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Aerodynamic Configuration Design for a Family of Advanced Technology Regional Aircraft (ATRA)

PRASETYO EDI
Department of Aerospace Engineering
University Putra Malaysia
43400 UPM Serdang, Selangor Darul Ehsan
MALAYSIA
p_edi@eng.upm.edu.my http://www.eng.upm.edu.my/webkaa/edi.htm

Abstract: - This work intends to present a feasibility study of the application of combined Hybrid Laminar Flow Control (HLFC) - Variable Camber Wing (VCW) to the ATRA aircraft family. The VCW can be used as a lift control during cruise and climb to find the best lift/drag ratio. The prediction of ATRA's performance used computational fluid dynamic and empirical methods. During cruise, compared to the turbulent version, the lift/drag improvement was achieved due to the application of the combined HLFC-VCW. This improvement leads to the reduction of maximum take-off weight (MTOW) for constant design requirements and objectives (DR&O) and to the increased of range performance for constant MTOW.

Key-words: aerodynamic configuration 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.

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].

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 ATRA Initial Baseline Design

The following section is a brief design methodology for conceptual sizing of aircraft based on the author's experience when he worked as an aircraft configurator at IAe (Indonesian Aerospace).

2.1 Design Requirements (R) and Objectives (O), DR&O

As a successor of the regional jet, the baseline (ATRA-100) will offer 108 seats in two class layouts, while the stretched (ATRA-130) and shortened (ATRA-80) versions can accommodate for 133 seats in two class layouts and 83 seats in two class layouts respectively (R). The cruise cost-economic speed was set at Mach (M) = 0.8 (O) at a range of 2,250 nautical miles (nm) (ATRA-100), 2,000 nm (ATRA-80) and 2,500 nm (ATRA-130). For all versions the maximum approach speed will be 127 knots (O).

The improvement of aircraft performance compared to the current technology is expected to come from the application of new technology (i.e. : HLFC and VCW).

2.2 Initial Sizing

Using a simple method [3], the main parameters of initial sizing of the three versions are as follow:

	ATRA-80	ATRA-100	ATRA-130
MTOW (kg)	45,538	56,260	69,576
Thrust/Weight (T/W)	0.291	0.291	0.291
Weight/wing area (W/S), (kg/m^2)	413.2	510.5	631.3

2.3 General Arrangement

Designing an aircraft can be an overwhelming task for a new configurator. The configurator must determine where the wing goes, how big to make the fuselage, and how to put all the pieces together.

Based on an existing aircraft there are two main types of general arrangement for a regional passenger jet transport aircrafts, i.e. :

1. Boeing, Airbus, Indonesian Aerospace (IAe) type : low-wing, low/fuselage-tail, engine mounted on the wing and tricycle landing gear attached on the wing and stowage on the wing-fuselage fairing.
2. Douglas, Fokker, Canadair type : low-wing, T-tail, engine mounted on the rear fuselage and tricycle

landing gear attached on the wing and stowage on the wing-fuselage fairing.

There are several advantages and disadvantages between the above two types of general arrangement, e.g.:

Consideration	Type 1	Type 2
a. aero. cleanliness wings	bad	good
b. bending relief	yes	no
c. cabin noise levels	better	bad
d. aircraft c.g. management	easy	difficult
e. one engine out trim	difficult	easy
f. engine rotor burst	critical	good
g. engine ground clearance	critical	good
h. engine accessibility	good	difficult
i. fuel system	lighter	heavier

The engine mounted on the wing configuration is typical transport aircraft and the most common for most airliners. For this study, general arrangement type number 1 is selected for the ATRA-100 baseline configuration, ATRA-80 and ATRA-130, as shown in Fig. 1.

3 Aircraft Family Concept

Many Aircraft manufacturers , i.e. : Airbus, Boeing, McDonnell Douglas, Fokker, British Aerospace, IAe, etc., develop their aircraft family based on one wing and one fuselage cross section to reduce development costs. For one fuselage cross section aircraft family, alternatives for Regional Airliner family are :

1. Fixed wing geometry on mid-size, then Direct Operating Cost (DOC) penalties for off-optimum.
2. Fixed wing geometry on mid-size, modification of wing extension/reduction, then development costs
3. Variable Camber Wing (VCW) which could be optimum for all family, but will have increased development costs

The ATRA family will use the third of the above concepts. Fig. 2 shows the ATRA Family concept. The Variable Camber Wing concept is described in following section.

The ATRA-100 has maximum design commonality with the ATRA-80 and ATRA-130. The level of commonality between the members of the ATRA

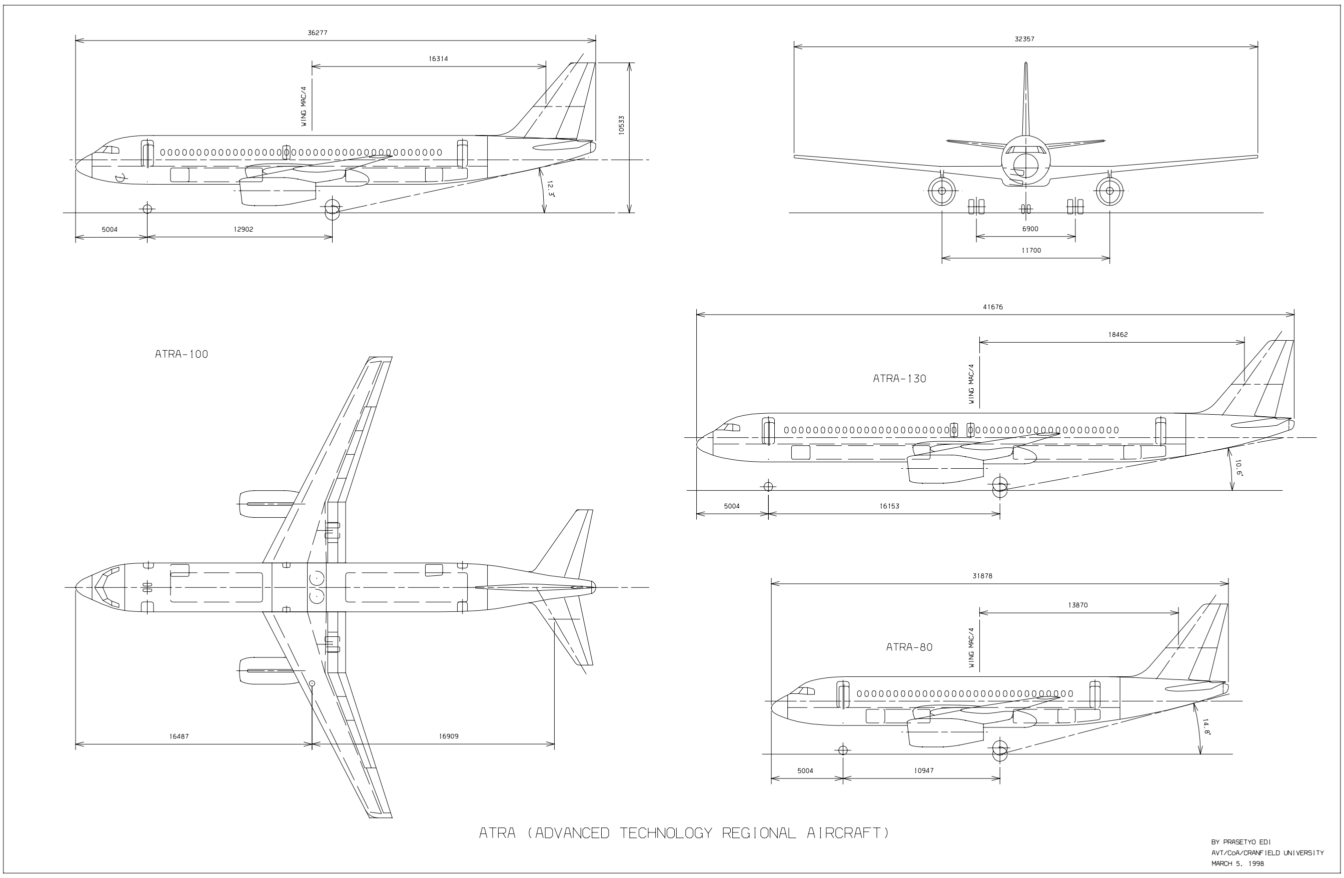


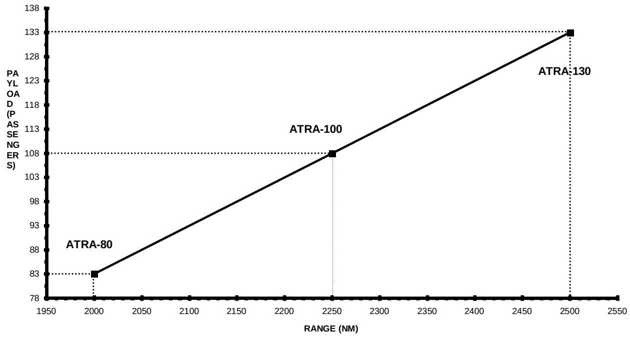
Figure 1. ATRA-100, with additional side views of ATRA-130 (centre) and ATRA-80 (below)

standard-body aircraft family is such that the ATRA-80, ATRA-100 and ATRA-130 can essentially be operated as one aircraft type with positive effects on crew training, maintenance and aircraft scheduling. In addition, a mixed fleet of ATRA-100 aircraft combined with other aircraft in the ATRA family will allow airlines to better match capacity to demand whilst reducing operating costs, increasing crew productivity and simplifying ground handling.

Being the reduced/increased size development of the ATRA-100 the ATRA-80/ATRA-130 key changes are primarily related to size and capacity as all aircraft share similar systems and the same flight deck. Key changes include : derated/uprated engines, adapted systems and two fuselage plugs removed/added.

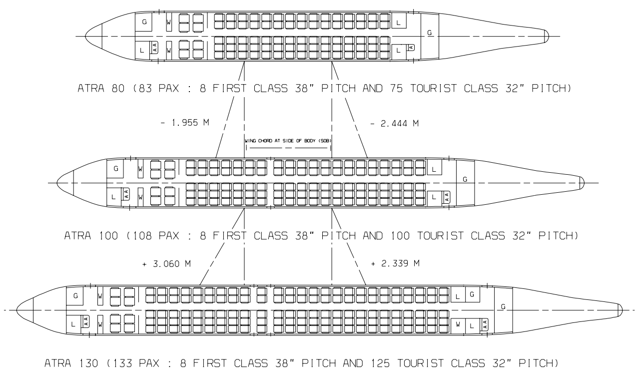
Payload-range concept trio regional airliner

System concept adapted systems

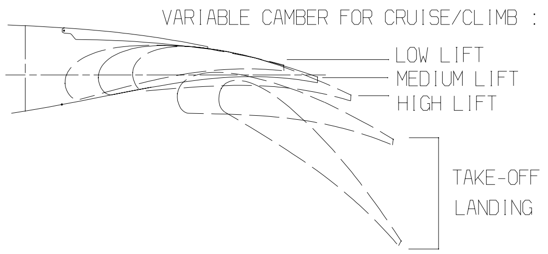


Fuselage concept

two fuselage plugs removed/added

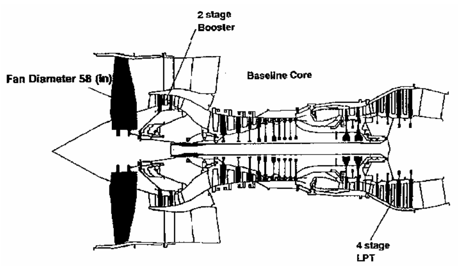


Variable camber wing concept



optimum cruise/climb management
constant altitude cruise management

Powerplant concept



derated/uprated engines

Figure 2.The ATRA Family concept

4 AERODYNAMIC DESIGN CONCEPTS FOR ATRA

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 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 realizing advanced laminar flow-variable camber technology is to reduce their additional system costs, weight and minimize maintainability and reliability costs.

4.1 Initial Wing Design

This section describes the initial design of wing for ATRA-100 baseline configuration. This wing design is unique, because it incorporates hybrid laminar flow control and variable camber wing technology.

Basic requirements that must be achieved for a successful wing design include :

(1) The configuration must satisfy the performance goals in the design specifications whilst achieving good economic returns.

(2) Flight characteristics, handling qualities, and aircraft operations must be satisfactory and safe over the entire flight envelope for all aircraft configurations (high speed, low speed, different flap settings, gear positions, power settings, and suitable ground handling).

(3) Design of a structure must be possible within the defined external shape to meet the strength, torsion, fatigue, flutter, weight, life cycle, maintainability, accessibility and engine requirements, together with suitable development and manufacturing costs.

(4) Sufficient space must be provided for fuel for the design range, for retraction of the main landing gear, and for the aircraft systems (flaps, ailerons, spoilers, fuel, gear, etc.), where appropriate.

Meeting all these requirements simultaneously is difficult and will most likely require compromise for a satisfactory configuration to be achieved.

A detailed examination of the very complex wing design is outside the scope of this work, but it is considered appropriate to mention some of the measures that may be taken, although not all of them are required for each design.

4.1.1 Performance Objectives

For a typical jet aircraft, the equation for cruise range (R) can be expressed as:

$$R = \left(\frac{a_0\sqrt{\Theta}}{TSFC}\right)\left(\frac{M\,L}{D}\right)\ln\left(\frac{W_{initial}}{W_{final}}\right) \qquad (1)$$

where : a_0 = speed of sound

Θ = temperature ratio, T/T_0

The above equation states that if the thrust specific fuel consumption (TSFC) is considered to be nearly constant (which it usually is in the cruise region), a jet aircraft will get the most range for the fuel burned between weights $W_{initial}$ and W_{final} by making the quantity M(L/D), a maximum. The basic aerodynamic performance objective is, therefore, to achieve the highest value of $M(L/D)_{max}$ at the cruise Mach number. Climb and descent performance, especially for short range mission, is also important and may suggest the "cruise" design conditions be compromised.

The improvement of M(L/D) compared to the current technology is expected to come from the application of new technology (i.e. : HLFC and VCW).

4.1.2 Wing area, planform and airfoil design

With MTOW of ATRA-100 = 56,260 kg and W/S = 510.5 (kg/m^2), wing area for ATRA-100 (S) = $110.21 m^2$.

Wing planform selection is based on a combination of criteria that require constant review during the design phase. Planform span, aspect ratio, sweep, and taper will be revised based on the trades taking place during the design. As sweep increases, the MTOW, operating empty weight (OEW), mission fuel and engine size increase for a constant aspect ratio and wing loading. As aspect ratio increases, OEW and MTOW increase while engine size and fuel burn decrease.

A detailed trade off study of planform parameters is outside the scope of this work. For ATRA-100 Baseline, sweep and taper ratio are taken from comparison with existing aircraft data, i.e.:

- A quarter chord sweep ($\wedge_{c/4}$) = 25 deg.
- Taper ratio (λ) = 0.274
- Aspect ratio (AR) = 9.5

The wing planform for ATRA-100 Baseline is illustrated in Fig. 3.

Selection/design of the outboard wing sweep and outboard aerofoil section are made at the same time. Usually for most swept wings, the outboard aerofoil section defines the wing Mach number capability. This is a result of the higher outboard wing section loading compared to the inboard wing. The lower inboard wing lift is due to wing taper and the lower lift curve slopes near the side of fuselage. The outboard wing aerofoil is selected/designed based not only on the design Mach number but also on the aerofoil off-design characteristics. Good low Mach number lift capability is required for climb performance and for aircraft gross weight growth capability. High Mach number characteristics should exhibit low drag creep below cruise Mach number and still maintain gentle stall buffet characteristics. Shock position should remain fairly stable with small changes in Mach number or angle of attack to maintain good ride quality and handling characteristics.

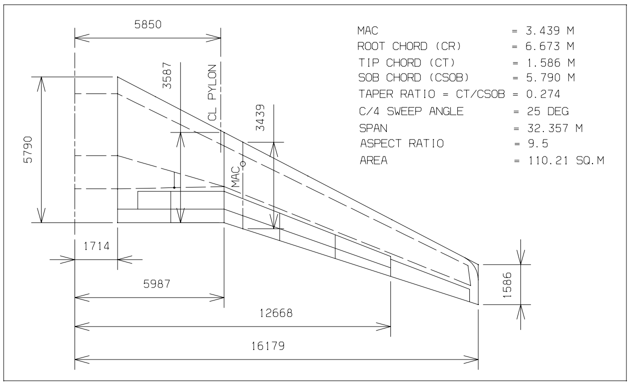


Figure 3. ATRA wing concept

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 (an adverse pressure gradient) over the suction region, after which the 'roof-top' has a mildly favorable pressure gradient . Such a pressure distribution has been found to maximize the extent of laminar flow.

For this study, three airfoils were designed, i.e. airfoil for root, inboard and outboard, as shown in Fig. 4.

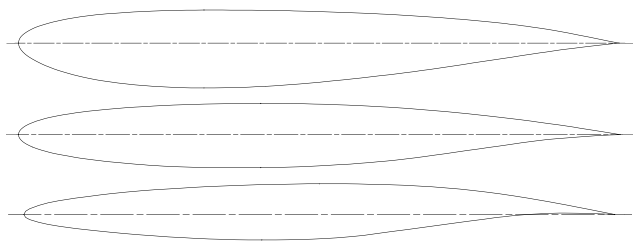


Figure 4. Airfoil for ATRA wing (root, inboard and outboard)

4.2 The Application of Combined HLFC-VCW

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. 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. With careful design of VC-flap, it can be used to reduce the wave drag penalty, and to sustain attached flow in turbulent mode.

4.2.1 Candidate laminar flow – variable camber section

Fig. 5 shows the section views of two wing configurations considered in this study. Configuration I has both upper and lower surface suction, from the front spar forward with leading edge systems as proposed by Lockheed [6]. Because it has no leading-edge device, it requires double-slotted fowler flaps to achieve maximum lift coefficient ($C_{L_{max}}$) 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 to leading edge systems as proposed by Douglas [6]. 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 [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.

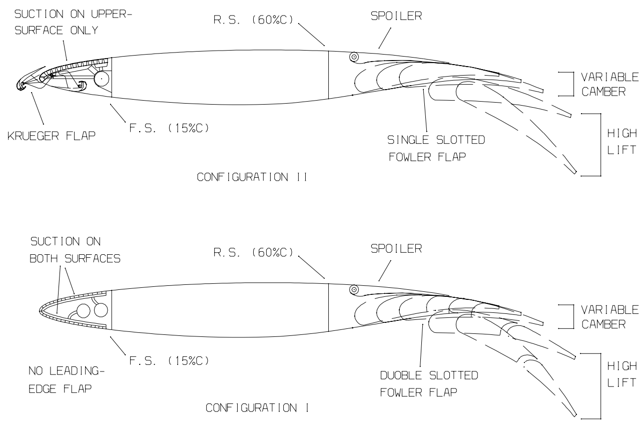


Figure 5. Cross sections of candidate combine HLFC-VCW configurations

4.2.2 Hybrid laminar flow – variable camber section baseline configuration

The Hybrid Laminar Flow Control - Variable Camber Wing (HLFC-VCW) section baseline configuration for use on the ATRA-100's wing is shown in Fig. 6.

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, 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 optimized 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 the ATRA-100's wing is quite similar to traditional high lift devices. 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.

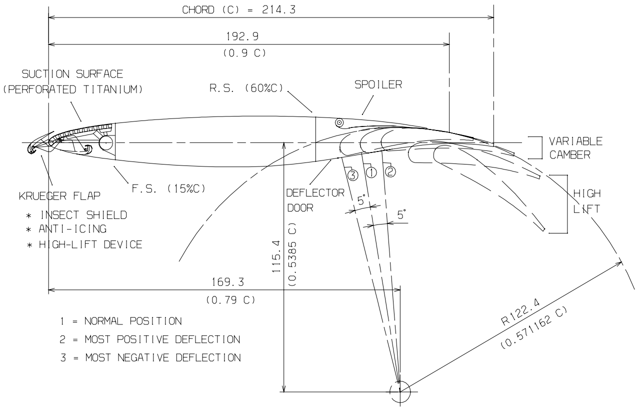


Figure 6. HLFC-VCW section baseline configuration

5 AIRCRAFT PERFORMANCE

5.1 Computational design analysis for ATRA-100 wing

Fig. 7 and Fig. 8 show the contours of static pressure in turbulent and laminar flow for variable-camber flap deflected respectively, for detailed flow analysis see Reference [3].

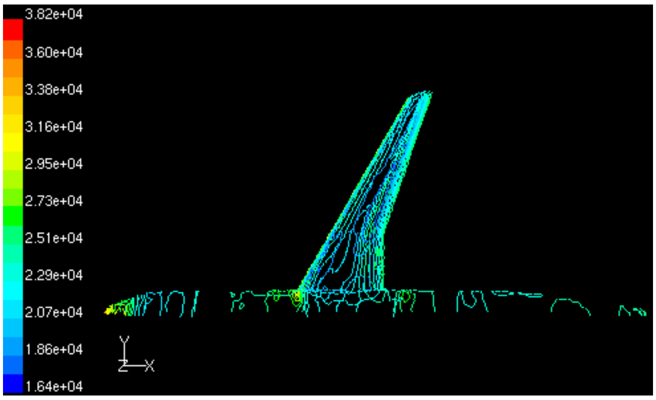


Figure 7. Configuration II : contours of static pressure, Pascal (turbulent flow)

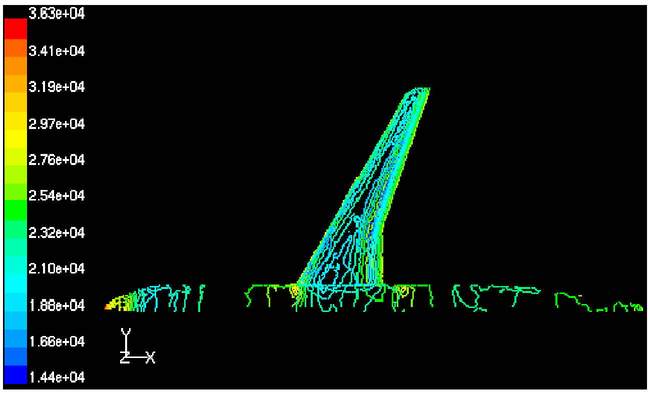


Figure 8. Configuration II : contours of static pressure, Pascal (laminar flow)

The lift coefficient versus angle of attack (alpha) for turbulent and laminar flow (HLFC-VCW) as featured in Fig. 9.

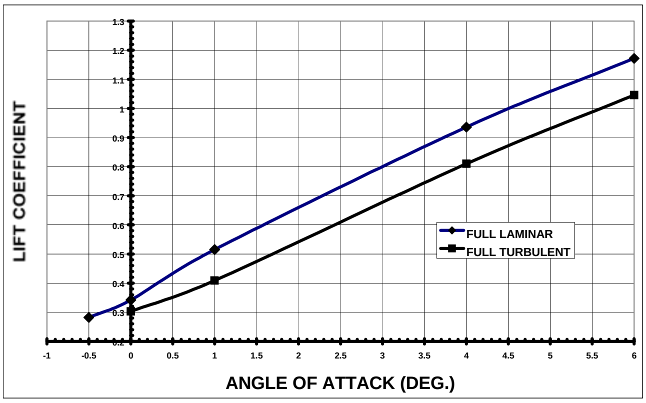


Figure 9. Configuration I : lift coefficient versus angle of attack (alpha)

5.2 Revision of the ATRA-100 aircraft

Technically, the application of the combined HLFC-VCW to the civil transport aircraft appears to provide significant performance gains in terms of fuel consumption and payload range performance. However, in order to justify the implementation of the technology economically, it is necessary to consider the associated costs throughout the entire program.

It was judged that the most appropriate method of examining the cost implications of the combined HLFC-VCW would be to examine it's effects on the direct operating costs (DOC) of the aircraft. Due to lack of time, for the purposes of this research, aircraft weight reductions and increased range performance due to the application of the combine HLFC-VCW would be examine rather than DOC, with the assumption if the aircraft weight is reduced DOC would also reduce..

The aircraft lift/drag improvement at cruise (Mach 0.8, 35,000 ft and $R_N = 6.28e^6$/m) was 7.675 % of total cruise drag [3].

Some of the advantages and disadvantages of the application of the combined HLFC-VCW to civil transport aircraft compared to the turbulent version are [3] :

- HLFC systems weight = 0.373 % MTOW,
- VCW systems weight = 0.5 % wing weight,
- Lift/drag increment due to VCW application = 2.5 %,
- The increment in fuel flow to maintain the specified net thrust due to power off-take of HLFC suction systems = 0.2 %,
- Assumption : the reduction of wing sections t/c due to the application of the HLFC is eliminated by the application of VCW and wing sweep is unchanged.

The above values are from aircraft that does not closely match of the ATRA aircraft types included in this study, preventing any direct comparisons. However, the benefits and/or drawbacks associated with the various HLFC and/or VCW applications are provided. In the absence of a detailed investigation, it was decided to use the above values.

With the above predictions and assumptions and simple sizing method, the benefits of the combine HLFC-VCW to the ATRA-100 aircraft compared to the turbulent version are : (1) for constant DR&O : MTOW reduction = 4.25 % and (2) for constant MTOW : range performance increased by 7.63 %.

6 CONCLUSIONS

The aircraft family concept using variable camber wing technology to manage the lift requirement is feasible from technical point of view.

During cruise (Mach 0.8, 35,000 ft and R_N = $6.28e^6$/m), compared to the turbulent version, the lift/drag improvement due to the application of the combine HLFC-VCW to the ATRA aircraft was 7.675 % of total cruise drag; and for constant DR&O : MTOW reduction = 4.25 % while for constant MTOW : range performance increased by 7.63 %. The VCW can be used as a lift control during cruise and climb to find the best lift/drag ratio.

The application of combined HLFC–VCW concept to reduce the aircraft drag is feasible for a transport aircraft from aerodynamic point of view, but must be shown to be cost effective.

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