

# Aircraft Family Concept for High Performance Transport Aircrafts

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**Abstract**— The objective of this research is to make a feasibility study of the aircraft family concepts using a combined Hybrid Laminar Flow Control - Variable Camber Wing (HLFC-VCW) for a high performance Advanced Technology Regional Aircraft (ATRA). The prediction of ATRA's performance used computational fluid dynamic and empirical methods. The aircraft family concept using a combined HLFC-VCW is feasible for ATRA aircraft family from aerodynamic point of view.

**Keywords**— Aircraft family concept, high performance transport aircraft, hybrid laminar flow control, variable camber wing, aerodynamics, aircraft design, advanced technology, regional aircraft.

## I. INTRODUCTION

APPROXIMATELY 65% of the world's commercial jet fleet consists of narrow-body, single-aisle aircraft with a capacity of 70 to 170 seats. These are deployed on routes of 1,300 nautical miles or less. This sector also dominates the current order-book. More than 60% of aircraft on order are in the short-haul narrowbody category. The trend since deregulation in the US has been towards hub-and-spoke networks and a reduction in average aircraft size. The liberalization of the European market could exacerbate this trend.

There are several forecasts for demand for the above type aircraft in the next 20 years. Bombardier Aircraft Company believes that there is a demand for a little over 3,000 aircraft in the 60- to 90-seat class. According to a DASA market forecast, published in June 1995, excluding the commonwealth of Independent States, 2,350 of the 71-130-seat aircraft will be delivered to regional carriers. IPTN (Indonesian Aircraft Industry) is forecasting demand for 2,757 passenger aircrafts in the 80- to 130-seat class. McDonnell Douglas predicts requirements for 1,700 in that class of aircraft.

To fulfill the above demand, the regional-jet manufacturers are trying to attract those airline carriers with their own designs. Aircrafts that already in the market are McDonnell Douglas MD-87, Fokker-70/-100, Airbus A319, Boeing 737-500/-600 and BAe-146/Avro RJ-70/-85/-100/-115. Models that still under development by regional-jet manufacturers are

Boeing-MD-95-20/-30/-50, IPTN's N-2130, Fairchild Dornier's 728JET and Bombardier's Canadair Regional Jet (CRJ) Series 700 programmed.

Only three models of the above aircrafts are smaller than 120-seats, the Avro RJ-70/-85/-100/-115, the Fokker-70/-100 and the Boeing 737-500/-600. The Avro RJ and the Boeing 737 family are 6 abreast seating, while the Fokker family is 5 abreast seating.

In order to increase their profit, many Aircraft manufacturers, i.e.: Airbus, Boeing, McDonnell Douglas, Fokker, British Aerospace, IPTN/IAe, etc., have developed their aircraft family based on one wing and one fuselage cross section to reduce development costs. For one fuselage cross section aircraft family, alternatives concepts 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, and
3. Variable Camber Wing (VCW) which could be optimum for all family, but will have increased development costs.

The third concept (VCW) will be used in the development of the high subsonic Advanced Technology Regional Aircraft family [1]-[5].

## II. ATRA INITIAL BASELINE DESIGN

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

### A. Design Requirements and Objectives

As a successor of the regional jet, the baseline (ATRA-100) will offer 108 seats in two class layout, while the stretched (ATRA-130) and shortened (ATRA-80) versions are accommodate for 133 seat in two class layout and 83 seat in two class layout respectively. The cost-economic cruise speed was set at  $M = 0.8$  at a nominal range of 2,250 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.

An improvement of aircraft performance compare to the current technology is expected as a result of the application of new technology (i.e.: HLFC and VCW).

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### B. Initial Sizing

Conceptual design is a “chicken or egg” problem. The configuration designer cannot draw the aircraft until he develops some information about the aircraft, such as takeoff gross weight (TOGW), wing loading, etc. The performance analyst needs to know about the geometry of the aircraft before he can determine the drag, and hence find aircraft payload-range capability, and hence takeoff gross weight.

Using a sizing method [1], 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
T/W	0.291	0.291	0.291
W/S (kg/m <sup>2</sup> )	413.2	510.5	631.3

### C. 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. [7], [8] and [10] :

a. Boeing, Airbus, 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.

b. 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.

The above two types of general arrangement have several advantages and disadvantages as given below.

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

A sound choice of the general arrangement of a new aircraft design should be based on a proper investigation into and interpretation of the transport function and a translation of the most pertinent requirements into a suitable positioning of the major parts in relation to each other. No clear-cut design procedure can be followed and the task of devising the configuration is therefore a highly challenging one to the resourceful designer.

The study of possible configurations should result in one or more sketches of feasible layouts. They serve as a basis for more detailed design efforts, and they can therefore be regarded as a first design phase.

Usually trade studies between several possible configurations will be required before the choice of the best configuration is made. The engine mounted on the wing

configuration is typical transport aircraft and the most common for most airliners. It is beyond this work to make a trade study, as described above. For this study, general arrangement type 1 in 2.3 is selected for the ATRA-100 baseline configuration, ATRA-80 and ATRA-130, as shown in Fig. 1.

### D. Aircraft Family Concept

Fig. 2 shows The ATRA Family concept. Because of wing fuel tank limitations, the payload-range for ATRA-130 can not be achieved. There are several options to solve this problem, namely : (1) increase the wing area and/or thickness, (2) to reduce the ATRA-130 range performance, (3) add fuel on empennage or fuselage tanks, and (4) investigate the use of winglets to reduce induced drag and therefore fuel burn.

There are several options to design the low speed performances of the ATRA-130, namely : (1) use the same wing and high lift devices as the ATRA-100 but with increase in take-off and landing field distance, (2) increase the wing area, and (3) improve the high lift devices performance,....

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

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

Two advanced technologies were investigated during this study, namely : laminar flow and variable-camber wing [3].

### Laminar Flow

There are three basic transition mechanisms on a swept wing. These are : viscous or Tollmien-Schlichting Instability (T.S.I.), inflectional or Cross Flow Instability (C.F.I.), and leading-edge Attachment Line Transition (A.L.T.). A

laminar wing must optimize pressure gradients taking into account T.S.I. and C.F.I. The Natural Laminar Flow (NLF) concept can only be applied to the following configurations : (a) low sweep and moderate Reynolds numbers; (b) high sweep and small Reynolds numbers. For the current high sweep and high Reynolds numbers encountered on large transport aircraft, it is necessary to maintain laminar flow by suction of the boundary layer over the entire wing surface (Laminar Flow Control, LFC) or near the leading edge only (Hybrid Laminar Flow Control, HLFC).

#### *Variable Camber Wing*

From the beginning of aeronautics, aircraft have used wing camber and twist variation to alter lift characteristics and achieve lateral control. Most aircraft today mechanically change their low-camber, high cruise - speed wings into high camber, low-speed wings for take-off, landing, and other operations. To date, the methods used are characterized by leading-edge and trailing-edge slat and flap systems that, in general, move in large increments with associated undesirable steps and gaps in both the high-camber and low-camber positions. The result is an airfoil that is never quite optimum for every flight condition and an excrescence drag that is appreciable under all conditions.<sup>2</sup>

A remarkable job of engineering has provided today's highly efficient civil transports with high ranges of speed and flight conditions. However, the spiraling cost of fuel requires renewed efforts to absolutely minimize the fuel consumed by these civil transports. In the area of camber-changing devices, structural and mechanical technology has advanced to where practical systems may be possible for changing the shape of an airfoil continuously and smoothly such that it is more nearly optimum for all flight conditions.

#### *A. 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.

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 which may be taken, although not all of them are required for each design.

#### *Performance Objectives.*

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

$$R = \left( \frac{a_0 \sqrt{\Theta}}{\text{TSFC}} \right) \left( \frac{ML}{D} \right) \ln \left( \frac{W_{\text{initial}}}{W_{\text{final}}} \right) \quad (1)$$

where :  $a_0$  = speed of sound

$\Theta$  = temperature ratio,  $T/T_0$

The equation states that if the thrust specific fuel consumption, TSFC, is considered to be nearly constant (which is usually in the cruise region), a jet aircraft will get the most range for the fuel burned between weights  $W_{\text{initial}}$  (initial weight) and  $W_{\text{final}}$  (final weight) by making the quantity (Mach number)(Lift/Drag),  $M(L/D)$ , a maximum. The basic

aerodynamic performance objective is, therefore, to achieve the highest value of  $M(L/D)_{\text{max}}$  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.

The aerodynamic advantages of the combined laminar flow - variable camber wing stem from two considerations [2], [3] and [4] :

a. Laminar-flow is potential means of reducing viscous drag in cruise, by up to 15 - 20%. Aircraft components such as wings, fin, tailplane, engine nacelle are candidates for laminar flow treatment.

b. Variable-camber is potential means of increasing lift/drag ratio in cruise and climb, by up to 4% (in cruise) due to cruise and climb always at optimum lift coefficient. Theoretically the aerodynamic advantages of variable camber wing stem from four considerations [6] :

1. A reduction in profile drag, resulting from the obtaining of lift by the use of an optimum amount of section camber.

2. Operation with the minimum induced drag, due to the achievement of an elliptical lift distribution at all lifts coefficients.

3. A reduction in wing/fuselage interference drag and fuselage drag, stemming from operation at a near constant angle of attack over a wide range of lift coefficients.

4. A higher buffet onset Mach number, resulting from minimal wing twist and minimal wing camber at high speeds/modest lifts coefficients. This creates the potential for a higher maximum cruise and limit Mach numbers.

However, the off-design considerations must not be neglected. The off-design characteristics should show no drop in lift or  $(L/D)_{\text{max}}$  at Mach numbers below cruise. The variation of  $L/D$  with lift at cruise Mach number should provide at least 95 % of  $(L/D)_{\text{max}}$  for a (+/-) 0.1 variation in lift about cruise [5].

#### *Wing area, planform and airfoil design.*

With maximum take-off weight (MTOW) of ATRA-100 = 56,260 kg and wing loading ( $W/S$ ) = 510.5 (kg/m<sup>2</sup>), wing area (S) for ATRA-100 = 110.21m<sup>2</sup>.

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 trade's studies 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 based on comparison with existing aircraft data, (Fig. 3) i.e. :

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

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.

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 Hybrid Laminar Flow Control (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 (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.

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.

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

#### *B. 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 would be

possible to reduce the wave drag penalty, and to sustain attached flow in turbulent mode. Flow control on such a wing, is shown schematically in Fig. 5.

#### *Candidate laminar flow – variable camber section*

Section views of the two wing configurations considered in this study are shown in Fig. 6. 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.

#### *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. 7.

Ideally the change in section profile at 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 itself. 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.

#### IV. AIRCRAFT PERFORMANCE

The computational design analysis and revision of the ATRA-100 aircraft due to lift/drag improvement from the application of HLFC on the ATRA-100 aircraft compared to the turbulent version will be described in the following section.

##### A. Computational design analysis for ATRA-100's wing

Many aircraft operate at transonic speed, where part of the flow field is subsonic and part is supersonic. At these speeds shock waves form on the wings, which cause an increase in drag and variable changes in the lift. Multiple shock waves can develop and interact in ways that are difficult to predict, but that have a large influence on lift and drag.

With detailed knowledge of the flow field and shock wave locations designers can shape the wing to delay the transonic drag rise and increase the lift to drag ratio. The results are higher transonic cruising speeds and reduced fuel consumption.

Fig. 8 and 9 show the contours of static pressure and Mach number in fully turbulent flow, while Fig. 10 and 11 show the contours of static pressure and Mach number in fully laminar flow, both for variable-camber flap deflected respectively, for detailed flow analysis see Reference [3] and [9].

##### B. Revision of the ATRA-100 aircraft

Technically, the application of the combine 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 combine HLFC-VCW

would be to examine its effects on the direct operating costs (DOC) of the aircraft. For the purposes of this research, aircraft weight reductions and increased range performance due to the application of the combine HLFC-VCW would be examined 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, 10,668 m 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 taken from aircraft which 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 using sizing method [1], it is reasonable to conclude that 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 %.

#### V. CONCLUSION

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

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.

#### ACKNOWLEDGMENT

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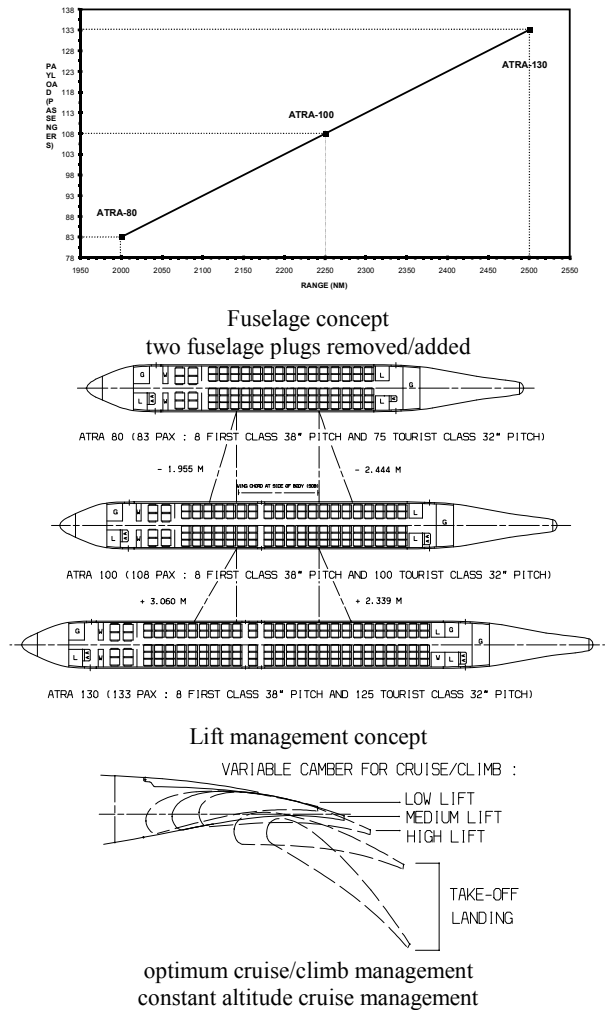


Fig. 2 The ATRA Family concept

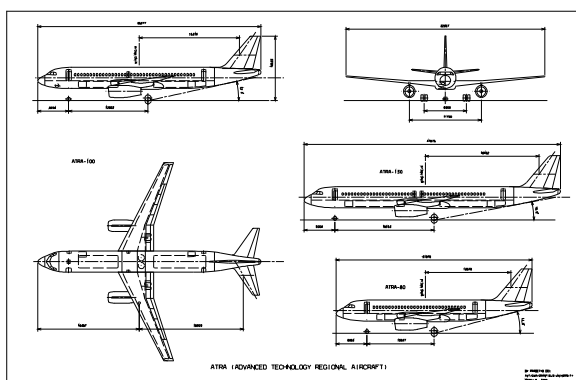


Fig. 1 ATRA-100, with additional side views of ATRA-130 (centre) and ATRA-80 (below)

Payload-range concept  
trio regional airliner

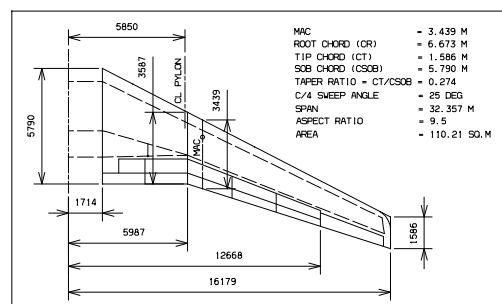


Fig. 3 ATRA wing concept

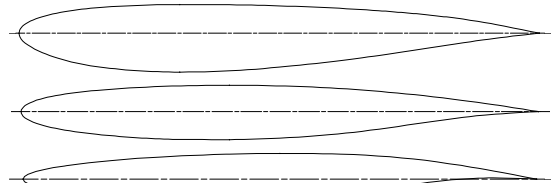


Fig. 4 Airfoil for ATRA wing (root, inboard and outboard)

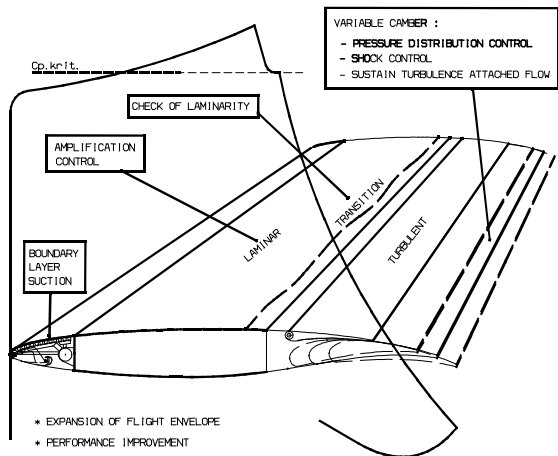


Fig. 5 Flow control on the wing

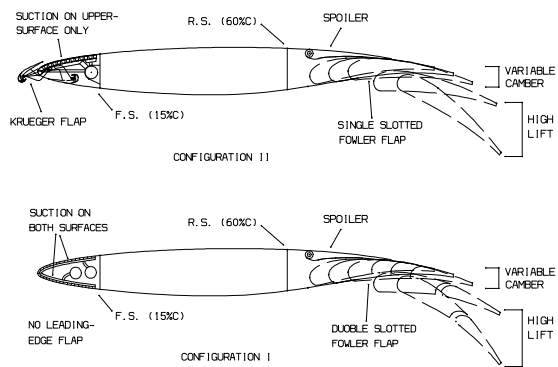


Fig. 6 Cross sections of candidate combine HLFC-VCW configurations

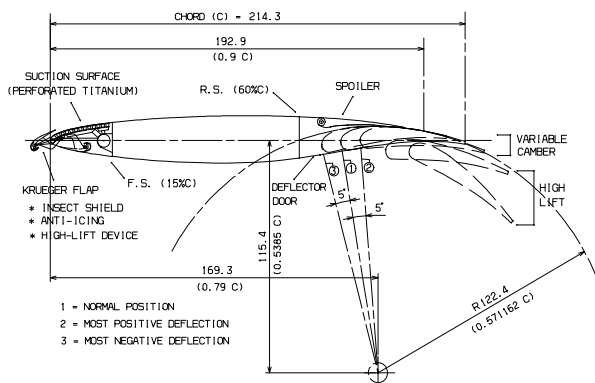


Fig. 7 HLFC-VCW section baseline configuration

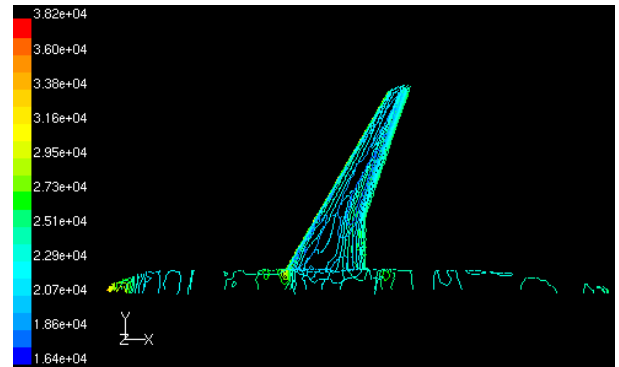


Fig. 8 Configuration II : contours of static pressure, Pascal (fully turbulent flow)

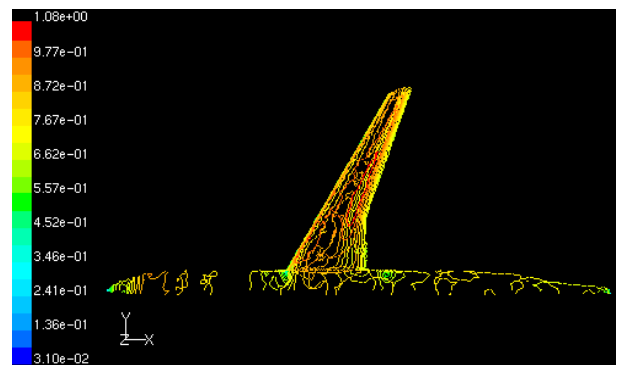


Fig. 9 Configuration II : contours of Mach number (fully turbulent flow)

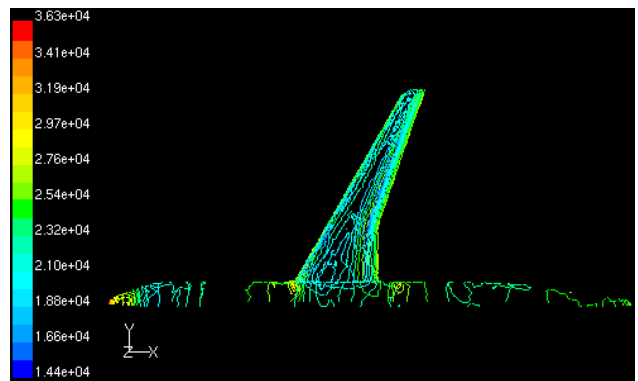


Fig. 10 Configuration II : contours of static pressure, Pascal (fully laminar flow)

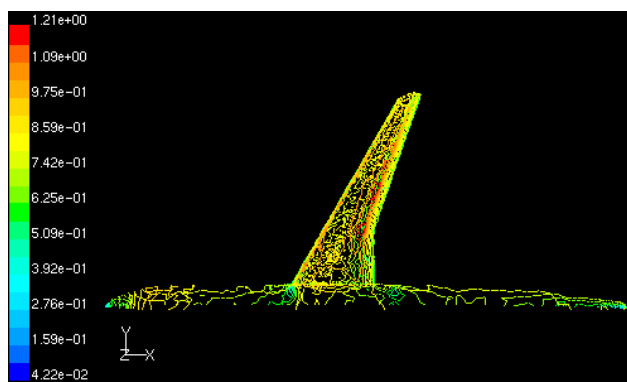


Fig. 11 Configuration II : contours of Mach number (fully laminar flow)

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