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PARSIFAL Project: a Breakthrough Innovation in Air Transport *

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Abstract

PARSIFAL is a Horizon 2020 project, started on May 2017, with the aim to design an innovative aircraft, based on the "PrandtlPlane" (PrP) configuration, for the civil aviation of the future. The PrP configuration allows us to reduce the fuel consumption and the external noise, especially during low speed flight. The high aerodynamic performances are used to limit the span to 36m, compliant with ICAO Aerodrome Reference Code C standard, and to extend the payload capacity to 250-350 passengers without significant penalties of aerodynamic efficiency. The paper presents the overall characteristics of this innovative aircraft and how the PrP configuration could allow to improve the civil air transport of the future, as far as aircraft manufacturers, airports, airlines and passengers are concerned; in particular, some aspects of the architectural solutions and the aerodynamic design and optimization are underlined in subsonic and transonic regimes. Some details are given here on the fuselage design and the lifting system.

1. Introduction

Project PARSIFAL (Prandtlplane ARchitecture for the Sustainable Improvement of Future AirpLanes) has been financed on January 2017 by the European Community in the framework of Horizon 2020, call MG1.4 "Breakthrough Innovation". The main challenges to be faced in the project are: increment of air traffic, cutting emissions, drastic reduction of noise per passenger, comfort improvement, reduction of turnaround time, reduction of landing speed, more safety on board and, also, to set up new tools for the design of a wide spectrum of PrandtlPlane aircraft with different cruise speed/payload/range.

PARSIFAL aims at facing these challenges by introducing into service innovative aircraft with the "PrandtlPlane" (PrP) configuration [1] and, in particular, with a medium size commercial aircraft. The PrP configuration, in honor of L. Prandtl, is based on the Best Wing System (BWS), introduced by Prandtl in 1924 [2] and consisting into a properly designed box wing in the front view; the BWS has the minimum induced drag among all the lifting systems with the same total lift and wing span. The efficiency of the BWS increases with the ratio (h/b) between the vertical gap of horizontal wings (h) and the span (b); thus, the limitation of the wing span with a given gap can allow us to improve h/b and to reduce the disadvantage of the span limitation.

In the next twenty years air traffic will be nearly the double of today, but very limited (or none) expansion of airport areas will be available, including the regional airports. Thus, the wing span of the PARSIFAL aircraft, limited to 36m, is compatible with ICAO (International Civil Aviation Organization) Aerodrome Reference Code C, the typical standard for the airports of the regional/continental air traffic, used (among others) by Boeing 737 and Airbus A320. PARSIFAL project aims at increasing the payload up to the upper aircraft category (as, for example, of Boeing 767 and Airbus A330) without penalties of efficiency meanwhile operating from the ICAO-C airports.

The previous challenges will never be fulfilled by conventional airplanes, because it is impossible to satisfy the performances requested and, at the same time, to comply the new requirements on the green aviation. In fact, the conventional aircraft have grown up to their maximum potential and, hence, have very small margins to improve their efficiency.

Other candidate configurations for future aviation are the Blended Wing Body (BWB) and Truss Braced Wings (TBW) concepts (Fig. 1).

Together with some possible benefits and weight saving, the Blended Wing Body configuration [3] presents many critical drawbacks, as: BWB solution

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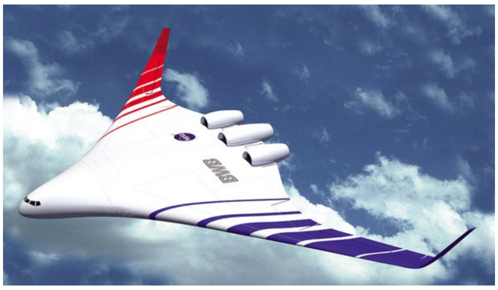


(a) Blended Wing Body

(b) Truss Braced Wings

Figure 1. Concepts of innovative configurations

is conceived for very large aircraft and, in the case of medium size aircraft, cannot be restricted to 36m span; the aerodynamic efficiency of a BWB is lower than PrP's one; emergency evacuation, flight comfort during roll maneuvers and static stability of flight could be very critical; lateral control is another open challenge.

The Truss Braced Wings concept aims at reducing the induced drag by improving the overall span of a conventional tube and wing; the consequent structural and aeroelastic disadvantages are resolved by connecting the wings to the fuselage by means of struts. Both the requirements of increased payload and reduced span in order to operate from ICAO-C airports cannot be fulfilled at the same time.

The research activities conducted in the last years on Aerodynamics (e.g. [4], [5]), Structures ([6], [7]), Flight Mechanics ([8], [9]), Aeroelasticity ([10], [11]), etc. have shown that the PrP configuration is more flexible compared to the other innovative aircraft concepts proposed so far to satisfy the new ACARE requirements in civil aviation. The aerodynamic efficiency of the PrP configuration allows us to improve the payload capacity for a given span, to reduce emissions during cruise and, in particular, during take-off and landing phases, where the induced drag is maximum and noise could be minimized correspondingly. The challenge of safety can be faced successfully because stall is smooth, pitch control is actuated with a pure couple and ailerons are positioned on both the wing tips. The structural efficiency is an open question; from one side the chords of the single wing are smaller and the local bending stiffness is reduced; from another side, the box wing is over-constrained to the fuselage with the consequent increase of stiffness. Other aspects to be solved during the project are the comfort during flight and the reduction of time for ground operations. The PrP configuration allows us to integrate different propulsion systems; in the project at hand, the solution with turbofan engines on the rear fuselage is adopted, but other solutions are fully compatible (i.e. open rotors), contrary to conventional aircraft. At the end of the project, the participants aim to demonstrate the economic benefits for airport companies, aircraft manufacturers, air transport companies, passengers and society, by introducing the PrP aircraft into the market.

PARSIFAL started on May 2017, and will finish in 2020; the participants are: Pisa University (Italy), Technische Universiteit Delft (Netherlands), ONERA-Office National d'Etudes et de Recherches Aerospatiales, Paris Meudon, (France), ENSAM-Ecole Nationale Superieure d'Arts et Metiers, Bordeaux (France), DLR-Deutsches Zentrum Fuer Luft-Und Raumfahrt Ev Hamburg (Germany), SkyBox Engineering, Pisa (Italy). Pisa University is the project coordinator and responsible also of aeroelasticity, dissemination and exploitation; TU Delft is responsible for mechanics and dynamics of flight, and propulsion; ONERA is responsible of aerodynamics, ENSAM will design the aircraft structures; DLR is responsible of the design requirements and the comparison with conventional aircraft; SkyBox is responsible of the optimization of the overall configuration of the aircraft.

The baseline configuration of PARSIFAL will be analyzed and assessed under the supervision of an Advisory Board composed by representative stakeholders of most important aircraft manufacturers in Europe, airlines and airport management companies and eminent personalities of European Academia and Research Institutions.

2. PARSIFAL proposal for a new air transport

The air traffic is constantly increasing in the last decades, with an average rate of about 5% and with a peak in the Eastern Asia; contrary to what it could be expected, the main increment occurs along the continental and domestic routes, to comply with the point to point traffic request.

All the experts agree that this trend will continue in the next decades with the same rate of today or greater, and also that the main air traffic increments will occur along the short-medium routes (maximum 4.000Km), with a peak around 1.000Km, as represented in the air traffic forecast for 2032 (Fig. 2).

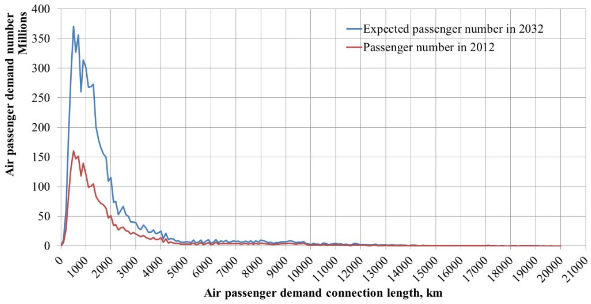


Figure 2. Air traffic demand: forecast for 2032 [12]

The airports deputed to sustain this increment are the ICAO Aerodrome Reference Code C, typical of regional/continental traffic, where the aircraft wing span is limited to 36m and the main landing gear span is in the range 6-9m. The aircraft used today to satisfy this kind of service are the well know Boeing 737 and Airbus A320 families, with a capacity of about 180 passengers in one class and a peak of about 220 passengers in the case of Airbus A321(fuselage length equal to 44m).
Figure 3 represents the aircraft produced by the two main competitors worldwide inside the pax-range diagram. The capacity of PARSIFAL with 36m span and 44m long (the same as A321) ranges from 310 to 330 seats in a single class (but a solution with two decks, not shown here, could allow to embark about 350-400 passengers). The route lengths are typically separated in medium and long ones, corresponding to continental and intercontinental flights. The actual utilizations of aircraft depend on geographical and economical situations; some details can be obtained from the data of Literature on the air traffic worldwide.

Figure 4 presents an overview of air traffic on the world's busiest air routes (Figure 4a) during 2015, and the same data in USA, Europe, India and Australia (b, c, d, e, respectively). As said before, the first nine busiest routes are domestic ones with a maximum range of 839nm and a number of passengers between 11 and 4 million per year. In Europe the busiest routes are no longer than 330nm (even though a lot of longer routes are present with a significant air traffic), about 1000nm in India, about 2200nm in the USA and less than 1800 nm in Australia.

Another interesting remark from Figure 4 is the great number of flights/day along the busiest roots,

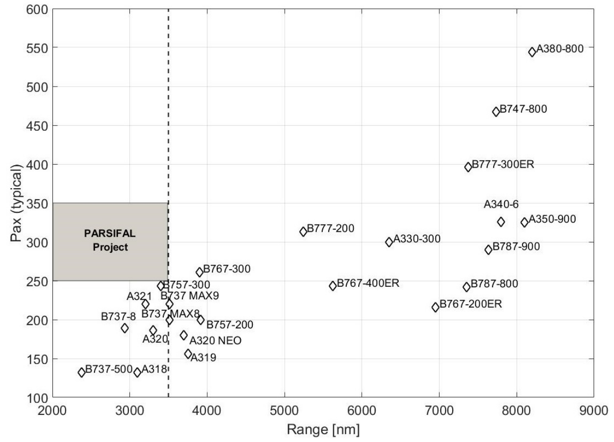


Figure 3. Civil aircraft market (Pax-Range Diagram)

with consequent increment of air pollution and noise in those airport areas; similar examples exist also in South America (e.g. S. Paulo-Rio de Janeiro in Brazil).
The low cost air companies have improved their traffic, and the trend is expected to continue in the next decades in the same segments of route lengths, while the airport slots will be saturated in a short time: consequently an increment of the aircraft capacity will be the challeng of the future. Conventional aircraft have reached both their maximum capacity and efficiency. PARSIFAL is concieved to fill these gaps by trasporting 310-330 passengers per flight; it also could reduce the number of flights to nearly the half.
Among the proposed new configurations for future aviation, the PrandtlPlane is the only one which satisfy the requirements of increasing the payload significantly with a limited span of 36m or, equivalently, it allows us to improve the transport capacity and, also, to distribute this traffic to a largest possible number of airports.
PARSIFAL is breakthrough innovation project; innovation is conceived here as the mean to reduce the costs and improve the efficiency for all the actors of air traffic: aircraft manufacturers, airport companies, air transport companies, citizens and passengers.
The advantages provided by PARSIFAL project are summarized in the following:

- To fill the gap of the continental aircraft with a greater number of passengers compared to the B737-A320 families; to improve the air traffic with the same airport areas of today, as depicted in Figure 3;
- To transport a larger number of passengers per flight in order to decongestion the hubs by reducing the number of flights per day and by eas-

Destinat. 1	Destinat. 2	Pax (mln)	Flights /day	Dist. [km]	Dist. [nm]
Seoul	Jeju	11.1	122	450	243
Tokyo	Sapporo	7.8	87	821	443
Tokyo	Fukoka	7.6	75	883	477
Delhi	Mumbai	7.3	67	1135	613
Sydney	Melbourne	7.2	98	706	381
Beijing	Shangai	6.1	56	1098	593
Sao Paulo	Rio de Janeiro	x	99	337	182
Tokyo	Osaka	x	62	405	218
Hong Kong	Taipei	5.1	42	807	436
Tokyo	Okinawa	x	40	1554	839

a. World

Destinat. 1	Destinat. 2	Pax (mln)	Flights /day	Dist. [km]	Dist. [nm]
Chicago	New York	4,2	87	1191	643
L.Angeles	S. Francisco	3,66	60	543	293
L.Angeles	New York	3,42	55	3983	2151
Chicago	Los Angeles	3,01	33	2808	1516
Miami	New York	2,75	35	1754	947
Atlanta	Chicago	2.72	40	975	526
Chicago	Minneapolis	2.72	41	538	290
Atlanta	New York	2.6	56	1223	660
Atlanta	Orlando	2.6	26	650	351
Chicago	Washingt DC	2.6	53	947	512

b. USA

Destinat. 1	Destinat. 2	Pax (mln)	Flights /day	Dist. [km]	Dist. [nm]
Tolouse	Paris	2,31	22	572	309
Madrid	Barcellona	2,25	23	484	261
Nice	Paris	2,11	25	676	365
Catania	Roma	1.97	22	539	291
Berlin	Munich	1.97	22	480	259
Oslo	Trondheim	1.95	22	364	196
Frankfurt	Berlin	1.90	18	435	235
Oslo	Bergen	1.81	22	326	176
Munich	Hamburg	1.81	17	600	324
London	Dublin	1.68	56	450	243

c. Europe

Destinat. 1	Destinat. 2	Pax (mln)	Flights /day	Dist. [km]	Dist. [nm]
Delhi	Mumbai	7,34	67	1135	613
Delhi	Bangalore	3,47	41	1703	919
Bangalore	Mumbai	3,36	34	832	449
Delhi	Kolkata	2,07	27	1313	709
Mumbai	Goa	1,71	23	423	228
Ahmedb.	Mumbai	1.71	19	442	239
Delhi	Hyderab.	1.25	23	1263	682
Mumbai	Chennai	1.13	24	1032	557
Delhi	Chennai	1.12	22	1754	947
Mumbai	Hyderab.	1.01	23	623	337

d. India

Destinat. 1	Destinat. 2	Pax (mln)	Flights /day	Dist. [km]	Dist. [nm]
Melbourne	Sydney	8,6	98	706	381
Brisbane	Sydney	4,47	59	751	405
Brisbane	Melbourne	3,53	42	1379	745
Gold Coast	Sydney	2,61	27	678	366
Adelaide	Melbourne	2,31	30	642	347
Melbourne	Perth	2.13	16	2706	1461
Adelaide	Sydney	1.83	19	1167	630
Gold Coast	Melbourne	1.81	20	1328	717
Perth	Sydney	1.76	14	3284	1773
Melbourne	Hobart	1.49	18	616	333

e. Australia

Destinat. 1	Destinat. 2	Pax (mln)	Flights /day	Dist. [km]	Dist. [nm]
London	New York	3,07	31	5555	2999
London	Dubai	2,86	16	5505	2972
London	Los Angeles	1,64	10	8781	4741
London	Hong Kong	1,58	9	9648	5209
Paris	New York	1,5	18	5849	3158
Paris	Guadaloupe	1.16	7	6775	3658
Paris	Montreal	1.14	9	5540	2991
Paris	Dubai	1.07	4	5245	2832
London	Chicago	1.06	9	6361	3435
London	Singapore	x	6	10888	5879

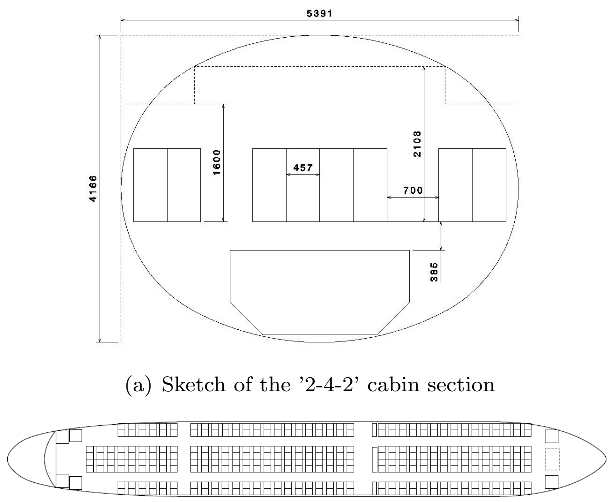
f. Europe to not-Europe

Figure 4. A preliminary view of air traffic all over the world

ily improving the transportation along the short and very crowded routes;

- To produce economical benefits for the air transport companies due to reduction of the costs (reduced costs per unit of transport and increment of traffic). Economical benefits are extended to airport companies as well, due to increment of passengers. Benefits derive also to passengers, thanks to higher comfort and lower costs at the same time; benefits for citizens are obtained by reducing noxious pollution and fuel consumption;
- Possibility to activate new routes connecting minor airports, thanks to the take-off and landing capability of PARSIFAL from shorter runways.

Another possibility to increment the air traffic with PARSIFAL is associated to a significant reduction of the turnaround time in the airports; this can lead to a better utilization of an airplane (i.e. more flights per day). The turnaround time, for domestic/continental flights, depends primarily on the boarding procedures (both of passengers and luggage), and this is strictly related to the interior design of the fuselage. Figure 5a shows a sketch of a section, with the following characteristics: the cabin aisle is 700mm wide, the arrangement is '2-4-2' (8 seats abreast); 2 hand luggage can be embarked on the cabin by any passenger; a third door between the front and the rear one could be installed, and in this case the passenger capacity is equal to 308 units (Figure 5b); each door is provided with autonomous stairs. The engines are positioned in the rear part of the fuselage, and very high by-pass ratio solutions are possible. The undercarriage are designed in order to have a small cleareance of the aircraft from the ground. The cargo deck is continuous, because the main landing gear is positioned on lateral sponsons, and it has a volumetric capacity higher than the present aircraft of the same category; it allows us to embark and disembark cargo and luggage more quickly than present, through a front and a rear door. A sketch of the initial design of the aircraft is shown in Figure 6.



(a) Sketch of the '2-4-2' cabin section

(b) High-density cabin arrangement

Figure 5. Interiors arrangement

3. Preliminary aerodynamic design and optimization

The preliminary aerodynamic design of the aircraft starts with the definition of the requirements of the typical mission.
The mission requirements are assumed as inputs to a constrained optimization procedure, where the objective function is the global efficiency in subsonic flight with the constraints of static stability of flight and trim; the outputs of the optimization are families of configurations for any wing load on the front wing and rear wing, set as constraints in each analysis; the configurations are defined by aircraft lifting system planforms together with the aerodynamic and geometric characteristics (e.g. twist and sweep angles, lift distribution along the span, wing loading on the horizontal wings, etc); the constrained optimization process is carried out by means of AEROSTATE, an in house developed code. Payload, preliminary empty weight distribution and fuel weights are taken into account in the optimization, which is conducted for a set of families based on the maximum wing loads (500, 600, 700 Kg/mq); the main correlations between the design parameters and the global performances of the aircraft are relevant results. More details about the optimization procedure in subsonic regime can be found in [13].
The aerodynamic solver is AVL (Athena Vortex Lattice) code, a Vortex Lattice Method (VLM). As the cruise phase is performed at high speed and the flight condition is transonic, some calibrations were necessary in order to increase the fidelity of aerodynamic results (VLM codes cannot take the compressibility effects into account). The first calibration is carried out by defining the thresholds of the transonic performances of a set of selected supercritical airfoils, in terms of Drag Rise Mach and maximum lift coefficient. A database of airfoils performances and aerodynamic characteristics was built by means of bidimensional CFD (Computational Fluid Dynamics) analyses for different Mach numbers and angles of attack; then, a comparison between the aerodynamic properties stored in the database and those calculated for each configuration during the potential optimization procedure is performed, in order to detect and remove the configurations which show Drag Rise effects, according to the 'infinite wing' model. However, as the transonic phenomena are strongly tridimensional, and the low fidelity model is meaningless in the tip and root regions of the wings, a second higher fidelity calibration has been carried out as follows: some efficient configurations have been chosen and CFD analyses (RANS models) have been performed on these wings-fuselage configurations. As a result, a more accurate calibration was conducted where the constraints and the boundaries of the design space (defined in the potential optimization procedure) are taken into account; typical examples are limitations on the maximum geometrical twist of the front wing tip regions or limits on the minimum tip chord length. The analysis allowed us to identify some local transonic critical issues of a boxwing; for example, it was possible to evaluate the effects of the wing-fuselage fillet on the global performance, or the complex interaction phenomena between the wings and the lateral vertical wing on tip zones, etc. The final result of the whole procedure is a narrow group of configurations that satisfy requirements and constraints, to be analyzed with the CFD accuracy in the transonic range.

4. On the transonic aerodynamic of PARSIFAL

A CFD analysis campaign has been performed on the reference configurations in order to calibrate the first solution based on potential aerodynamic optimization and, also, to isolate the critical issues due to the influence of shock waves on the aircraft performance in cruise flight. The reference configuration has no correlation with the final design of PARSIFAL. The analyses campaign has also been set for investigating the boxwing aerodynamic behavior in detail in transonic flight condition, where the level of knowledge is low. The most relevant parameters investigated are wing loading, cruise Mach number, sweep angles and local geometrical details. The selected supercritical airfoils for the reference configurations belong to the

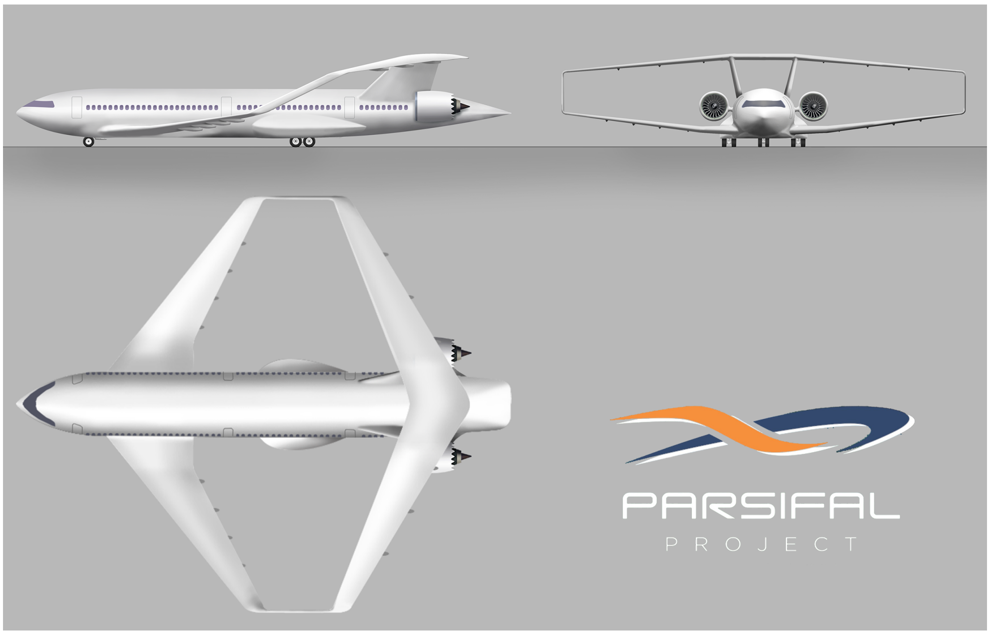


Figure 6. Three plane view of a reference PARSIFAL configuration

NASA SC2 family. The starting reference configuration has been analyzed at cruise Mach equal to 0.85, in order to enhance several critical issues in transonic regime, like high twist angles and interaction between wings and tip-wings; then, a set of modifications have been conducted in order to arrive in cascade to reference configurations in the operative conditions with minimized effects of Drag Rise, or without remarkable local detrimental effects. As shown in Figure 7a, the front wing has a wide area in the tip region where an extensive and detrimental shock induces separation of the boundary layer, that extends also on the lower part of the vertical tip-wing.

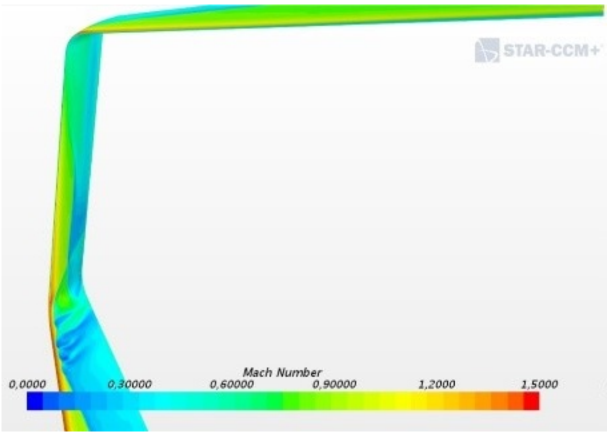
The transonic analyses have been performed with STAR-CCM+ software and a supercomputer of Cubit s.c.a.r.l.; a calibration activity on the meshes was performed starting from 110 million cells to 10 million cells, for a half model of the aircraft; 30-40 million cells proved to be the best compromise. This first analysis gave many relevant starting information on the high loaded tip behavior in the transonic flight. Afterwards, some sequential modifications have been applied in order to identify the intervals in which the design parameters are allowed to vary; these results were the input for a second stage optimization. The information collected in these analyses on several design parameters, allowed to isolate the main critical issues for the boxwing in transonic flight, and also to design some starting reference configurations with performance higher than the first configurations analyzed, as shown in the example in Figure 8. These configurations will represent the basis for the following aerodynamic development and optimization of the aircraft.

5. Concluding remarks

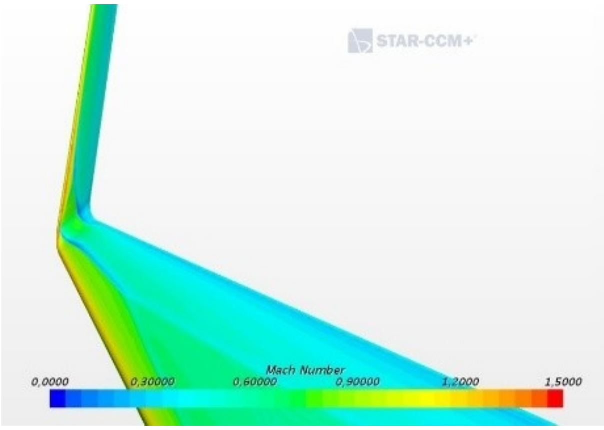
PARSIFAL is a research project financed by the European Community in the framework of Horizon 2020. The project aims to design an aircraft with a span limited to 36m in order to operate from ICAO-C airports but with a capacity of transporting 250-350 passengers. The paper reports some information on the worldwide air traffic that justify the design requirements of the project and an initial configuration has been identified in this regard. Some preliminary activities conducted on the optimization of the aerodynamic shape have been briefly presented; one of the lessons learned is that a subsonic analysis, also calibrated, of a PrandtlPlane in transonic flight is totally inapplicable; a second lesson is that the CFD analyses in the transonic range need to be conducted by means of supercomputer, on models of very high resolution, in order to avoid wrong conclusions on the transonic effects.

6. Acknowledgments

The present paper presents part of the activities carried out within the research project PARSIFAL ("Prandtlplane ARchitecture for the Sustainable Improvement of Future AirpLanes"), which has been funded by the European Union under the Horizon 2020 Research and Innovation Program (Grant Agreement n.723149).

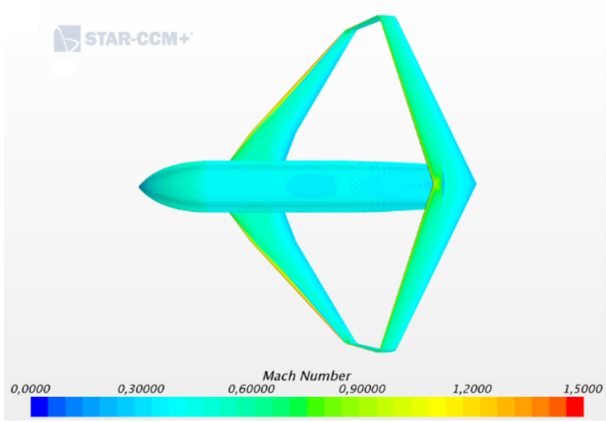


(a) Starting reference configuration

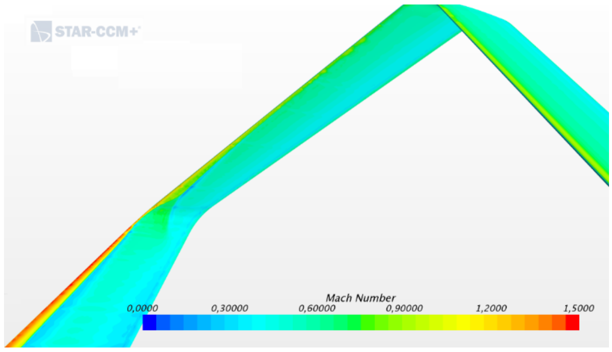


(b) Modifications on front wing tip

Figure 7. Mach contours



(a) Top view



(b) Front wing tip detail

Figure 8. Reference configuration: Mach contours

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