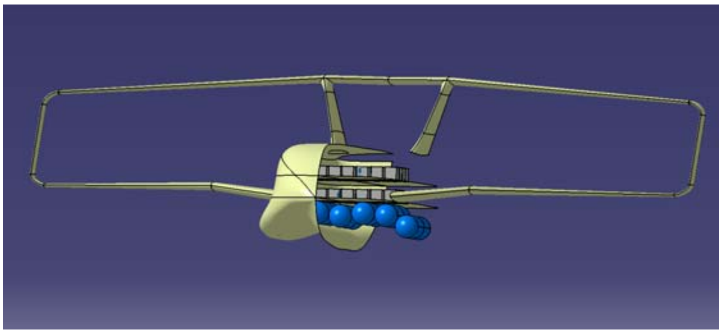

Figure 8: Artistic view of a cryogenic aircraft.

Seaplane freighter aircraft could allow us to transport containers from point to point in the world, far from the passenger routes, 24 hours a day.

Application to small aircraft

The small aircraft industry has to become more and more important in the next future and important benefits could be obtained from PrandtlPlane configuration. With reference to figure 9 ([8]), a ULM PrandtlPlane aircraft presents the following characteristics: (i) high structural safety against crash (the passengers are positioned after the front wing crossing), (ii) high structural safety against damage (the lifting system is damage tolerance), (iii) safety against fire (the engine is behind the passengers and far from them), high stability of flight (with a proper definition of wing chords and twist angles), (iv) high aerodynamical efficiency (due to the best wing concept), (v) possibility of a tandem configuration (in this case the second passenger is positioned close to the C.G.).

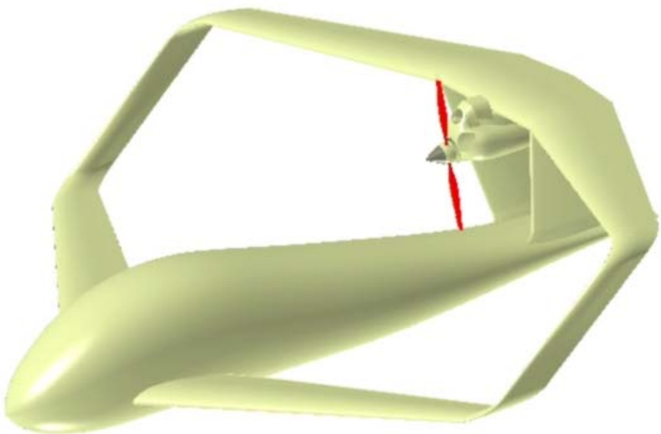

Figure 9: ULM PrandtlPlane concept

(vi) possibility of a seaplane configuration (e.g. sketch in figure 10) or amphibious one.

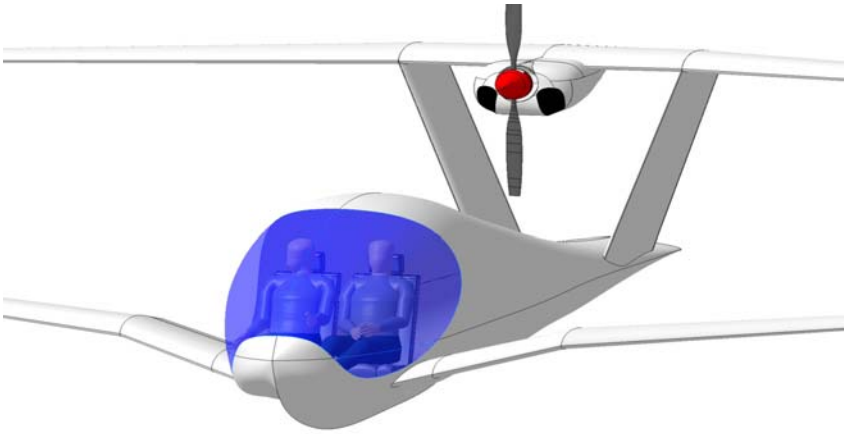

Figure 10: ULM Seaplane PrandtlPlane aircraft

The PrandtlPlane configuration has the potential for achieving, simultaneously, the top level objectives, identified by the Strategic Agenda for European Aeronautics, that is: *Strengthening the competitiveness of the manufacturing industry in the global market* (more economical, performing, safe, clean and better quality aircraft could be designed), *Improving environmental impact with regard to noxious emissions and noise* (the PrandtlPlane concept is based on an increase of aircraft performances during cruise flight and low speed flight), *Improving aircraft safety* (Damage Tolerance properties of wing structures, pure moment pitch control, total separation of engines, fuel separation, smooth stall, etc.) and *Increasing the operational capacity and safety of the air transport system* (as shown in the example in the next paragraph).

So far, no showstopper is evident, but many questions are open as well as many subjects for research.

A list of the main open questions is the following:

- Friction drag of the configuration,
- Optimization of the aerodynamic efficiency with the high lift devices extended,
- Structural efficiency of the wings and new materials (composites or hybrid materials),
- Fuselage structural optimization.
- Comfort of passengers during flight and ground maneuvers,
- Structural dynamics and aeroelastic phenomena,
- Engine position and integration, etc.

An example of a medium size PrandtlPlane aircraft is given in the next section.

4. A MEDIUM SIZE CIVIL TRANSPORT PRANDTLPLANE AIRCRAFT

The example shown in this section is the application of the PrandtlPlane concept to a 250-300 seat civil transport aircraft ([10]). The aircraft is designed to follow the new requirements contained in the document "Vision 2020" and, in particular, in order to meet, simultaneously, the main challenges regarding: (a) Quality and affordability, (b) Environment, (c) Safety, (d) Efficiency of the air transport system.

A sketch of a typical configuration of the aircraft is shown in figure 11**.** There are two decks, one for passengers and the lower one for goods and luggage. The cockpit is positioned at the cargo deck level to meet the visibility requirements shown in figure 12 and, for security reasons, is fully separated from the passengers; behind the cockpit a bed room can be present for the pilot rest.

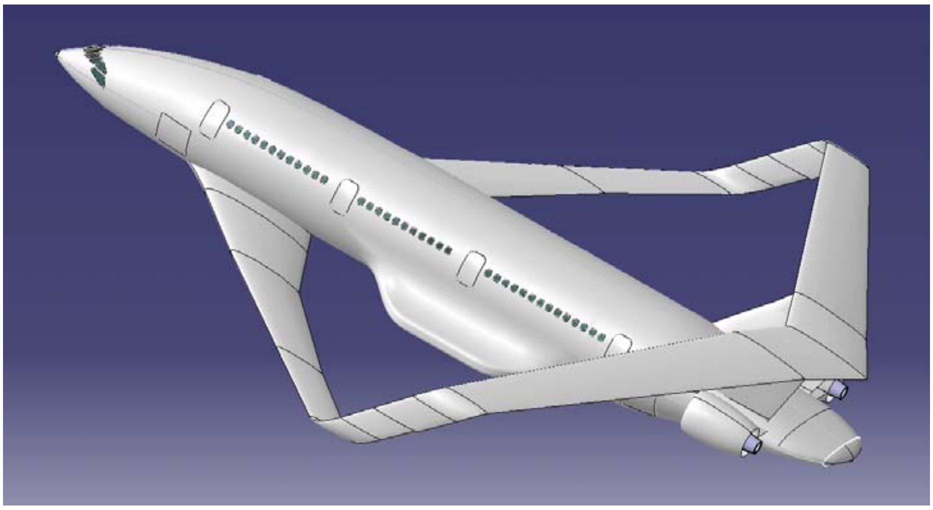

Figure 11: View of PrandtlPlane aircraft

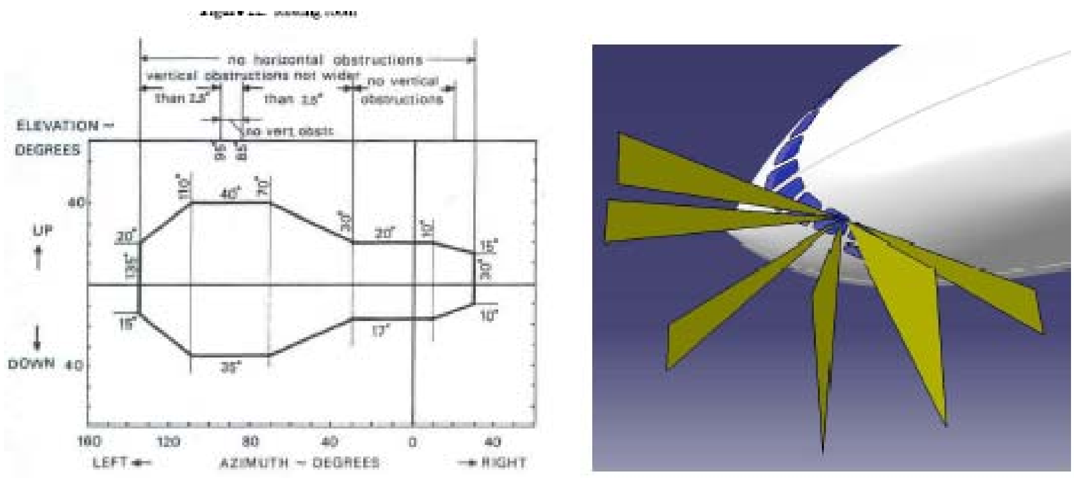

Figure 12: Vision Requirements and cockpit window solution

Figure 13 shows an artistic sketch of a possible solution for the passenger layout (258 passengers in two classes, 210 + 48).

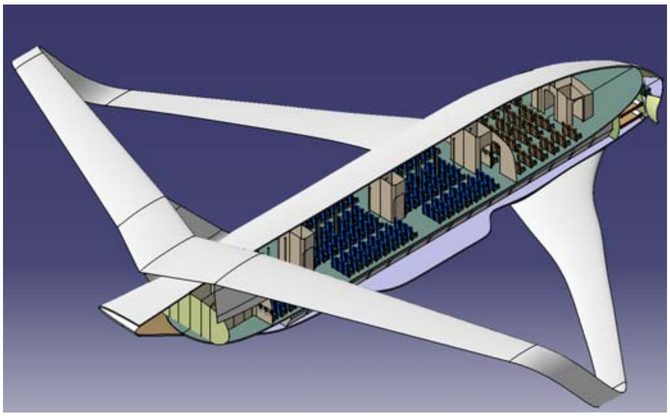

Figure 13: View of 258 passenger accommodation in two classes.

The PrandtlPlane proposed configuration permits us many possible passenger accommodations. For example, Figure 14 shows a solution with 329 passengers (270 economy, 49 business and 16 first class on the lower deck level.). Figure 15 shows a simulation of the livability in the business class

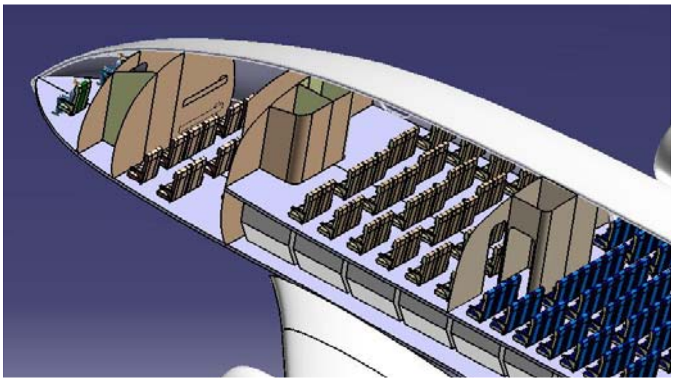

Figure 14: Passenger accomodation

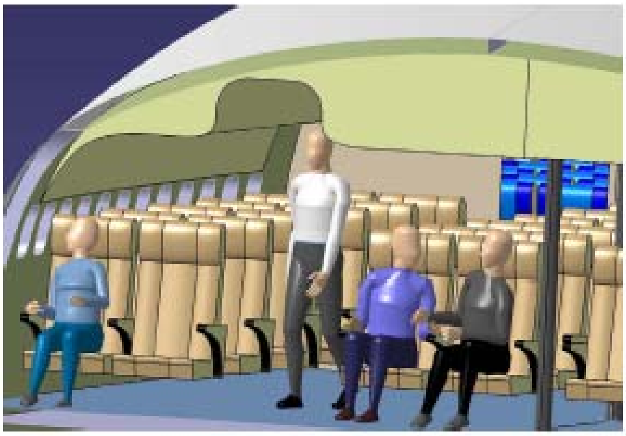

Figure 15: Simulation of business class livability

The cargo compartment of the present aircraft contains 32 LD3 (figure 16) or 38 LD1 (figure 17) containers, the double of an equivalent conventional aircraft. In both cases, the containers are loaded through the two front doors and unloaded by the rear doors (or vice versa) in such a way that the time spent is halved.

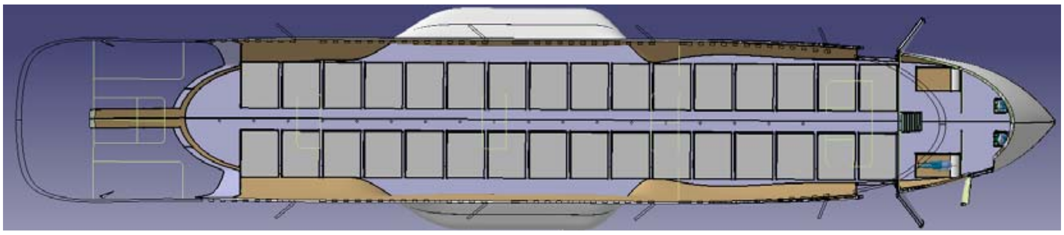

Figure 16: The cargo deck with 32 LD3

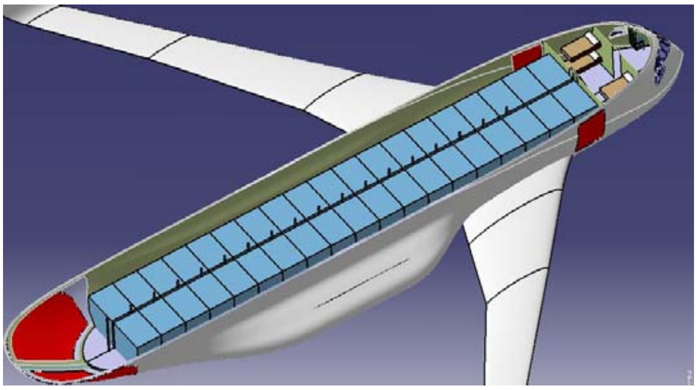

Figure 17: The cargo deck with 38 LD1

Figure 18, 19 and 20 show three views of the proposed PrandtlPlane aircraft. The upsweep angle of the rear fuselage is designed in order to minimize the fuselage drag. In the solution proposed, two engines have been mounted in the lateral rear fuselage, at the passenger level, intermediate between the upper and lower wings.

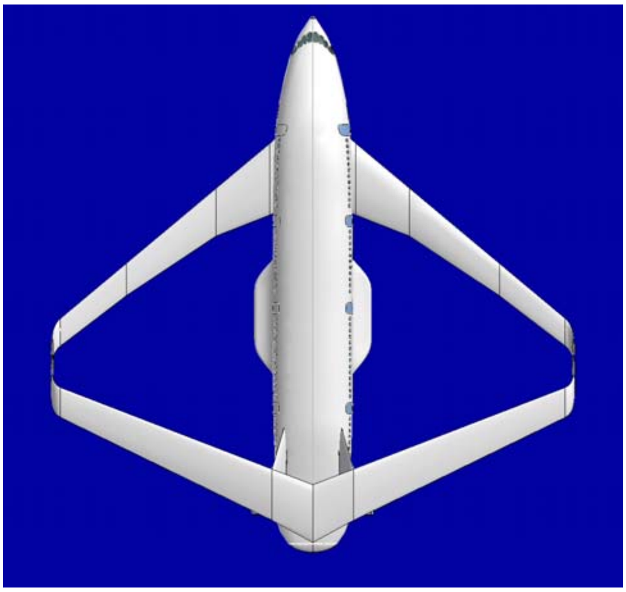

Figure 18: Horizontal view

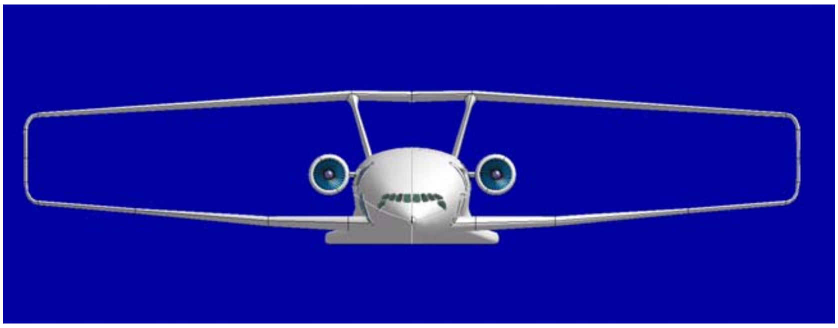

Figure 19: Front view

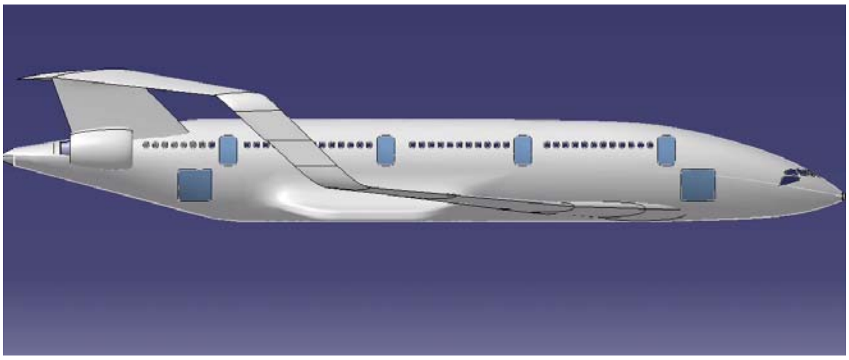

Figure 20: Lateral view.

Figure 21 shows a outer perimeter of the fuselage, made of three circular parts, joined each other with continuous first derivative.

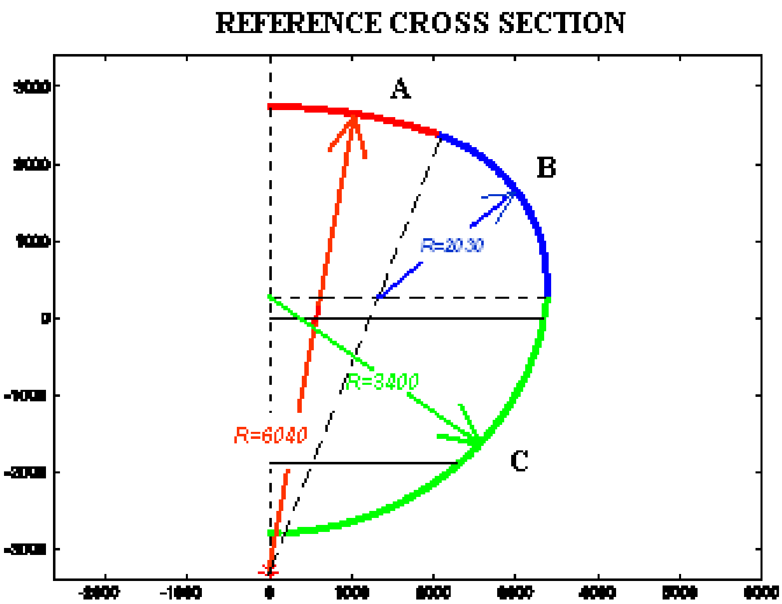

Figure 21: Outer perimeter of a typical fuselage section.

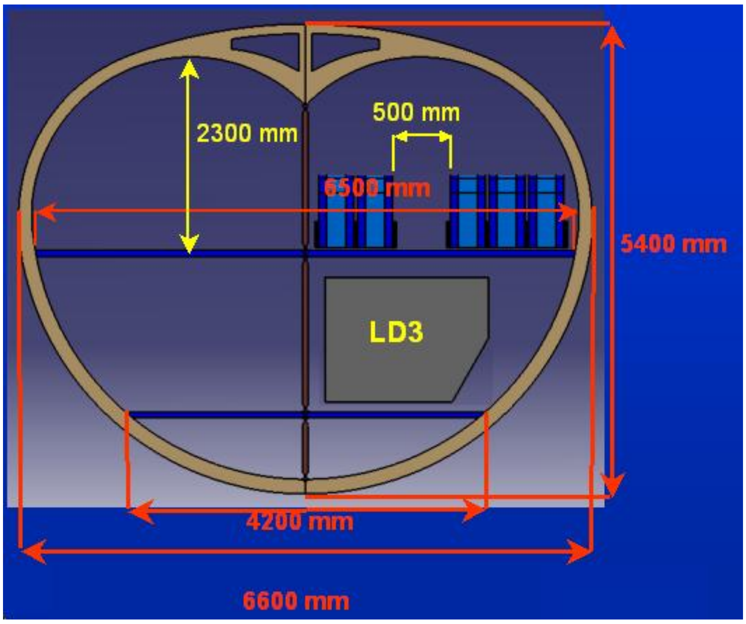

Figure 22: Sketch of the structural solution of the fuselage.

A sketch of the structural solution is shown in figure 22. The internal width of the passenger compartment is 6500 mm, the maximum height is 2300 mm, the cargo deck width is 4200 mm and the height is 1700 mm; the overall dimensions are: 46m wing span and 47 m length. As shown in figure 22, a vertical strut connects the top and bottom fuselage; the struts are removed close to the exit and emergency doors. Two keel beams are present, one on top and the second on bottom of the fuselage. The top beam is introduced to prevent the compression instability during flight of the central fuselage between the two wings. The pressurized fuselage is the outer contour; the air ducts and the other installations occupy the two top fuselage spaces and the lateral spaces in the cargo deck. The passenger and cargo beams have a central vertical support; this solution reduces the empty weight significantly compared to conventional solutions; this result is possible due to the unconventional large fuselage width. The structural solution have been defined preliminarily and the dimensions have been modified on the basis of a Finite Element Method analysis, taking the loads in flight and pressurization into account.

Ground operations have been considered, as shown in figure 23.

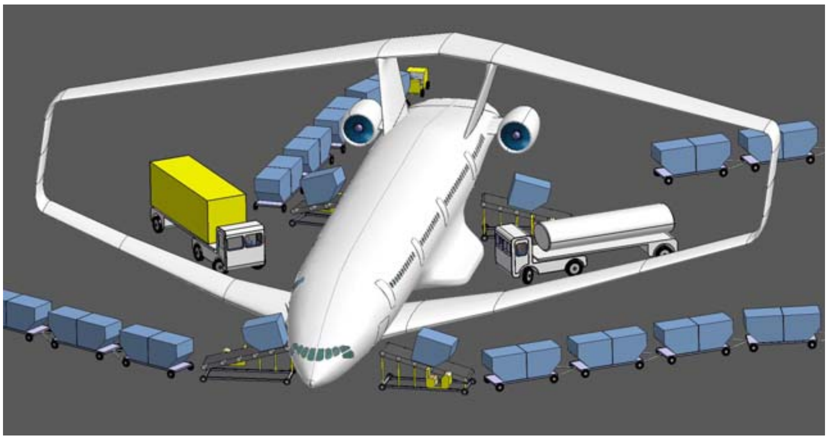

Figure 23: A sketch of ground operations before flight.

Figure 24 shows a typical aerodynamic result obtained with Fluent CFD code in the transonic range (0.85 Mach). The sponsons are not critical from the aerodynamic point of view; the critical regions for wave drag are the connections between the fin and rear wing and the front wing root.

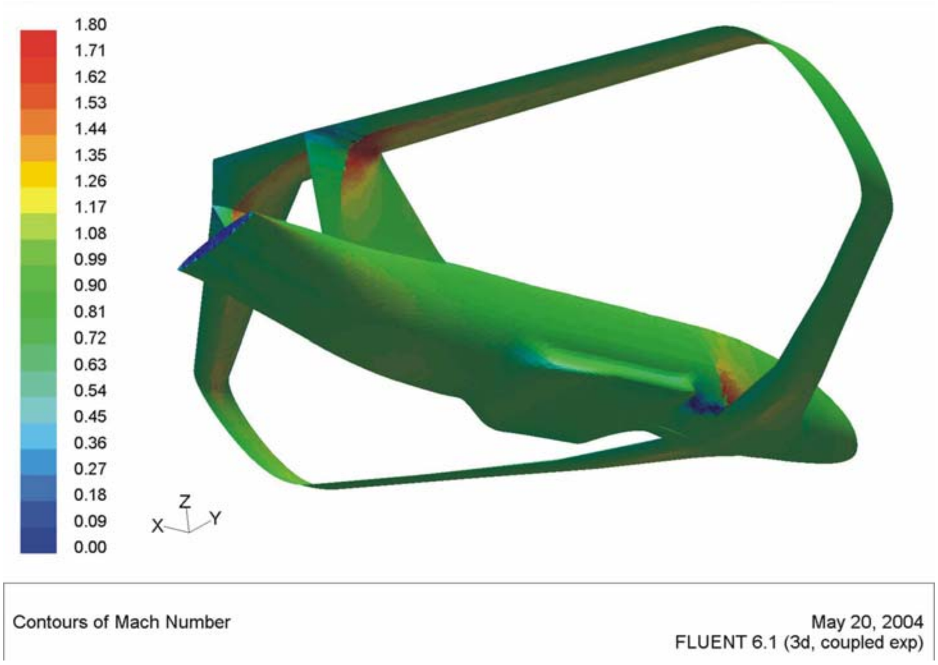

Figure 24: Typical aerodynamic result.

Figure 25 shows the results of a FEM analysis of the central fuselage which includes the sponsons of the main undercarriage (external sheet is omitted for the sake of clarity).

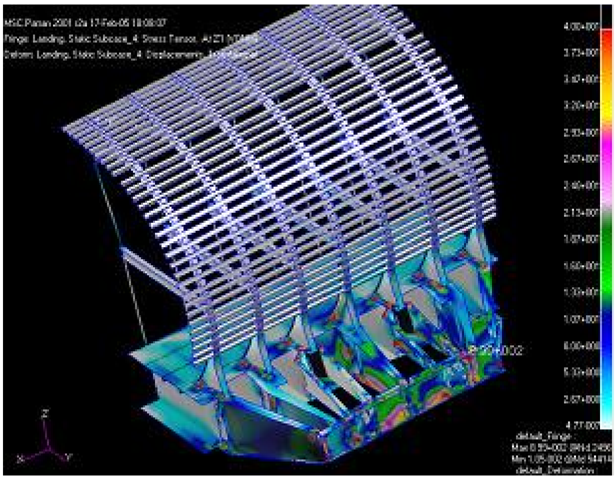

Figure 25: Finite Element model

The main landing gear is made of four groups with 4 wheels for a total of 16 wheels (30 inch diameter). Figure 26 shows an example of the kinematics of the main landing gear and Figure 27 shows a sketch of a view in the extended position.

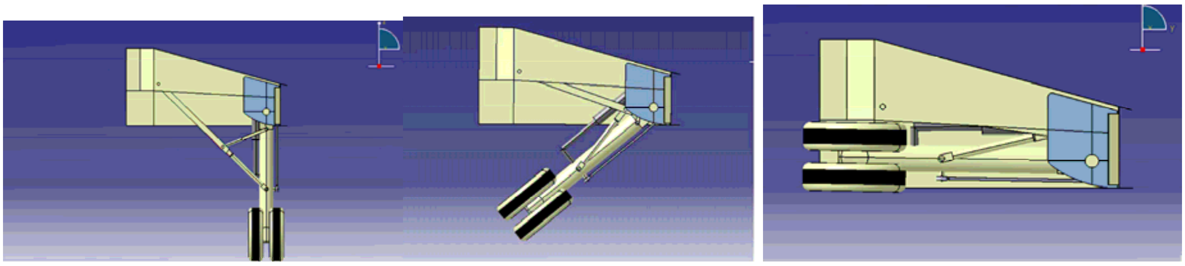

Figure 26: Kinematics of the main undercarriage

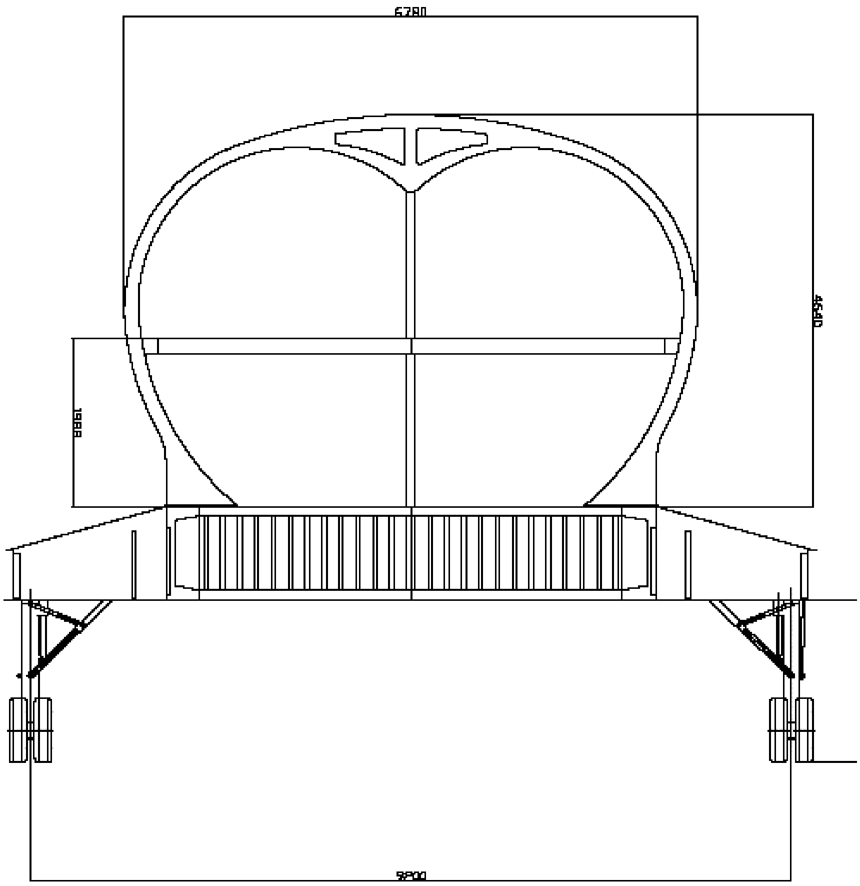

Figure 27: A sketch of the main undercarriage in the extended position.

Figure 28 ([11]) shows the flaps and slats on the lifting system and, also, the pitch control surfaces on front and rear wings. The high lift device system is very efficient and allows us to trim the aircraft, to apply an equal lift increment on both the wings and, finally, to obtain the static stability of flight in all the operative conditions; hence, the Best Wing System condition of equal lifts on both wings is satisfied with a good accuracy.

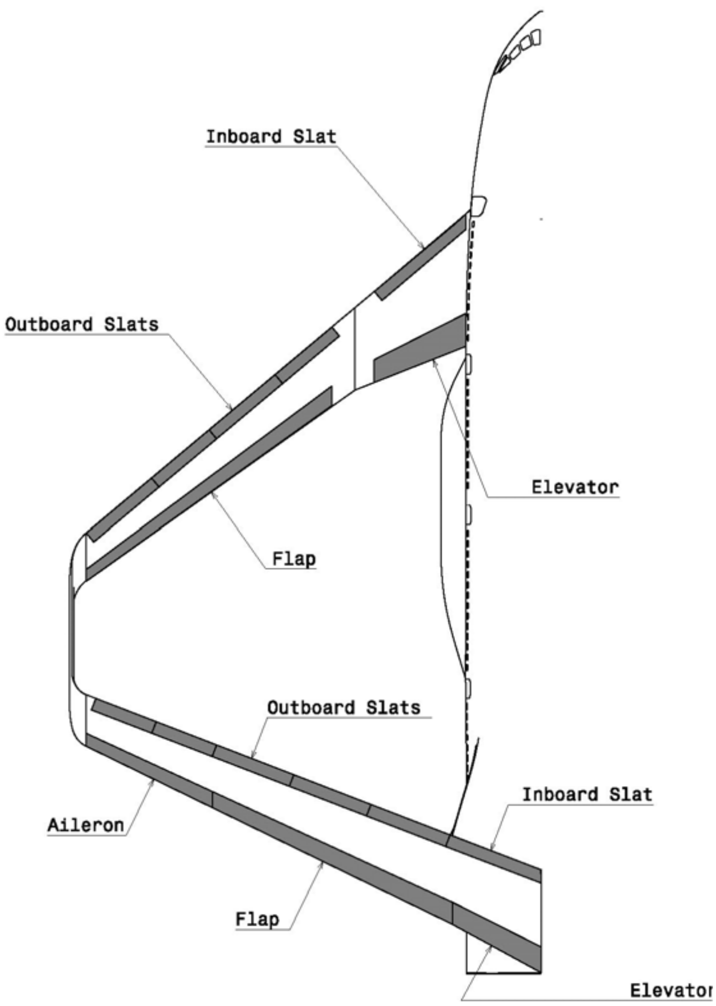

Figure 28: High lift devices and pitch control

5. CONCLUSIONS

The PrandtlPlane aircraft was conceived in order to fulfil all the requirement which define a sustainable growth in the civil aviation of the future. For simplicity sake, we refer to the challenges defined by the European Community.

<u>The challenge of quality and affordability</u>.

The following goals are related to quality and affordability: passenger choice, reduction of travel charges, air-freighter services, halving the time to market for the new products.
The passenger choice is related to the availability of a wide range of ticket prices, time to destination, (including the time spent in airports), specific services, with more space and activities available, more personal catering, more comfort (less noise and vibrations and good dynamics of flight)

The fall in travel charges depend on the possibility of reducing aircraft cost, maintenance cost, crew cost, fuel cost, fees/charges.
A reduction of fees/charges in the future depends on many factors but, however, the improvement of productivity of the aircraft is essential. The improvement of productivity grows with aerodynamic efficiency and ground organisation; in this context, the reduction of the time spent for boarding and disembarking is very important. As shown before, the PrandtlPlane proposal allows us rapid cargo loading and unloading, because of the lateral doors on back and front fuselage.
The dynamics of flight could allow us more comfort in flight; a more flexible utilization is also possible for the airliner companies. The PrandtlPlane configuration can be applied to a large family, which includes both passenger and freight aircraft. For all the aircraft of the family, a set of possible propulsion configurations is available. The aerodynamic efficiency is very high due to the low induced drag and, at the same time, the aircraft is stable as far as flight mechanics is concerned. Very large PrandtlPlane aircraft could be designed for more than 600 passengers, with a wingspan compatible with the actual airports.
The design problems, especially those coming from the pressurization of fuselage, require proper structural solutions and materials; indications in this context have been shown in the previous section.
The PrandtlPlane proposal is very suitable for a hybrid freighter aircraft, due to the wide cargo compartment. In the case of a pure freighter aircraft, the same design concept can be applied without the structural problems deriving from the fuselage pressurization. In this case, a new world transportation system can be conceived by designing PrandtlPlane for both airports and sea ports (SeaPrandtlPlane or SPP). The SeaPrandtlPlane could allow us to use both sea and internal waters (rivers, lakes, hydro ports) for transporting goods from point to point in the world. This solution will be possible only if the approach and landing speeds will be significantly reduced; a SPP aircraft, by a proper design of the high lift devices in both the wings, has the potential to fulfill these requirements. It is quite clear that waters must be saved from pollution
The SeaPrandtlPlane proposal is particularly suitable for application of cryogenic power plant in the distant future.

The challenge of the environment.

The challenge of environment could be faced by introducing new technologies, novel airframes and engines in order to reduce weight and increase aerodynamic efficiency. The main challenges connected to the environment are:
to reduce fuel consumption and CO_2 emissions,
to reduce perceived external noise by 50%,
to reduce NOx by 80%,
to reduce the environmental impact in the manufacturing phase
A reduction of CO_2 up to 50% can be obtained by the following main contributions: (i) aerodynamic efficiency and weight reduction, improvement of aircraft capability, new aircraft concepts (ii) improvement of low speed thrust by means of better cycles, (iii) efficient route operations, (iv) new Hydrogen or CH_4 engines.
The main challenge for 2020 is the “quiet aircraft”, in which the noise reduction is 10 db in 2020 and the noise perceived at the boundaries of the airfield is reduced by 50%. The quiet aircraft is a target concept, to be obtained by means of different activities on lighter airframes, new engines, aero-acoustic design, active control, etc. But more radical solutions and new concepts of “quiet aircraft” are needed.

The PrandtlPlane configuration is a new concept with the potential to reduce significantly emissions and noise. In fact, according to the previous considerations, the Best Wing System concept can be applied also in the take off and landing with a proper design of the high lift devices, extended all over the wing span.
In the present research project, a large amount of computation is needed to design and optimize the low speed configuration in order to minimize drag in a stable aircraft in any flight condition. Some preliminary wind tunnel tests are also necessary to validate the CFD analyses and assess the aerodynamic derivatives to carry out the flight mechanics simulation.
As already said, the high aerodynamic efficiency at low speed could be used to reduce the power plant installed and, hence, to reduce noise and emissions/passenger.
As already said, the PrandtlPlane configuration is particularly suitable for adopting H_2 or CH_4 innovative fuels; in particular, due to the large width fuselage, the large tanks can be positioned under the lower cargo floor.

The challenge of safety.

The air transport scenarios for the years 2020 in relation to the safety is based on: air traffic improvement, development of freight transport, need to separate passengers and freight transport to optimize costs and safety, more automatic flight control for freight aircraft, more use of satellites in communication and navigation. In this vision the congestion of airports is the bottle neck for the traffic improvement
The challenge has the goals of reducing accidents by 80% with a triple traffic growth and all weather operation, having 99% of flight within 15 minutes of schedule and 24 h per day operation.
The largest number of accidents takes place on approach/landing, controlled flight into terrain and loss of control.
The proposed configuration can contribute to improve safety significantly.
As already said, the flight control in pure pitch or canard-type, reduces the possibility of loss of pitch control close to the ground. Besides, as shown in preliminary wind tunnel tests, the pitch control is not lost even at high angles of attack, because of the high aerodynamic stability of the rear wing. Finally, the catastrophic buffeting phenomenon at the fin is not critical in this aircraft.
Another important aspect is the vorticity in the airfield. The vorticity left in the field is less intensive than that of a conventional equivalent aircraft; thus, the separation safety level is enhanced.
The problem of congestion of airports in the next future is connected also to the possibility of flying 24h per day. The proposal of transferring the new big freight aircraft to the open sea or proper internal water fields could be a solution for improving both the traffic volume and the safety level of transportation of both passengers and freight. As already said, the routes for freight transportation could be fully separated from those for passenger transportation and, once more, the safety will improve.

The challenge of air transport system efficiency**.**

The potential aerodynamical efficiency of a PrandtlPlane have been shown.
The proposed non conventional aircraft can be designed with capacities and all of them are part of the same family. The technological risks required for the development of a new aircraft are enormous but, when the financial resources are invested towards the development of a family of aircraft, the risks are lowered. In this context, the bigger aircraft of the family

could be manufactured together with the increase of the traffic demand. All the aircraft of the PrandtlPlane family, even those bigger than A380, are compatible with the major airports.

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