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AERODYNAMIC DESIGN AND INTEGRATION OF A VARIABLE CAMBER WING FOR A NEW GENERATION LONG/MEDIUM RANGE AIRCRAFT

Dr. E. Greff *
Messerschmitt-Bölkow-Blohm GmbH, Bremen, F.R.G.

Abstract

Transport aircraft manufacturers usually try to achieve a high fleet commonality by creating an aircraft family on the basis of one wing and stretched fuselages. The wing designer has to choose an appropriate wing area for the maximum stretched variant then. A transonic wing however shows optimum performance at high loadings which are not achieved at entry-into-service with such a conventional fixed geometry wing. Variable Camber (VC) is offering an opportunity to achieve considerable improvements in operational flexibility, buffet boundaries and performance which allow a reduction in optimum wing size. During the aerodynamic development and design integration described in this paper a change in design strategy and several off-design constraints were found. Theoretical and windtunnel results are given as well as a discussion of the effects on the system design, loads, weight, handling qualities, propulsion integration and mission performance.

I. Introduction

The economical success of a transport aircraft depends highly upon its fuel efficiency in terms of specific range. Major contributions in increasing the specific range can be achieved by technology improvements in aerodynamics, propulsion, structures, flight controls and avionics. For all disciplines involved in the development process a trade-off analysis of potential new technologies for a new aircraft program has to be done especially in the limelight of the stagnating jet fuel prices, capital costs and increasing costs for development, labour and materials[1]. The current fuel share of the direct operating costs is about 20% for a long range mission, while it used to be more than 40% in 1980. Investment costs (interest, depreciation, insurance), however, increased to 40%. This is a major reason why the airlines, which are recovering from a worldwide depression, currently prefer to maintain their long/medium range fleet or order derivatives of existing aircrafts.

An all-new long/medium range aircraft program facing these scenarios, which are of course subject to change, has to combine high technology standards resulting in significant improvements in specific range with low costs for R & D in order to be competitive. For the end of the century a threefold amplification of revenue miles are foreseen due to market growth and deregulation of air traffic. This leads to the market prospect [2] given in Fig. 1 in the order of 320 billion $ for wide body aircrafts. The long-range market, however, is much smaller than the medium range share. Since the advent of EROPS (Extended Range Operations) and the proven reliability of several twins [3] over the north-atlantic (B767, A300-600R, A310) it is obvious that there will be a further shift from long range quadros to extended range high capacity twins.

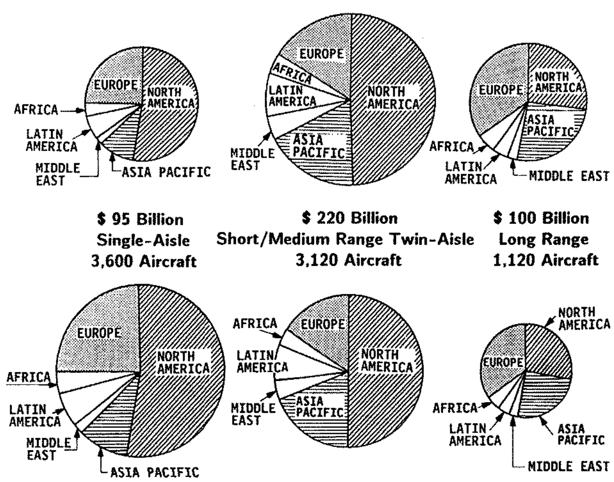

Fig. 1. Airbus Industrie Market Forecast 1986-2005

In the past decades aircraft manufacturers tried to answer changing markets with a deliberate product strategy which usually aims to create an aircraft family on the basis of the same wing by stretching the fuselage. Due to this policy of high fleet commonality the costs for development, manufacturing and maintenance can be reduced [4]. Airbus Industrie which will complete its family with the A 330 and A 340 (Fig. 2) is also following this strategy. Due to the changing scenarios on the long range sector a sufficient production number for an all new long range quadro is uncertain. Hence we see the compelling need to introduce some more flexibility in the aircraft in order to cope with the actual requirements later on. One solution in this field is the design of

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* Research Scientist & Project Manager Aerodynamic Development

a common wing for both the medium range high capacity twin and the long range quadro aircraft. As the wing contributes more than 50% of the development costs, about 45% of the structural weight and more than 60% of total drag it is the major keystone for the economical success. Provided the wing has got a high operational flexibility and can cover the diverging mission requirements of the two programs without significant performance penalties such a high degree of commonality will not only allow a substantial reduction in non-recurring and recurring costs but also reduce maintenance costs at the airlines.

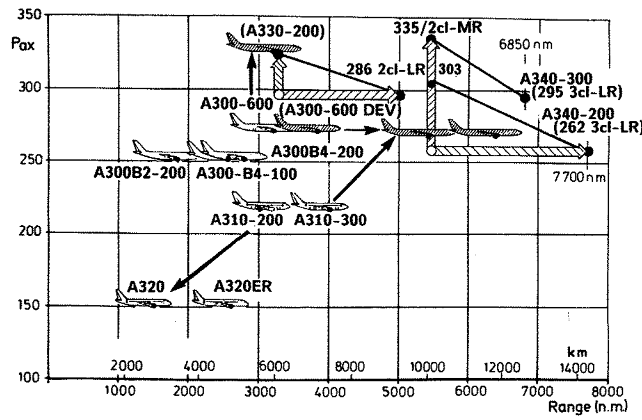


Fig. 2. The Airbus Industrie Product Line

When designing a wing for a certain baseline aircraft the designer has to choose an appropriate wing area for the maximum stretched version and try to find the best trade-off between design and off-design conditions. Fig. 3 shows a wing area optimization chart with several constraints. Such a conventional fixed-geometry wing is designed for a particular Machnumber and achieves the best performance at high loadings. The optimization for a medium range twin would normally come out with a ≈ 10% smaller wing area despite the fact that the inherent growth potential must be higher (c. 20-25%) than it should be for the long range version (c. 15%-20%, see Fig. 4). For a common program both aircrafts will operate at fairly low lifts at entry-into-service and hence with worse performance.

Fig. 4 illustrates the different design requirements and operating conditions with a CL-range from 0.3 to 0.7 for a given altitude and wing area. Especially the twin is penalized with such a compromise wing. Variable Camber is offering an opportunity to achieve a considerable improvement in operational flexibility and aerodynamic efficiency throughout the entire operating range. Moreover it would enable the designer to select a somewhat smaller wing area thus improving the compromise between the two programs saving structural weight and fuel.

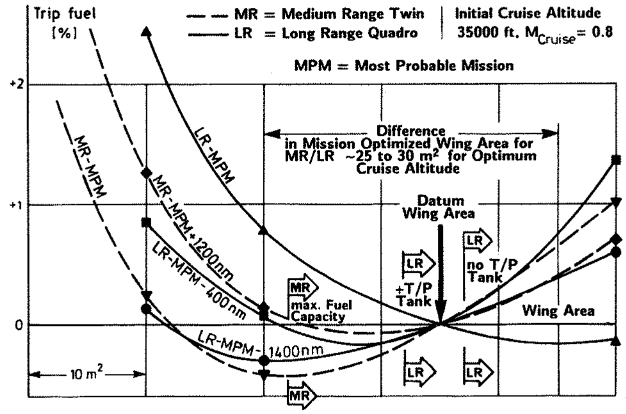
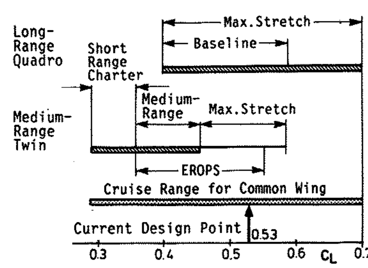


Fig. 3. Wing Area Trade-offs for Medium/Long Range

• AIRBUS A300	ca. 25%	TOW Increase of Wide Body A/C
• AIRBUS A310	ca. 16% *	
• BOEING 747	ca. 17%	
• BOEING 767	ca. 15% *	
• MC DONNELL DOUGLAS DC 10	ca. 37% **	
• LOCKHEED 1011 TRISTAR	ca. 19%	

* Further Increase Possible
** Span Increase + Structure Reinforcement



Mach-No.	TOBFL (ft)	Approach-Speed (kts)
0.82	10000-13000	135 - 145
Initial Cruise Altitude ~ 35000 ft		
0.78 - 0.82	8000-10000	135 - 145

C_L - Range

Fig. 4. Design Requirements

II. The variable camber concept

From the very beginning of aeronautics planes already used wing camber and twist variation to alter lift characteristics and achieve lateral control. In the field of sailplane design camber flaps for optimization of glide performance were continously developped and are well established nowadays. Some military airplanes have already applied flaps to improve manoeuvrability in combat by enabling the aircraft to turn or pull up at higher g-levels without buffeting onset since World War II.

With developping technologies in the field of transonic aerodynamics, materials and systems aircraft manufacturers began in the 1970's with in-depth studies of camber optimization of fighter aircrafts. These investigations finally culminated in the highly sophisticated mission adaptive wing (MAW), which was tested on the flying testbed AFTI/F111 [5,6] in different automatic control modes for cruise & manoeuvre camber control as well as gust load alleviation.

However, the main issue in transport aircraft application of new technologies is the ability to employ them at low cost. A flexible skin and the complex drive mechanisms of the MAW are not feasible and cost-effective for a transport aircraft which cruises within a relatively limited range of altitudes and speeds. In contrast to the combat aircrafts a transport needs much more lift enhancement during take-off and landing resulting in rather complex combinations of slats, fowler flaps and drooped ailerons.

In order to ease development and certification with low development costs a camber variation in transport aircraft by using the traditional high lift devices [7] was proposed and investigated under the sponsorship of the German Ministry of Research and Technology [8/9].

A schematic of the system solution is given in Fig. 5. The camber variation is achieved by small fowler motions, where the wheels of the flap carriage are guided by two individual tracks in such a way, that in VC-operation the flap body slides underneath the spoiler trailing edge. The control track and the flap upper surface have to be shaped such, that camber variation is performed with minor discontinuities in surface curvature.

basic effects of a trailing edge camber flap on the aerodynamic forces of a transonic wing are:

- o A significant drag reduction with increasing camber at higher lifts is combined with increased lift capability,
- o The shift in buffet boundary is a powerful tool to increase operational flexibility and in consequence to design smaller wing areas for a given mission,
- o A further drag reduction at lower lifts by means of decambering. As a negative effect we recognize an increase in pitching moment (nose down). It is interesting to note, however, that the trim drag penalty is one order of magnitude less than the gain in total drag.

The potential of VC as an add-on item to existing wings highly depends upon the pressure distribution type. The entire potential can only be exploited if the wing is especially designed for variable camber which will be discussed in chapter 3. According to the system solution in Fig. 5, which only allows positive camber deflection, the design point is shifted to CL = 0.4. At this reduced lift the wing is optimized with respect to minimum drag with relaxed off-design constraints. This will be the setting at low altitudes, low weight (medium range mission) and towards the end of cruise. At start of cruise, step climbs to higher altitudes or increased weight the lift demand is satisfied by discrete camber/fowler settings resulting in the envelope in Fig. 5.

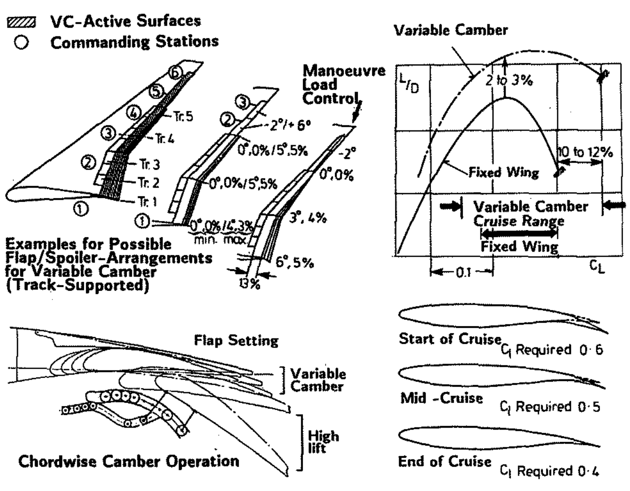


Fig. 5. Principle of Variable Camber Operation

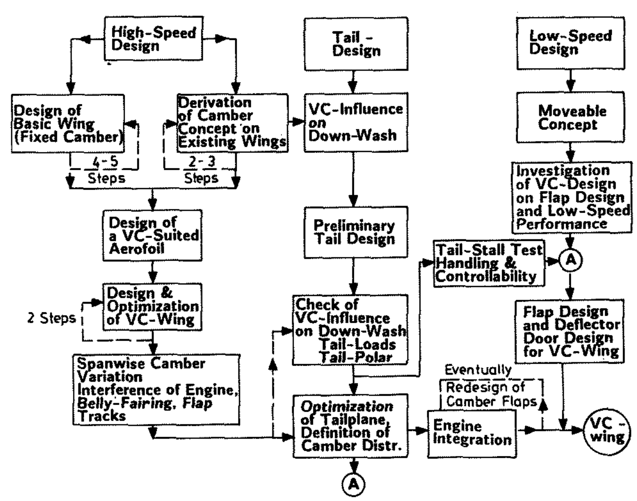


Fig. 6. Aerodynamic Development Concept for a VC-Wing

From the highest camber position the flap proceeds on its normal track into the high lift positions. No mechanical additives besides the second track nor additional drives related to VC are needed. Further details of the system requirements will be discussed in chapter 4. The

The aerodynamic development concept to achieve this goal is depicted in Fig. 6. After developping a basic fixed camber design and preliminary investigations on existing wings to develop a camber concept in terms of flap chords, flap deflections and pressure distribution type the main steps are

- Design and verification of a basic VC-airfoil
- Integration of this airfoil in a 3D wing design
- Spanwise variation of camber deflections
- Optimization of wing-root setting and fairings with VC
- Engine/airframe integration with VC
- Determination of down-wash changes due to VC and design of a horizontal tail adapted to VC requirements.

III. Aerodynamic Design of VC-Wing

3.1 Preliminary Investigations on existing wings

In two different research programmes camber modifications on existing wings were investigated They were directed towards a payload increase of the Airbus A300 und A310 thus excluding changes of the wing box. The results were reported earlier in [10, 11, 12]. One camber modification has successfully been applied to the A300-600 resulting in 10% more passengers and 15% more range [13].

The further investigations were mainly based on A310 research wings which were already highly loaded supercritical wings. As wind-tunnel results have shown, the L/D can be controlled by different flap settings throughout a wide CL-range.

What did we learn from these preliminary tests? The pressure distribution of the basic wing has to be carefully adapted to the requirements of VC in order to achieve the optimum gain. A conventional highly loaded airfoil usually has a large supersonic region (Fig. 7) with a general tendency to strong reexpansions downstream of the shock wave. The following recompression exhibits steep gradients resulting in thick boundary layers and trailing edge values close to separation. Small flap deflections already tend to evoke separation on such an airfoil type and especially the reexpansion is dangerous the closer the flap hinge line moves towards the supersonic region. For the design of the VC airfoil the following criteria for a "VC-suited" pressure distribution were concluded which are illustrated in Fig. 7.

At the design point ($C_l \approx 0.45$)

- the supersonic region should be confined to $X/C \approx 0.4$ and terminated with a weak shock;
- the region close to Cp* should exhibit small gradients in order to guarantee a stable shock position in off-design conditions;
- the subsonic recompression gradients should not be larger than $dCp/dx=3$;
- the trailing edge recompression gradient should be degressive (Stratford-Type), which is beneficial for the turbulence structure and hence reduces the friction drag;
- the balance of front loading and rear loading at the lower surface should be altered towards front loading to reduce the adverse effect of pitching moment.

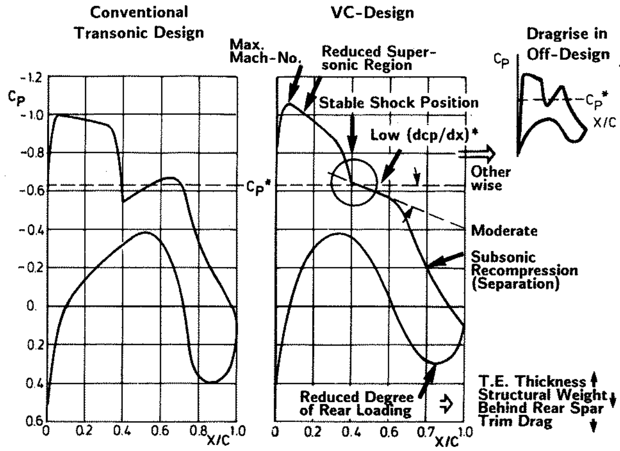


Fig. 7. Considerations on Properly Prescribed Pressure Distributions for a Variable Camber Airfoil

The hinge line should be well clear of the end of the supersonic region at all operating conditions, i.e. at X/C=0.8 to 0.9. Further large scale tests with the A310 model have shown that a combination of fowler action and camber deflection is very beneficial at higher lifts by increasing the recompression distance.

Buffet improvements of ≈ 16% (transposed to full scale) were achieved compared to the basic wing with a 3° deflection and 5% fowler translation whereas the wing area increase due to the fowler motion has only been 2%. Therefore the VC-wing design described in chapter 3.3 incorporates a fowler movement.

3.2 Development of a basic VC-airfoil

The VC-airfoil was developed in reference to a fixed camber optimum airfoil which is designed for comparison purposes to show the effect of variable camber. This airfoil is highly loaded and designed for CL=0.53, which means a local Cl of 0.6, and a local Machnumber of 0.74 which is equivalent to a 3D-Machnumber of 0.8. The design conditions for the VC-airfoil were shifted due to the above mentioned system requirements to a lower Cl-value of 0.48 which correlates with a global CL of 0.42. Finally both airfoils were compared at the same thickness of 11,15%.

According to the aforementioned criteria a design pressure distribution was prescribed and the airfoil designed by means of an efficient direct-inverse transonic design code which was reported earlier [14]. The analysis for off-design conditions was done with a well-proven and reliable full potential solver coupled with a semi-inverse boundary layer integral method simulating the wake curvature and thickness distribution. A comparison of this code in competition with others and experiments on well known test cases is given in [15, 16].

For this basic airfoil an off-design analysis including a variation of flap chords and flap deflections was performed. Without a flap deflection the VC-airfoil is superior in minimum drag by 4% vs. the reference airfoil. At higher Cl, however, the supervelocities of the less cambered airfoil result in stronger shock waves thus creating a significant drag increase. The cross-over point is at $Cl \approx 0.5$ and it is obvious, that such an airfoil cannot be used without variable camber unless only low lifts are required. Once a flap deflection is applied the VC-airfoil shows once again its superiority because of the very little minimum drag increase with camber deflection. As earlier results gave some hint on the importance of flap chord length a variation from 13% to 25% chord length was investigated in theory and experiment. The best results in theory were achieved with a 13% flap although the data for the 20% flap are only slightly worse.

A calculation for flight Re-No. with a 3,5 deg (Fig. 8) camber deflection and 20% flap chord shows a nearly shockfree pressure distribution and increased skin friction at the trailing edge (TE), i.e. the higher the Re-number is, the risk for TE-separation with flap deflection is decreasing.

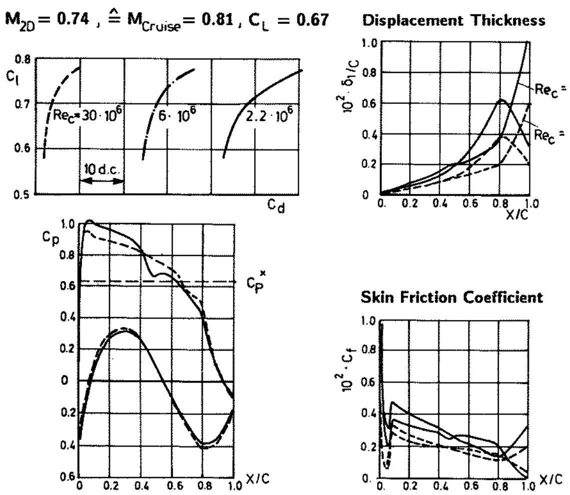


Fig. 8. Influence of Reynoldsnumber Variation on VC

A windtunnel model with different trailing edge segments representing a 20% flap with three settings and a 13%, 25% flap with one setting was built and measured in the TWB at the DFVLR at Brunswick at $Re = 6 * 10^6$. The measured increase of minimum drag with camber deflection is much smaller than it uses to be with conventional airfoils and the change with Machnumber is nearly negligible. A much better insight into the operational flexibility is given by the comparison of aerodynamic efficiencies $M \cdot L/D$ for the VC-envelope and the reference fixed camber airfoil which are plotted in the Cl-M-plane in Fig. 9. For each level of efficiency the VC-airfoil can cover a greater flight regime, i.e. it has a more levelled optimum with small gradients towards off-design conditions as it was anticipated. The maximum efficiency is at the design Machnumber 0.74 at an optimum lift coefficient which is 20% higher than for the fixed camber airfoil. This clearly indicates the necessity to adjust the wing area to a somewhat smaller size in order to exploit this potential. An evaluation of the different flap chord sizes indicates a benefit of 2-4 drag counts in the interesting Cl-range for the 13% flap, but generally the influence of different flap sizes is of minor importance as already predicted by computation.

A derivation of a control law is given in Fig. 10. The envelope of minimum drag for all camber settings was transferred into the corresponding Cl-α-polars. At nearly all Machnumbers camber variation has to start at the same angle of attack. To maintain optimum efficiency with increasing lift demand camber variation is to be done at nearly const. angle of attack up to the maximum flap angle. Based on this successful design a transposition into a wing design could be done, which will be discussed in the next chapter.

As fas as the computational methods are concerned, a confirmation of design and off-design pressure distributions was found (Fig. 11). The comparison of drag cofficients however is getting worse with increasing flap deflection (Fig. 12).

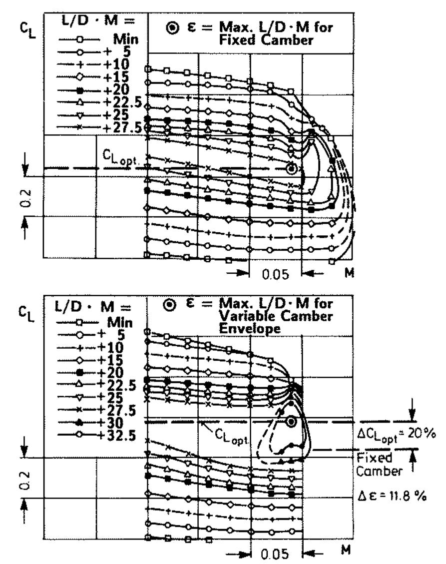


Fig. 9. Aerodynamic Efficiency of the VC Airfoil in Reference to a Fixed Camber Design

A comparison of drag components shows a relatively good representation of the wave drag. The friction drag, however, is too small at higher lifts. A reason could be that with increasing flap deflection the wake is becoming more asymmetric with intensive mixing downstream the trailing edge which is not computable with the integral boundary layer method. An improvement can be expected with the implementation of an inverse finite-difference boundary layer code which is under way.

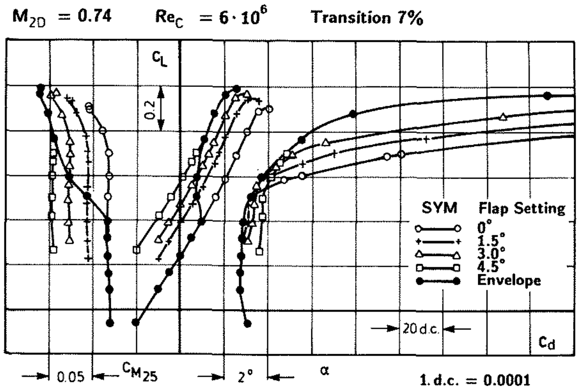


Fig. 10. VC Airfoil Forces and Control Law for VC-Envelope

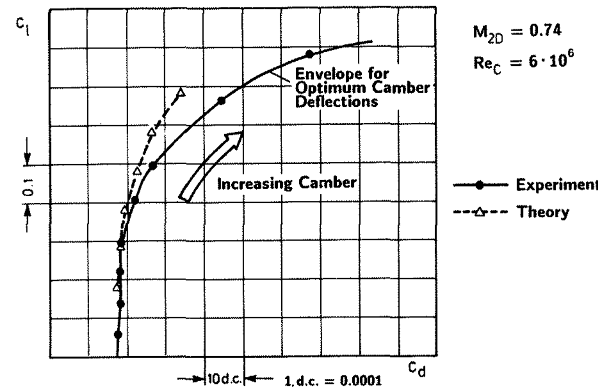


Fig. 12. Comparison of Drag Polar Envelopes in Experiment and Theory

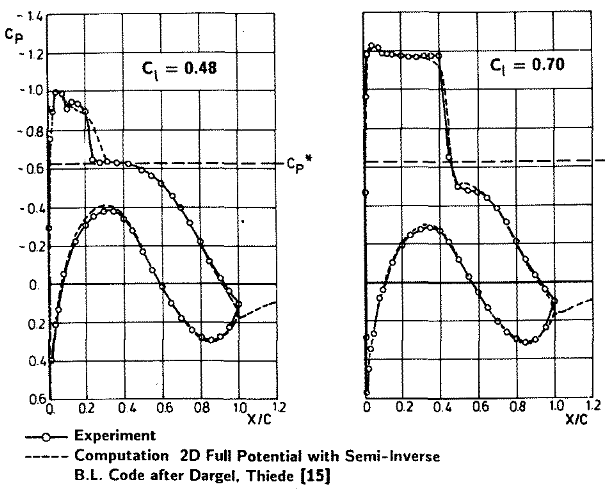


Fig. 11. Comparison of Pressure Distributions from Experiment and Theory for VC Airfoil

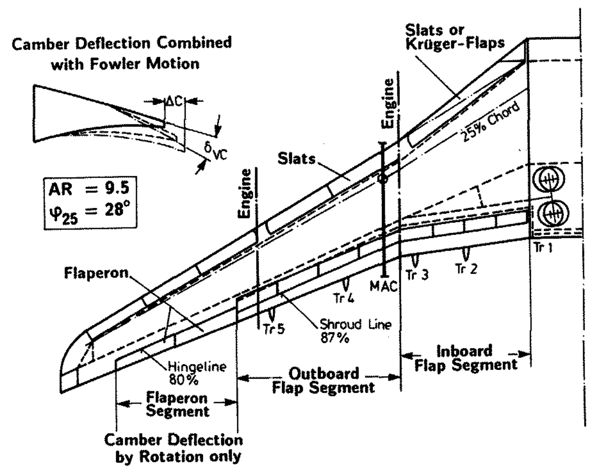


Fig. 13. VC Research Wing Planform and Segmentation for Wind-Tunnel Testing

3.3 Design and verification of a VC-wing

After verification of the concept in 2D a first VC-wing was designed. With the aim to achieve a best compromise between the different medium/long range missions (Fig. 4) the wing area was sized 6,5% smaller than it would have been for the conventional long range aircraft. Special attention was payed to the optimization at low CL - the operating regime for medium range. The design CL-range was therefore limited to 0.3 to 0.45; i.e. in this range the wing with camber flaps retracted had to be improved with respect to fixed camber design according to the 2D procedure and above CL = 0.45 the flaps would be deployed according to a control law similar to Fig. 10.

Besides the pure aerodynamic viewpoints other constraints had to be obeyed as to mention fuel volume, landing gear installation, field performance and handling qualities. The research wing planform in Fig. 13 with increased inboard sweep and a crank in leading and trailing edge was the best compromise to achieve small wing area with high aspect ratio of 9.5 combined with a large fuel volume. As earlier results had shown a slight benefit for small camber flaps the shroud line (spoiler trailing edge) was designed to 87% local chord on the outboard wing which is also beneficial for lateral controllability. After transposition of the VC-airfoil design into a 3D-design by means of the 3D direct-inverse method in [14] and the lofting of the basic wing a concept for realizable camber flaps on the model was derived in close cooperation with the system department.

In order to keep effective flap chords small and reduce the perturbations in curvature the spoiler will not be pivoted. In the most retracted position the spoiler trailing edge rests on the flap crest and is spring loaded. Once the flap is travelling into a VC-position the flap body slides underneath the spoiler TE keeping the gap closed (Fig. 14). On the lower surface there must be either a flexible or moving panel to guarantee

- a sealing up to the utmost camber/fowler position,
- a smooth variation of curvature,
- a sufficient gap for the first take-off position.

From the last camber position to the take-off position a significant vertical displacement must be achieved with hardly a longitudinal motion thus producing high actuator loads. In order to avoid this the maximum VC position was restricted to 4% chord and 5° deflection and combined with a deflected panel. The moving panel (A300 deflector-door type) is actuated via a linkage system driven by the movement of the flap-track fairing (see chapter 4).

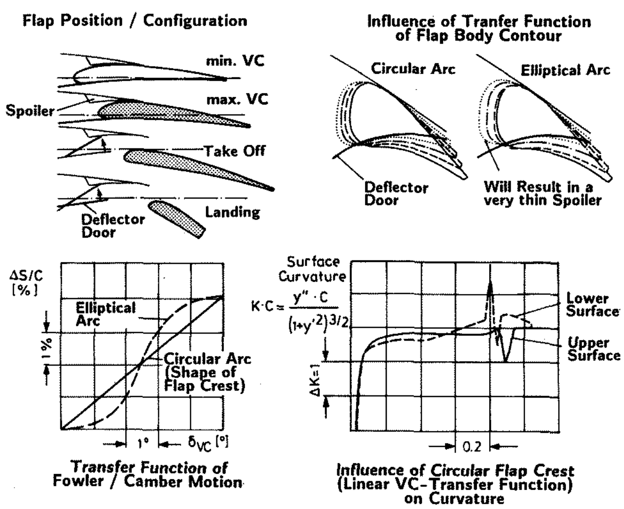


Fig. 14. Geometrical Constraints for a Fowler/Camber Flap

The relationship between fowler motion and deflection could be used to reduce the curvature discontinuity while cambering. From the aerodynamic viewpoint an elliptical flap contour would have been desirable resulting in a fowler/camber law in Fig. 14. In fact, this is not feasible as this would result in a very thin spoiler structure. Hence a linear relationship was chosen, i.e. the flap contour from the spoiler TE towards the flap nose is a circular arc. The resulting curvature distribution in the utmost camber position is also given in Fig. 14. These imperfections were represented in the wind tunnel model in order to include the penalties due to the system requirements which would have been difficult to estimate.

The wind-tunnel model was equipped with segmented trailing edges (see Fig. 13) representing 4 camber settings, which could be adjusted independently on the inboard and outboard fowler flap as well as the two ailerons which were also used as camber flaps (flaperon). A very little increase in minimum drag with flap deflections was achieved. The cross over points in CL of different camber settings are 0.05 lower than expected resulting in a superiority of the VC-envelope in the whole range. The buffet boundary is increased by 10% for the maximum deflection with respect to the fixed camber wing. The aerodynamic efficiencies in Fig. 15 of the VC-envelopes show the improved flexibility in Machnumber and performance. More insight to understand these improvements is given through the effect of flap deflection on the shock wave development (Fig. 16) and corresponding development of the trailing edge pressures.

Following conclusions can be drawn:
- at the same lift a flap deflection reduces the strength of the shock considerably at the expense of an increased rear loading, i.e. lower trailing edge pressure;
- the trailing edge pressure divergence, however, and hence the buffet onset is increased;
- due to the increased rear loading and the more aft shock position the pressure gradients over the rear part increase resulting in higher viscous drag;
- consequently flap deflection increases the drag for subcritical lifts and decrease it at increasing lifts due to reduced shock Machnumbers and the delay of separation.

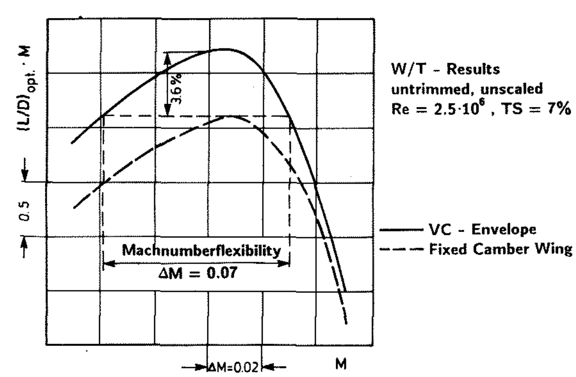


Fig. 15. Effect of VC on Aerodynamic Effiency

The wind-tunnel results had to be scaled to flight conditions which is already difficult with standard wings, where the so-called reference method using the windtunnel-to-flight correlation of an existing aircraft is applied [10]. If lift-enhancing measures as camber modifications are applied, differences at the same lift coefficient cannot be transposed in the whole CL-regime as the break in the lift curve of the reference wing is at lower lifts than it would be in flight. Therefore the improvements at higher lifts have to be reduced.

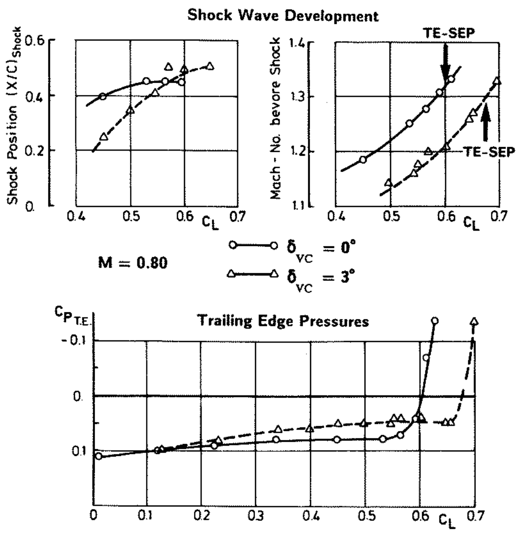


Fig. 16. Effect of Flap Deflection on Local Flow Properties at 42% Span of the VC Wing (Fig. 13) TE-SEP = Trailing Edge Separation

The results were trimmed and scaled to the long-range aircraft configuration under investigation and represented in the L/D-ratio in Fig. 17, where the dashed curves are the discrete settings and the full curve denotes the envelope. At the design point of the fixed camber wing there is an improvement of 4%, which is due to the relaxed off-design constraints for the VC-wing.

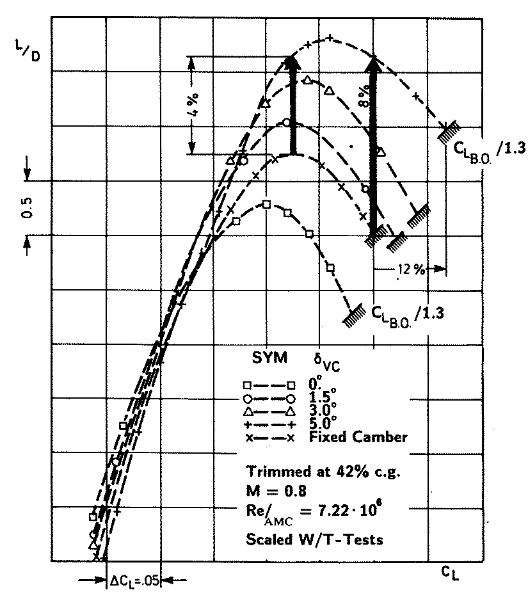


Fig. 17. VC Effect on Scaled L/D (B.O. = Buffet Onset)

Further improvements are envisaged due to the compensation of structural tolerances like flap upfloating, assumptions on aeroelastic distortion at design freeze of the wing box and the possibility to optimize the wing root setting. This will be dicussed in chapter 5.

IV. System design

The general mechanical realization of the VC-System was already discussed in the previous chapters. The intention of this chapter is to present the specific solution and its further potential to increase the flexibility as well as the integration of the variable camber function in the flight management computer.

As already illustrated in Fig. 5 a spanwise camber variation could be used to redistribute spanwise loading in order to control buffet or minimize drag [17]. This would require independent input commands at six spanwise stations through differential gears thus increasing the complexity of the system and maintenance and reducing the reliability of the mechanical drives.

From the current wing design there is no evidence, that a spanwise camber variation is required, as wind-tunnel results with the segmented flaps have shown only minor effects of a spanwise differential camber versus a collective camber of fowler flaps and flaperons. This might be misleading as there were vortices emanating from the edges of the flap segments in this experiment and a smooth spanwise camber variation by twisting the flap body could probably achieve a gain. Further investigations in a research work with flexible and self-optimizing wind-tunnel models will give an answer to this question. At this stage it seemed wise to restrict ourselves to the most simple solution, the chordwise camber variation with fixed relationship in spanwise camber distribution (which can of course be altered within the rigging capability of the flap at each track by $\pm$ 1°).

The natural conical motion (spanwise constant percentage of the chord) of the outer flap is combined with a constant motion of the inboard flap (Fig. 18) thus working on a common torque shaft and avoiding additional drives for variable camber. The flaps are actuated by dual load path rotary actuators.

The A 300-type deflector doors on the lower side are actuated by a linkage system driven by the movement of the fairing. In the VC-mode the deflector door slides upon the lower side of the flap nose.

Besides the mechanical realization with a quite ordinary fowler flap system which can be implemented with only minor weight increases (i.e. less than 0.5% of the wing weight) and low risk a further question is how to control the VC-operation. In [18] a comprehensive investigation on the integration of VC in the modern computer architecture of an A320 type Flight Management System (FMS) is reported.

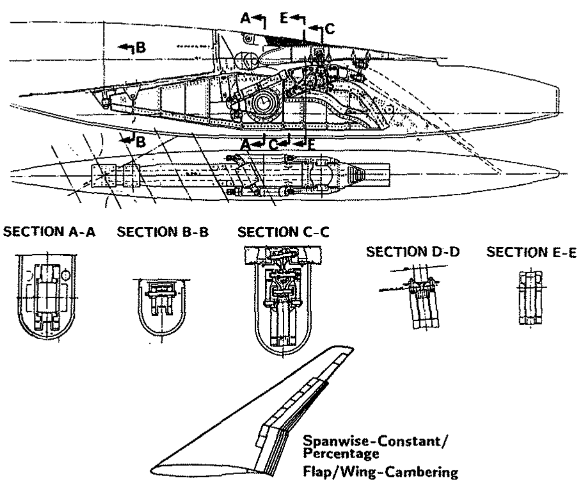


Fig. 18. Flap Support and Drive Mechanism

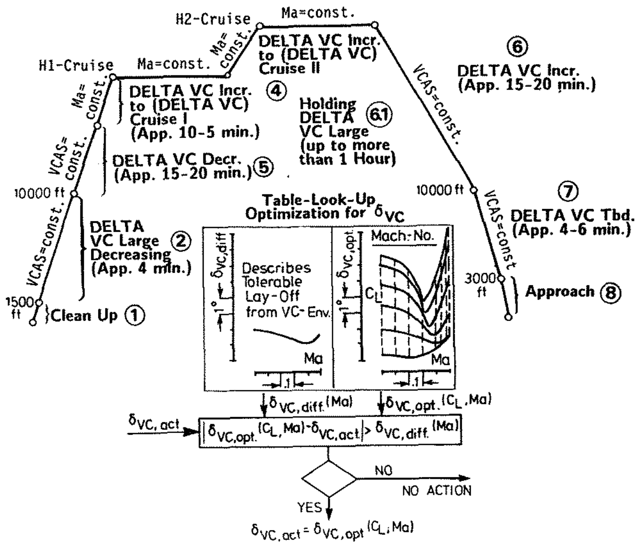


Fig. 19. Flight Envelope Optimization

The modification consists in the flap-control-computer being programmed such, that in addition to the conventional discrete high lift settings it will be able to flexible start/stop the flaps in the VC-regime. The functional additives in the Flight Augmentation Computer (FAC) can be summarized as follows:

- Extend the existing memory by a few new functions such that optimum camber settings can be calculated at any time for the actual mass and speed. A recamber command is initiated only if the lay-off of the optimum envelope exceeds the programmed threshold, preventing permanent actuation of the system. This optimization is actually a simple table-look-up procedure (see Fig. 19). Based on the complete equations for the trimmed aircraft including thrust conditions for minimum required thrust as a function of mass (i.e. lift coefficient), Machnumber and flap setting δ_{VC} can be derived. Selecting the settings from the table means flying along the envelope of Fig. 5;
- the fixed camber operating envelope is substituted by the VC-envelope thus guaranteeing protection for overspeed (VMO, MMO), stall and buffet onset and allowing a load control by excluding operation of high camber settings at low altitudes and high dynamic pressures (see chapter 5).

For a long range flight of 6800 nm the block time will be approximately 13 hours. The lift variation within this time with one or two step climbs will be from 0.6 to 0.4 on each flight level, i.e. actually a recamber command will only be given once or twice per hour to mimimize the lay-off to the envelope. Thus there is no need for continous adaptation during the cruise.

Following these conclusions the implementation of VC can be achieved without additional drives at minor weight increase and just reprogramming a few computers of an A 320 type flight management system.

V. Further Design Integration Aspects

In the following some secondary design aspects with increasing interaction of various disciplines are briefly discussed some of which may have "snowball effects" on the optimization of the total aircraft.

Load Control

Besides the L/D-optimization the system may also be a powerful tool to gain control over dimensioning loadcases, i.e. an increase of the ratio payload/structural weight and hence a further increase in transportation efficiency. In Fig. 20 the potential of a spanwise camber control (i.e. load redistribution) is demonstrated. Compared with the typical lift distribution for optimum performance (valid only for the typical cranked planforms) the setting I will give the best aerodynamic solution for buffet optimization resulting in a 13% reduction of root bending moment (RBM) whereas setting II denotes a manoeuvre case with 24% reduction RBM. This potential must carefully be balanced with the increased complexity of the spanwise camber system (chapter 4) combined with a structural optimization. For the time being this was not included.

Rear fuselage and tail loads, however, may be influenced in a beneficial way with the straightforward collective chordwise VC-system under investigation. At dive speed the multiplication of large zero lift pitching moment (for fixed camber wings) and maximum dynamic pressure at 20.000 ft. is a measure for the high design loads. With VC the wing may be decambered with increasing dynamic pressure for a given weight, i.e. decreasing lift demand. Actually the required lift for the long range version at MTOW and Mdive would be less than 0.4, thus demanding the retracted setting (δ = 0°). The reduction in design loads for the current rear end design would be 15 to 20% with corresponding weight reductions of the horizontal tail.

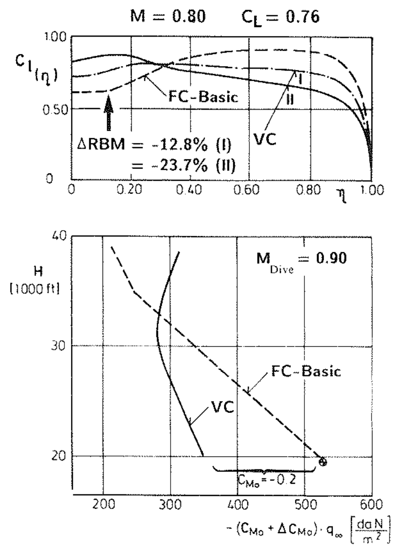


Fig. 20. Load Control by Means of Variable Camber

Tailplane Design

As already mentioned earlier the wing area may be adapted with VC to improve the commonality between the long/medium range aircrafts (chapter 3.3). The proposed reduction of 6.5% in wing aera (≈ 20m^2) consequently reduces the manufacturers weight (MWE) by 1,5 to 2%. A reduced wing area, however, would also require a reduced tail size in the same order of magnitude provided stability & control margins are not affected.

A camber deflection changes the downwash at the location of the horizontal tail. First measurements with different tail settings to determine the mean downwash have shown a shift in zero downwash but hardly an influence in downwash gradients. The change in tail lift demand with camber setting and c.g. is given in Fig. 21. It seems worthwhile to think about a camber adaption of the tailplane corresponding to the wing camber setting in order to minimize trimmed aircraft drag. Only slight deflections of the elevator would already achieve a 1% drag improvement. In fact a so-called software flying tail is proposed for the modern long-range aircraft which foresees a software gearing between elevator and stabilizer to avoid negative tailstall during certain critical pushover manoeuvres in the approach and the recovery from those manoeuvres. Actually this has been the design case for the horizontal tail size whereas the required size for stability in cruise is 10% smaller. Such a flying tail could be minimized in area and the software gearing in cruise altered to work corresponding to the VC-optimization schedule.

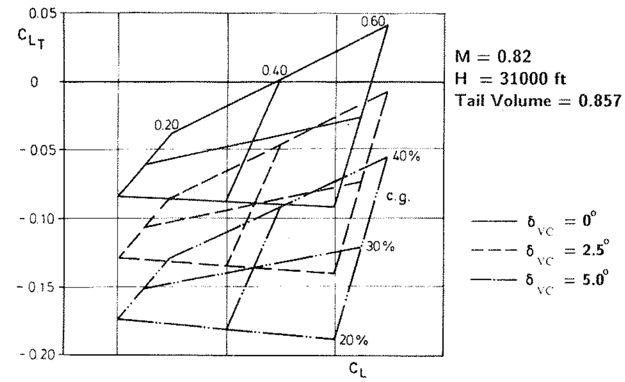


Fig. 21. Tail Lift Demand due to VC-Setting and C.G.-Shift

Wing/Body Interference

According to the VC-Control law the aircraft will fly at nearly constant angle of attack thus enabling the designer to minimize the wing-body interference, the fuselage upsweep drag and the trim drag by selecting a max. floor angle below the operational limitations of the airlines (< 2°) and adjust the wing root setting accordingly (Fig. 22). It was found, that a reduction of ≈ 1° in wing-root setting is feasible. This results in a reduction in pitching moment, down-wash and effective upsweep of the tail cone and a total gain of 1-1,5% total drag is deduced which is nearly const. with CL. Combined with other improvements the potential for VC is about 5% at L/D-optimum of a fixed camber wing.

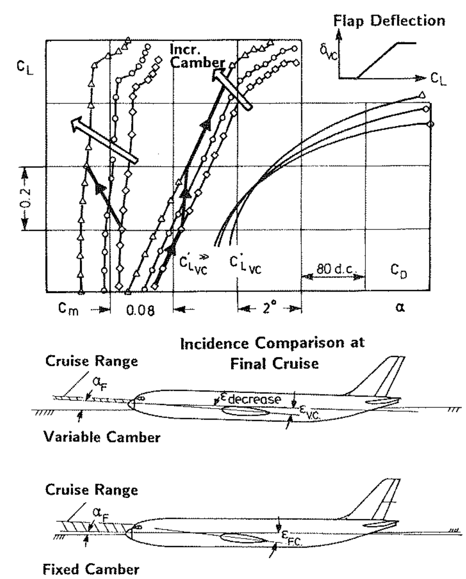


Fig. 22. Influence of VC on Fuselage Incidence and Wing-Root Setting

Propulsion integration

The two different missions with a twin engined or a quadro configuration imply the rather difficult task to optimize a common wing with respect to engine installation drag for engines of different size. Especially on the outboard engine a significant break in load distribution is depicted in Fig. 23.
Windtunnel experiments with through-flow nacelles were conducted and a significant increase in installation drag especially on the outer engine with increasing camber was found or vice versa the VC improvement is decreasing with installed engine. Oil flow photographs have already given some insight in this phenomenon and it seems necessary to adapt the lower surface pressure distribution of the VC-sections locally. It tends to develop higher supervelocities on the crest of the airfoil which are enhanced by the nacelle thus increasing the pressure gradients towards the trailing edge. As the jet was not simulated turbine powered simulator tests are to be conducted in further research programmes with detailed pressure measurements on wing, pylon and engine to solve this very delicate problem. A spanwise differential camber seems to be an effective tool to cope with the quite different installation problems of the twin/quadro jet.

Surface quality assessment

The existing surface tolerance catalogue of the A320 was reviewed and in general no significant improvement of the already high quality standard seems necessary. The trailing edge of the deflector door however needs special attention to guarantee sealing and the gap between the spoilers is subject to special sealing requirements. Special attention should be payed on the structural layout of the flap and the optimization of the track locations. A maximum displacement of 5 mm combined with a flap upfloating of 0.9° is tolerable with minor drag penalties.

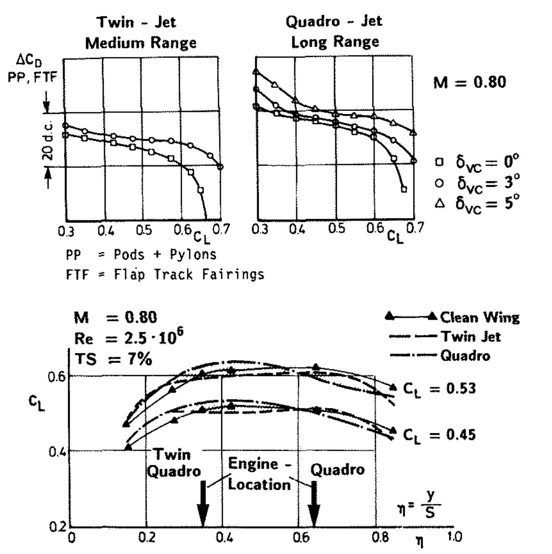


Fig. 23. Influence of VC on Installation Drag and Lift Distribution

Repercussions on flight testing

Preliminary estimates on the additional efforts during flight testing and certification were made after internal discussion with flight test engineers and pilots. Mainly four ATA-chapters are influenced, i.e. performance, handling qualities, AFS and structure.

For the performance additional flight test data points are required to establish the optimum criterion and buffet boundaries. Flights with 3 settings will be sufficient to establish a tunnel-to-flight correlation. Discrete values in between may be interpolated. As far as the handling is concerned, it is necessary to see the influence of VC on the manoeuvre point and for the AFS an en-route proving of the camber optimization schedule is necessary. The structural limits are certified for a changed operational envelope with changing placard speeds due to VC-deflection. The additional flight time for performance and certification is about 8% of the total flight-test time with 3 prototypes, which is equivalent to 1,5% of total development costs.

VI. Mission performance and operational Aspects

Aircraft cost comparisons today are still made on the basis of "typical missions, ideal flight, profiles, no wind", etc. How often do these theoretical assumption materialize in practical operation? Over Europe about 50% of all commercial flights are operated at non-optimum levels and in other areas of the world the situation will be even worse in future due to EROPS and increased traffic as a result of deregulation. Hence airlines are eager to get more operational flexibility of their aircrafts in order to fly above congested areas.

The operational buffet limits for the long range quadro (Fig. 24) show the altitude capability of the fixed camber wing compared to the 6.5% smaller VC-wing impressively. For the baseline aircraft both wings are well cleared at FL 350 but

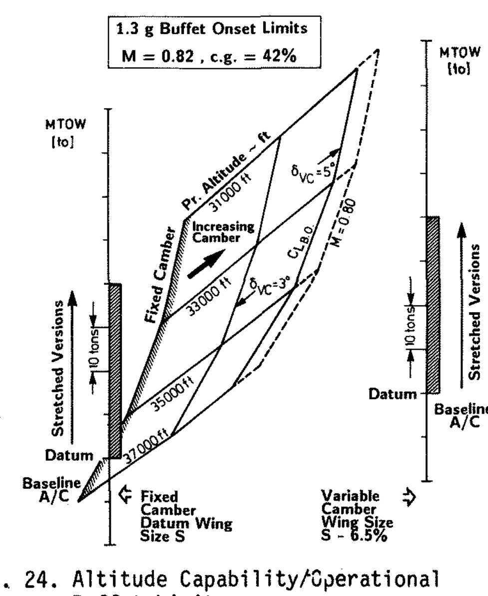


Fig. 24. Altitude Capability/Operational Buffet Limits

the VC-wing may climb to FL 370. At FL 350 the VC-wing has got a stretch potential of 11% whereas the conventional wing is forced to lower flight levels. The ultimate stretch which is currently seen (≈ 18%) could start at FL 330 and rapidly climb to FL 370 after 1/4 of the mission. A conventional wing however would be pushed to FL 310, which is not acceptable. The designer will therefore increase the wing area by ≈ 6% which will improve the long range version but vice versa offset the medium range twin. Especially at short stage length the twin will operate at considerably low lifts around 0.3 then, which is 25 to 30% off the optimum L/D. Fig. 25 illustrates the influence of VC in blockfuel which is up to 5% for the long range mission. If the medium range twin can climb to FL 370 the gain is 2%, but in case of charter flights it might be pushed down to FL 290 and below where VC could retain an 8% fuel advantage.

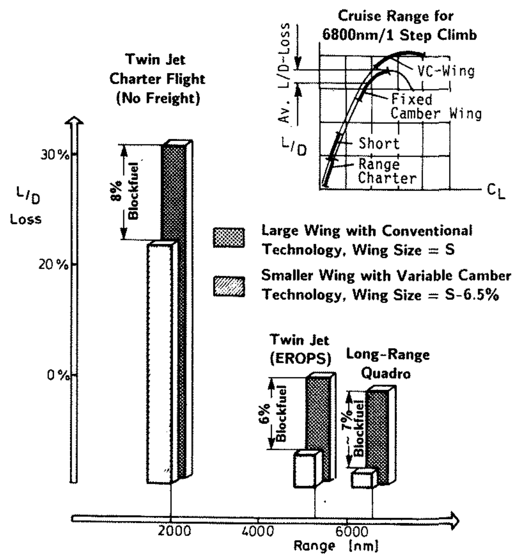


Fig. 25. Influence of VC on Mission Performance

VII. Conclusion

Changing scenarios in world air traffic as to mention EROPS, the deregulation, the trends in fuel prices and investment costs will triple world passenger miles and hence congestion and on the other hand force the airlines to buy technology and competitive aircrafts at low cost and to ask the manufacturers to provide more operational flexibility without drastic performance losses. The variable camber (VC) system which is described in this paper was developped for a typical new generation long/medium range aircraft as for instance the A 340/A330. Variable Camber will contribute an average reduction of 3 to 6% in fuel burn and enable the use of one wing for medium range and long range missions respectively. The introduction of VWCC will set off a new generation of intelligent airliners which will optimize their camber schedule automatically throughout the entire mission. A further improvement potential due to leading edge camber devices and spanwise differential camber is emphasized and should be investigated.

From research work significant drag reductions and increases of the buffet boundary were found. This work led to the current concept where the trailing edge flaps and ailerons are used to modify the wing camber while cruising. An efficient system requires a change in design philosophy and several new constraints in the design problem were found as to mention the extent of the supersonic region, the acceptable pressure gradients in the recompression zone and the required surface curvature.

Experimental and theoretical results for different design stages are given as well as a discussion of the influence on VWCC on handling qualitites, loads, weight, propulsion, performance and stretch potential. Problems which had to be tackled during the design integration and validation of improvements by means of windtunnel tests are reported. Especially the engine installation problem needs further research work as there is a reduction of VC-improvement due to the engine interference with the current design.

For the time being the conclusion can be drawn, that VC is engineerable for a modern transport aircraft at relatively low cost without major mechanical additives. Automatic control is feasible within the framework of a modern A 320-type flight management system with little effort. For a given wing size only minor weight increases (0.5% wing weight) have to be faced. A consequent adaptation to VC, i.e. reduce wing size and take advantage of several "snowball" effects in overall design as to mention

- an adapted tail with camber capability
- control of dimensioning load cases thus saving weight,
- wing/body interference optimization by reduction of wing root setting,
- spanwise differential camber control to improve commonality and engine/interference

would result in a superior overall design with improved structural weight/payload ratio and tripfuel. For future advanced designs incorporating natural laminar flow, which are actually under way for an all-new commuter aircraft (MPC 75), the application of variable camber is a prerequisite to control the laminar bucket.

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