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Preliminary transonic CFD analyses of a PrandtlPlane transport aircraft

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Abstract

In the framework of the PARSIFAL research project, funded by the European Community in the Horizon 2020 program, the PrandtlPlane (PrP) configuration has been proposed as an innovative alternative to the current commercial aircraft of conventional architecture; the PrP configuration development is presented in order to satisfy the future air traffic growing requirements with better performances than conventional one, in terms of fuel efficiency, safety, pollution and noise emissions. In this paper a preliminary aerodynamic investigation of the transonic behaviour of the PrP wing system is presented; this study has been carried out by means of CFD analyses, with the aim to collect relevant information and to detect the proper design and operative space, fundamental for the following aerodynamic design activity of the aircraft. Investigations have been made on macro parameters (like wing loading or cruise Mach number) and also on local critical issues. The results obtained allows to design some initial reference configurations with satisfactory cruise performance in this very initial stage of the design process.

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Keywords: Box-wing; PrandtlPlane; PARSIFAL; CFD; Transonic Aerodynamics

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1. Introduction

A preliminary investigation of the transonic aerodynamics of an innovative commercial aircraft, with a box-wing configuration known as PrandtlPlane (PrP), is presented in this paper; this activity has been developed in advance to the main design activity of a commercial PrP aircraft, in the framework of the European Project PARSIFAL ("Prandtlplane ARchitecture for the Sustainable Improvement of Future AirpLanes") funded by the European Union under the Hori-

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zon 2020 program, and coordinated by the University of Pisa; the other partners of the project are: Delft University of Technology (Delft, Netherlands), ONERA (Meudon, France), ENSAM (Bordeaux, France), DLR (Hamburg, Germany), SkyBox Engineering (Pisa, Italy).

The PARSIFAL project is focused on the design of a PrP commercial aircraft capable to transport 250-350 passengers on continental routes, adopting a lifting system with a maximum span limited to 36 meters, according to the ICAO Aerodrome Reference Code C standards, and with a significant reduction of fuel consumption per passenger.

One of the on-going activities of the project is the definition of Top Level Aircraft Requirements, which include the cruise speed. According to common values of present continental flight, cruise Mach numbers (M) within the interval [0.77-0.80] have been considered. Therefore, it has been necessary to perform a series of detailed aerodynamic analyses (CFD calculations) in order to investigate preliminarily the aerodynamic behaviour of a box-wing lifting system, designed according to the Best Wing System (BWS) theory by Prandtl (1924), in transonic flight condition. A low fidelity design methodology, based on a constrained optimization procedure, described in Frediani et al. (2017), has been used in order to define the initial configurations.

As described in Frediani et al. (2017), during the development of the PARSIFAL project, different fuselage layouts have been proposed and studied; for the transonic CFD analyses campaign described in this paper only one fuselage model has been used, with the following features: 10 abreast cabin with two aisles (3-4-3 layout), total fuselage length of 36 meters, capability to carry a maximum number of passengers equal to 320. Although such configuration does not represent the final design of the fuselage, in the present work it has been considered as a common model to compare the performances of different lifting systems.

The logical flow, with which the series of analyses have been performed, follows two parallel phases:

- A first analysis campaign addressed to the identification of the sensibility of the global transonic cruise performance of the aircraft on the macro parameters, in order to define the domain in which the overall design of the airplane can be performed;
- A second analysis campaign focused on the identification and isolation of the local critical issues of the lifting system in transonic flight (in example the critical regions where strong shock waves are located).

The results obtained in this phase have been used both to calibrate the low fidelity design procedure (e.g. as maximum limit of the design parameters variation, or as optimization constraints), and to define reference configurations with satisfying cruise performance also in this extremely preliminary design phase, and also to increase the currently low knowledge level on the aerodynamic behaviour in transonic flight of the innovative lifting system proposed in PARSIFAL.

2. CFD analyses model

The CFD analyses have been performed with the software STAR CCM+, using steady compressible RANS models on a half model of the aircraft (the symmetry condition is imposed with respect to the longitudinal plane), in order to simulate, at this stage, only the cruise phase, obtaining information on the overall high speed performance of the aircraft.

A mesh sensitivity analysis has been done, in order to identify the grid features that provide the best results reliability with the minimum computational cost; grids with a minimum of 10 million cells to a maximum of 110 million of cells have been evaluated. The selected mesh, used in the following analyses, has these features:

- Approximately 30 million of trimmed volume cells;
- Surface discretization with minimum size equal to 5 mm and maximum size equal to 25 mm;
- Wake refinement up to 50 meters, with maximum size of 500 mm;
- Prism layer with a height equal to 100 mm and grow rate equal to 1.1 (25 layers); the y+ values are between 30 and 150.

The model used is a RANS with “Coupled Flow” and “Coupled Energy” models; the turbulence model is the “$k-\varepsilon$ Realizable” with an “All $y+$” wall treatment; a comparison between the “$k-\varepsilon$ Realizable” and the “$k-\omega$” turbulence

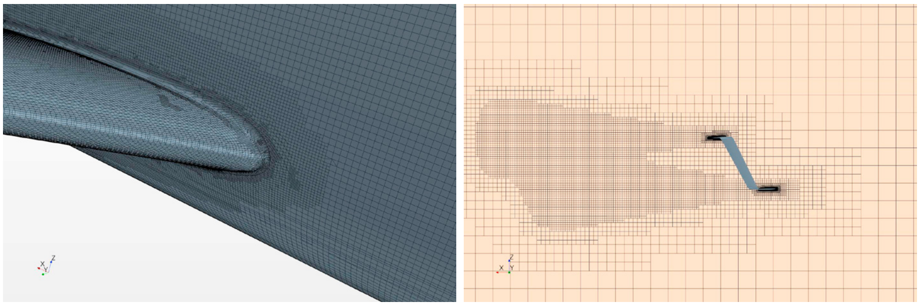

Fig. 1. Mesh Details

models has been done, giving comparable results: the “$k-\varepsilon$ Realizable” turbulence model was chosen in order to reduce numerical instability and computational times. The “wall” boundary condition has been set for the airplane surfaces and the “free-stream” boundary condition has been set for the external sides of the computational domain, with the proper assignment of Mach and altitude. In order to take into account the compressibility effects, the fluid was considered as “ideal gas”.

3. Analysis campaigns and results

3.1. The starting reference configuration

A starting reference configuration (Fig. 2) has been selected in order to initialize the analysis campaign, with the aim to identify the main critical macro-issues in transonic regime of the box-wing lifting system, optimized with the low fidelity methods. This configuration, in the following called “Configuration A”, has been chosen since its very high potential performance, in the sense of a good trade-off between the main requirements, as well as for its critical behaviour in transonic flight, such as:

- a high value of the predicted wing loading, mostly for the front wing;
- high values of the geometrical twist;
- overestimation of the cruise equilibrium speed (M=0.85);
- complete lack of previous information on the aerodynamic interference at the fillet between wing tips and vertical tip-wing in transonic.

These unfavorable features for the cruise phase have been useful in the first analyses to detect and isolate the most relevant problems, and to define some thresholds on the macro parameters. Hence, by adopting a top-down logical design flow, such thresholds have been then used in the following design stages.

The results of the first analyses show a non-efficient behaviour of the starting reference lifting system; in particular, in the front wing tip region there is an extensive shock-induced boundary layer separation, as shown in Fig. 3. Reynolds number for such analyses is $2.1 \cdot 10^7$ referred to the mean aerodynamic chord.

A strong shock wave is also present on the internal lower area of the vertical tip-wing; it disrupts in a very strong way the overall aerodynamics, moving away the loading distribution from the optimum predicted by the theory. The two combined detrimental effects are reflected on the global value of the aerodynamic efficiency that is much lower than the value calculated with the first approximation methods: this value of the efficiency will be taken as a reference in the following, in order to perform comparisons and to evaluate the percentage increase of the performance of the modified configurations analysed during the CFD campaign.

The problem of the local flow separation at the front wing tip has been investigated considering the effects on the flow of the twist and chord distribution; first of all, the effect of a reduction of the geometrical angle of attack in the outboard bay of the front wing, with a consequent increase of the corresponding chords in order to maintain the same

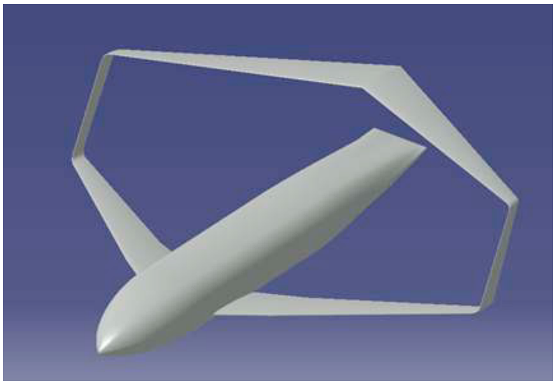

Fig. 2. Starting Reference Configuration

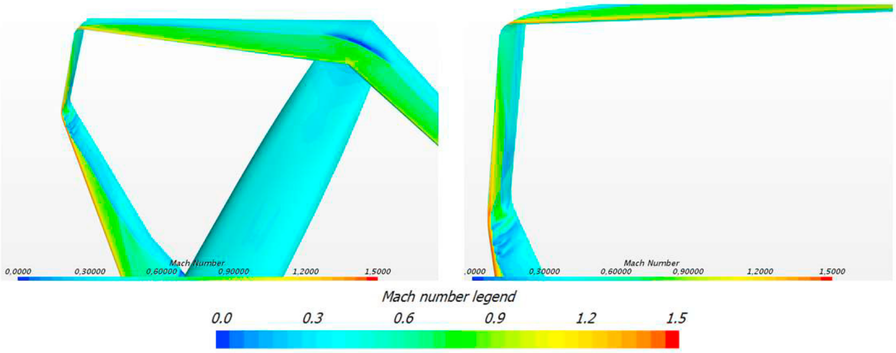

Fig. 3. Mach contour on the reference configuration A (M_∞=0.85)

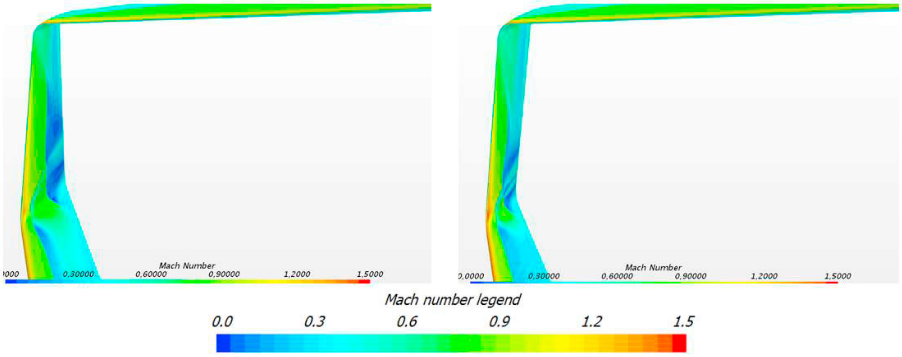

Fig. 4. Mach contour of the reference configuration with the two tip modifications

predicted global lift of the previous case, was evaluated; then, the same modifications were applied both on front wing and rear wing (it should be noted that modifying the tip regions of the wings coincides also on the global geometry modification of the vertical tip-wing). The results of the analyses, in terms of Mach contours, are shown in Fig. 4.

It can be noted that these modifications cause an improvement of the flow conditions on the front wing, mainly in terms of attenuation of the strong shock induced boundary layer separation on the tip region, but also in terms of more orderly isobars distribution; instead the aerodynamic behaviour of the vertical tip-wing still remains highly penalizing. Tracks of shock waves interaction in the fillet zone appear. Some relevant information, to use in the development of the preliminary aerodynamic design, have been obtained by the analysis of these results: the necessity to find a threshold for the geometrical twist of the front wing tip (related to the type of supercritical airfoil selected and its thickness),

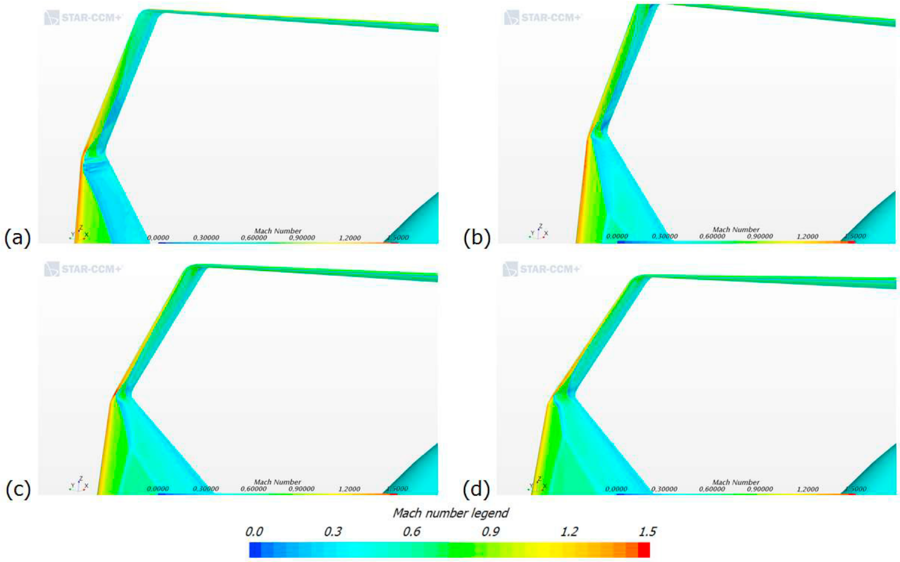

Fig. 5. Mach contour of four configurations with different predicted W/S

to be used as a constraint in the design procedure in order to define a space without transonic critical issues, and the necessity to investigate the three-dimensional transonic interactions between the wings and the vertical tip-wing, as well as the capability to identify the independent critical issues of the tip-wing isolated. These aspects have been preliminarily investigated and they are exposed in the following sections.

3.2. *Definitions of operative design space*

The information deduced from the analyses on the first reference configuration, extremely critical in transonic flight, have been translated in input and used to perform an analyses campaign focused on the identification of the design field of the aircraft, in terms of macro parameters, that are fundamental to start the overall design process; the aim is also to obtain a large amount of generalizable information, to be used in the following development of the PARSIFAL project, also for configurations that conceptually differs from this first references proposed. Once fixed a valid range for the geometrical sweep angle of the lifting surfaces, the first analyses have been performed on configurations with different reference surfaces, for equal predicted global lift (and so varying the wing loading): the aim is to identify a trade-off between the potential aerodynamic requirement, in which the PrP offers the best performance with the increase of the wing loading, because the induced drag coefficient increases slower than the increasing of the lift coefficient, with respect to the conventional monoplane, and the transonic performance, in which having high values of load, hence high lift coefficient, can lead to high increase of global drag due to wave drag.

Starting from the first reference configuration, other three configurations designed with the low fidelity optimization have been selected, with different values of predicted wing loading W/S (respectively 700, 600, 500 kg/m^2, referring to the front wing; the configurations are called “B”, “C”, “D”) and CFD simulations have been performed with the same models and the same operative conditions of the reference “A”. Every lifting surface of each configuration have the same selected supercritical airfoil (NASA SC20410), with a constant thickness distribution along the span; the contribution of the airfoils thickness to the reduction of the wave drag was separately investigated, in order to isolate, in this preliminary phase, the contribution of every single macro effect of the most relevant parameters on the transonic performance. In Fig. 5 the Mach contours of the four configurations are shown.

It is apparent the gradual improvement of the flow over the lifting system with the decrease of the predicted wing loading value; this can also be inferred by the values of the percentage increase of cruise performance, in terms of aerodynamic efficiency of the lifting system (E), with respect to the reference value calculated on the starting Configuration A, as summarized in Table 1.

Table 1. Performance variation compared to Configuration A

Configuration	ΔE
B	+16.67%
C	+29.36%
D	+37.30%

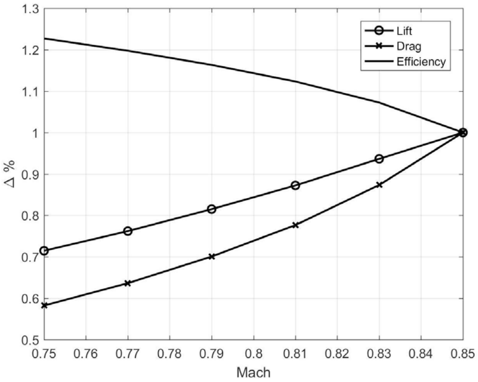

Fig. 6. CFD results for reference configuration B

The information extracted from these analyses gives important indications on the design choices to be carried out in the development of the project, as well as the first trends of performance of a PrP aircraft in transonic flight. In particular, it is evident the limit that the need to avoid increases of wave drag imposes on the design lift coefficient, in opposition to the subsonic performance requirements of the Best Wing System, in which at higher lift coefficient values correspond higher values of cruise aerodynamic efficiency.

A second fundamental investigation, subsequent to the previous one, has been carried out focused on the design operative condition, that must be fixed, as a requirement, before starting the whole loop of aerodynamic design and optimization of the aircraft; the choice to perform the first analyses at a Mach number equal to 0.85 indeed was useful for the identification of the global and local severe critical issues related to the compressibility effects, however the cruise Mach of continental commercial aircraft are considerably lower than this value; typical values for actual aircraft are in the range of M=[0.77-0.80]. A series of analyses varying the cruise speed has been performed; the variation of the Mach number is set in the range M=[0.75-0.85] with a step between two analyses equal to ΔM=0.02. The reference configuration selected for these calculations is the "Configuration B" previously defined, but with a reduced thickness distribution along the span, as suggested by the results previously shown. As CFD results shown in Fig. 6 underline, as the Mach number decreases, the total drag (D) decreases more than lift (L), with a consequent increase of the global aerodynamic efficiency, defined as L/D.

The results obtained by this series of calculation give relevant indications about the performance of the Best Wing System in cruise, that present levels of efficiency very satisfying also in this early stage of the design process, for cruise Mach number typical for the class of the medium range-continental aircraft. In Fig. 7 the Mach contours of the configuration at four different cruise Mach number are presented.

3.3. Identification of local critical issues

In parallel to the analyses focused on the identification of a possible design space (macro parameters), necessary for the initialization of the aerodynamic design of the aircraft, further investigations have been carried out in order to identify local critical issues and to isolate local detrimental phenomena; this also because the low level of knowledge about the transonic aerodynamics of a box-wing BWS; in particular the investigation of the interaction between the main lifting surfaces and the vertical tip-wings, above all in the fillet region, appears to be interesting. However, in this phase, it has been decided to operate mainly on the parameters useful to wave drag reduction, starting from critical

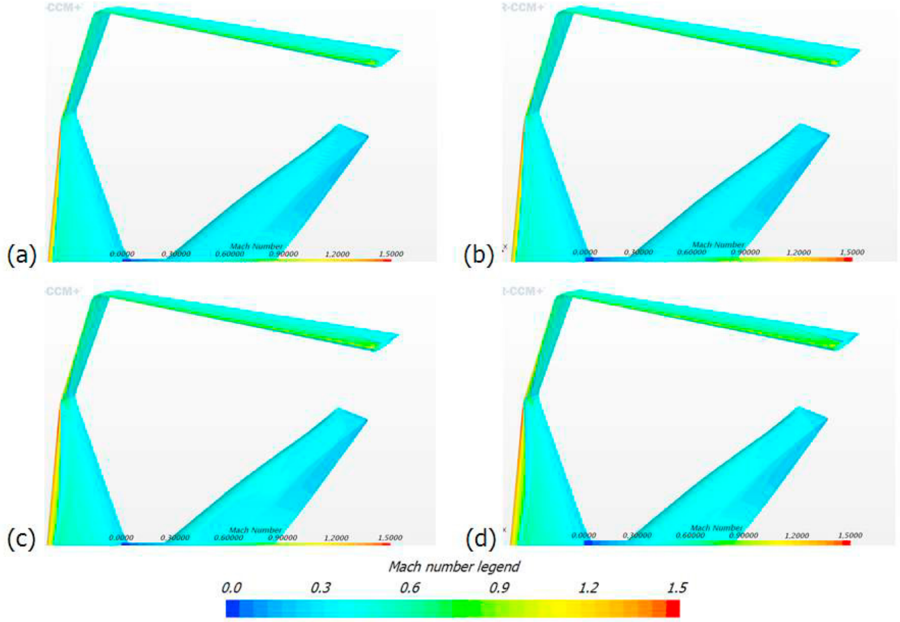

Fig. 7. Mach contour at M=0.75 (a), M=0.77 (b), M=0.79 (c), M=0.81(d)

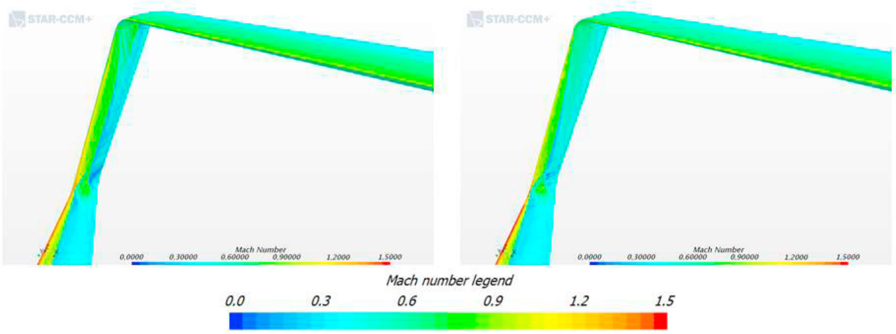

Fig. 8. Mach contour of the reference configuration B without and with t/c reduction

transonic conditions: also in this calculations the cruise Mach number is set equal to 0.85. The starting reference configuration, on which apply the modifications, is the Configuration B (configuration with a high predicted wing load); each modification is applied individually.

The first modification made is the reduction along the span of airfoil thickness to chord ratio (t/c) on both wings, and consequently on the vertical tip-wing: the supercritical airfoils selected are the NASA SC20410 for the first section of the wing bay, and the NASA SC20406 for the tip airfoil. This configuration has a percentage increase of efficiency equal to +4.08% with respect to the reference value of the Configuration B; in Fig. 8 the Mach contours of the two configurations are shown.

The second modification is referred to the vertical tip-wing: it is increased the leading edge geometrical sweep angle of a value of 10° compared to the reference; the modification was realized by properly spacing the two wings on the horizontal plane. This geometrical change was tested in order to try to achieve a better flow condition on the vertical tip-wing, with weakened shock waves with respect to the reference, and to quantify the impact of these changes on the global performance. In this case it is obtained a percentage increase of the lifting system efficiency equal to +2.72% in comparison to the reference; the Mach contours of the two compared configurations are shown in Fig. 9.

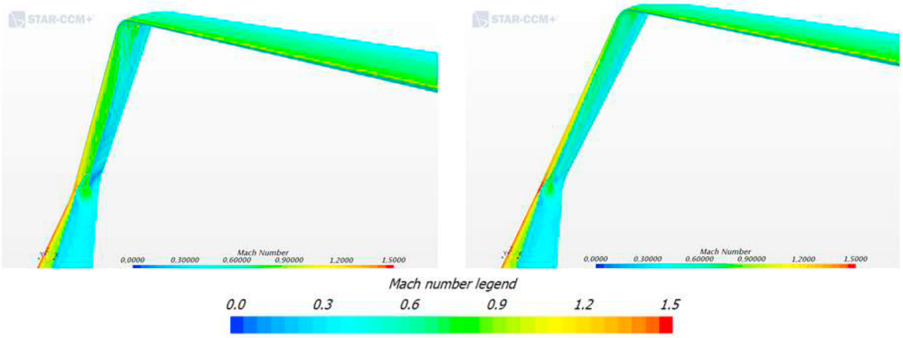

Fig. 9. Comparison between the reference B and the configuration with an increased vertical tip-wing sweep angle (Mach contour)

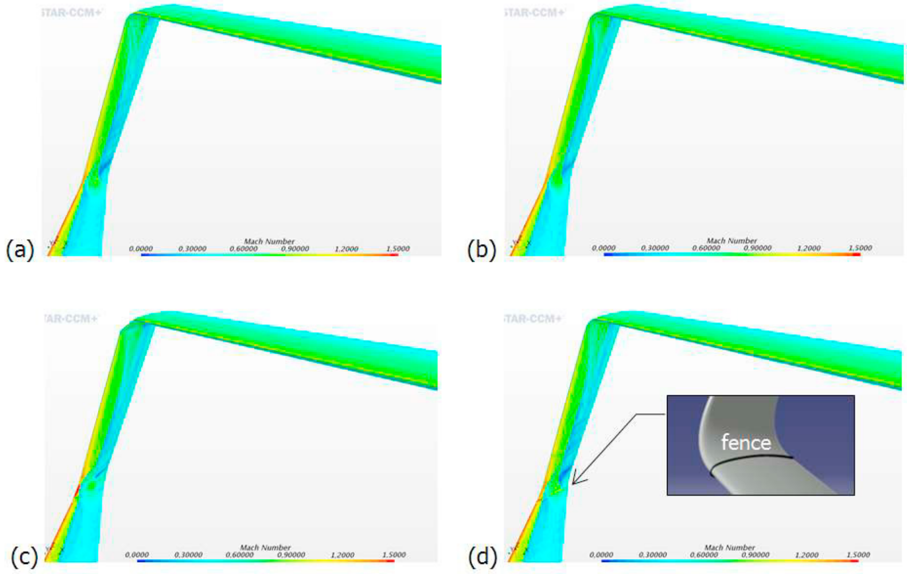

Fig. 10. Mach contour of the configuration with tip modifications: reference B (a), reduced tip-wing twist angles (b), plain fillet (c), fence (d)

It is noted that the vertical tip-wing offers in this case a better aerodynamic behaviour than every previous case analysed, and that the local flow improvements imply also significant improvement on the global efficiency, for the whole lifting system. So, in the following, the modifications operated are focused on the possibility to get better aerodynamic conditions on the front wing-vertical tip-wing fillet region (that seems more critical than the rear wing fillet condition, due to a lower load on this lifting surface) by trying to limit the strong flow acceleration present on the leading edge of this zone. Three different changes are applied: a reduction of 1° of the twist angle of the first lower and first upper airfoils of the vertical surface, which does not affect the global efficiency but improves local flow conditions; a substitution of the rounded fillet with a plain one, that causes a percentage increase of efficiency equal to +0.68%; an introduction of an aerodynamic fence, useful to stop the transversal flow at the tip of the front swept wing (upper part), that may cause an improvement of the local flow condition, but in this case variations in terms of global efficiency are not noticed: further analyses should be performed, with different fence geometry, positions and number. In Fig. 10 the Mach contour of these configurations are reported.

These are qualitative indications; the complexity of the aerodynamic interactions at the tip regions needs more detailed analyses, that will be carried out during the aerodynamic advanced design of the selected configurations. A last modification has been made in this activity: the introduction of a front wing-fuselage fillet, in order to remove or to weaken the shock waves, or to avoid the boundary layer separation at the intersection, as shown in Fig. 11; however,

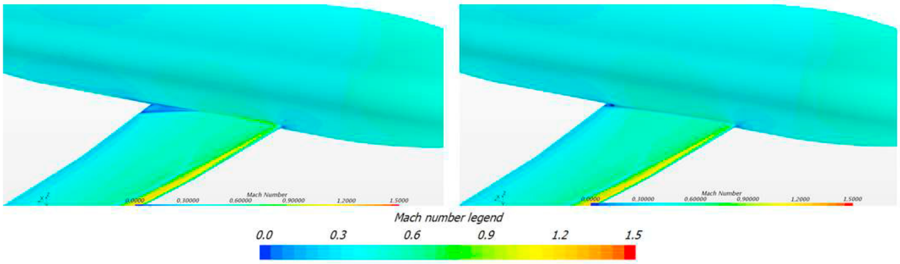

Fig. 11. Mach contour of the reference configuration B without and with wing-fuselage fillet (M_∞=0.79)

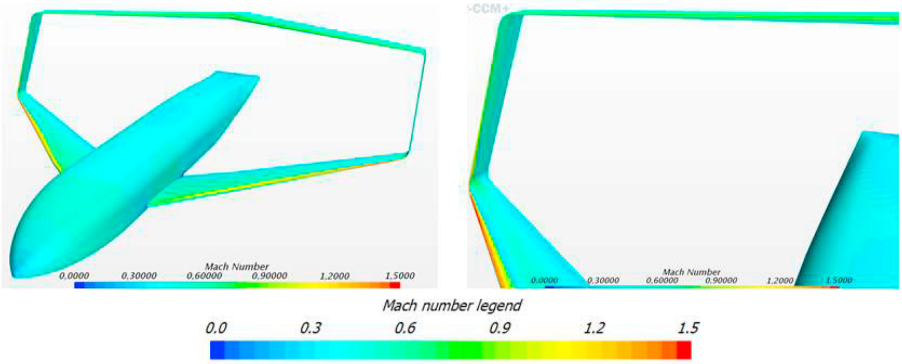

Fig. 12. Mach contour of the last reference configuration

it was decided to give to this aspect a lower importance in this phase, because it is preliminary known that the design of the fillet will need a dedicated multidisciplinary detailed design.

As an example, a reference configuration has been realized using the information collected during all these analyses: the cruise Mach number has been fixed equal to 0.79, the predicted wing loading for the front wing is about 500 kg/m^2, the lifting surfaces have the same span thickness variation previously described, the geometrical incidence of the vertical tip-wing is reduced, a wing-fuselage fillet is designed and, at the moment, a round fillet is maintained. Comparing this configuration to the reference B (M=0.85) it is obtained an increase of efficiency equal to +23.8%; indeed, comparing this configuration with a same one in the same condition, with only the local geometrical modification applied, at root and tip, it is obtained an increment equal to +2.24%. In Fig. 12 is shown the Mach contour for this configuration.

4. Conclusions

An activity of CFD transonic analyses is presented; this activity has been carried out in order to obtain some preliminary indications on the aerodynamic behaviour, and performance, of a box-wing designed according to the Best Wing System theory, in transonic flight. This information is necessary as a starting point of the preliminary aerodynamic design process to be carried out within the PARSIFAL project. The analysis campaign is focused on the overall effects of macro parameters, like wing loading or cruise Mach number, and on the local effects of the geometry variations, above all on the critical region of the front wing-vertical tip-wing fillet. The results obtained in this activity allow to define a design field in which to perform the overall aerodynamic design, as well as to avoid detrimental local effects in transonic flight.

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