The PrandtlPlane

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Summary

In the next twenty years, civil transport aircraft are requested to reduce the Direct Operative Costs by 30% or more and to cut noise and noxious emissions. These results can be hardly obtained by conventional aircraft, because their efficiency, as a result of decades of progress, is close to the maximum. So, a great interest is now devoted towards new non conventional aircraft for future civil aviation. The present paper shows a preliminary aerodynamic project of a non conventional aircraft, in which the aerodynamic efficiency is improved through a significant reduction of the induced drag. The starting point of the project is a theoretical result by Prandtl, published in 1924, on the lifting system with the minimum induced drag and, in honor of Prandtl, the aircraft configuration is named as "PrandtlPlane". In the PrandtlPlane configuration, Aerodynamics, Flight Mechanics, Structures, Aeroelasticity, etc. into account The concept can be applied to any dimension aircraft; examples of application are shown in the paper.

Introduction

Passenger and cargo traffic are estimated to grow by a factor of three in the next two decades, especially along medium and long range routes worldwide. The civil aircraft of the future are requested to improve significantly their performances. Typical required performances were defined at the beginning of 90s by the airline companies. More recent definitions of the required performances in the framework of the European Community were given in Vision 2020, by the Advisory Council for Aeronautics Research in Europe, October 2002. 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, improvement of cargo capacity, possibility of operating from present runways and airports, 30% reduction of Direct Operative Costs, improvement of the operative life, reduction of initial investment and costs for maintenance, 0.85 Mach cruise speed, more cargo in addition to luggage, reduced approach and landing separations due to wake vortex turbulence. In addition, new noise and emission requirements are considered to be a major concern.

The problem of reducing Direct Operative Costs and noise and emissions can be faced by using technology advancements (new materials for structures and engines,

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reduction of production and maintenance costs, etc). The increase of aircraft capacity is another way for reducing the unit costs, but the biggest possible aircraft compatible with existing airports must be included in an 80x80m horizontal square, in order to be compatible with present airports [1]. So, the advantage of increasing dimensions came to its end with the A380 aircraft.

The conclusion is that future requirements for DOCs and noise and emission reductions will not be satisfied, without a significant improvement of aircraft performances. The improvement of the aerodynamic design against drag is essential for the commercial success of any transport aircraft programme and for reducing pollution and noise. The need of improving the aircraft performances is mandatory; a 1% reduction of drag for a large transport aircraft saves 400.000 l of fuel and, consequently, 5000 Kg of noxious emissions per year [2]. International authorities indicate the dangerous improvement of pollution due to the aircraft's share in global emissions. The improvement of the low speed aerodynamic efficiency of aircraft is one of the main challenges of the future.

In a large transport aircraft during cruise flight, drag is mainly due to friction drag (about 47%, according to [3]) and induced drag (about 40%), where the induced drag depends on the lift distribution along wing span. The lift distribution of to-day large transport aircraft is so optimized that any further significant reduction of induced drag can be easily obtained. Ways of reducing friction drag are suction of the boundary layer or use of devices on the outer surface of the aircraft but, till now, the overall benefits are not well quantified. A possible jump forward in air transport will come from the introduction of completely new, non-conventional, aircraft.

According to Prandtl, the lifting system with minimum induced drag is a box-like wing (named as "Best Wing System" by Prandtl), in which the following conditions are satisfied: same total lift and same lift distribution on each of the horizontal wings and butterfly shaped lift distribution on the vertical wings. When this condition of minimum occurs, the velocity induced by the free vortices is constant along the two horizontal wings and identically zero on the vertical side wings. The efficiency increases with the gap between the wings. 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 published in NACA TN 182, 1924 [4]. In this paper, Prandtl used an approximate procedure; a closed form solution of the Prandtl problem was given by Frediani and Montanari, in 1999 [5], confirming that the Prandtl results, at least in the range of the wing gaps of interest for applications, were correct. The ratio between the induced drag of the best wing system and the optimum monoplane is shown in figure 1; in the range of interest of h/b (10-20%), the induced drag is reduced from about 20% to 30%. Owing to the Munk theorems, the induced drag is independent of the sweep angles of the wings and, therefore, the Prandtl concept can be applied also to transonic aircraft. In honor of Prandtl, the configuration is named as "PrandtlPlane".

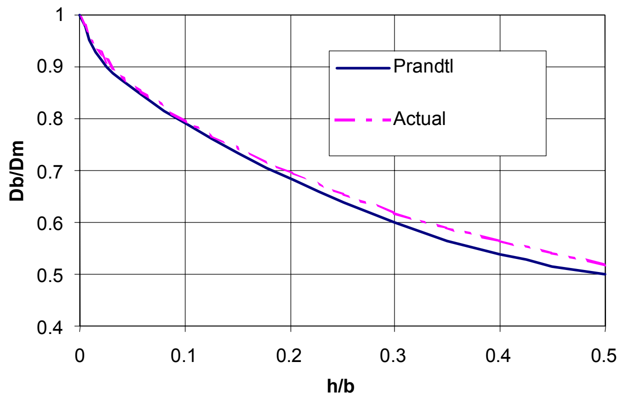


Figure 1

The problem of friction drag and wave drag is still open and no definite answer is available at this stage. 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 are compatible with the 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 inside 80m, without drag penalty with respect to conventional aircraft. The possibility of improving the PrandtlPlane capacities beyond the largest possible conventional aircraft is one of the possible advantages for reducing drag.

The PrandtlPlane Aircraft Concept

In the case of very large aircraft the PrandtlPlane configuration was conceived as shown in figure 2 [6],[7]. The fuselage is a wide body, enlarged vertically as A380. The front wing, positive swept, is connected to bottom fuselage and the rear wing, negative swept, to top fuselage. This solution shows a high structural efficiency of the lifting system but, also, a conflict between aerodynamical efficiency and static stability of flight. In fact, rear negative swept wing shows a low aerodynamical efficiency at the root and inside the fuselage; hence, the center of pressure of the whole aircraft (coincident with the center of gravity during the trimmed flight), must be closer to the front wing. The front wing becomes more loaded than the rear one and the conditions of best wing system mentioned before are violated (and the aerodynamic efficiency is reduced. In the period 2000 - 2002, five Italian Universities (Torino, Milano, Roma “La Sapienza”, Roma Tre and Pisa) carried out a national project, financed by the Ministry of University, to develop the PrandtlPlane configuration with application to a 600 passenger aircraft

Figure 2

One major result of the project was the solution of the conflict between aerodynamic efficiency and stability of flight; the new configuration is shown in figure 3.

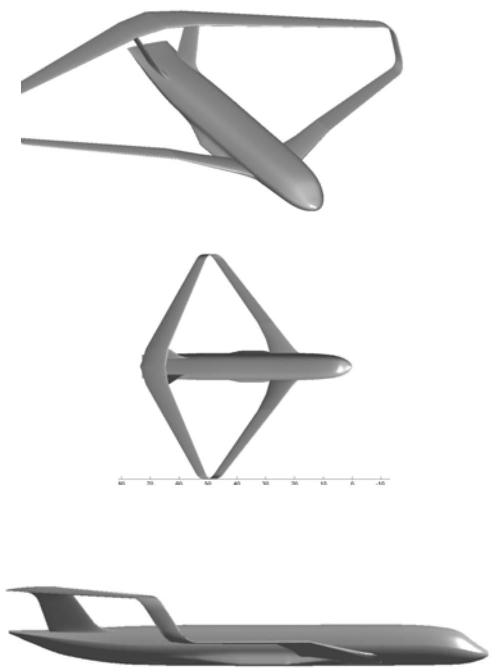


Figure 3

In the new solution, the fuselage is enlarged horizontally with a single deck for passenger and with a constant width up to the end. The rear wing is positioned over the fuselage by means of two fins. This aircraft is stable in cruise flight; the margin of stability can be controlled and modified and, at the same time, the lift is equal on the front and rear wings. This result is the consequence of the high aerodynamic efficiency of the central segment 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 the PrandtlPlane configuration of reference can be summarized as follows

Fuselage. The fuselage is enlarged horizontally, with a constant width along the longitudinal axis, and the end fuselage has a trailing edge in the lateral view. The front wing crosses the fuselage under the cargo floor. Passengers occupy one single deck, even for very large aircraft (a second upper deck could be introduced for aircraft bigger than A380). The main landing gear is positioned inside lateral fairings of the fuselage; this solution allows one to obtain a cargo bay as long as the whole aircraft, without any interruption. In practise, the PrandtlPlane concept is a mixed passenger-cargo aircraft. From the structural point of view, the fuselage is equivalent to a doubly supported beam, the supports being the front and rear wing attachments; so, the fuselage bending moments are minimum in the connections between fuselage and wings, contrary to conventional aircraft and, during touch down, the fuselage bending stresses are relaxed.

Lifting system. The lifting system is over-constrained to fuselage. The lifting system provides an intrinsic structural safety as far as Damage Tolerance is concerned and, due to the possibility of tailoring the primary structures, the lifting system could be manufactured in composites. Fuel is contained into both the wing boxes and can be consumed in the same amount; hence, small variations of the center of gravity occur during cruise and one single flight condition can be optimized. The static aeroelastic phenomena are completely different from conventional aircraft. For example, the high stability towards divergence of the front wing produces the stability to the rear negative-swept wing through the vertical wings. The friction drag problem is an important aspect of the project and a larger amount of research activity is needed, with both Navier Stokes CFD computation and wind tunnel tests.

Flight Mechanics and Control. As said before, a Twin Fin PrandtlPlane aircraft is stable in flight, with a proper margin of stability and with nearly equal lift on front and rear wings. The pitch control could be obtained by means of two elevators, one on the front and the other one on the rear wing, moved in phase opposition; this control is a pure couple in pitch. Another strategy of pitch control is that of using the elevators on the front wing only; in this case, the behavior of the aircraft is the same of a canard. In any case, pitch maneuver is much safer than conventional aircraft, especially close to the ground. Trimming the PrandtlPlane is obtained by means of small aerodynamic forces, because the distance between aft and rear control surfaces is much larger than that of a conventional aircraft. The to-day available results 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. The lateral control is unconventional due to the double rudder and, also, to the presence of the vertical tip wings. The ailerons could be positioned on the rear negative-swept wing. They could be used as flaperons; in this case, the front and rear wings are fitted with high lift devices along the whole span and the best wing system condition can be obtained also in take off and landing.

<u>High lift devices</u>. With a proper design, the theoretical condition of "Best Wing System" could be valid with the high lift devices extended, contrary to conventional aircraft, with lower noise and noxious emissions in take off and landing. In fact, in the Prandtl best wing system, the lift on the horizontal wings is made of the elliptical and constant contributions. A near-optimum configuration in take off and landing could be obtained by increasing of the same amount the elliptical part of the lift on both the wings. In this case, as said before, slats and flaps must be positioned along the whole span of both the wings. The design and optimisation of the high lift devices is one of the main challenges of the aerodynamical design.

<u>Application as a freighter.</u> The application of Twin-Fin PrandtlPlane configuration as a freighter aircraft is straightforward, due to the fuselage shape. As already said, the main landing gear is made of multiple legs with small wheels, in order to be contained inside the lateral fairings and obtain a continuous low cargo deck. Besides, cargo doors can be positioned on the back of the fuselage, and, hence, the loading and disembarkation of goods and luggage is simpler and quicker. 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 horizontal tail for flight stability. Hence, the very large freighter of the future can not be conventional aircraft. The development of the cargo PP configuration is a great challenge of the future transport aviation. In particular, the PrandtlPlane configuration is very suitable for a cryogenic power plant application, in which the hydrogen tanks are positioned under the lower cargo deck. Figure 4 shows a sketch of a section of a cryogenic freighter PrandtlPlane aircraft. The aircraft can be designed according to the Low Noise Aircraft in order to fly 24 hours per day all weather.

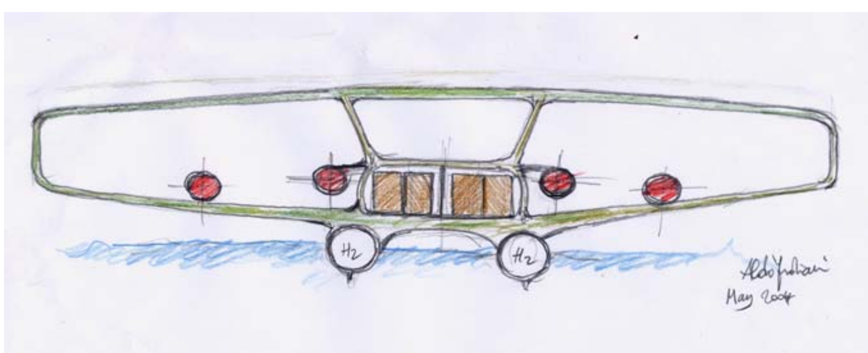


Figure 4

Application to small aircraft. The PrandtlPlane configuration can be applied also to small aircraft, taking structural safety, high stability of flight, high efficiency, new design, etc. into account (Figure 5).

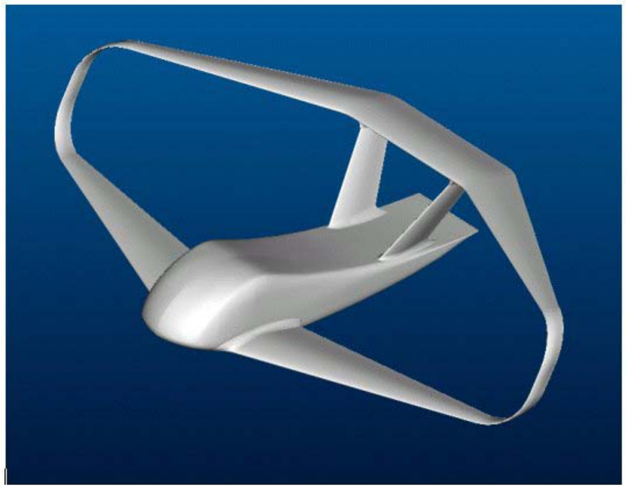


Figure 5

An example of application: a 250 passenger PrandtlPlane transport aircraft

A preliminary configuration is presented in this section. The aircraft is shown in the following figures.

Figures 6 and 7 show a sketch of the lateral and front views of the aircraft, respectively.

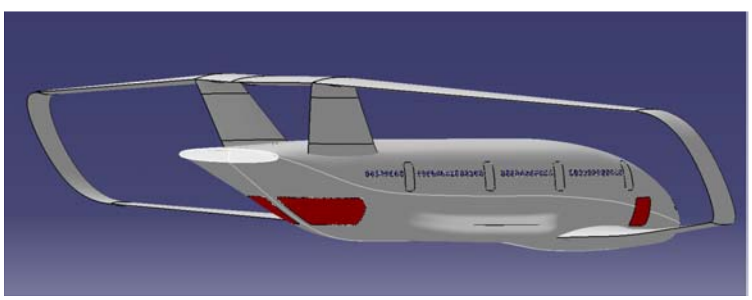
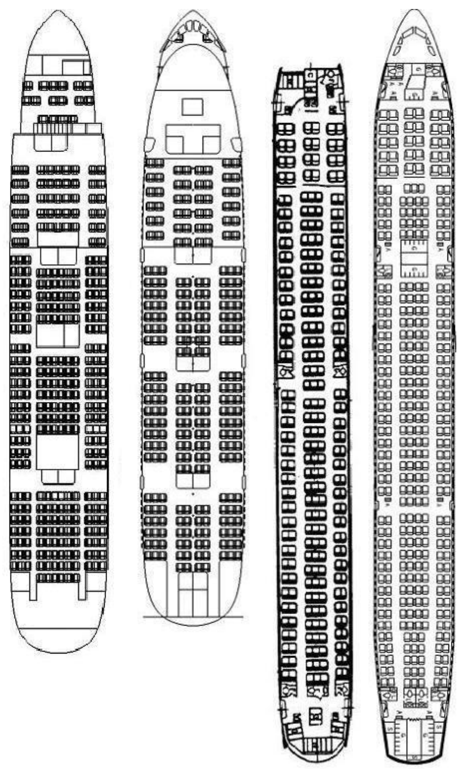


Figure 6

Figure 7

Figure 8 shows the passenger accommodations for the stretched (up to 350 passengers) and the low density (258 passengers) Prandtlplane aircraft and, also, for Boeing B767 and A330, respectively.



(A) (B) (C) (D)

Figure 8

The PP fuselage is larger and shorter than conventional, but more flexible as far as passengers are concerned. The cargo compartment is shown in figure 9. Some details of the stretched version are shown in figure 9,which the first class is present in. All the PP versions have a rest rooms for pilots.

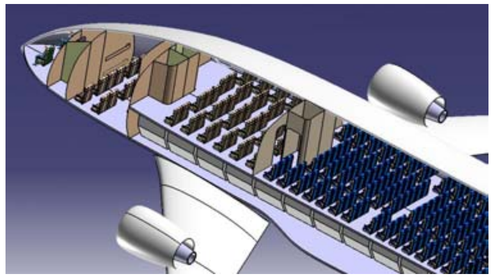


Figure 9

The cargo compartment is shown in figure 10. It can contain 38 LD1 pallets, nearly the double of equivalent aircraft, in order to reduce significantly the unit DOCs of the aircraft. The access doors to the bay are positioned in front and rear fuselage. This solution allows us to load and unload contemporary goods and luggage and, as requested to the future aircraft, to save much time for these operations.

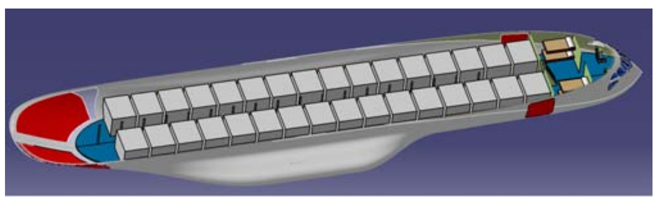


Figure 10

Reference

1 Acton, R.J. (1993): "British Airways' requirements for a New Large Airliner" presented at the Royal Aeronautical Society.
2 Schneider, W.(2000): "The importance of Aerodynamics in the development of commercially successful transport aircraft" Notes on Numerical Fluid Mechanics, Vol 76, (Aerodynamic Drag Reduction), pp 9-16.
3 Marec, G.P.(2000): "Drag Reduction; a major Task for Research" Notes on Numerical Fluid Mechanics, Vol 76, (Aerodynamic Drag Reduction), pp 17-27.
4 Prandtl, L. "Induced Drag of Multiplanes"(1924) NACA TN 182.
5 Frediani, A., Montanari, G., Pappalardo M., (1999) "Sul problema di Prandtl di minima resistenza indotta" (in Italian), Proceedings of the XVCongress of AIDAA, Turin, pp267-278.
6 Frediani A. "Large Dimension Aircraft"(1999), U.S. Patent n.5 899 409,
7 Frediani A. "Large Dimension Aircraft" (2002), European Patent Office n. EP0 716 978 B1.