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Natural Laminar Flow Transonic Wing Design

Applied to Future Innovative Green Regional Aircraft

I. Salah el Din¹, J.-L. Godard¹, A.-M. Rodde¹, F. Moens¹
G. Andreutti², D. de Rosa²
M. Di Muzio², R. Gemma², E. Baldassin², N. Calvi³, M.A. Averardo⁴

¹ONERA, The French Aerospace Lab, 92190 Meudon, France
²C.I.R.A., Fluid Dynamics Dept., Via Maiorise, 81043 Capua (CE), Italy
³Alenia Aermacchi, Airvehicle Dept., Corso Francia 426, 10126 Torino, Italy
⁴Alenia Aermacchi, Airframe Dept., Viale dell’Aeronautica, 80038 Pomigliano d’Arco (NA), Italy

ABREVIATIONS

AoA Angle of attack
CD Drag coefficient
Cl Airfoil lift coefficient
CL Lift coefficient
CLmax Maximum lift coefficient
CM Pitching moment coefficient
Cp Pressure coefficient
Cpmin Minimum pressure coefficient
D Drag
GRA Green Regional Aircraft
ISA International Standard Atmosphere
ITD Integrated Technology Demonstrator
JTI Joint Technology Initiative
L Lift
LoD Lift-over-drag ratio
LNC Low Noise Configuration
M Mach number
NLF Natural Laminar Flow
RANS Reynolds Averaged Navier Stokes
2D Two-dimensional
3D Three-dimensional
Xtr Laminar-turbulent transition position

INTRODUCTION

Regional aircraft typically operates over airports located in the neighbourhood of densely populated areas, with high frequency of takeoff / landing events and, hence, they strongly contribute to community noise and gaseous emissions. These issues currently limit further growth of traffic operated by regional airliners which, in the next future, will have to face even more stringent environmental constraints worldwide as prescribed by civil aviation certification normative.

Therefore, in accordance with Flight Path 2050 toward a drastic reduction of air transport environmental impact over next decades, several mainstream technologies have been considered in the frame of Clean Sky JTI – Green Regional Aircraft (GRA) ITD project for application to next-generation regional aircraft. Such technologies are concerning: i) advanced aerodynamics and load control to maximise lift-to-drag ratio in both design and off-design conditions of the whole flight mission profile, thus reducing fuel consumption/ air pollutant emission and also allowing for steeper/ noise-abatement initial climb paths; ii) load alleviation to avoid loads from gust encounter and manoeuvre exceeding given limits, thus optimising the wing structural design for weight saving; iii) low airframe noise to reduce aircraft acoustic impact in approach/ landing flight configurations.

Natural Laminar Flow (NLF) has been recognized as one of the key green technologies which may lead to significant improvement in the aircraft aerodynamic performance by reducing skin friction drag in cruise conditions, with consequent reduction of fuel consumption and, hence, of environmental pollutants emission. Therefore, in the overall scenario as above outlined, a NLF wing design has been developed in the frame of the GRA – ITD project to be applied to rear-fuselage engine, 130-seat future regional aircraft concept, featuring 3000 nm range / cruise Mach 0.74 / 35,000 ft flight level.

The wing CFD design, as described in the present paper, accounting for both cruise and low-speed aerodynamic performance, the wing aero-elastic design based on a Multi-Disciplinary Optimisation (MDO) approach and, finally, the aerodynamic design/ actuation system preliminary definition of suitable High-Lift Devices (HLD) able to meet aircraft requirements (speed and attitude) at approach and landing phases have been the main steps of the wing design process, as it will be described in the following paragraphs. Even beyond the scope of this work, it is worth mentioning the Wind Tunnel Tests which will be carried out during the last part of the GRA ITD work programme in order to demonstrate in a realistic experimental environment (TRL 5) the performance of the concerned NLF wing technology at different simulated flight conditions. In particular: i) transonic WT tests on a 1:3 innovative flexible model reproducing the full-size wing structural static response to assess the NLF wing aerodynamic/aero-elastic design and ii) low-speed WT tests on
a 1:6 complete A/C powered model to assess relevant high-lift performance in take-off and approach/landing conditions.

**AIRCRAFT SPECIFICATIONS AND REQUIREMENTS**

The whole design process has been performed following the expected next generation regional aircraft configuration specifications provided in document [1]. For the purpose of designing a robust laminar wing, a small leading edge sweep angle wing plan form has been specified (see plan form in Figure 1). The main features of the geometry are: a 111 m² wing area, a 34.14m wing span, an aspect ratio of 10.5, a crank positioned at y=5.804m, a tapering of 0.2426, a leading edge sweep angle of 18° and an outboard trailing edge sweep of 15°. The targeted flow condition at cruise is M=0.74 at 35,000 ft while maintaining low speed requirements at M=0.2 near ground level.

![Figure 1: Wing planform and reference sections locations](image)

**PRELIMINARY DESIGN**

**BASELINE AIRFOIL**

The first and most crucial step toward the design of a three dimensional wing is the definition of suitable performing 2D airfoil geometries from which the baseline wing surface will be designed. In the present study the wing initial design is based on reference airfoils placed at the root, crank and tip locations. The chosen methodology is to design an airfoil having ideal performance with maximal laminar extent and aerodynamic performance at a theoretical outboard mid-span conditions (i.e. local Reynolds driven by chordlength). Such approach is meant to efficiently define a laminar outboard wing where a local infinite swept wing flow behaviour can be expected, fitting best the 2.5D airfoil design assumptions. The reference airfoils are then deduced mainly by relative thickness to chord ratio adaptation.

The reference airfoil is defined with the thickness to chord ratio of 12.2% and with 2D aerodynamic conditions (M=0.724 Re=12.4 10⁶ and a target lift coefficient Cl of 0.7) corresponding to the outboard mid-span location flow conditions when the aircraft is in cruise conditions (M=0.74, Re=21 10⁶ and Cl=0.56).

The airfoils are computed with the ISES [2] solver. The Euler equations are discretized on a conservative streamline grid and are strongly coupled to a two-equation integral boundary-layer formulation, using the displacement thickness concept. A transition prediction formulation of the e^3 type is derived and incorporated into the viscous formulation.

The reference airfoil (Figure 2) is designed using a pressure gradient optimisation. The pressure gradient retained for this airfoil gives a backward location of the transition over 60% of the chord on the upper and lower surfaces. The curvature of the airfoil is generated to fit the pressure gradient. On the upper surface, the Mach number upstream of the shock wave is equal to M=1.2 and shock induced separation is avoided for the range of Cl which is considered. The rear load insures a great part of the required lift level. For a lift coefficient of 0.5 and above, the transition on the upper and lower surfaces exceeds 60% of the chord, and the drag coefficient is lower than 0.004. The lower surface shows a degradation of the NLF performance for Cl smaller than 0.5.

![Figure 2: Reference airfoil 2D global performance](image)

The three airfoils, necessary to generate the wing, are obtained from the reference airfoil by fitting the thickness-to-chord ratio by a homothetic transformation with respective thickness-to-chord ratios of 14.8% at the root, 13.7% at the crank and 12.4% at the tip.

![Figure 3: Reference airfoil 2D global performance](image)
In Figure 3 the performance of these airfoils verified with 2D computations are plotted. Each airfoil is computed with the Reynolds number based on its local chord. The drag coefficient remains small and the transition location is near 60% of the chord for all the considered lift conditions on both the upper and the lower surfaces. The tip airfoil shows a good NLF performance over a wider range on the pressure side than the two other airfoils, starting at $C_l=0.1$ instead of $C_l=0.4$. The pressure distributions for the two lift targets ($C_l=0.5; C_l=0.7$) show the strengthening of the pressure gradient with the thickness on the upper side, however the Mach number upstream of the shock wave still remains lower than 1.3 at $C_l=0.7$, even on the root airfoil.

3D REFERENCE WING DESIGN

Once the airfoils designed, the CAD of the 3D wing was generated and integrated into a fuselage baseline with a 2 degree global trimming angle using CATIA V5, as shown in Figure 4. The resulting CAD is meshed as the first baseline using structured ICEM HEXA mesh generator software, leading to a grid of $3.6 \times 10^6$ nodes. At this stage the resulting wing local twist still needed to be adapted to the local flow to retrieve the 2D design airfoil performance properties and control the spanwise load distribution, this even before any structural considerations.

![Figure 4: 3D configuration CAD generation](image)

FINAL CLEAN WING AERODYNAMIC

The local twist adaptation has been performed using an automated aerodynamic optimisation process using a python based workflow management environment. The parameterization and mesh deformation are performed using an ONERA in-house tool, SeAnDef tool based on analytical deformation functions. Fully turbulent computations are performed using the elsA solver [3]. RANS equations with Spalart-Allmaras model are solved thanks to a Jameson scheme. The wing has also undergone a second phase of low speed enhancement with slight modifications in leading edge radius and in camber. The pressure distribution resulting from a calculation at $C_l=0.52$ is given in Figure 5. It can be seen that the pressure distribution remains typical of laminar airfoils. Concerning the spanwise load given in Figure 6, the maximum local loading is obtained at the outboard mid section. The slight shift which appears at 35% of span is due to the kink. The objective of enhancing the load distribution has successfully been achieved. The aerodynamic performance extracted for the wing alone in fully turbulent flow corrected by the stability analysis post-processing (in friction drag reduction) for the $M=0.74$ flight condition is summarized in Figure 7. The configuration reaches, for the design point, a lift to drag ratio of 22 at the design flight condition and the low speed performance is complying with the specification under the assumption of high-lift devices. The redesign phase has increased the computed $C_{l,\text{max}}$ of 0.11 on the 3D clean configuration.

![Figure 5: 3D configuration CFD results for $M=0.74$, $C_l=0.535$ flight conditions](image)

![Figure 6: 3D configuration load distribution for $M=0.74$, $C_l=0.535$ flight conditions](image)

![Figure 7: 3D LoD performance at $M=0.74$ and 0.2](image)
The stability analysis is performed extracting the information from the CFD results and post processing the turbulent data with a 3D boundary layer computation using the ONERA 3C3D software [4]. The RANS computations provide, among other pieces of information, the pressure field on the aircraft model surface. Assuming that there is no wall curvature effect, the corresponding boundary layer velocity field is rebuilt and is taken in as input for the laminar boundary layer computations. The boundary layer properties are then taken as input for the stability analysis.

The transition position is determined using single factor critical value criteria, above which the transition is triggered, based on an $e^T$ envelope strategy [5] combined with a simplified analytical 3D database technique [6] which takes into account Tollmien-Schlichting (TS) as well as cross flow instabilities.

![Figure 8: 3D stability analysis using external boundary layer coupled with 3D $e^T$ approach for $M=0.74$, $CL=0.535$](image)

The N factor distributions on the wing in cruise conditions are plotted in Figure 8. The results confirm the laminar extent capability of the designed baseline wing. On the suction side (left), the laminar extent on the outboard wing reaches almost 60% of chord length, which can be considered as a very satisfactory result. On the pressure side (right), the laminar extent is sensible but the benefit is damped by the need of integrating a high-lift device which is presented in the last section of the paper.

The resulting wing geometry has been used as a starting point for the multi disciplinary process which is described in the following section.

**BASELINE MDO DESIGN**

The Multi Disciplinary Optimisation (MDO) wing design process involved disciplines of aerodynamics (CFD), weights, static/dynamic loads and aeroelasticity, and, brought to optimise the wing geometry and its structural layout for several selected design points in order to achieve the best structural efficiency still preserving the target laminar flow extent.

The Multi Disciplinary Optimisation process has been applied to the baseline wing, aiming at minimum weight and minimum twist deformation, in order to keep the Natural Laminar Flow (NLF) extent, to develop, considering a multiple disciplines design scheme, an adaptive wing concept via aeroelastic tailoring. Laminar flow versus wing flexibility and loads control capability will be tested by means of WTT within ETRIOLLA CIP project.

In order to preserve the target laminar flow extension, the main constraints of the MDO have been relevant to the aerodynamic shape under loads. Therefore, the main constraint of the baseline wing design has been to apply a negligible torsional deformation in order to keep, in cruise, an optimal aerodynamic shape able to maximise the aerodynamic cruise performance: lift to drag ratio as well as the target laminar flow extension.

The MDO objective function was the wing weight saving while considering constrains on relevant stress, deformed shape, aerodynamic performance and aeroelastic requirements (Figure 9 and Figure 10). In order to obtain the "optimal wing structural solution", the optimisation process has adapted the staking sequence of the composite material (resin carbon fibre), the skin and spar web panels thickness as well as the spar flanges bending resistance area. The structural weight of the MDO wing is about 800 kg lighter than wing weight of similar A/C (i.e. MD80).

![Figure 9: Multi-disciplinary design problem definition](image)

![Figure 10: Multi-disciplinary design process overview](image)
Nevertheless, on the base of static aeroelastic mechanism (Figure 11), a more flexible wing:
- yields more wash-out (airfoil nose-down due to back sweep angle)
- favours more inboard lift distribution
- reduce bending moment hence stress & structural weight

Figure 11: Flexible Wing Effects (Aeroelastic phenomena)

For a flexible aircraft, structure stiffness can influence loads; therefore this flexibility effect can be applied to any stiffness driver like structural sizing.

The basic idea behind the adaptive wing through an aeroelastic tailoring design of the wing is to take benefit from the flexibility effect to reduce structural weight. Therefore the previous flexibility constraints on the wing (i.e. torsional stiffness) have been removed in order to modify the lift distribution spanwise and maximising, in terms of bending reduction in this case, the beneficial effects of the flexibility. The flexibility of the wing has been tailored in order to reshape the lift spanwise distribution aimed at minimising the critical bending moment. Then, the reduced loads due to the increased flexibility has been then used to further reduce the wing structural mass.

The adaptive wing concept has been developed via aeroelastic tailoring design by means of a multi-level optimisation approach. Aeroelastic tailoring alone or combined with structural optimisation (minimum mass oriented) allowed wing structures design in a more efficient way to meet structural and aircraft performance requirements. However, the design of such adaptive wing concepts requires the consideration of aerodynamic-structure coupling within the design loop.

The novelty of the presented work lies in the use of an aeroelastic steady scheme with aero-structure embedded within a multi-level global optimisation, which accounts for composite material anisotropy, lift distribution variation as well as load redistribution under structural and aerodynamic constraints (Figure 12). The wing-box panels (skin and web-spar are assumed to be symmetric or mid-plane symmetric laminates with ply angle restricted for manufacture purpose to 0, 90, +45 and -45 degree, while constraints of balanced laminate have been removed in order to increase and tailor the cross-coupling between bending deformation and twisting angle rotation.

The optimal laminate lay-up, which allows the wing to adapt and optimise its deformed shape to the minimum bending moment spanwise flexible lift distribution (Figure 13), has been found out, as long as strength and buckling requirements are not violated. A feature of the proposed lay-up is strong unbalanced laminates which allow to increase the cross-coupling between bending deformation and torsional twist angles. Since the wing structural element sizes have been kept constant and the design variables are the ply thicknesses of each laminate, the wing structural weight has not been influenced by the aeroelastic tailoring.

Figure 12: Aeroelastic Tailoring Design scheme

Figure 13: Adaptive Wing: favourable more inboard lift distribution due to increased wing flexibility (cruise – strip lift coefficient spanwise distribution)

Figure 14: Adaptive Wing: spanwise bending saving compared to Baseline Wing (Thetas) (cruise and max load factor manoeuvre)
The further step of the adaptive wing concepts development will be to optimise, from the previous laminate lay-ups which realise the minimum critical bending moment lift distribution, the size of the wing structural element in order to save mass thanks to the design load reduction (Figure 14) brought by the aeroelastic tailoring design.

The adaptive wing developed via aeroelastic tailoring design allows a critical bending saving up to 8% associated to a wing structural saving up to 13%. On the other side the increased and tailored flexibility of the wing aimed to the maximisation of the passive loads control, reduced the control surfaces effectiveness, the main devices for the active loads control and gust alleviation.

To mitigate the loss of ailerons effectiveness an adaptive wing with a limited flexibility has been developed. The potential benefit of the passive load control has been reduced, less than 5% critical bending saving associated to a 7% mass saving, in order to recover a 10% of the ailerons effectiveness at cruise condition.

A comparison between the two proposed adaptive wings, the one with extra tip rotation (OPT2_ExTR_MM) and the one with a limit on the maximum torsional flexibility allowed (OPT2_MM), are reported in following table.

<table>
<thead>
<tr>
<th>Wing</th>
<th>Height Saving</th>
<th>Bending Saving</th>
<th>Tip Twist Angle</th>
<th>Deflection Angle</th>
<th>Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPT2 ExTR_MM</td>
<td>7.2%</td>
<td>4%</td>
<td>3%</td>
<td>1.27°</td>
<td>97%</td>
</tr>
<tr>
<td>OPT2 MM</td>
<td>2%</td>
<td>0.8%</td>
<td>0.19°</td>
<td>0.78°</td>
<td>0.49°</td>
</tr>
<tr>
<td>Theta</td>
<td>1%</td>
<td>0.8%</td>
<td>0.19°</td>
<td>0.78°</td>
<td>0.49°</td>
</tr>
<tr>
<td>xmin</td>
<td>2%</td>
<td>16%</td>
<td>0.19°</td>
<td>0.78°</td>
<td>0.49°</td>
</tr>
<tr>
<td>xmax</td>
<td>120°</td>
<td>1.6%</td>
<td>0.19°</td>
<td>0.78°</td>
<td>0.49°</td>
</tr>
</tbody>
</table>

Table 1: Adaptive wings performance comparison

**HIGH LIFT DEVICES**

**2D HLD DESIGN AND OPTIMISATION**

The original high-lift system was not able to match the requirements in take-off and landing phase. As it was not possible to modify the shape of the wing and/or the flap in order to keep the flow laminar, it was decided to introduce a leading edge high-lift device, namely a Krueger flap. The design of the leading edge device is based on a 2D approach. A preliminary analysis confirmed the usefulness of the device. An optimisation procedure was then assembled using in-house built codes. The optimisation is a single-objective, two design point and is performed modifying shape and settings of the device. The cove is not modelled during the optimisation, but is introduced in the post analysis the resulting effects are evaluated. In order to generate a baseline for the optimisation study, a 2D model was re-engineered. Several geometrical parameters have to be taken into account, such as the minimum and maximum absissa, the device thickness, the deflection angle and the gap and step of the slot in deployed conditions. These geometrical parameters are constrained by the front spar position and have to be compatible with the actuation system installation. These variables are shown in Figure 15.

In Table 2 the parameters expressed in percent of the chord length are reported. To preserve the laminar flow, at least on the upper side, xmin is set after the stagnation point in cruise condition.

<table>
<thead>
<tr>
<th>Param</th>
<th>OPT2</th>
<th>OPT2 ExTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>xmin</td>
<td>2%</td>
<td>16%</td>
</tr>
<tr>
<td>xmax</td>
<td>120°</td>
<td>1.6%</td>
</tr>
</tbody>
</table>

Table 2: Geometric parameters

The optimisation process was performed by using in-house built codes and Figure 16 shows the flowchart of such procedure. The main component of the optimisation procedure is the GA-ME [10] evolutionary optimizer (Genetic Algorithm for Multi-Element airfoil design). WG2AER (WeiGhts-to AERofils) [11], manages the shape modification while the parametric domain modeller PARDOMO, based on ENDOMO [12], coupled with the grid generator ENGRID [13], is used to generate the structured grid. The fitness (objective function value) of each new shape generated by GA-ME is obtained using the ZEN [14] code solving the aerodynamic flow field.
In Table 5 the modification functions used to reshape the initial geometry are listed.

| Rear Loading | 0.006625 $10^9 (x^{15} (1-x) \exp(0.2 - 20x))$ |
| Rear Loading | 0.0175 $10^9 (x^{10} (1-x) \exp(0.25 - 20x))$ |
| Rear Loading | 0.04444 $10^9 (x^{23.69} (1-x) \exp(0.35 - 20x))$ |
| Rear Loading | 0.09 $10^9 (x^{30} (1-x) \exp(0.5 - 20x))$ |

Table 5: Modification function

In Figure 18 the final shape is shown, while in Figure 19 the comparison of lift coefficient between the original HLD and the optimised one is shown. The new design is able to give an important improvement of both $C_{l_{max}}$ and stall angle. The obtained optimised shape has been further developed and integrated on the whole wing by ALA. A more detailed description of the work is available at ref [15] and [16].
Moreover a shorter chord Krueger flap was investigated (a 65 mm shorter Krueger as in Config. K02S+F06 decrease CL_{max} of some 0.1), a Krueger flap with a bigger leading edge radius as in Config. K05+F06 (to provide room for a piccolo tube installation for instance), and also some possible failure conditions. In the end, despite higher CL_{max} could be obtained, the reference high-lift configuration chosen is K01+F06 because more similar to that already assessed during 2D optimisation. Configurations K05+F06 and K06+F06 are possible backup solutions to be used if anti-ice system issues optimisation. Configurations K05+F06 and K06+F06 are because more similar to that already assessed during 2D integration for transport aircraft, March 1996

**Figure 23**: Full 3D approach configuration – CL vs Alpha

Computations carried on this configuration proved that the maximum trimmed lift coefficients reaches 2.69, which is slightly greater than the requirement (2.66). The maximum lift is obtained at an angle of attack of 14.5 deg.

**Figure 24**: Stall (left) and post stall (right) friction lines

**CONCLUSIONS**

The design of a high laminar flow extent potential in cruise conditions has been described in this paper. The process has successfully undergone multiple steps from single to multiple disciplines considerations using high fidelity tools and up-to-date optimisation and workflow management environment. The take-off and landing performance enhancement has been tackled with the definition of efficient high-lift devices. In each of these steps optimisation processes have been used to further improve the performance of the wing. The resulting wing has since been integrated in an updated fuselage geometry equipped with a realistic belly fairing and its performance improved by the addition of a winglet. The aerodynamic and aeroelastic designs will be validated through transonic tests of a high scale 3D wing model with the objective of assessing the laminar flow extent and load control alleviation devices.

**ACKNOWLEDGEMENTS**

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