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A Flow Control for an Advanced Technology Regional Aircraft (ATRA) Using a Variable Camber Wing with Hybrid Laminar Flow Control

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Abstract: - This paper intends to present a feasibility study of a flow control using a Variable Camber Wing (VCW) with Hybrid Laminar Flow Control (HLFC) for the Advanced Technology Regional Aircraft (ATRA). Practical use of HLFC requires that laminar flow be maintained through a range of cruise lift coefficients and Mach numbers. Variations in lift coefficient and Mach number will change the wing pressure distributions from the optimum and may result in some loss of laminar flow. Deflection of the variable-camber-flap (VCF) permits controlling the pressure distribution over the forward part of the airfoil, keeping it similar to the design pressure distribution, even when the lift coefficient and Mach number differ considerably from the design values. With careful design of VCF, it can be used to reduce the wave drag penalty, and to sustain attached flow in turbulent mode. For purposes of this work a wing for ATRA was designed. The aerodynamic performance of the above wing was analysed using RAMPANT (an unstructured, multigrid flow solver). The wing performance appears quite reasonable, and almost met the aerodynamic design objectives. The conclusion can finally be drawn, that the application of combined HLFC –VCW concept as a flow control on the wing to reduce the aircraft drag is feasible for a transport aircraft from an aerodynamic point of view.

Key-words: Flow control, Wing design, Hybrid Laminar Flow Control, Variable Camber Wing

1 Introduction

For commercial transport aircraft, one of the basic aerodynamic performance objectives is to achieve the highest value of (Mach number)(Lift/Drag), $M(L/D)_{max}$, at the cruise Mach number. Climb and descent performance, especially for short-range missions, is also important and may suggest the “cruise” design conditions to be compromised.

In the past 20 years, much airframe development has been aimed at reducing lift-dependent drag, leading to higher-aspect-ratio-wings and winglets coupled with overall optimisation of wing design [1].

To achieve further major advances it is necessary to look at other aspects of design, in particular, the reduction of profile drag. Boundary layer control, aimed at extending laminar flow over greater areas of the wing has been pursued intermittently since the early days of aviation. Laminarisation of other aircraft components such as tailplane, fin, and engine nacelle offers additional advantages.

Variable camber (VC) offers an opportunity to achieve considerable improvements in operational flexibility, buffet boundaries and performance; it does this by increasing the lift/drag ratio in cruise and climb, because the variable camber enables cruise and climb to be always at an optimum lift coefficient [2].

It is believed that the application of a Hybrid Laminar Flow Control (HLFC) and Variable Camber (VC) as a flow control on the wing would assist in achieving such a goal, but must be shown to be cost-effective [3, 4].

This paper describes the exploration of the above concept and technologies to the initial design of Advanced Technology Regional Aircraft family (ATRA, twin turbofan with 83 - 133 passengers).

2 Wing Design

2.1 Wing Sweep Selection

The application of laminar flow on swept wings is effectively limited at high Reynolds numbers by a high sweep angle, as cross flow instability and attachment line transition lead to fully turbulent boundary layers on the wing [5]. Theoretical and experimental investigations on finite swept wings show, because of three-dimensional displacement effects, an effective increase of wing sweep for rearward swept wings and an effective decrease of wing sweep for forward swept wings, compared to the geometrical sweep. For a laminar flow wing, the reduction in sweep in the case of a forward swept wing leads to a more stable laminar boundary layer concerning transition because of cross flow instability and attachment line transition. Thus, with this concept, a laminar forward swept wing can be realized more easily than a comparable swept back wing [6].

For forward swept wings the major technical disadvantages of a further outboard centre of lift and the potential of divergence could possibly be overcome in the future using active load alleviation, Variable Camber and/or composite tailoring designed to reduce bending and minimize centre of pressure movement. The main problem of forward swept wings is natural divergence, and the tendency towards flutter.

2.2 HLFC-VCW Aerofoil Design Criteria

The introduction of laminar flow represents an additional design criterion that must be satisfied along side existing considerations. The issues raised for NLF section design are also relevant to HLFC sections although leading edge suction reduces the severity of the constraints imposed for NLF [4, 7 & 8].

The HLFC airfoil design criteria [9] are summarized in Figure 1.

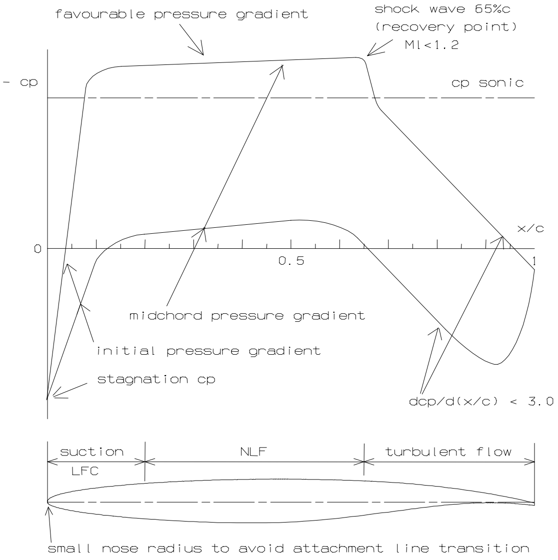


Figure 1. HLFC airfoil design criteria

2.3 Low Speed Design

In the case of a laminar aerofoil, due to its specific geometry (high curvature of the leading edge, rearward maximum cross section, etc.....) and absence of leading edge slats, special attention is required in high-lift conditions, mainly concerning prediction of leading edge stall. The main feature of the flapped laminar airfoil is the dramatic loss in α_{max} occurring when the flaps are deflected. This loss in α_{max} is probably a consequence of the leading edge type of stall, as expected from the small leading edge radius. To increase α_{max} capability, two alternatives can be considered [10 & 11]:

a. Compromise between low-speed and cruise may lead to greater value of leading edge radius (can increase attachment line contamination possibility), compatible with acceptable value for α_{max}.
b. A leading edge high-lift device (Krueger flap) may be used, but this will make the laminarization of the lower surface more difficult.

2.4 Flow Control on the Wing

2.4.1 Cost issues

The main issue in the application of new technologies in transport aircraft is the ability to employ them at low cost without reduction of their benefits.

Laminar flow flight research in the 1950's and 1960's demonstrated that manufacturing techniques needed to obtain the stringent surface smoothness and waviness criteria required for laminar flow aircraft presented a major challenge. Today, it is recognized that conventional production aircraft wing surfaces can be built to meet these design constraints [12].

2.4.2 Combined HLFC-VCW Techniques for Flow Control on the Wing

The most significant advance made in the development of the laminar flow technology is the concept of Hybrid Laminar Flow Control, an idea that integrates the concepts of NLF and LFC. It avoids the undesirable characteristics of both. NLF is sweep limited and full-chord LFC is very complex. The key features of HLFC are : a) conventional spar box construction techniques are utilized, b) boundary-layer suction is required only in the leading edge, c) natural laminar flow is obtained over the wing box through appropriate tailoring of the geometry, and (d) the HLFC wing design has good performance in the turbulent mode. Typical aircraft drag reductions of around 10% - 11% are expected for this approach [4 & 12]. The Leading Edge Flight Test (LEFT) on the NASA Jetstar aircraft addressed HLFC leading-edge system integration and reliability questions and set the stage for a commercial transport demonstration of HLFC [13].

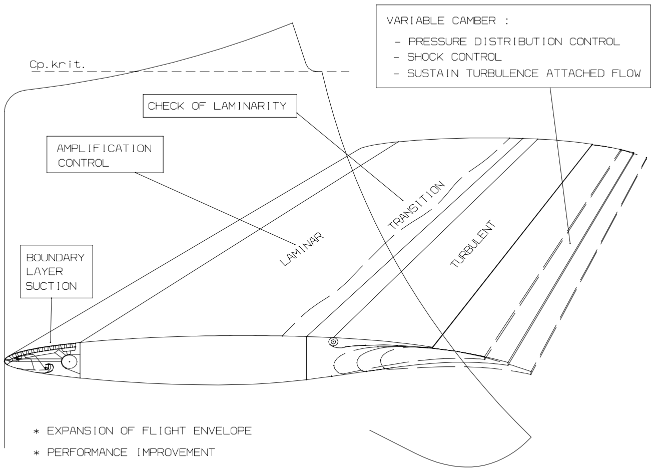


Figure 2. Flow control on the wing

Practical use of HLFC requires that laminar flow is maintained through a range of cruise lift coefficients and Mach numbers. It was therefore decided to investigate a HLFC wing together VC-flap. Deflection of the VC-flap permits controlling the pressure distribution over the forward part of the airfoil, keeping it similar to the design pressure distribution, even when the lift coefficient and Mach number differ considerably from the design values [4]. With careful design of a VC-flap, it can be used to reduce the wave drag penalty, and to sustain attached flow in the turbulent mode [2]. Flow control on such a wing, is shown in Figure 2.

2.4.3 Candidate combined HLFC-VCW section configurations

Section views of the two wing configurations considered in this studies are shown in Figure 3. Configuration I has both upper and lower surface suction, from the front spar forward with leading edge systems as proposed by Lockheed [13]. It has no leading-edge devices, so requires double-slotted Fowler flaps to achieve $C_{L_{max}}$ requirements. Configuration II replaces the lower surface suction with full-span Krueger flaps, which, combined with single-slotted Fowler flaps, provide an equivalent high lift capability. The Krueger flaps also shield the fixed leading edge from insect accumulation and provide space for the anti icing system. The upper surface, is the only one with suction panels. The leading edge system used on configuration II is similar as proposed by Douglas [14].

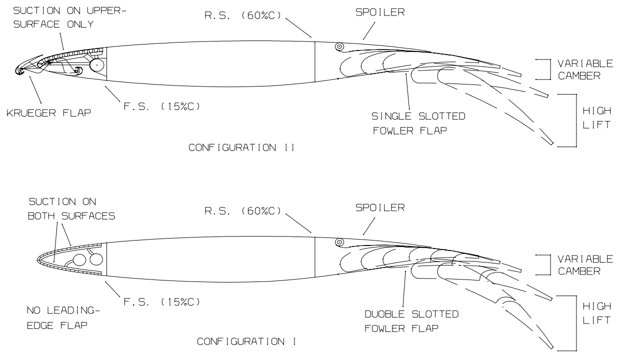


Figure 3. Cross sections of candidate combine HLFC-VCW configurations

A summary of the advantages, risks, and disadvantages are :

Configuration I: the advantages are that it is a simple system with no leading edge devices and it has upper and lower surface laminar flow for least drag. The disadvantages and risks are of more potential for insect contamination on the suction devices, which may cause boundary-layer transition. It leads to high approach speeds and landing field lengths and/or a more complex trailing-edge high lift system. It has longer take-off field lengths, particularly for hot, high-altitude conditions, and has a trim penalty due to higher rear loading (when the flaps are deployed).

Configuration II: the advantages are less potential insect contamination on the suction device, hence the laminar boundary layer will be more stable. It has simpler trailing-edge high lift devices, lower approach speeds and shorter take-off and landing field lengths, and smaller trim penalty when the flaps are deployed. The disadvantages are less drag reduction due to laminar flow being only on the upper surface and a more complex leading-edge system.

Preliminary estimates by Boeing [4] indicated cruise drag reductions of about 11% for HLFC having laminar flow on the upper and lower surfaces, while the reduction for HLFC having laminar flow only on the upper surface was only 7%. The deficiencies noted for configuration I are related to low speed performance and insect contamination problems. The potential exists for high lift performance improvements if wings are specifically designed for the HLFC task. Although it has an inherently lower drag reduction, configuration II is more likely to provide a stable laminar boundary-layer due to a lower likelihood of being contaminated by insects. Taking into account the above considerations, configuration II was selected, for this study, but results for both configurations are shown later, for completeness.

2.4.4 Combined HLFC-VCW section baseline configurations

The HLFC-VC section baseline configuration used in this work is shown in Figure 4. The leading edge system used on this configuration is similar to leading edge systems as proposed by Douglas [14]. While the variable camber concept is described in the following paragraphs.

Ideally the change in section profile aft of the rear spar should not cause separation of airflow, which would otherwise give rise to higher profile drag. To overcome the problem of separation, the radii of local curvature must be greater than half the chord [15], but not too high, as the section will have a higher pitching moment, and hence higher trim drag, which then will reduce the benefit of variable camber itself. The radii should be optimized between these two constraints. The radius is inherent in the trailing-edge upper surface of the aerofoil, so when the aerofoil is used for a VC concept, the aerofoil should be designed taking into account the above considerations from the beginning.

The concept of variable camber used for this configuration is quite similar to traditional high lift devices. To keep the systems simple, the camber variation is achieved by small rotation motions (in two directions for positive and negative deflections). In high speed, low deflection VC-operation the flap body slides between the spoiler trailing edge and the deflector door.

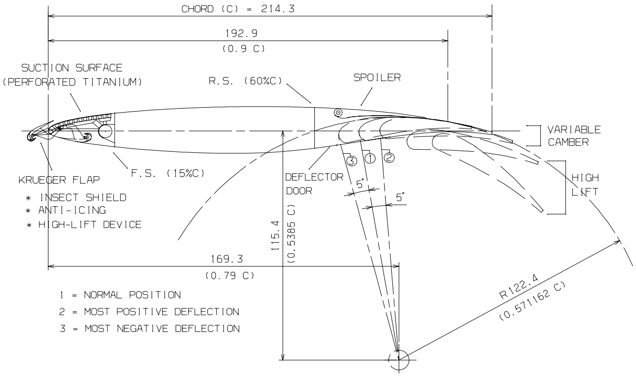


Figure 4. HLFC-VC section baseline configuration

2.5 Development of Three Dimensional Geometry

For this study, a wing of a typical regional aircraft (W-ATRA) was sized [3] as shown in Figure 5.

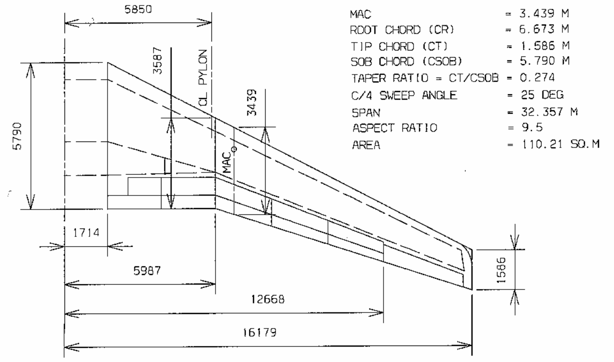


Figure 5. W-ATRA wing concept

A generic code (i.e. RAMPANT [16]) could be utilized for aerodynamic analysis. SWEPTDES [17] is used for airfoils design. Figure 6 shows the profile (streamwise) of the wing aerofoil sections.

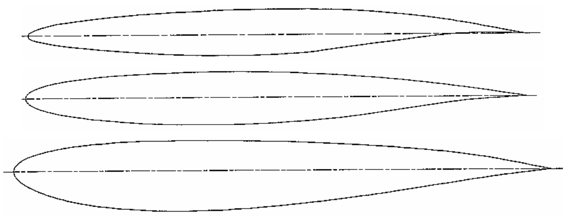


Figure 6. The profile of the wing aerofoil sections

Practical use of HLFC requires that laminar flow be maintained through a range of cruise lift coefficients and Mach numbers. Therefore, the W-ATRA wing incorporates a VC-flap. The design concept of the variable camber wing for this work is described in section 2.4.4.

2.6 Wing Performance

2.6.1 Configuration description

The analysis was performed for a half wing-body configuration only. Two flap configurations of HLFC-VC baseline configuration as shown in Figure 4 were used in this analysis, i.e. :

a. Configuration I : VC-flap undeployed (VC-flaps deflection or dvcw along the span = 0 degree)
b. Configuration II : VC-flap deployed (VC-flaps deflection or dvcw along the span are varied)

VC-flap deflection distribution for Configuration II is linear, +2 degree at wing root and – 1.5 at wing tip. The variation of VC-flap deflection along the span is not optimized yet, but these analyses show the effect of VC-flap deflection on the section pressure distribution along the span.

The WB-ATRA's surface grids are for $M_{\sim} = 0.8$, angle of attack = 0 degree, and Reynolds number of 21.6×10^6. The computational domain was a rectangular box that extends a 5 fuselage length in front, behind, above, and below the wing, and 3 fuselage lengths (6.8 wing semispan) to the side of the wing. The size of the mesh of the above two configurations were as follows :

a. Configuration I =
35,019 Nodes, 344,787 Faces, 165,256 Cells
b. Configuration II =
36,215 Nodes, 355,903 Faces, 170,522 Cells

Laminar flow was assumed for those computations.

2.6.2 Result

The wing surface pressure and Mach number distributions were measured at 6 different spanwise stations : 2y/b = 0.106, 0.191, 0.37, 0.578, 0.786 and 1.00. Figures 10 and 11 show pressure and Mach number contours on the surface of configuration I. Figures 12 and 13 show pressure and Mach number contours on the surface of configuration II.

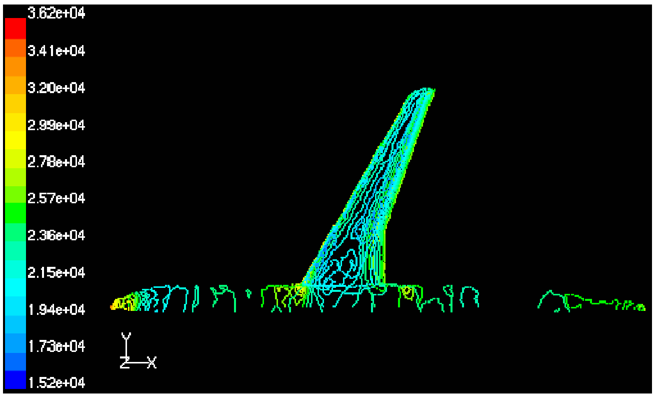


Figure 10. Configuration I : contours of static pressure, Pascal

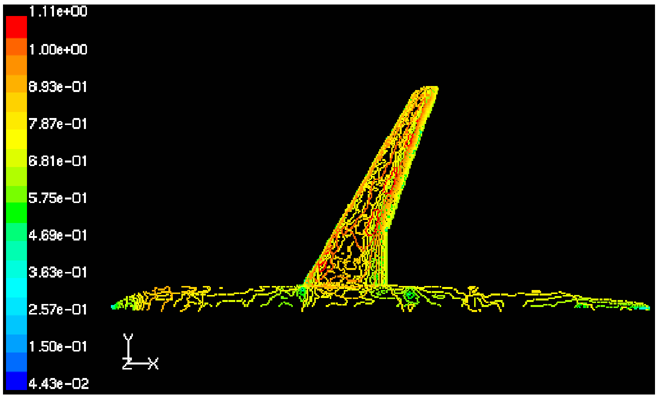


Figure 11. Configuration I : contours of Mach number

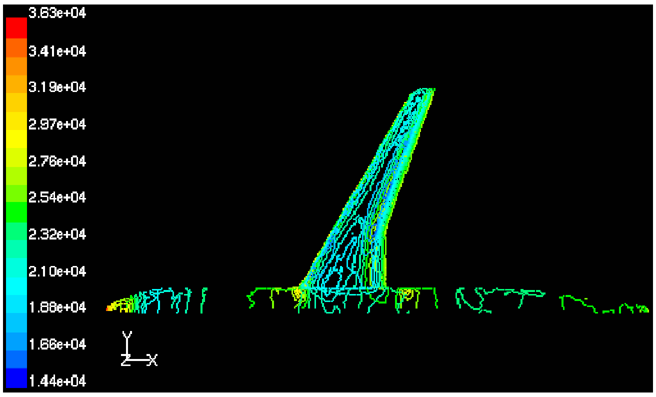


Figure 12. Configuration II : contours of static pressure, Pascal

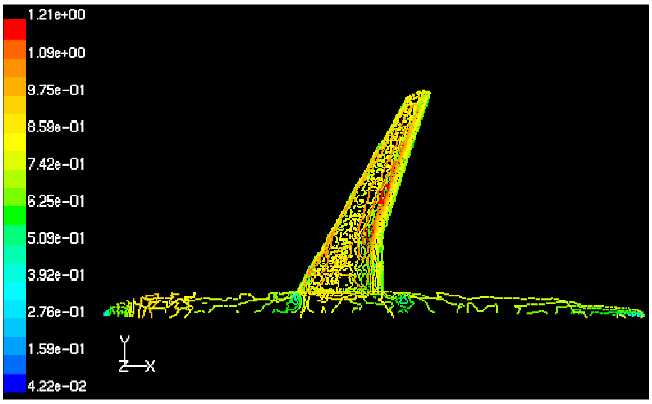
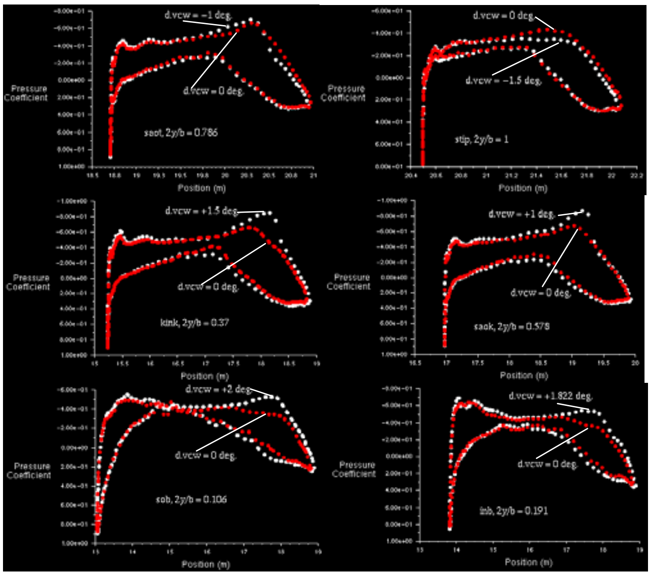


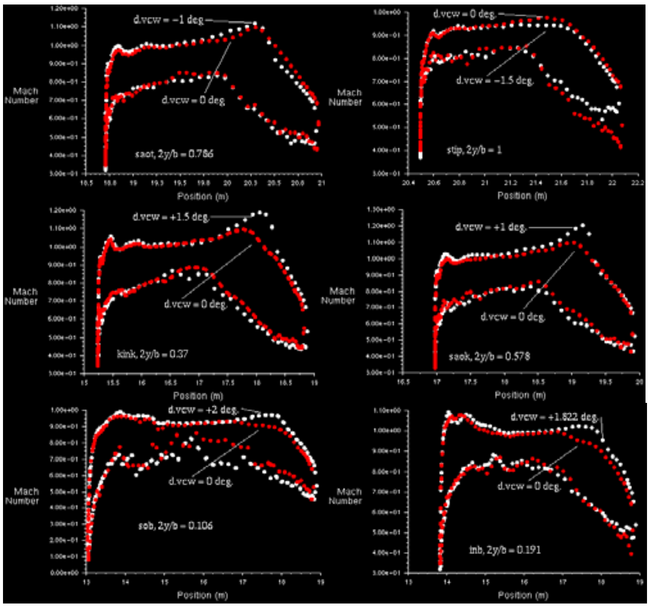
Figure13. Configuration II : contours of Mach number

The pressure and Mach number distributions at spanwise stations : 2y/b = 0.106, 0.191, 0.37, 0.578, 0.786 and 1.00 of configuration I and configuration II are shown in Figures 14 and 15.

From Figures 10 and 12, for both configurations, the average wing upper surface isobar sweep angle (taken at 50% chord) is approximately 21.8 degrees, instead of 25 degrees (wing quarter chord sweep angle). Thus, the isobar sweep efficiency is = 21.8/25 = 0.872. The inboard wing upper surface isobars are characterized by more sweeps forward at the front and less sweepback at the rear, and the shock strength is quite weak.



Figures 14. Configuration I (red) and II (white) : pressure distribution



Figures 15. Configuration I (red) and II (white) : Mach number distribution

3 DISCUSSIONS

From Figure 14, for configuration I and II, it can be seen that all of the pressure distributions (especially on the outboard wing, i.e. : from the kink to the tip) are characterized by a steep initial gradient (rapidly falling pressure), followed by a negative pressure gradient (falling/favourable pressure) and a single weak shock wave and finally a recovery region with a soft aft pressure gradient. Based on guidelines of section 2.2, the above pressure distribution characteristics make it is possible to apply the HLFC concepts on the wing of configurations I and II.

As shown in Figures 14 and 15, with the deflection of VC-flap, the pressure distribution shape at the front of shock does not change too much; this is good for HLFC application. The VC-flap deflection makes the shock stronger and increases aft loading (producing greater pitching moment and hence more trim drag).

The W-ATRA wing configuration results were produced from only the first iteration of a very complex wing design process. The above wing is not yet optimum both for undeflected and deflected VC flap. To improve the wing aerodynamic performance, it is recommended that further optimization be made of the airfoil sections, twist and VC-flap deflection distributions along the wing span, together with LFC suction requirements.

4 CONCLUSIONS

The application of combined HLFC –VCW concept as a flow control on the wing to reduce the aircraft drag is feasible for a transport aircraft from an aerodynamic point of view, with the same reservations that apply to the feasibility of any laminar flow control (LFC) aircraft, i.e. that the economic aspects depend on manufacturing and operational data. Before HLFC and VCW technology can be applied to transport aircraft, a large multidisciplinary research effort is needed in order to master the technology and to demonstrate it on flying test-beds, and during in-service operational tests.

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