THE APPLICATION OF HYBRID LAMINAR FLOW CONTROL AND VARIABLE CAMBER FLAP AS A FLOW CONTROL ON THE WING FOR REGIONAL AIRCRAFT FAMILY

Prasetyo Edi

Head of Configuration Design Department – ERDC - IAe
Bandung, West Java, INDONESIA

Keywords : *wing design, flow control, hybrid laminar flow control, variable camber wing*

ABSTRACT

The combination of Hybrid Laminar Flow Control (HLFC) and Variable Camber Flap (VCF) can be use as a 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. 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 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 VC (Variable Camber)-flap, 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 typical family regional aircraft (W-ATRA) was designed. The aerodynamic-performance of W-ATRA was analysed using Rampant (an unstructured, multigrid flow solver). Regardless of its weakness, its performance appears quite reasonable. To improve the wing performance, it is recommended to optimised the airfoil sections, twist and VC-flap deflection distributions along the wing span together with suction requirements.

1. INTRODUCTION

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

In the past 25 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 a further major advance 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 (increasing lift/drag ratio in cruise and climb, due to cruise and climb always at 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].

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 backward 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 could possibly be overcome in the future when active load alleviation, VC and/or composites are designed to reduce bending and minimize centre of pressure movement. There is little to choose between forwards/aft swept wings in terms of nacelle integration. Stability and control characteristics of forwards swept wings are not well understood. The main problem of forward swept wings is natural divergence stall and can lead to a flutter.

2.2. HLFC-VCW airfoil design criteria

The introduction of laminar flow represents an additional design criterion that must be satisfied along with all 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. Typically transonic HLFC aerofoil sections have been designed with pressure distributions having a small peak close to the leading edge, followed by a region of increasing pressure over the suction region, after which the ‘roof-top’ has a mildly favourable pressure gradient. Such a pressure distribution has been found to maximise the extent of laminar flow [4, 7, 8].

Development of an aerofoil is concerned mainly with the selection of the desired pressure distribution. Once this is done, the shape can be computed by a mathematical procedure. However, not all pressure distributions correspond to physically meaningful airfoil shapes; real flow constrains the pressure distribution to have a leading edge stagnation point, low pressure forward, and gradually rising pressure aft, ending somewhat above ambient at the trailing edge. Within these constraints, details must be tailored to meet the specific requirements of HLFC and of low drag rise due to compressibility. The following points should be observed [9] :

- A steep initial gradient (rapidly falling pressure) is helpful in preventing attachment line transition on a wing having substantial leading-edge-sweepback. P. W. C. Wong and M. Maina [8] give the initial pressure gradients for an Airbus type and a Pfenninger type aerofoil.
- The midchord pressure distribution affects susceptibility to the two other principal transition mechanisms. Falling pressure tends to suppress the growth of Tollmien-Schlichting disturbances, and rising pressure will generally promote their rapid amplification. Hence, a negative gradient (falling pressure) is often called “favourable”, and a positive gradient (rising pressure) is termed “adverse”. However, substantial gradients of either sign will combine with sweepback to produce boundary layer cross flow, which tends to amplify disturbances and to promote transition. The favourable pressure gradient should not be so great to avoid excessive loss of lift for a given shock strength compared to the turbulent design.
- The fundamental technical strategy of HLFC is to confine the unavoidable large negative gradients to the region ahead of the front spar and to use boundary layer suction to suppress disturbance amplification due to cross flow there. Downstream of the front spar,

gradients are kept in the weakly favourable to zero range.

- The minimum pressure level on the upper surface must correspond to a slightly supersonic velocity on an efficient high-speed wing. To limit wave drag, the local Mach number has to be restricted to a value less than Mach 1.2. The shock strength at the return to subsonic flow must not be so great as to cause excessive wave drag or separation of the turbulent boundary layer.
- Extended regions of favourable pressure gradient would correspond to extended regions of laminar flow. Therefore, it was required that the pressure gradients be favourable as far aft as the design transition points.
- To ensure attached flow, the maximum slope of the aft pressure gradient, $dC_p/d(x/c)_{max}$, is to be less than 3.0.
- The pressure level on the lower surface is determined by the desired lift coefficient and airfoil thickness ratio. The flow will normally remain subsonic and therefore shock-free. A recovery region having an adverse pressure gradient and turbulent flow must occupy the aftmost portion.
- To control the pressure gradients and the off-design behaviour, it is therefore HLFC is incorporated with variable camber flap.

These are summarised in Figure 1.

However, aerofoils described above are often prone to increased shock growth which result in earlier occurrence of drag rise conditions, relative to an aerofoil with an adverse 'roof-top' pressure gradient. In fundamental wing design terms this implies increased sweep, reduced thickness/chord ratio, and/or reduced wing loading, all of which reduce the aerodynamic and/or structural efficiency of the wing for a specified design condition. An alternate approach may be to use an aerofoil with a mildly adverse 'roof-top' pressure gradient to improve wave drag and lift capabilities, although with a reduced extent of laminar flow. Careful consideration would be required to select/design an aerofoil section to achieve maximum aircraft efficiency and minimum operating economics with laminar flow and a suitable off-design performance. In addition, it is necessary to ensure adequate efficiency and economics with turbulent boundary layers [7, 9].

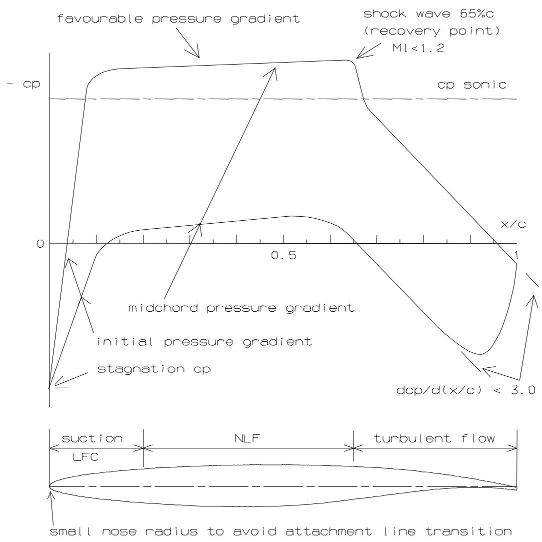

Figure 1. HLFC airfoil design criteria

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 for 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

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. This cost is reflected in the following shares of Direct Operating Costs (DOC) : fuel, ownership and maintenance. Laminar flow-variable camber technology will only produce acceptable DOC if the penalties due to additional weight and the complexity of the system do not exceed those of the fuel savings. Hence the most important objective in realising advanced laminar flow-variable camber technology is to reduce their additional system costs, weight and minimise maintainability and reliability costs.

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 recognised that conventional production aircraft wing surfaces can be built to meet these design constraints [12].

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].

Practical use of HLFC requires that laminar flow is 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. Therefore, it was 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 VC-flap, it can be used to reduce the wave drag penalty, and to sustain attached flow in turbulent mode [2]. Flow control on such a wing, is shown in Figure 2.

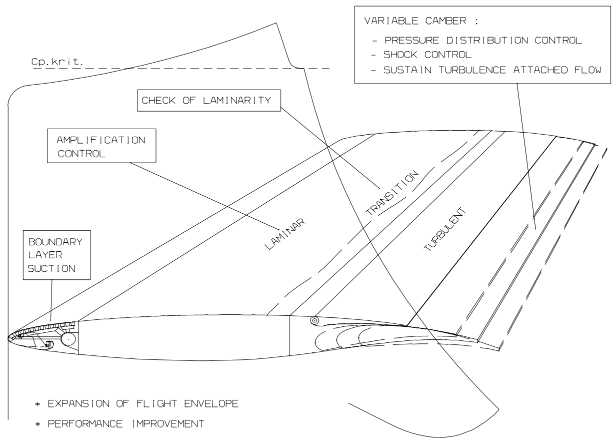

Figure 2. Flow control on the wing

2.4.1. Candidate combined HLFC-VCW section configurations

Section views of the two wing configurations considered in this study 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]. Because it has no leading-edge device, it 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 equivalent high lift capability. The Krueger flaps also shield the fixed leading edge from insect accumulation and provide a mounting for the anti icing system. Only the upper surface, however, has suction panels. The leading edge system used on configuration II is similar as proposed by Douglas [14].

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

- Configuration I : the advantages are (1) a simple system with no leading edge device and (2) upper and lower surface laminar flow for least drag. The disadvantages and risks are (1) more potential for insect contamination on the suction device which may cause boundary-layer transition, (2) high approach speeds and landing field lengths and/or a more complex trailing-edge high lift system, (3) longer take-off field lengths, particularly for hot, high-altitude conditions, and (4) a trim penalty due to higher rear loading (when the flaps are deployed).
- Configuration II : the advantages are (1) less potential insect contamination on the suction device, hence laminar boundary layer will be more stable, (2) simpler trailing-edge high lift devices, (3) lower approach speeds and shorter take-off and landing field lengths, and (4) less a trim penalty (when the flaps are deployed). The disadvantages and risks are (1) less drag reduction due to laminar flow only on the upper surface and (2) 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 surface, 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 were 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.

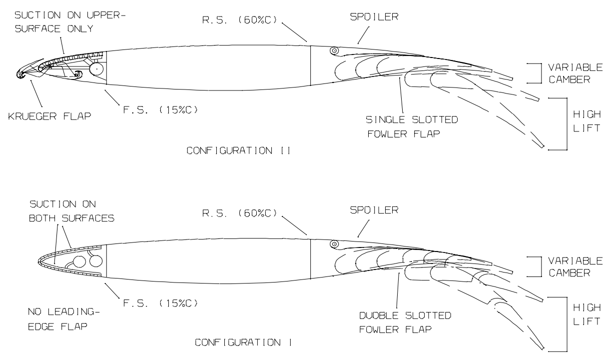

Figure 3. Cross sections of candidate combine HLFC-VCW configurations

2.4.2. Combined HLFC-VCW section baseline configurations

The HLFC-VC section baseline configuration for use 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.

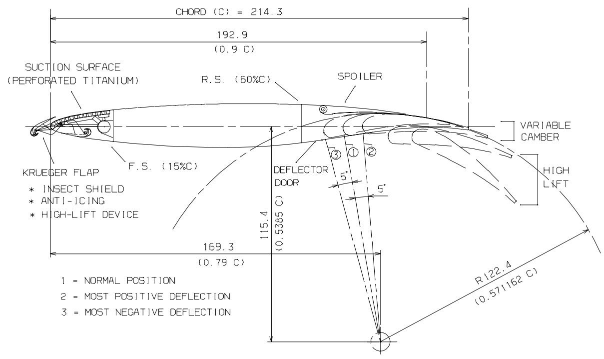

Figure 4. HLFC-VC section baseline configuration

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 it self. The radii should be optimised between these two constraints. The radius is inherent to the trailing-edge upper surface of the aerofoil, so when the aerofoil is used for a VC concept, the aerofoil should be designed with 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 are simple, the camber variation is achieved by small rotation motions (in two directions for positive and negative deflections). In VC-operation the flap body slides between the spoiler trailing edge and the deflector door. The radius of flap rotation is picked-up from the radius of curvature of the aerofoil trailing edge upper surface at about 90% chord. Camber variation is therefore performed with continuity in surface curvature at all camber settings. During this process the spoiler position is unchanged. This concept also has been proposed by E. Greff [2], but camber variation is achieved by fowler motion, instead of rotation.

2.5 Development of three dimensional geometry

For purposes of this work a wing for typical family regional aircraft (W-ATRA) was sized as shown in Figure 5.

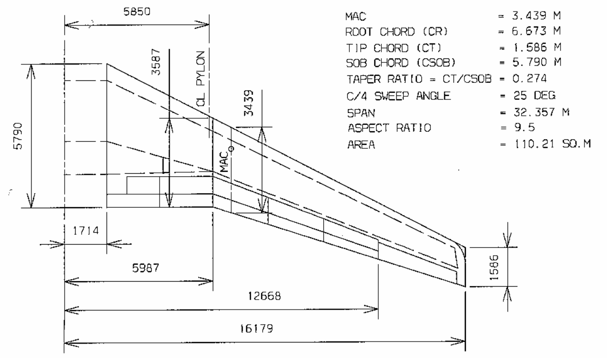

Figure 5. W-ATRA wing concept

An inverse code suitable for use as a design tool was not available at Cranfield University. During the course of the study, only a generic analysis code could be utilised (i.e. RAMPANT), offering 2D & 3D, inviscid/viscous & incompressible/compressible capabilities). Experience shows that it is best to begin with a subcritical design case [4]. To get good results from a subcritical design code such as SWEPTDES [16], the target pressure distribution also must be subcritical. Despite the simplification afforded by use of a subcritical analysis, it still was necessary to design the wing iteratively.

Subcritical pressure distributions corresponding to a candidate aerofoils were then computed by SWEPTDES. These pressure distributions were then adjusted to meet the previously discussed requirements (see section 2.2). The aerofoil design process was necessarily iterative. A SWEPTDES aerofoil design computer program was then used to design a set of wing sections plus a twist distribution that gave the required spanwise lift variation. A preliminary transonic analysis was also undertaken using RAMPANT.

2.5.1. Aerodynamic design objectives

The main objectives of the wing design, which incorporates HLFC and VCF technology are :

a. To obtain a pattern of approximately straight isobar sweep at an angle at least equal to the wing sweepback angle, with the upper surface generally being critical for drag divergence. If this aim is achieved, the flow will be approximately two-dimensional and the drag-divergence will occur at the same Mach number every where along the span.
b. To obtain the greatest possible amount of laminar flow on the wing (3D flow), which will significantly improve wing efficiency (L/D) in cruise flight. The maximum reduction in drag for the wing must be obtained for the cruise C_L corresponding to the design case for the proposed aircraft. To achieve the laminar flow objectives for the design, it also was required that the pressure distributions determined in section 2.2 (suitably interpolated over the span) should be realized by the three-dimensional wing.
c. To have a good performance in off-design operation.

2.5.2. Outboard wing design

Design goals of the outboard aerofoil section use in the W-ATRA wing were : (1) to sustain laminar flow to 55% chord (or more) on the upper surface with minimum suction quantity and (2) to suffer little or no flow separation or wave drag at Mach 0.8, wing lift coefficient 0.5, and 25 degrees quarter-chord sweepback.

An outboard aerofoil section, which is used for Boeing 757 HLFC research [4] was used as an initial guess. This aerofoil was designed for a typical outboard section at a normal Mach number (M_N) of 0.744, reflecting a sweepback angle of 21.5 deg., corresponding approximately to the 50% chord line outboard. The design lift coefficient (C_{l_N}, based on the normal flow) was 0.64 and the airfoil thickness chord ratio (t/c) is 10.3%.

To facilitate design process, the outboard wing thickness distribution was selected constant and therefore, a constant airfoil section is used in generating the outboard wing geometry. Figure 6 shows the profile (streamwise) of the outboard wing aerofoil section.

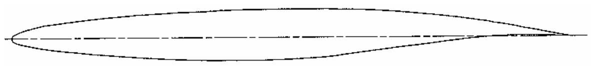

Figure 6. The profile of the outboard wing aerofoil section

2.5.3. Wing root design

The root section for the W-ATRA wing, a higher thickness ratio was required. To keep the same maximum local Mach number on the upper surface, the pressure on the lower surface has to fall, thus reducing C_{l_N}. Because of the increased chord inboard of the planform break, this was still consistent with smooth and monotonic spanwise loading variation. Another difference was that maintaining isobar sweepback required shifting the upper surface pressure recovery point forward. Figure 7 illustrates these differences. The design C_{l_N} was 0.4. Note that the resulting profile will not produce this pressure distribution when located close to the fuselage in a real flow. It is only one step in the design of the three-dimensional wing geometry in this section. Figure 8 shows the profile (streamwise) of the root wing aerofoil section.

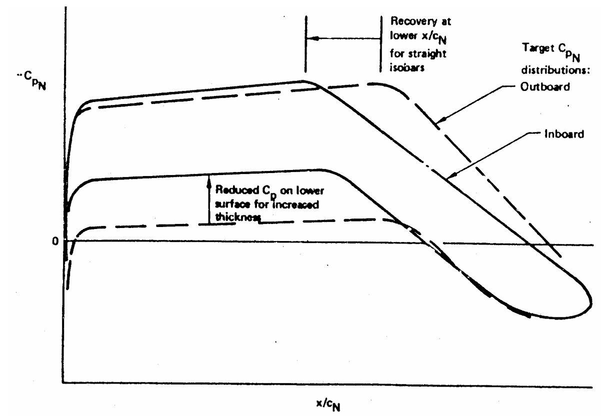

Figure 7. Root section pressure distribution considerations

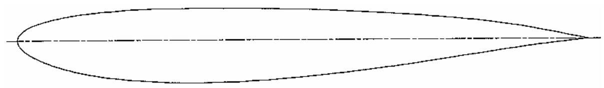

Figure 8. The profile of the root wing aerofoil section

2.5.4. Wing inboard design

The middle (inboard) aerofoil section, illustrates a transition shape in the part of the wing (between side of fuselage and planform break/kink) where thickness chord ratio (t/c) is decreasing. Figure 9 shows the profile (streamwise) of the inboard wing aerofoil section.

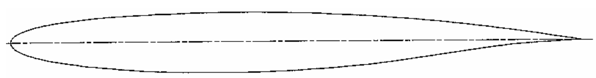

Figure 9. The profile of the inboard wing aerofoil section

2.5.5. Off-design operation consideration

Practical use of HLFC requires that laminar flow be maintained through a range of cruise lift coefficients and Mach numbers. Changes in lift coefficient and Mach number will change the wing pressure distributions from the optimum and may result in some loss of laminar flow.

Therefore, the W-ATRA wing incorporates a VC-flap. Deflection of the VC-flap permits control of the pressure distribution over the forward part of the airfoil, keeping it similar to the design pressure distribution even when the lift coefficients and Mach numbers differ considerably from the design values. The desired pressure gradient control can be achieved not only during cruise, but also during a significant portion of climb and descent. The design concept of the variable camber wing for this work is described in section 2.4.2.

2.6. Wing performances

The transonic flow over the W-ATRA wing attached on a typical regional aircraft fuselage configuration (WB-ATRA) is calculated. The computation was performed using RAMPANT, an unstructured, multigrid flow solver. A 3-D model of the above configuration was created using CATIA (CAD). A corresponding grid was created using preBFC and Tgrid. Laminar flow was assumed for the above computations. The results shown here are for $M_\infty = 0.8$, angle of attack = 0 degree, and Reynolds number of 21.6×10^6 (laminar flow was assumed for the above computations). The flap deflection and spanwise load distribution for configuration I (VC-flap undeployed) and configuration II (VC-flap deployed) are shown in Table 1 and Figure 10.

Wing section, x and y in	SOB	INB	KINK	SAOK.	SAOT	STIP
Spanwise station, m 2y/b (b/2 = 16.179 m)	1.714 0.106	3.236 0.191	5.986 0.37	9.350 0.578	12.713 0.786	16.719 1
Configuration I : Chord (C.I), m Lift coefficient (c_{lI})	 5.79 0.258	 5.005 0.298	 3.588 0.38	 2.926 0.439	 2.266 0.343	 1.586 0.24
Configuration II : Chord (C.II), m VC-flap deflect. (d), deg. Lift coefficient (c_{lII})	 5.873 2 0.387	 5.082 1.822 0.395	 3.649 1.5 0.4534	 2.96 1 0.4935	 2.239 -1 0.3463	 1.558 -1.5 0.1889
C.II/C.I	1.0143	1.0153	1.017	1.0115	0.9882	0.9822
$(c_{lII}-c_{lI})/d$, /deg.	0.0645	0.084	0.0489	0.0545	-0.003	0.0341

Table 1. Section lift coefficients for configuration I and II

At the aircraft design lift coefficient (C_L = 0.5), the comparisons between pressure distribution at subcritical Mach number and design Mach number for the outboard wing sections is shown in Figures 11.

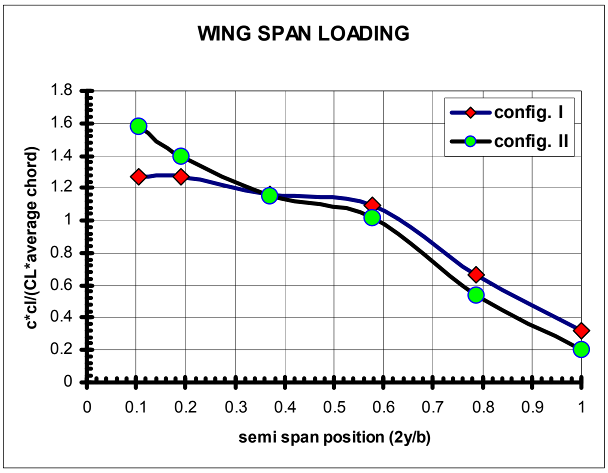

Figure 10. Wing span loading for configuration I and II

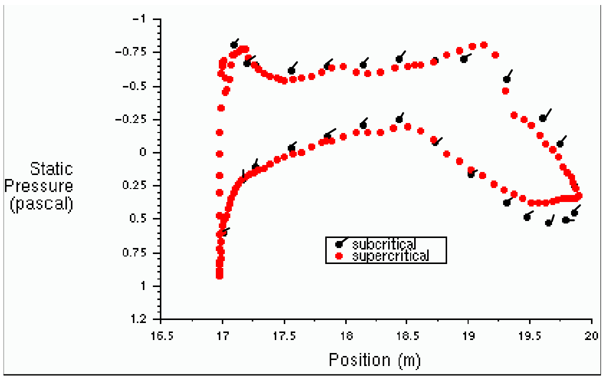

Figure 11. The comparisons between pressure distribution at subcritical Mach number and design Mach number for outboard wing section (at $C_L = 0.5$)

The above wing configuration results from just the first iteration of a very complex wing design. Regardless of its weakness, its performance appears quite reasonable. To improve the wing performance, it is recommended to optimized the airfoil sections, twist and VC-flap deflection distributions along the wing span together with suction requirements.

3. CONCLUSIONS

A methodology of an aerodynamic wing design allowing for the used of a combined HLFC-

VCW as a flow control concept for transonic transport aircraft was developed. The W-ATRA wing is not yet optimum both for undeflected and deflected VC flap. Further revisions would be necessary to produce a more optimum design.

The simple wing aerodynamic design (using SWEPTDES as subcritical wing section design tool) methodology use in this work seem reasonably accurate. This can be seen from the comparison with RAMPANT (supercritical analysis) result.

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

REFERENCES

1. Denning, R. M., Allen, J. E. and Armstrong, F. W. Future large aircraft design - the delta with suction. *The Aeronautical Journal*, 2212, 187-198 (May 1997).
2. Greff, E., (Deutsche Airbus GmbH, Bremen, FRG). Aerodynamic design and technology concepts for a new ultra-high capacity aircraft. *ICAS*, 96-4.6.3. (1996).
3. Edi, P. Investigation of the application of hybrid laminar flow control and variable camber wing design for regional aircraft. PhD thesis, AVT/CoA/Cranfield University, Cranfield - UK (1998).
4. Boeing Commercial Airplane Company. Hybrid laminar flow control study final technical report. NASA CR 165930 (October 1982).
5. Atkin, C. J. and Poll, D. I. A. The correlation between linear stability analysis and cross flow transition near an attachment line. Presented at the colloquium on transitional boundary layers in aeronautics, Amsterdam (December 1995).
6. Redeker, G. and Wichmann, G. Forward sweep-a favourable concept for a laminar flow wing. *J. Aircraft*, 28, 2, 97 - 102 (February 1991).
7. Wilson, R. A. L. and Jones, R. I. Project design studies on aircraft employing natural and assisted laminar flow technologies. *SAE* 952038, (1996).
8. Wong, P. W. C. and Maina, M. Study of methods and philosophies for designing laminar flow wings. ARA - Bedford – UK. Contractor Report M275/1, (August 1995).
9. Boeing Commercial Airplane Company. Natural laminar flow airfoil analysis and trade studies final report. NASA CR 159029, (August 1977 - June 1979).
10. Capbern, P. Theoretical and experimental study of high-lift device for a natural laminar flow airfoil. *ICAS* 92-01-032, (1992).
11. Morgan, H. L. High-lift flaps for natural laminar flow airfoils. NASA CP-2413, (1985).
12. Collier, F. S., JR. (NASA Langley Research Center, Hampton, VA 23681-0001). Recent progress in the development of laminar flow aircraft. *ICAS* proceedings 1994, 19th congress Of the international council of the aeronautical sciences; Anaheim, California, USA, 3, 94-4.7.1., (18-23 September, 1994).
13. Wagner, R. D., Maddalon, D. V. and Fisher, D. F. Laminar flow control leading-edge systems in simulated airline service. *Journal of aircraft*, 27, 3, (March 1990).
14. Douglas Aircraft Company Staff. Evaluation of Laminar Flow Control System Concepts for Subsonic Commercial Transport Aircraft. NASA CR-159251, (1983).
15. Rao, A. J. Variable camber wing for a transport aircraft. PhD thesis, CoA/Cranfield University, Cranfield - UK, (1989).
16. SWEPTDES. A computer program of RAeS TDM 6312 for calculating the subcritical inviscid flow over a finite wing, with compressibility effects updated to the standard of ESDU TDM 7312.