DESIGN INVESTIGATION OF VARIABLE - CAMBER FLAPS FOR HIGH-SUBSONIC AIRLINERS

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Abstract

Fixed-camber wings of current transport aircraft are designed for an optimum cruise lift coefficient and obtain efficient flight by means of stepped cruise-climb flight profiles. Future pollution legislation may preclude flights of this type and an alternative means of lift/drag optimisation may be required. Fixed-camber geometry can also be detrimental in terms of the development of a family of airliners, using a common wing. The wing may be optimum for the mid-range derivative aircraft, but will not be the case for larger and smaller variants. One solution is the use of variable-camber flaps for use in cruise as well as for take-off and landing. This paper will describe Cranfield University's linked 15 year programme of studies into this area.

These studies showed that there could be cost-benefits from such systems, in certain circumstances, as well as providing operational flexibility, which is the main driver for the variable-camber concept.

1 Introduction

Current high performance jet transport aircraft achieve high cruise lift/drag ratios by the use of modestly swept high aspect ratio wings. They have moveable leading and trailing-edge devices to vary lift during take-off and landing operations, but wing camber remains fixed for other flight phases. Aerodynamic performance can only therefore be optimum at a limited number of flight conditions. The well-established method of cruise-climb reduces the consequences of this, providing Air Traffic Control allows such flight profiles.

Cranfield University, and other researchers, have investigated the possibility of varying the camber of the wings during all flight phases, to give much more flexibility of operation. This has the potential for improved aerodynamic efficiency, but has consequences in terms of mechanical complexity and operating costs.

This paper outlines the extensive Cranfield study - programme that has, and continues to, investigate aerodynamic, systems, structural and cost aspects of variable-camber wings (VCW).

Figure 1 shows the major elements of the programme.

2 Initial Studies

2.1 Basic Configuration

Spillman (Reference 1) proposed a novel method of camber variation by means of rotation and translation of leading edge (LE) and trailing edge (TE) elements. The top surface was kept smooth and continuous to generate a family of cambered aerofoil sections. This proposal was tested in a low-speed wind tunnel by Rao (Reference 2) using a quasi two dimensional (2-D) wing.

This work was performed between 1986 and 1989. The Programme was continued by McKinnon, for aerodynamic design, and Macci for structural design, between 1989 and 1992 (Reference 3). This was a study supported by the British Department of Trade and Industry and British Aerospace PLC. It had been realised, from the earlier work, that a realistic study could not be limited to aerodynamic aspects alone.

CFD was used to design a supercritical aerofoil of 14% thickness/chord ratio. It had generous section thickness between 50% and 70% chord and significant TE thickness, to assist in accommodating the camber-actuation equipment. (Figure 2).

A flexible upper surface plate joined the wing box and the TE element to permit extension, yet maintaining curvature. The lower surface used a rigid closing plate, hinged from the centre box at 60% chord and held by spring links to the TE element. This geometry maintained a smooth top surface when deployed.

The purpose of LE deployment was to control the LE suction pressure peak caused by camber changes. Deployment of the LE element on a circular arc presented insurmountable design problems, which were overcome by simply drooping the LE element, without extension.

Variable-camber devices can provide maximum benefit when they are sub-divided across the span, and differentially deflected to control lift distribution. This feature has been employed in all the Cranfield VCW work.

2.2 VCW Wind Tunnel Model

The variable camber (VC) half wing wind tunnel model shown in Figure 3 was of a rectangular planform, swept at 25°. A semi-span of 1.6m and chord of 0.6m gave an aspect ratio of 5.33 which, combined with a tunnel speed of 50 m/s, resulted in a test Reynolds No. 2×10^6.

Extensive testing was performed using various deflections of the trailing edge devices in several spanwise locations. The results showed that at the minimum t/e deflection used (5°) the wing / VCW device combination led to improved L/D, relative to fixed camber, at C_Ls greater than 0.8. This is too high for high-subsonic cruise and calculations showed that deflections of 2° would give better performance in the C_L range between 0.2 and 0.6. The 10° deflection, combined with large extension gave excellent take-off L/D ratios, but that an additional slotted - flap segment would be required to generate enough lift for landing.

2.3 Initial Wing Structural and Mechanical Design

The large chordwise extension and requirements for a smooth contour posed significant challenges for the structural and mechanical design tasks. Many two - and three - dimensional schemes were investigated by means of computer - aided design (CAD) and physical models. Figure 4 shows elements of the final 3-D structural model whilst figure 5 shows a photograph of the whole trailing - edge model. The flap segments and, flap-track supports were modelled using finite - element structural analysis, which were confirmed by physical structural tests. It was found that the flap was able to successfully translate and rotate, when subject to aerodynamic loads simulated by sand - bags.

The tests showed the concept to be viable, but the resulting mechanisms were complex and the study recommended that future V-C flaps should have lower chordwise extensions and smaller radii of rotation. These recommendations were heeded on subsequent work. Parallel work, by MBB in Germany, showed similar configurations (Ref. 4)

3 Reliability, Maintainability and Cost Aspects

The above work demonstrated the aerodynamic and structural feasibility of VCW technology, but the use of such systems on operational aircraft required much more study. There is a need to show that VCW is cost-effective, or not, and that it will have sufficient levels of reliability and maintainability.

Ref. 5. Describes some of the work that has been performed to investigate these aspects of VCW.

3.1 Organisation Method

Vaziry (ref. 6) shows how be produced CA CAD, a multi - variate aircraft design synthesis and optimisation, based on (ref. 7). This is a conceptual design tool which allows the design of conventional - configuration subsonic jet transport aircraft, following input of aircraft requirements, and calculates and optimises the aircraft shape, aerodynamics, mass and direct-operating costs.

This was the basic tool which was modified to allow for VCW - induced changes in aerodynamics and the other features mentioned below. It also allowed the study of such sensitivity factors as final cost, mass changes, manpower costs and development difficulties, associated with such new technology.

3.2 VCW Aerodynamic Modelling

A design scheme was chosen which is technologically possible, with the least additional production cost and has good R&M features. Listed below are the technology features and assumptions which were chosen for VCW modelling using as many generic features as possible, while incorporating features of both the MBB and Cranfield concepts

a) camber variation by using the traditional high lift devices at the wing TE, similar to the MBB design philosophy
b) provisions for differential camber variation across the span
c) variable camber devices (VCD) composed of inboard, and out-board flaps, and two segmented flaperons.
d) extra actuators are required for the variation of camber across the span
e) there will be an allowance for the flap chord to increase to a maximum of 40% of the clean wing chord.

VCW principally influences the drag aspects of aircraft aerodynamics. Chordwise variation causes a reduction in cruise drag, as well as allowing a reduction in fuselage upsweep drag. The spanwise variation of camber can result in the reduction of viscous interference drag, induced drag due to twist, induced drag factor, and an increase in Mach-critical drag. Relatively simple analytical models were derived for each of these effects, which were then incorporated into the overall CACAD system.

3.3 Mass and System Modelling

VCW operation requires extra mass to be added, relative to conventional flap and aileron systems to allow for extra fittings, tracks, and higher loads due to high speed deployment as well as low speed operation. This requires the addition of terms to the existing prediction formula to account for variable camber operation. The extra masses are mainly due to the VCD deflection during cruise.

The VCW requires the use of more actuators and hinges, together with consequent increase in hydraulic power requirements. These changes were allowed for by modification of empirical mass prediction formulae. The wing box mass was modified to reflect the fact that the structural chord may be reduced if VCW devices are used.

CACAD is capable of modelling maintainability features of airframe systems and it was modified to reflect the increased complexity of the flight control and hydraulic systems. The final modification was to the development cost element of aircraft acquisition, and therefore depreciation costs.

3.4 Modelling Results

CACAD was run for different classes of transport aircraft. These included low to ultrahigh capacities, and short to long range designs. Configurations included twin rear engine, and twin and four underwing-engined aircraft. In the design process, CACAD designed and optimised a conventional aircraft for minimum DOC as the baseline aircraft. Thereafter, all VCW models were operated within CACAD, to design and optimise VCW aircraft.

Results confirmed the initial assumption that such technology would only be cost-effective on medium and long-range aircraft at current fuel and maintenance costs. The fuel burn savings caused by the reduced drag being the dominant factor (fig. 6)

The results for fuel and DOC improvements were validated against Boeing and MBB studies and showed good correlation. Sensitivities studies were then performed, with results which included those in figure 7 which shows results for an Airbus A3XX-class aircraft where:-

FDIF =	Factor for Development Intensity, which relates to the development cost risk of a new technology such as VCW. A factor of 1.0 is equivalent to conventional flap systems, whilst 2.0 indicates and extreme case of development cost penalty. Expected values are between 1.25 and 1.5.
Fdifm=	Maintenance cost difficulty , relative to a conventional aircraft.
Nf=	Number of functions of the hydraulic system where VCW is expected to increase hydraulic system mass in proportion to the number of extra functions (typically 1).
Dcl=	Is a function to vary the VCW benefit to Mach Critical Drag. The nominal value was 0.1.

It can be seen that, under reasonably benign conditions, that VCW could produce a D.O.C. benefit of 3.5%, but expected values are between 2.5 and 3.0%.

4. Aerodynamic Design of a Common Wing for a Family of Regional Aircraft (ATRA)

Prasetyo Edi (ref. 8) studied the conceptual design of a family of relatively long - range regional jet aircraft, termed ATRA (fig. 8). The wing planform was based on the mid-range 100 - seat aircraft and VCW was used to optimise the wing for the extreme cases of 70 and 130 passenger aircraft. The aerofoil section was designed so that it could also be used with the incorporation of hybrid laminar flow control, but this aspect will not be described in this paper.

Fig. 9 shows a typical section through the wing including the leading - edge Krueger flap and upper surface suction region. The trailing - edge VCW flap uses a nested flap which slides under the spoiler to provide continuous - contact VC motion for up to 10° deflection in cruise. It opens up to form a slotted - flap for low-speed, high lift flight regimes. It can then be seen to be a compromise between conventional flaps and the continuous surface of earlier Cranfield designs. Fig. 10 shows the spanwise segmentation of the trailing - edge flaps.

The wing design was initially performed using conceptual design methods and then progressively refined using the RAMPANT Navier - Stokes CFD code. Considerable work was done to improve the two - dimensional geometry at a number of spanwise locations, for a range of deflections and Mach numbers. The wing was then modelled three - dimensionally for several configurations and was refined to minimise transonic shocks and optimise the pressure distributions. A special study was performed to assess the airflow over the junction between two differentially deflected flap segments. These showed that there was a local increase in shocks and drag, that could be alleviated, or eliminated by splitter plates. The final design of the ATRA had a good aerodynamic design, but did not achieve its target levels of lift during the limited number of refinement cycles that were possible within the available resources. It provided a good basis for the current work that is being performed.

5 Current Aerodynamic and Structural Developments of the ATRA VCW

Dwicahyono (ref.9) has continued the aerodynamic design of the ATRA wing, to improve its high and low-speed lift performance, working in conjunction with Ammoo, (ref.10) who is performing the preliminary detailed design of the trailing edge flap system.

Fig. 11 shows a recently - produced wing / flap pressure distribution for a low speed case. The basic flap shape was derived from theoretical and empirical methods and then modelled using a CAD system then analysed using the Euler MSES CFD code. The pressure distributions are being used as imputs into the structural loading process, which is leading to an optimised structural design.

VCW wings often have, complex three-dimensional extension / retraction schedules, which are being investigated by a sophisticated CAD package (fig.12).

The output of the latest aerodynamic and structural models will be used to provide more accurate inputs into the CACAD procedure described in paragraph 3, above.

6 Conclusions

The paper describes the efforts of a considerable number of people over a 15 - year period. The whole work is continuing and building on previous activities. A large number of lessons have been learnt, the most important of which are:

- Variable - camber wings have the potential for improvements in fuel burn and operating costs, in the right circumstances. At current fuel price levels they might lead to D.O.C. penalties for short-range flights but for long - range aircraft they could produce D.O.C. savings of up to 3.5%
- VCW may also have a place in the production of a common wing for a disparate family of medium - range regional aircraft. This work may be further improved by the use of wing tip devices (ref. 9)
- VCW gives the possible of a flexible “intelligent” wing which can produce good Off-optimum performance. This could be particularly useful if environmental concerns preclude flights in the stratosphere.
- VCW presents a number of technical challenges which have been initially addressed in this work, and continuing studies. Particular issues are transonic Flow between spanwise segments and successful structural mechanical design of flap segments and flap deployment mechanisms.

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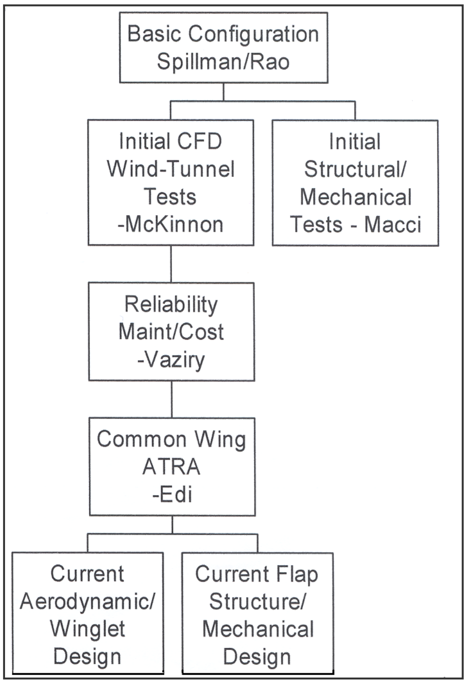


Fig. 1 Cranfield VCW Studies

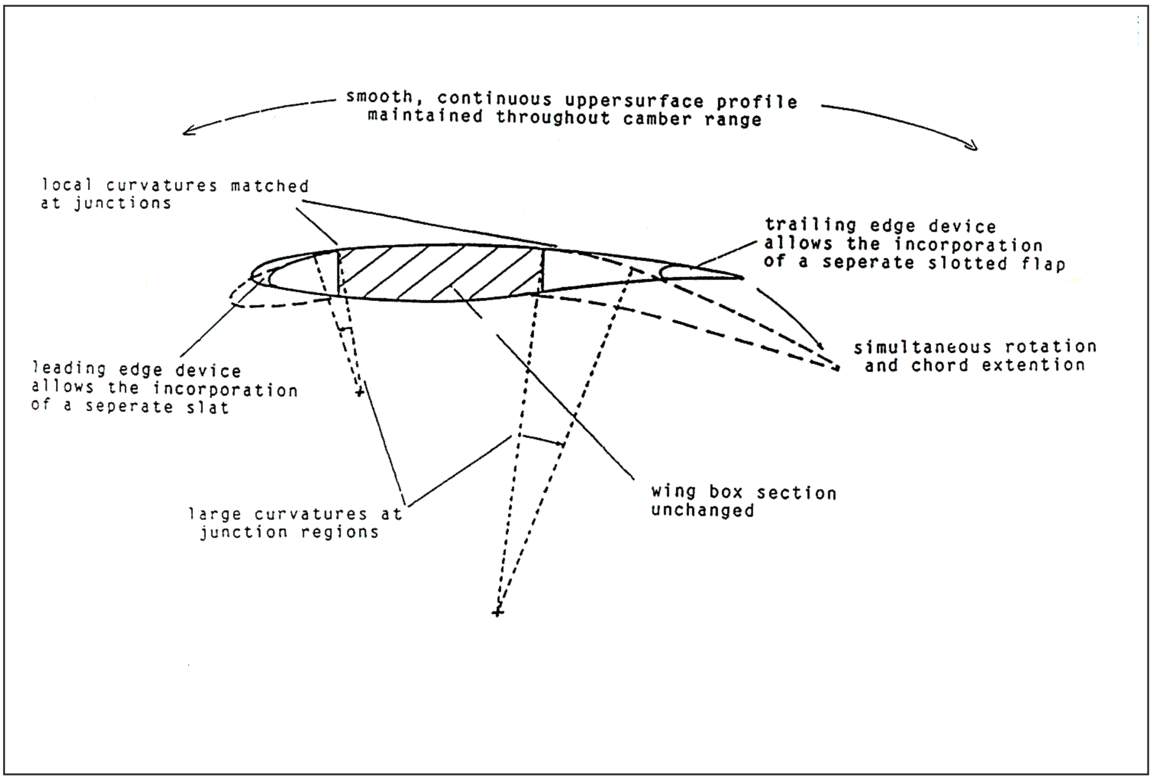


Fig. 2 Initial VCW Configuration

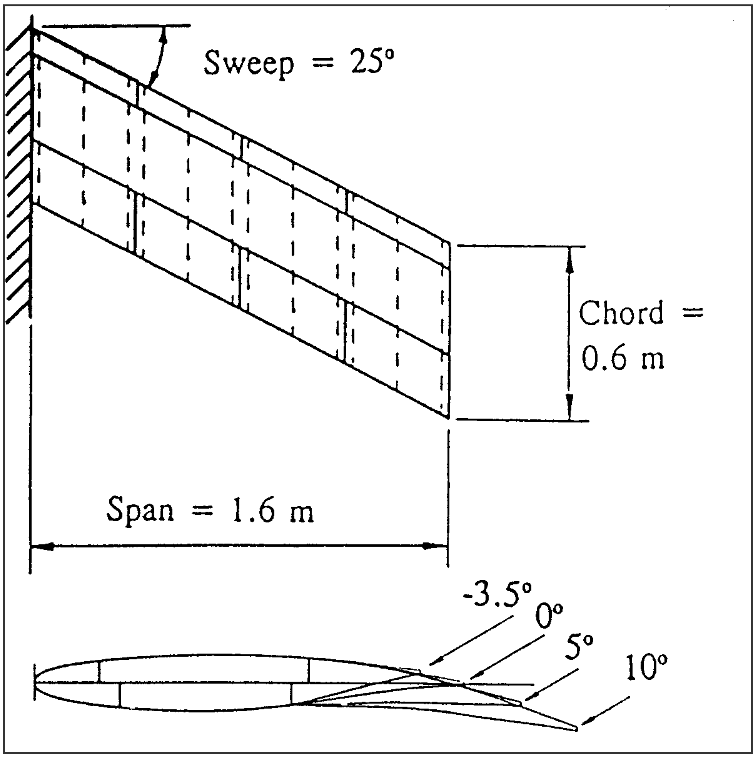
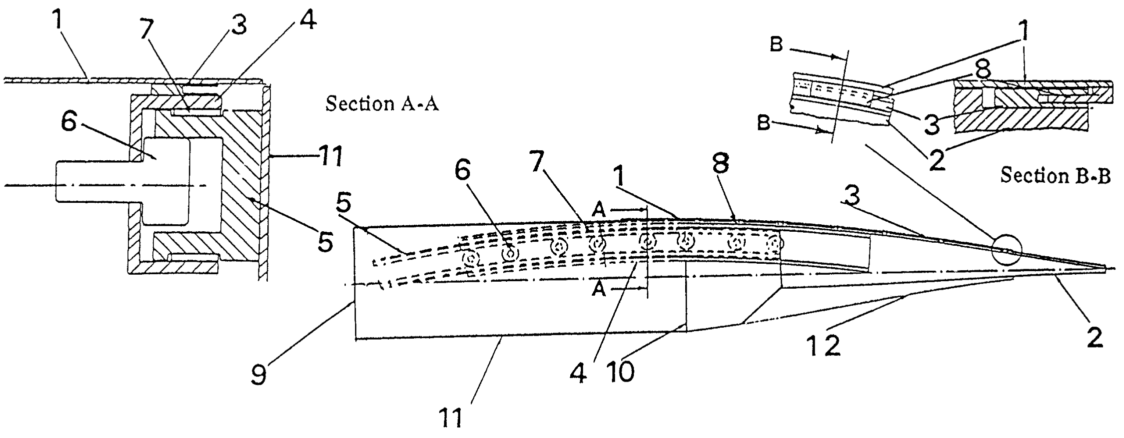


Fig. 3 Four-Segment Wind-Tunnel Model



1 - Carbon fibre upper surface skin
2 - Solid trailing edge device
3 - 'C' channel conforming rails
4 - Extending track
5 - Support track
6 - Cam rollers
7 - Needle rollers
8 - Sliding tags
9 - Front spar
10 - Rear spar
11 - Side support rib
12 - Lower surface flap panel

Fig. 4 Details of Structural Model

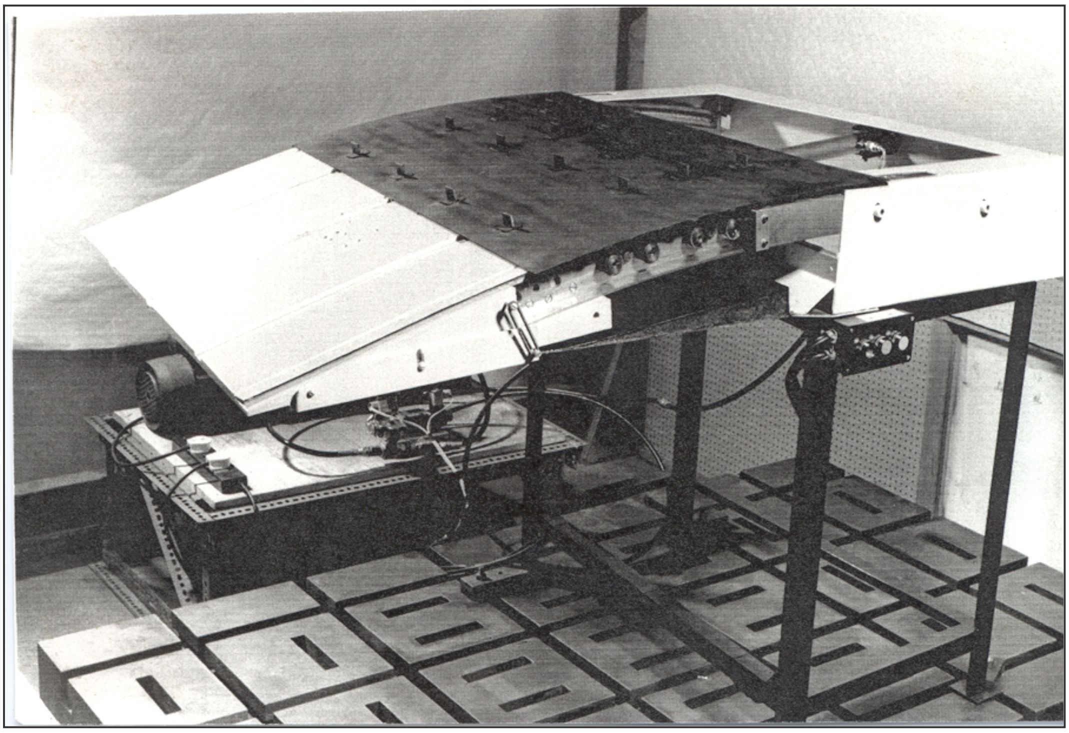


Fig. 5 Photograph of Structural Model

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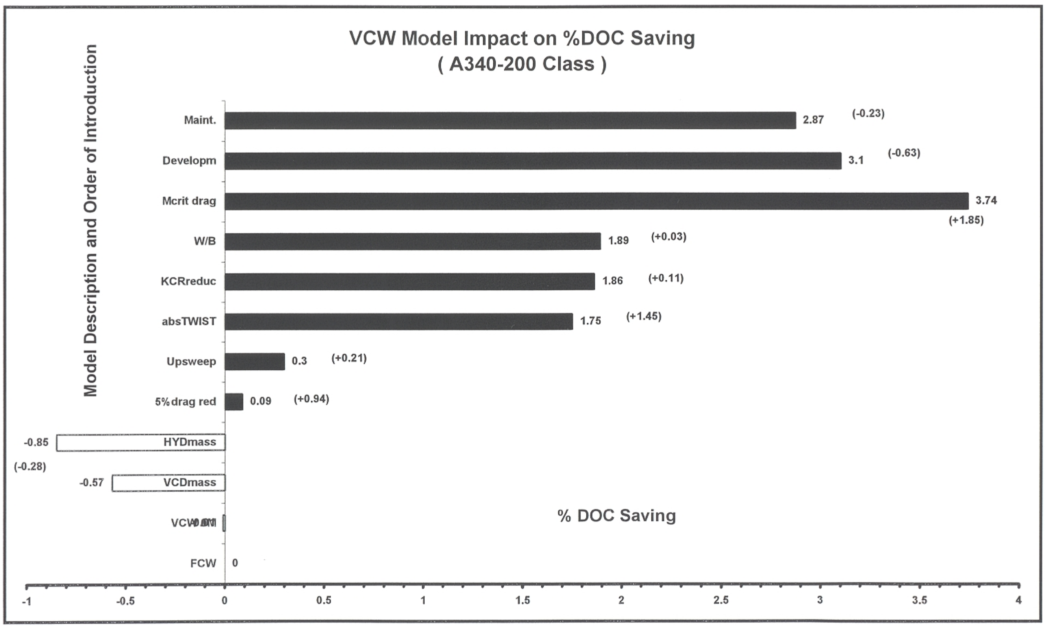

Fig .6 D.O.C Savings of Various VCW Aspects

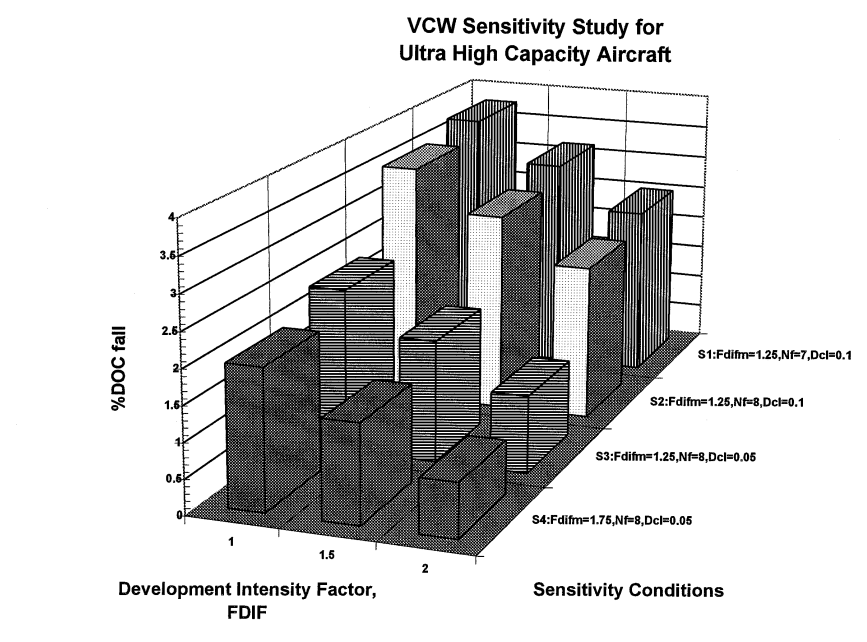

Fig. 7 VCW Sensitivity Results

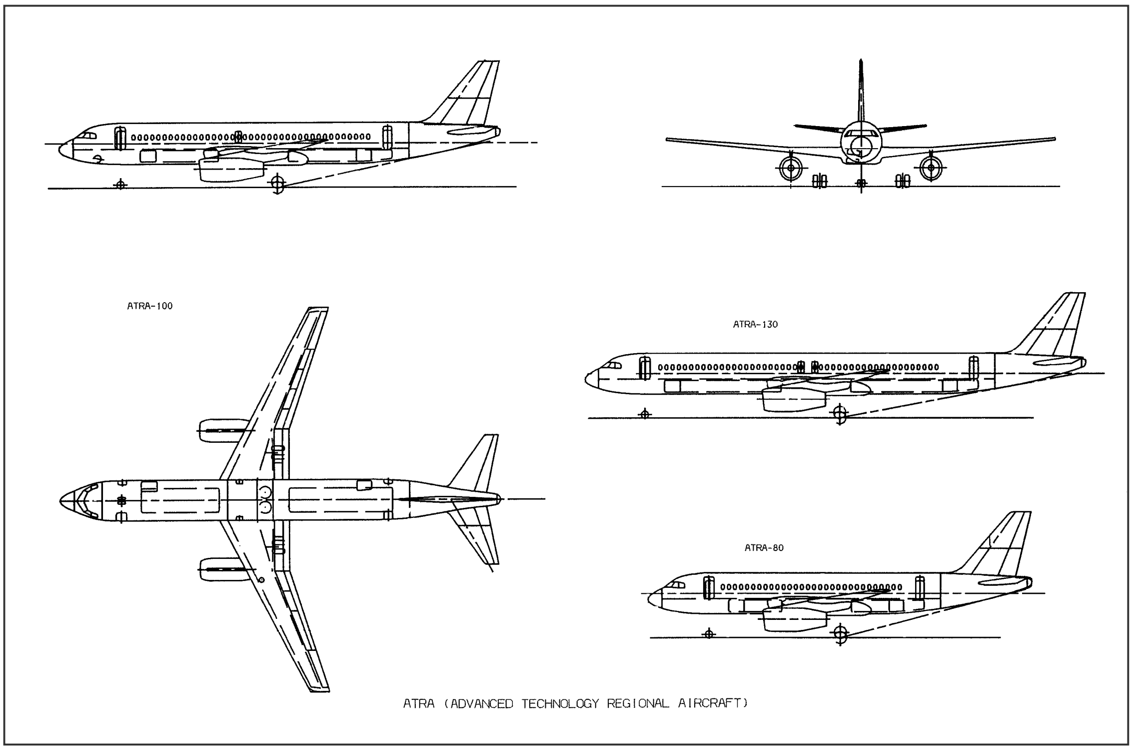

Fig. 8 ATRA Family

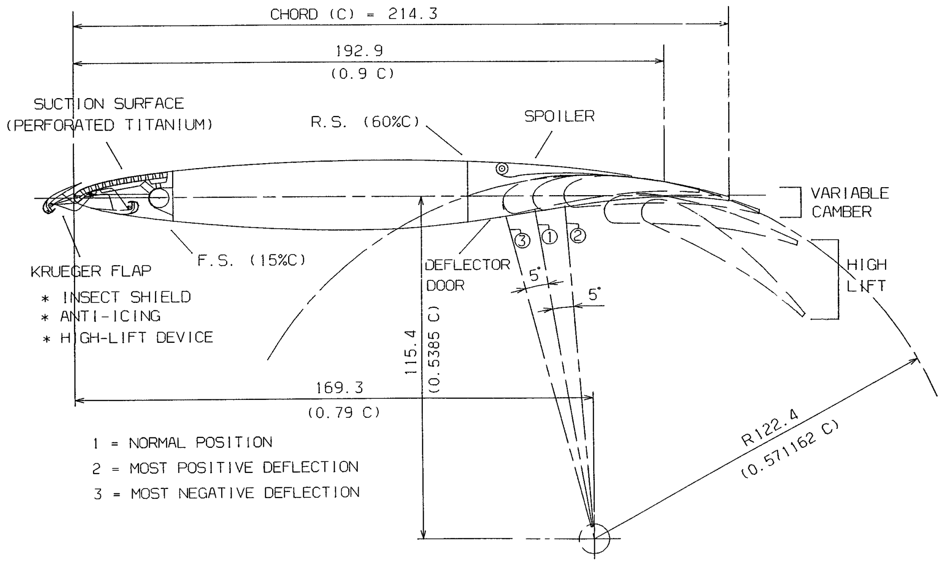

Fig. 9 ATRA VCW

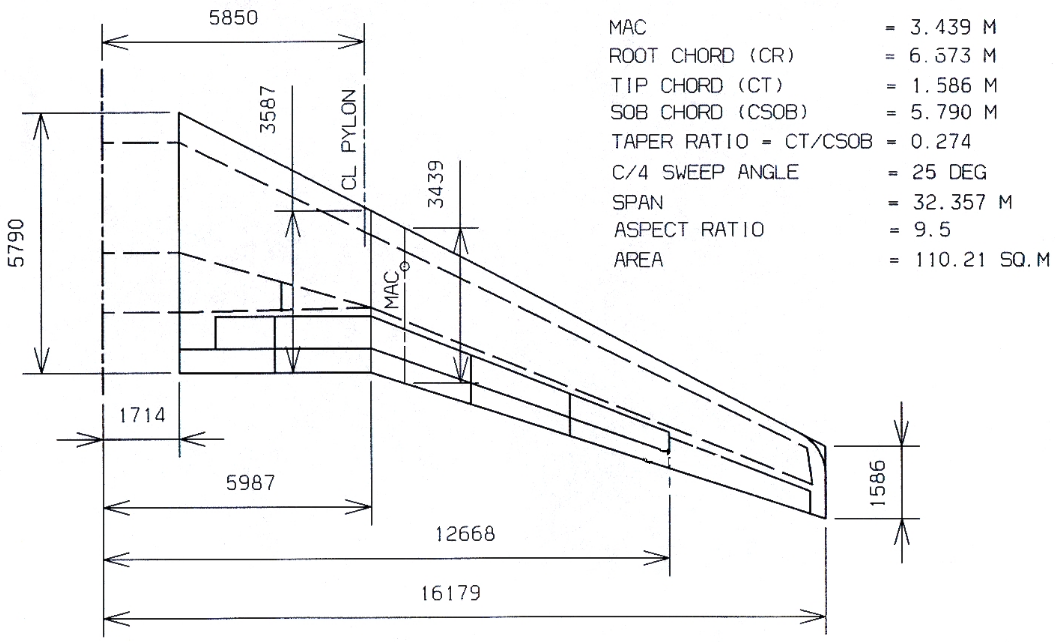

Fig. 10 ATRA Wing

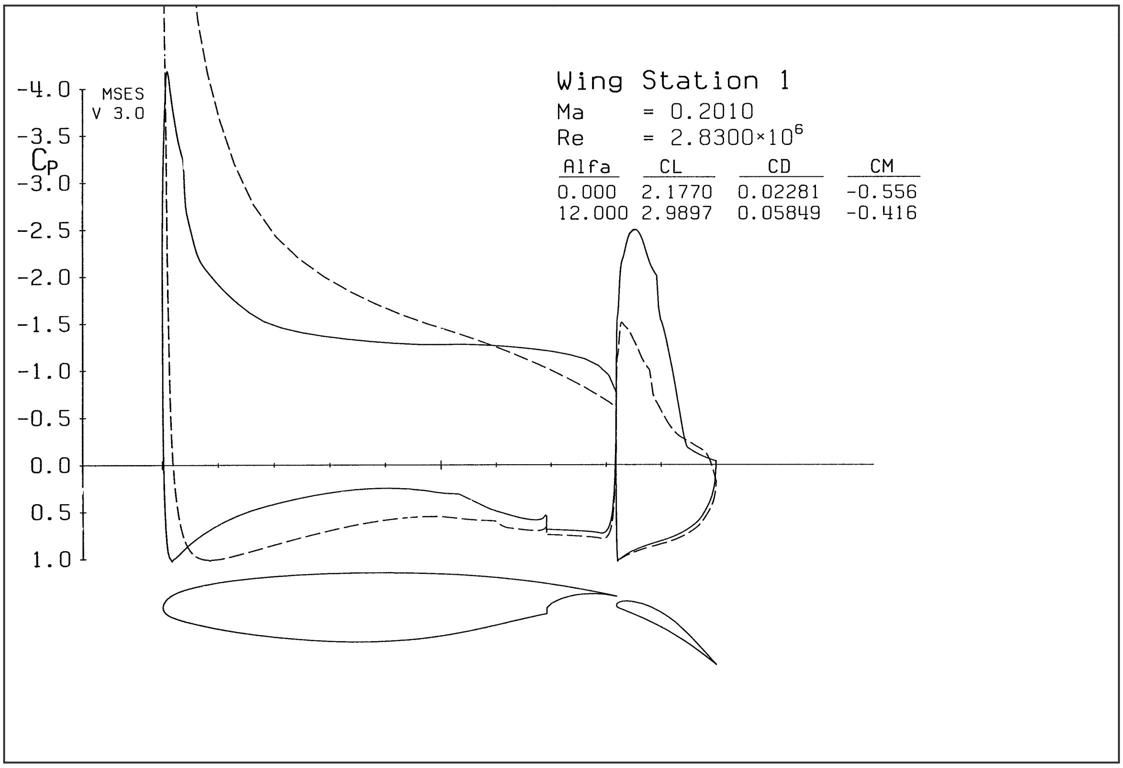

Fig .11 ATRA Modified Wing/Flap Pressure Distribution

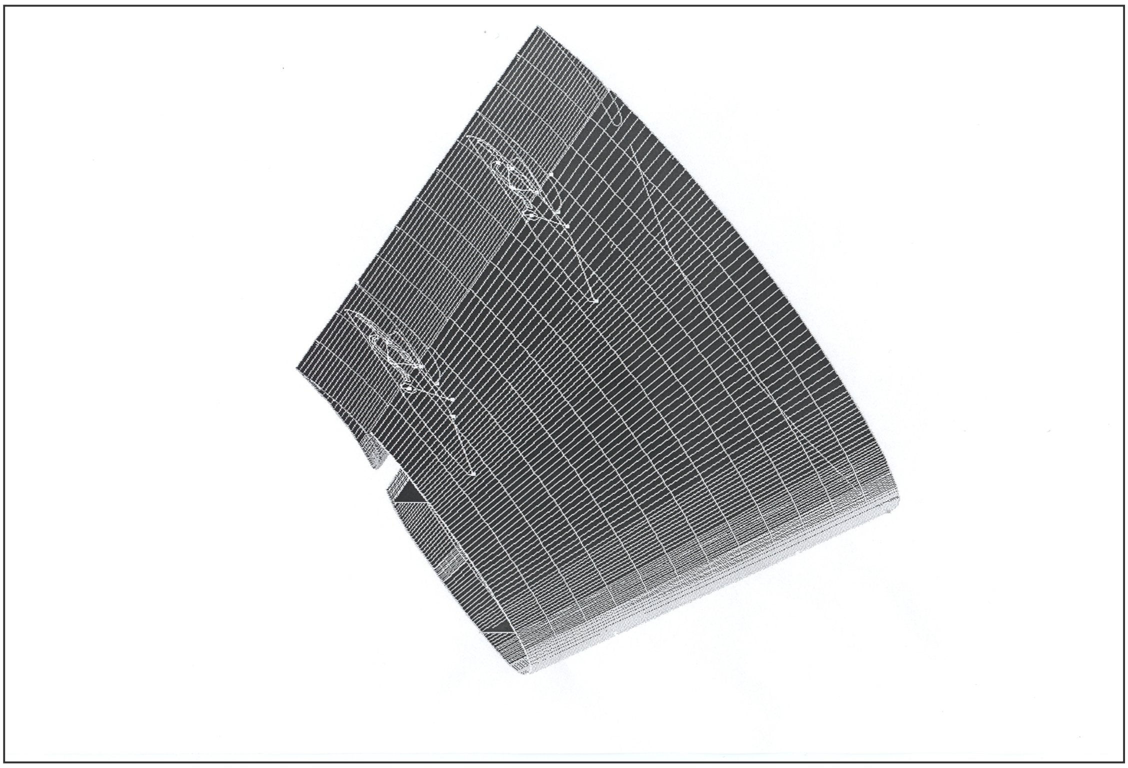

Fig. 12 CAD Model of Inner Wing/Flap Actuation