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AERODYNAMIC DESIGN AND TECHNOLOGY CONCEPTS FOR A NEW ULTRA-HIGH CAPACITY AIRCRAFT

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Abstract

The predicted annual growth rates result in a doubling of air travel in the next 20 years. Congestion affects growth and hence the identifiable need to replace current large aircraft. Satisfying the growing Pacific/Asia market leads to a requirement for an UHCA whose feasibility is being investigated at Airbus Industries and partners.

The DOC targets to be fulfilled for economic success are well below a scaled A340 technology level for a 530 - 700 pax family concept. Aerodynamic technologies were reviewed and first designs derived using a new hybrid design strategy. Application of a 3D Navier-Stokes code in the design cycle as well as a multi-point airfoil design optimization tool was successfully demonstrated.

In the aerodynamic development concept trade-offs in sweep/thickness of a turbulent wing with Variable Camber (VC) are compared with a Hybrid Laminar Flow Control (HLFC) wing showing the feasibility of a low sweep/high aspect ratio wing in an interdisciplinary approach. HLFC is offering a high potential in a phased introduction but still needs a large research effort in design, theory and windtunnel supported by flying demonstrators to investigate stability limits with nose suction and operational aspects such as decontamination of insect debris and anti-icing.

The landing-gear integration is a difficult task requiring more efficient flap systems, which are also needed to alleviate vortex wake effects and enhance roll power. Finally an overview is given on tailplane alternatives because a double-deck configuration leads to high trim loads. An attractive option could be a three-surface aircraft (TSA) which would rely on a demonstrator for control law verification.

I. Introduction

The advent of deregulation, massive mergers with only a few majors surviving and international code sharing alliances have posed a tremendous pressure on airlines to reduce costs and increase efficiency. In the last years the net losses were as high as all accumulated profits since the 1950s. 1994 has been the first profitable year since 1989 in net terms. This economic recovery already led to a surge of orders and this is continuing.

Assuming a world average growth rate of 4.6 % for the next 20 years, the in-house annual market forecast from 1995 to 2014 predicts a demand of 13, 300 new aircraft worth 845 billion $. This average growth, however, will be subject to large variations. Areas which are approaching a state of maturity (north-American and transatlantic routes) will grow at a rate below average. Others, for instance intra-Asian routes, those crossing the Pacific, and the links between Asia and Europe will prosper at a growth considerably above the world's average. 58 % of this market is single aisle and 42 % are for twin-aisle with 48 % replacement. Altogether the capacity of the world passenger fleet will more than double. About 17 % of the total demand is generated by opening of all-new routes. Interesting to note is, that the cargo sector is growing by 9 % annually!

The airport and airways situation however poses major constraints on this huge fleet expansion. The hub-and-spoke system led to a significant increase in traffic delays, which can be alleviated by the oncoming code-sharing alliances to some extent. New technologies and improvements in air traffic control procedures could increase the airspace capacity by 30 % but will reduce horizontal and vertical separation thus resulting in a more unified cruise speed and more complicated manoeuvring for ascent and descent avoiding the traditional long ILS glide path (4D-array-navigation). This in turn will require aircraft with enhanced operational flexibility and more efficient flap systems.

A further increase of traffic can only be realized, when the system is restructured. As only few new airports are being built a possible relief is the switch to more point-to-point services with larger

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twins and reduce the hub-spoke-service (Fig. 1). High-speed rail systems such as magnetic levitation trains will replace some uneconomic short range flights whereas on the upper range the answer is more capacity on a given range. Larger twins up to 400 pax will serve ETOPS routes and the identifiable need to replace current large aircraft leads, early next century, to a requirement for an Ultra-High-Capacity Aircraft (UHCA), which can operate from international airports provided their span is below 80 m. An increasing demand for feeder service to a new kind of airport under discussion as a remedy to congestion - the wayport [1,2], a huge transfer airport in a remote area for large intercontinental services, with such UHCA - is forecast. The split into aircraft categories shows, that in terms of business the long-range sector (210 - 500 + pax) is most important with 4 935 aircraft where 40 % is located in the Asia/Pacific sector (Fig. 2).

The market above 500 seats where still none of the airframers offers a product is yielding a number of up to 900 aircraft. Hence UHCA are currently receiving wide-spread industrial interest [3]. Airbus Industries and its partners are currently investigating the feasibility of an UHCA in a triple family concept from 530 to 700 pax while Boeing announces to rewing the 747 [4].

The economic success of a long-range aircraft depends highly upon its fuel efficiency in terms of specific range. Major contributions to an increase in the specific range can be achieved by technology improvements in aerodynamics, propulsion, materials and systems (Fig. 3). The current fuel share of the direct operating costs is, however, about 20 % while it used to be more than 40 % in 1980 on a long-range sector. Ownership costs (interest, depreciation, insurance), however, increased to 40 %. This is a major reason why globally manufacturers are aiming at a substantial cost reduction by 30 % and cut down of lead times by 50 %. An all-new UHCA facing these scenarios, which are of course subject to change, has to combine high technology standards with low costs for R & D and manufacture in order to be competitive to a 747-X. The DOC targets (Fig. 4) are then well below a scaled A340 technology level and imply drag reduction targets of more than 10 % besides the application of advanced materials and very-high by-pass ratio engines (VHBPR).

Of increasing importance for airline managers are ecological aspects such as a reduced impact of the aircraft emissions on the atmosphere. Latest research results show, that these emissions, which are in total only 0.4 to 3.2 % depending on pollutant, have a damaging effect on the atmosphere and aggravate the greenhouse effect [5]. Especially nitro-oxygens play an important role in the production of ozone in the upper troposphere. The produced ozone acts in these altitudes as a greenhouse gas with detrimental effect on the world climate. This situation motivated Airbus Industries to start the Mozaic experiment, where A340 in-service aircraft of Air France, Lufthansa and Sabena automatically measure ozone and water vapour on international routes. The amount of emissions can of course be reduced by minimizing fuel burn and optimize the aircraft configuration for lower altitudes [6] as lower cruise altitudes offer a potential to reduce the impact of emissions due to atmospheric cleaning processes. The increasing ecological consciousness since the world climate conferences in Rio and Berlin, where a 25 % reduction of total emissions (industry and households) until 2005 was set as a target, may well change the priorities of airline managers and manufacturers, especially in view of potential emission taxes. This is current practice only in Sweden, but very recently a fuel tax was proposed by the US administration which created substantial opposition among US airlines [7].

In the following the paper will focus on the basic configuration of the UHCA and trade-offs to improve fuel efficiency. State-of-the-art transonic wing technology may be improved further, but only laminarization is offering a large potential as a single technology which seems feasible on an UHCA with suction devices depending on the time-schedule and research work spent on this field.

II. Configurational Aspects and Basic Technologies

2.1 Design Requirements and Basic Configuration

The set of requirements derived for the UHCA whose project designation is now A3XX is subject to change within a changing scenario (Fig. 5). Hence we see a compelling need to offer a design with high operational flexibility. As a successor of the jumbojet the cost-economic cruise speed was set at M = 0.85 at a nominal range of 7 400 nm. The baseline will offer 530 seats in tri-class layout, while the stretched versions are expected to accommodate up to 966 in an all-economy layout, which is applicable at reduced stage lengths or even short-haul routes, for instance in Japan. The aim of the extended range version - 100 R is to tempt Pacific Rim carriers with a product, which will give non-stop flights between Hong Kong and the US east-coast or Australia and Europe - an issue which was responded recently by the A340-8 000 as well as the 777-100X.

One of the limitations of the design is wing span, which exceeds the current span limit of 65 m (ICAO Code E) based on the 747-400. The 747-X wing is aiming, however, at 79 m span [8], which is the maximum span possible to allow an UHCA to use present 747-size gates without a wingfold. Oelkers [9] has discussed UHCA design trade-offs at

DASA earlier, which showed a flexibility of span up to 90 m at European airports and a length range of 80 - 90 m. The A3XX-baseline configuration was confined to a box 80 m x 80 m so far (Fig. 6). Even this is a step in size, which will require an airport and passenger handling facilities up-grading in order to have satisfactory turn-around time.

The aircraft is technically feasible but most of the critical problems increase with size. The wing weight versus structural weight is following a square-cube-law resulting in a high sensitivity of weight changes on empty weights and design weights (weight growth factor) which may eliminate the DOC gains with increased size. Hence the implementation of new lighter materials in lifting structures are of utmost importance to reduce the factor of structural weight/MTOW well below 0.3. The large moments of inertia and short tail-arms of the double-deck configuration will create an unsufficient roll response and unfavourable trim penalties, which call for more effective control surfaces and stability augmentation systems. More efficient high-lift systems are needed to cope with more efficient take-off/landing procedures with steeper glide slope, provide sufficiently low rotation angles and reduce wake vortex effects to ensure that potential gains in passenger frequency are not greatly eroded. The landing-gear will pose also a great challenge to the vendors as it will have up to 5 % MTOW with a four-leg main landing-gear and limited steering capability to minimize tyre scrubbing.

The application of latest state-of-the-art to the aerodynamic design of an A3XX, i. e. A340 technology level, would already give an all-new design, which could surpass existing large airplanes but the size effect which usually reduces drag is counteracted by the reduced aspect-ratio (8.2 instead of 9.3) and increased trim-drag (Fig. 7). Only a trim-tank and a c. g. travel to 45 % can recover a drag level at M = 0.85, which is comparable to the A340 at M = 0.82. Further improvements are seen in a phased approach with respect to the inherent risk or maturity of the technology. At relatively low risk, an improvement potential of more than 7 % can be imagined being composed of an improved tip device, a thrust-vectoring nacelle, riblets, variable camber (VC) and a restoration of higher aspect ratio by utilizing the maximum span limits.

Intermediate risks are associated to Hybrid-Laminar Flow-Control (HLFC) on nacelles and the fin where dedicated demonstrator programs were already flown or launched within the time schedule of A3XX. Altogether this yields an improvement close to the target of 10 %. The more promising component, the wing, and the horizontal tailplane need demonstrators to be launched, which show the feasibility of the technique in operation. This is hard to imagine within the given time but configurational trade-offs should demonstrate whether a retrofit solution is feasible where the leading-edge including all systems are exchanged. As a prerequisite this requires the availability of VC on the baseline and the appropriate planform of the wing.

The advent of the transonic wing technology allowed us to increase aerodynamic performance by more than 30 % since the A300 and enabled us to offer a reduced sweep/increased thickness and hence less structural weight for a given speed/payload than earlier aircraft, that could reduce the critical Mach number mainly by increasing sweep. It appears that project methods used in sizing processes seldom reflect the changed sensitivities since these days. A comparison of current wing-designs shows, that for a given level of technology sweep is now 2.5 times less sensitive while thickness sensitivity is twice as high as the value used in the B727 case study (Fig. 8). This was also validated by a multitude of wind tunnel tests over the last decades and can be verified with modern 3D numerical methods, which describe the cross-flow in the trailing-edge region correctly.

Consequently a trade-off was performed in order to show the feasibility to maintain sweep comparable to A340 for the A3XX. Fig. 9 shows the alternative wing layouts considered, namely an increased span/aspect ratio with either 33 ° or 30 ° quarter-chord-sweep. Besides the obvious advantage to reduce weight, increase low-speed performance and alleviate aeroelastic distortion, less sweep gives a higher probability to achieve attractive laminar flow runs on such a wing.

2.2 Variable Camber

Variable camber is offering on opportunity to achieve considerable improvements in operational flexibility, buffet boundaries and performance at relatively low cost without major mechanical additives. This technique was developed in an extensive interdisciplinary research program with the A340 as lead project [10]. The principle is depicted in Fig. 10 showing, that the adaptation of the wing shape to the actual flight conditions is achieved by a small fowler motion, where the wheels of the flap carriage are guided by two individual tracks in such a way, that the flap body slides underneath the spoiler trailing edge keeping the gap closed. Thereby a linear correlation between camber deflection and fowler motion is achieved. According to this system solution, which allows only positive camber deflection the designer can relax the off-design constraints and minimize drag at low lifts. At start of cruise, step climbs, or increased weight the lift demand is satisfied by discrete flap settings resulting in the envelope in Fig. 10. A consequent adaptation to VC would take advantage of a wing/body interference optimization by reduction of wing root setting and control of limiting load cases. Because of the latter capability and the possibility to compensate structural tolerances (wing twist), VC is a prerequisite for the feasibility of an UHCA.

2.3 Turbulence Management (Riblets)

Besides HLFC, another way of boundary layer control is possible due to a reduction of turbulent friction drag by manipulation of the turbulence structure within the turbulent boundary layer. So-called riblets suppress vortex formations near the wall. A potential of 8 % friction drag reduction is envisaged from experiments on flat plates. The structure of these films is very fine, only about 0.05 mm between two ridges. The realization problems are more in the operational area, for instance the application on the surface, the cleaning, the tensile strength and degradation due to environmental effects or aggressive fluids like skydrol. A 0.7 % overall drag improvement was estimated for this configuration so far, which has to be verified. In a technology working group within the Airbus partners a flight test on an A320 was performed, which supports this target value and additionally a long term test with a Lufthansa A300-600 was conducted to check the operational aspects. Generally the method is feasible and it is a question of trade-off analysis, manufacturing and maintenance whether this technique will be applied or not. Hence this subject is not detailed further in this paper.

2.4 Thrust Vectoring

The common key to better SFC is driving the by-pass ratio to high values and thus increasing the propulsive efficiency. For the A3XX baseline there is no need for VHBR engines, as improved A330-engines (RR Trent 772) are available to satisfy the thrust requirement. The stretched versions would however need engines of GE 90 type. The installation especially on the outboard wing will create substantial interference drag, which have to be minimized by position, pylon and wing design.

In the last years a further field of drag reduction attracted the integration specialists at the Airbus partners, i. e. drag reduction by vectorized nacelles, which was successfully demonstrated in the wind tunnel [11]. Through a new type of thrust reverser a variable thrust vector can be achieved (5 ° deviation), which will be demonstrated on an A340 within the time schedule of A3XX.

2.5 Hybrid Laminar Flow Control (HLFC)

Since the 1930s aerodynamic research was devoted to laminar flow especially to LFC and HLFC. NASA's halfbillion dollar program ACEE, which began in 1976 revived the efforts in LFC significantly [12, 13, 14] and let to outstanding in-flight experiments culminating with the B757 HLFC tested [15] but no application in service so far. Todays manufacturing tolerances and new materials however have already decreased the parasitic drag level to ~ 3 % aircraft drag while it used to be twice this value 20 years ago. With these tolerances laminar flow runs of more than 50 % chord seem feasible. In 1986 a national research program devoted to Natural Laminar Flow (NLF) as a joint effort of German industry and research was initiated. It was continued as a European Laminar Flow Investigation (ELFIN I, II), which focussed on HLFC also and successfully demonstrated the feasibility of HLFC with leading-edge suction devices in the S1 wind tunnel. A flight test on the A320 with a HLFC-Fin is currently under preparation for early 1997.

In Fig. 11 the relationship between wing sweep, Reynolds number and leading-edge (L. E.) radius is shown. NLF by shaping the airfoils is confined to the region left of the boundary, which is supported by the successful flight-tests with the VFW614-ATTAS and Fo 100 aircraft, which carried laminar wing gloves. Airbus category aircraft beyond 100 pax require HLFC where the boundaries are not yet known precisely.

The different modes of laminar-turbulent transition on a swept wing require different optimum pressure distributions to obtain laminar flow runs of the desired extent. Boundary layer profiles on a swept wing can be splitted into a profile in direction of the outer flow and a cross-flow profile which exhibits a maximum shear close to the wall. In relation with these profiles there are three different modes of instability which may cause transition to turbulent flow, namely:

- the amplification of a plane disturbance wave in the main flow direction, termed Tollmien-Schlichting instability (TSI)
- the cross-flow instability (CFI)
- the attachment line transition (ALT)

The transition location as a function of pressure distribution, Reynoldsnumber and sweep angle is quite different for the three modes and it is of utmost importance to accurately predict the transition location and find a good compromise with respect to off-design cases. For the prediction of TSI, efficient empirical criteria are available and for ALT the Poll-criterion seems to work also at high Re-numbers [16].

For cross-flow instability the only access is to use the stability theory for laminar boundary layers. The solutions of the Orr-Sommerfeld equation, which is a two-dimensional disturbance equation in direction of the disturbance wave front, are amplification ratios for disturbance waves of different wave length, frequencies and propagation direction. The integration of the amplification rates yields the amplitude ratio at each point of the airfoil. This is an exponential function e^N, where N = ln (A/Ao) is the factor to be determined by correlation of stability analysis and experiment. For the calculation of the N-factors, the SALLY-Code was developed [17, 18] which is valid for incompressible parallel flow without curvature effects. More recently a compressible code with curvature effects named COAST was developed at DA [19].

In this scope limiting N-Factor bands were determined by correlating measured transition loci from flight-test and wind tunnel, which can be used for further designs provided the pressure distribution type is kept and the two modes are more or less decoupled. The research activities have shown, that suction confined to the region before the front spar can reduce cross-flow instability significantly but the achievable laminar flow runs are then determined by TSI again, which can be controlled only by large negative pressure gradients. The gradient is however increasing with Re-number thus creating significant wave drag even at the design point. One goal of the configurational optimization is hence to find a compromise with less sweep as mentioned above.

Before HLFC technology can be applied to an aircraft, a multidisciplinary effort in the best sense of concurrent engineering has to be made (Fig. 12) to

- find a good compromise for high-speed off-design with VC, and find solutions to sustain sufficient maximum lift and handling qualities
- find solutions for anti-icing and insect decontamination
- minimize installation space for suction system and high-lift system
- design and test the suction system in-flight and find a productionized solution with minimum required suction power and quality assurance of suction panels (hole geometry, pressure losses)
- minimize production costs and define a new wing manufacturing process guaranteeing the required tolerances
- Convince the authorities and airlines

The latter can only be achieved by flying demonstrators and in-service evaluation. Hence the presumptions in Fig. 7, where only HLFC nacelles and a fin were assumed until EIS of the A3XX.

As a first approach to a laminarized wing a system layout is schematized in Fig. 13. Variable Camber is needed to control the pressure gradients and attachment line on the wing. A Krüger system is used for high-lift as it can be used as insect shield also. Suction is confined to the region outboard of the kink in the first step and probably on the upper-surface only. Suction on the lower side behind the Krüger requires a very small gap/step there. Furthermore laminarity will be reduced by pylon interfaces, engine noise, access panels and flap-track fairings. For de-icing, bleed air is blown in reverse direction through the suction system. Such a system is foreseen to be demonstrated on an A340 wing-glove demonstrator in the framework of the European more efficient aircraft program (3E).

III. Aerodynamic Development Concept

The aerodynamic design of a transport aircraft with transonic wings requires configuration iterations through repeated wind tunnel test loops. Yet, CFD methods are becoming more important in the predevelopment phase in order to limit the number of iterations. The efficient 3D flow simulation code MELINA based on the Euler- and Navier-Stokes equations is used instead of the wind tunnel in a hybrid design strategy [20] using a direct-inverse design code [21] for residual correction of the section design towards a desired 3D pressure distribution. Fig. 15 illustrates this design cycle, which allows the designer to sort out different design philosophies and increase the maturity of the design for experimental verification as limited budget and time frame confine these experimental cycles to a minimum [22]. Further enhancements are possible through the implementation of a 3D-residual correction method based on the N. S. equations. Earlier applications of numerical optimization at DA were not so convincing [21]. A breakthrough was achieved by a new approach of van der Velden [23] who coupled a combination of a genetic/simplex-optimizer with an aero-shape function based on Joukowsky transforms. This optimizer was also used in the design of first UHCA wings in a multi-point design mode.

In the aerodynamic development concept for the UHCA three branches can be identified, a turbulent fixed camber wing (TFC), a turbulent variable camber wing (TVC) and a HLFC wing with VC (Fig. 14). At first a trade-off in sweep/thickness is performed to select a planform. Then follows an iterative improvement including engine integration in order to have mature designs to be compared when a decision has to be taken whether a HLFC wing in turbulent mode is a good starting point, and a retrofit of the L. E. at a later stage of the program is feasible. In the high-lift development a feasibility of a HLFC glove on a DNW model with a Krüger flap and high-Re checks of a HLFC and TVC wing with Krüger or slats leads to a decision on the L. E. device, which has to be further optimized on a large model in DNW. The rear-end development focusses on the comparison of turbulent tails with HLFC tails in order to verify the tail-stall boundary and efficiency at high Mach number in turbulent mode before a HLFC tail is selected. Wind tunnel testing must be supported, however, by flying test-beds in order to investigate stability limits with suction and operational aspects such as decontamination of insect debris and anti-icing.

IV. Design of a Turbulent Reference Wing

4.1 Verification of the First Reference Wing Designs

The first turbulent fixed camber design (TFC1) used a planform with AR 9,3, φ_{25} = 33 ° (Fig. 9). As a reference served the A340 wing with same AR but three degrees less sweep. The design goals were to shift the dragrise to M = 0.85 and achieve the same drag as the A340 at M = 0.82 and reference lift coefficient.

In the course of the design cycle the aforementioned hybrid design strategy implementing the 3D-N. S. code evolved, as the available tools failed due to the strong viscous effects and the upper surface contours, which require very small curvature changes to sustain a nearly shock-free flow.

Wind tunnel results were very encouraging as the predicted pressure distribution was nearly achieved and the drag target also. Fig. 16 shows the pressures vs. span at five stations from the test at M = 0.85, which is close to the initial cruise lift for the - 200 version. The shock strength is very moderate outboard, while inboard a certain waviness is observed on the upper side. This slight trend to a double shock wave is to be eliminated in the next step. As regards drag Fig. 17 clearly demonstrates, that exactly the same drag as on the reference (model wings were scaled to same wing area) but for ΔM = 0.03 was established with a gain at lower lifts and small deficiencies at higher lifts. The α_0 is higher which is beneficial for rotation, but trim drag is increasing due to the higher pitching moment. The aerodynamic efficiency $M*L/D_{opt}$ from these tests is given in Fig. 18, as well as the dragrise boundary (20 drag counts increase with respect to M = 0.6 at C_L = const., 1. d. c. = 0.0001). The TFC wing is enveloping the reference completely and the optimum is shifted by 0.03 in Mach.

This is also valid for the dragrise with the exception of the bucket at lifts below 0.4 where the inboard double shock emerges and for extremely high lifts. The target shall be achieved with the modification in pressures already shown in Fig. 16.

As a second step the trade-off in sweep was performed. A new wing (TFC1.1) with slightly adapted pressures for the higher normal Mach number was designed for the planform in Fig. 9 with AR 9,3, φ_{25} = 30 °, which is almost the same than on the A340. The thickness was only reduced by 0.15 % in average according to the sensitivities discussed earlier. The result was very convincing as the aerodynamic efficiency in Fig. 19 shows (trimmed and scaled to flight). The TFC1.1 is equivalent in performance at cruise Mach number and towards MMO despite its reduced sweep and both TFC wings offer an improvement of more than 4 % compared to the reference A3XX-100 with AR 8.2.

An interdisciplinary trade-off on the wing planforms in Fig. 9 was then initiated to show the effects on aeroelasticity, weights and performance.

4.2 Aeroelastic Deformation

One major issue of these large structures is structural stiffness and already for the Airbus A340 the elasticity effect on performance was not negligible. With increasing MTOW the influence of elasticity has to be taken into account for weight estimates as it reduces wing weight [24]. A high aspect ratio of the wing improves the aerodynamic performance. On the other hand, the increase of the aspect ratio leads to a growing weight, higher elastic distortions and premature aileron reversal.

Preliminary estimates have shown a very large aeroelastic twist for the UHCA preventing us initially to apply an aspect ratio as high as on the A340. A follow-on study gained momentum after the successful demonstration in the wind tunnel of the aerodynamic concept having less sweep.

During the A340 development & certification phase a method was validated with A340 flight-test results to predict the aeroelastic twist from jig-shape to flight-shape. This is accomplished by iteratively coupling of a 3D transonic potential code with a 3D boundary layer, using a structural model which can be a simple beam model with a mass-/ stiffness-distribution or a FEM model. It was found, that the elastic twist could be predicted with a tolerance of 0.1 degree compared to in-flight measurements.

For the A3XX datum wing with AR = 8.2, elastic twist of 3 - 3.8° was calculated depending on altitude (Fig. 20). This is almost comparable to the A340, so we were encouraged to reconsider the aspect ratio. The corresponding values for the TFC1 wing (AR 9.3, φ_{25} = 33°) are increased by 0.4° at the tip whilst the TFC1.1 (AR 9,3, φ_{25}=30°) achieves nearly the same values than the datum wing. The reduced sweep compensates the AR effect completely and hence a recommendation arose to adopt the new planform for the project. In-depth aeroelastic investigations with refined structural models (FEM) also with respect to flutter cases will be continued. Especially the application of carbon fibre for the outboard wing could reduce the elastic distortion to even lower values than for the reference.

4.3 Effects on Cruise Performance

Besides the clear advantage in L/D and the fairly small influence in static aeroelasticity the wing weight will increase due to the higher aspect ratio. This can be reduced by reducing the sweep. Despite this increase in OWE, the cruise performance is still in favour of the higher aspect ratio/span. For a mission of 7, 400 nm all three wings were using an optimal step-cruise-climb schedule. The result in Fig. 21 clearly shows that about 2 % block fuel reduction is possible for the $\varphi_{25} = 30°$, AR = 9.3 wing. This is about 5 t of fuel, which is very attractive not only from the DOC point of view. It is an asset for the ecological balance also, because a fleet of up to 900 UHCA would save several million tons per year depending on utilization (Fig. 3). Hence a significant reduction in NO_X will be achieved.

The study will be continued in order to have a complete picture, also taking into account the recurring cost aspect for the manufacturer.

V. Design of a HLFC Wing

5.1 Basic Airfoil Design

Following the general criteria discussed in chapter 2.5, a basic laminar airfoil was designed and transposed into a 3D wing concept for the UHCA. In the HLFC concept, suction is assumed in the region before the front spar (20 % cord), which can suppress cross-flow instability. Sufficient laminar flow runs in the box region are then determined by TSI again, which can be achieved by a pressure distribution which accelerates the flow (Fig. 22). The figure already points out the problem of significantly higher recompression gradients towards the T. E. A careful analysis of different recompression types, i. e. degressive (Stratford) or progressive, and the magnitude of rear loading must be carried out in order to avoid separation. Especially at higher Mach numbers the shock-wave boundary-layer interaction may offset the gain in friction drag. Off-design cases with fully turbulent flow should be feasible without significant separations and lift losses, thus evoking unfavorable handling characteristics.

Compared to an optimum turbulent airfoil with a weak shock, the HLFC airfoil looses considerable lift on the upper side at a given α having already a higher wave drag. The search for a higher attainable lift is then a compromise between feasible rear-loading, thickness and achievable laminar flow run with acceptable wave drag. In off-design conditions laminarization effects tend to reduce, due to either pronounced suction peaks at lower Mach number and corresponding Tollmien-Schichting instability (TSI) or significant wave drag increase at higher Mach numbers. This adverse effect must be avoided and a comprehensive tool for this purpose is available with the Variable Camber (VC). The VC envelope is achieved at nearly constant angle of attack, which is beneficial for the HLFC airfoil also as the attachment line does not vary. Hence, suction chamber layout is simplified.

A typical HLFC airfoil design A is compared in Fig. 23 for a design Mach number of 0.82 and Re = 35.10^6 with a conventional turbulent airfoil B. The HLFC airfoil is offering a 20 d.c. reduction (- 32 %) with 40 % laminar flow on the upper side and 50 % on the lower side (The equivalent suction power has to be subtracted from this figure). In turbulent mode it is equal at lifts below 0.5 and M $\leq$ 0.82. At higher Mach number it has a higher wave drag as the turbulent one, which can only be alleviated with VC. A design process of a HLFC airfoil as illustrated in Fig. 24 is then clearly dominated by off-design constraints and VC implementation. The basic design starts with an optimization with respect to TSI at constant suction level as there is a minimum N-Factor with increasing suction for TSI. Then follows an optimization of suction for cross-flow and ALT, which requires an increase towards the nose. In this context it may be necessary to modify the nose shape also to achieve a sufficiently low level in NCFI at the nose and damping downstream. Once this basic design is established, off-design calculations including a variation of VC flap geometry have to be carried out in order to reduce the wave drag penalty, and to sustain attached flow in turbulent mode. An overall optimum can therefore be a design with somewhat reduced laminar flow areas on the upper surface (40 % instead of 50 %), if no additional means of wave drag reduction, as for example passive ventilation or a surface bump, are considered.

5.2 First HLFC Wing Design

Based on the planform of the successful TFC1.-1 wing with reduced sweep ($\varphi_{25} = 30°$, AR = 9.3) a first HLFC wing was designed to gain knowledge about its specific problems, demonstrate it in the wind tunnel with transition free and fixed and offer an aero-specification for the systems group. The basic airfoil was transposed to the higher Mach number 0.85 and used in the kink region as a generator airfoil. In the course of the design-cycle, the Navier-Stokes code was intensively used as well as the optimizer, which yielded a solution of acceptable thickness, which would probably not have been found with the classical sorting through pressure distribution variations. Yet, the design lift coefficient had to be lowered to 0.45, which would result in a significant wing area increase unless VC is applied.

Due to the very high Reynolds number the aforementioned compromise a reduced laminar flow extent was necessary. Fig. 25 shows the calculated transition with COAST. The decrease towards the root is inherent in the design as the generator airfoils at 21.7 % span and root gradually transformed the HLFC airfoil into a turbulent one. The root will in any case be turbulent and the continuation of the pressure distribution would lead to a strong aft shock, almost normal to the fuselage. Given a large wetted area of the inboard wing, this would reduce the gain of HLFC substantially. In a first step the system concept envisages suction only outboard of the kink (Fig. 13).

A result of a N. S. calculation clearly shows this pressure distribution concept with a shock-free inboard wing and moderate to stronger shocks outboard, but a substantially larger laminar flow extent (Fig. 26). From this distribution the required suction rates were determined as an input to the systems concept (Fig. 27). This wing will be tested in a high-speed wind tunnel soon in order to verify the pressure distribution and measure drags with transition fixed at the transition loci predicted for full scale. Initial results from the N. S. code showed a ~4,9 % drag reduction potential (suction drag included).

This is a considerable improvement for a single technology, but less than expected from earlier publications [25]. These were, however, confined to a design condition similar to our example A at considerably lower Mach/Reynolds number. The attainable HLFC improvements are obviously a function of aircraft size, but a figure of the aforementioned order is still attractive for an UHCA and would save some 10 t of fuel per flight. Even though a practical application on the first UHCA is unlikely, as the necessary flight demonstrations will not be finished and evaluated before box freeze, it seems worthwhile to continue a trade-off for a later retrofit with a L. E. suction system in view of such improvements and the asset for the ecology.

VI. Landing-Gear Design and High-Lift System Alternatives

The landing-gear design needs special attention on such a giant aircraft as it will weigh ~ 5 % MTOW, with limited steering capability to minimize tyre scrubbing. Initial studies on this issue were reported in [9] where four to six-leg tandem bogeys were investigated. The datum aircraft features now a 4-leg design with two wing-mounted and two body-mounted 6-wheel bogeys, which give an improved growth capability with respect to runway loading (Fig. 28). The rotation angle limits shown in the side-view impose a major problem on low-speed aerodynamics.

Initial estimates of different high-lift configurations have indicated already that:

- o the A3XX-100 could retain a Slat/SSF system
- o the A3XX-200, however, is rotation angle limited.

Therefore a DSF system is considered eventually in combination eventually with a TSF inboard

- o a Krüger flap can compensate the drag penalty of the DSF at take-off while maintaining the max. lift of a slat version (see Fig. 30).

A potential arrangement is shown in Fig. 29. Moreover, the advanced high-lift system could optimize the lift distribution during take-off by means of a twisting outboard flap/fowler flaperon in order to enhance L/D and reduce vortex wake effects. Vortex wake hazard to following aircraft is receiving increasing attention and a European collaborative research project Eurowake will be started in 1996. Potential gains in passenger frequency through higher capacity aircraft could be greatly eroded if vortex wake effects are not reduced.

A first check of L. E.-stall-criteria has shown, that the HLFC airfoil A is close to the boundary of prevailing L. E. stall where a short bubble exists with a potential risk of bubble burst. Fig. 31 shows a computational result of the clean C_L-α curve with respect to the turbulent reference airfoil. The loss in α_{max} of more than 3° and the abrupt stall characteristic is not acceptable. A first L. E. modification was designed thereafter with a combination of radius and camber increase resulting in a flattened nearly constant pressure zone on the lower surface in high-speed. As the Krüger flap will be positioned there with no suction device, it has to be checked whether such a constant pressure zone is overrun by the boundary layer without premature transition. The change in stall behaviour, however, is still too small. Hence the HLFC wing introduction greatly depends upon a successful low-speed design, which minimizes the short fall in max. lift. Additional wing area will be needed to compensate this. Earlier investigations on NLF wings at DA [26] had shown that despite the lower maximum lift of the clean configuration, a similar lift with deflected flaps than a conventional wing due to the much thicker flap and more favorable flap pressure distribution was achieved. A similar conclusion is drawn in [25]. Experimental investigations of such trade-offs at high-Re are necessary and foreseen in the development concept.

VII. Stability and Control Aspects

Handling qualities are of paramount interest in the design process of an UHCA from the very beginning. Due to this fact the specialist departments started already in the feasibility phase to set up a data base for handling qualities including elastic effects.

The horizontal tailplane layout is one crucial point, because a conventional trimmable tail will require a large area due to the short tail-arm. With 5 % stability margin a tailplane area of 24 % wing area is needed, i. e. a stabilizer close to the size of an A310 wing (!), which needs to be actuated via multiple jacks (Fig. 32). The structural integration in the rear-end and the sealing of the gap throughout the trim-setting range constitutes a major challenge to structural designers. Hence alternatives are being investigated; namely a:

- fixed horizontal tailplane with different elevator designs
- three-surface aircraft with a movable canard

Fixed stabilizers need slightly higher area, but gain structural weight through a simplified rear-end structure. Controllability can be achieved by slotted elevators , double-hinged elevators or double-segment elevators, which need to be split over the span in two segments. This will necessarily result in a higher complexity of the actuation system, that must be fail-safe with a failure rate of 10^{-9}/h. A favourite candidate is the double-hinge elevator where the first element serves for trim and the second for manoeuvre or VC-function of the tail (Fig. 33).

An attractive alternative for such a double-decker seems to be a three-surface configuration proposed by AI with a movable canard surface (Fig. 34). For c. g. positions beyond 25 % this configuration is statically/dynamically unstable and needs a close loop stability augmentation system through the feedback gain of the flying canard and the HTP elevator inputs per change of α. Further canard functions are trim through canard setting and control through a camber flap. Canard size and HTP size are defined by controllability in low-speed and allow an overall reduction of tail area (canard + HTP) by 8 % while the wing area is significantly reduced by 11 % due to the almost negligible trim loss in lift. The overall saving potential in MTOW of > 5 % and reduced trim drag results in a block fuel reduction of 6.5 %, which is the highest potential discussed so far for a single technology.

It is important to note, that as in all canard layouts, the wing is subject to the distorting trailing vortex shed from the foreplane. This has to be compensated by a camber adaptation on the inboard wing, i. e. a VC system is needed. As the TSA was recognized as a very promising technology a flying demonstrator, especially for the verification of the control laws, is currently under consideration, which shall by flown on an A340 test-bed.

As the outboard aileron will have poor efficiency, also with respect to aeroelastic effects, a review of roll control power was initiated early. It turned out, that the low-speed 60 ° bank angle, to be rotated in 7 seconds including acceleration time, is critical in clean configuration due to poor aileron efficiency and the large moment of inertia. Various alternatives were investigated and for the time being a most attractive alternative with 13 % higher roll rate is seen in the combination of aileron, spoilers and a taberon on the outboard flap, which are anyway incorporated in the VC-system for spanwise load and L/D control (Fig. 35).

VIII. Conclusions

In the feasibility phase of an Ultra-High Capacity Aircraft, technology concepts were investigated to improve the overall efficiency and reduce weight as the weight-growth factor is a critical issue.

Referred to a baseline aircraft with state-of-the-art technology, a drag improvement potential of more than 10 % at an intermediate risk level was identified. A major contribution to this is the restoration of a high aspect ratio, as in-depth studies supported by wind tunnel results showed the feasibility of a lower sweep/high aspect ratio wing with similar aeroelastic distortion, but better cruise and field performance than the datum wing.

Hybrid laminar flow is offering a high drag reduction of more than 7 % (including nacelles, fin, tailplane and outboard wing) in a first step. Before HLFC technology can be applied to an UHCA, 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. A phased approach is under way with a laminar A320 fin flying in 1997, and an A340 glove demonstrator thereafter. A first HLFC wing was designed and system lay-outs were considered, which could be installed later in a retrofit package, as the first design showed an equivalent turbulent drag level for the design Mach number. Variable Camber is a prerequisite for a HLFC wing to control the pressure gradients and the off-design behaviour.

Variable Camber is engineerable at relatively low cost [10] and is already a powerful tool for the turbulent baseline to enhance the operational flexibility and reduce weight through the reduction of limiting load cases. Moreover it can compensate structural tolerances (e. g. twist).

Advanced high-lift systems were highlighted, which can reduce rotation angles significantly while maintaining a high take-off L/D through a spanwise load control and/or a Krüger device, which can serve as an insect shield for HLFC also.

Finally an overview of tailplane sizing aspects and roll control was given. A substantial gain in block fuel and weight could be seen in a three-surface-aircraft. Special attention must be paid to the control law verification with a demonstrator and the suppression of interference affects on the wing for which again a VC system is the best tool. Roll control in low-speed was found to be marginal, which can be improved by a taberon, that is part of the VC concept.

The conclusion can finally be drawn, that an UHCA is feasible with current technology. Significant improvements can be achieved by a phased approach to new technologies. As trade-offs have shown the feasibility of a low sweep/high aspect ratio wing, the probability of a later retrofit with HLFC is given, provided a Krüger flap is existing on the baseline and VC also, which is a keystone for a variety of further technologies.

IX. Acknowledgements

The author likes to thank the staff of the aerodynamic design office for their valuable contribution as well as the departments for theoretical aerodynamics (potential flow, viscous flow), who contributed a variety of new codes and took part in the validation with experiments. A multidisciplinary design work on the different wing concepts in the best sense of concurrent engineering was made possible by the cooperation of the project, weights and systems engineers, aeroelastic experts and flight mechanic specialists to whom the author extends his special thanks.

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XI. Figures

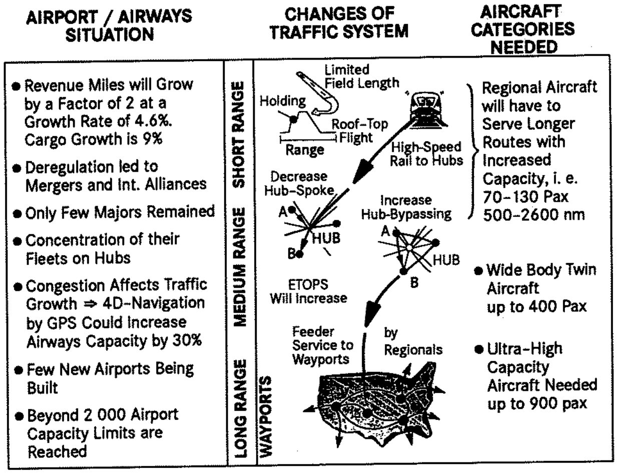


Fig. 1 Airline/Airways-Szenario 2014

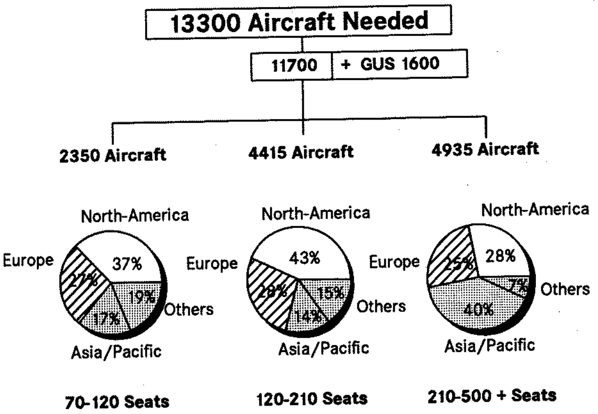


Fig. 2 Market Potential of Civil Aviation until 2014

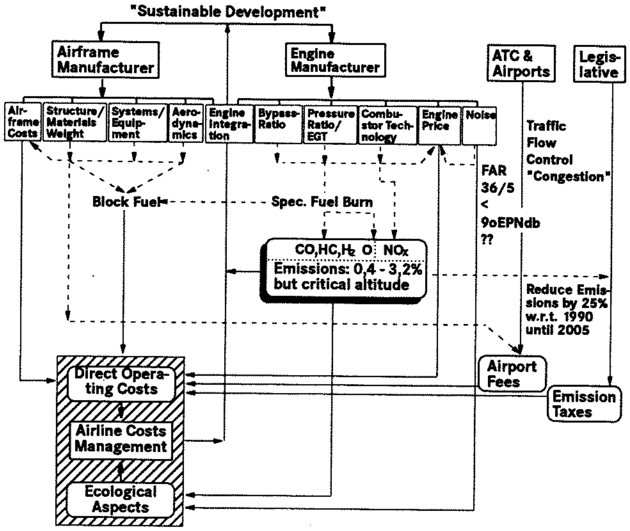


Fig. 3 Economical and Ecological Influences

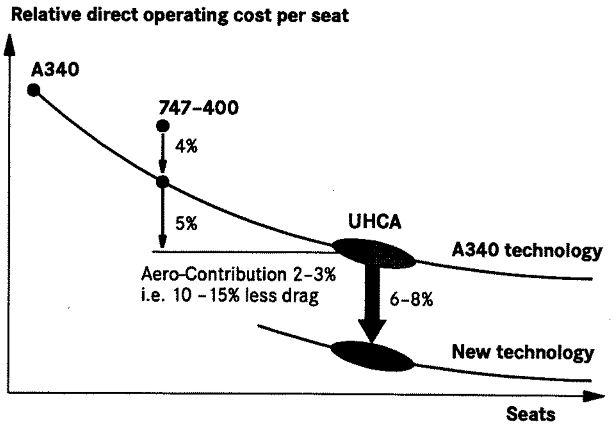
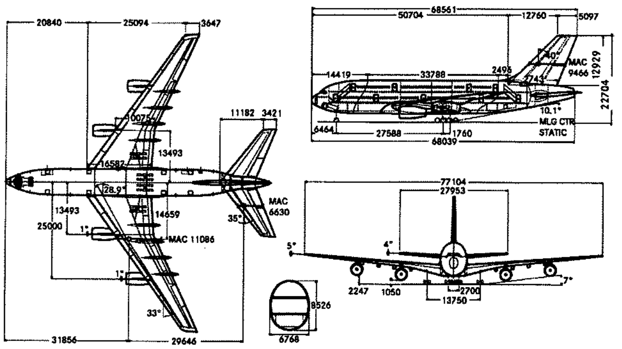


Fig. 4 DOC Targets for an UHCA

ITEM	A3XX-100	A3XX-100 R	A3XX-200	A3XX-300
Passenger Capacity 32" 3cl-Layout Typical Single Class	530 854	530	630 966 (6000nm)	700
Range	7400 nm	8400 nm	7400 nm	~ 7000 nm
Cruise Speed MMO	M_{CR} = 0.85 (99% SR, 35000 ft 0.88 Av. Cruise Weight)			
Initial Cruise Altitude Max. Altitude	35000 ft Baseline/31000 ft Max. Stretch 41000 ft			
Take-off Distance	≤3000 m (9842 ft) S. L., ISA + 15°C, MTOW			
	≤ 12000 ft (Denver) S.L. + 5330 ft, + 31°C TOW for 5500 nm			
One Engine Out Ceiling	≥20000 ft			
Approach speed 1.3 Vs_{min}	140-145 kts (Max. Stretch)			
Thrust (klbs) SLST Engine Option	66 Klbs RR Trent 772		71 Klbs CF6-80E1-A3 up to GE90	

Fig. 5 Design Requirements for A3XX Family Concept



SEATING CAPACITY THREE CLASS HIGH DENSITY	530 APPROX 810 APPROX
ENGINE-NO./TYPE	RR TRENT 772
THRUST EACH	68000 LBF

Fig. 6 A3XX Baseline Configuration

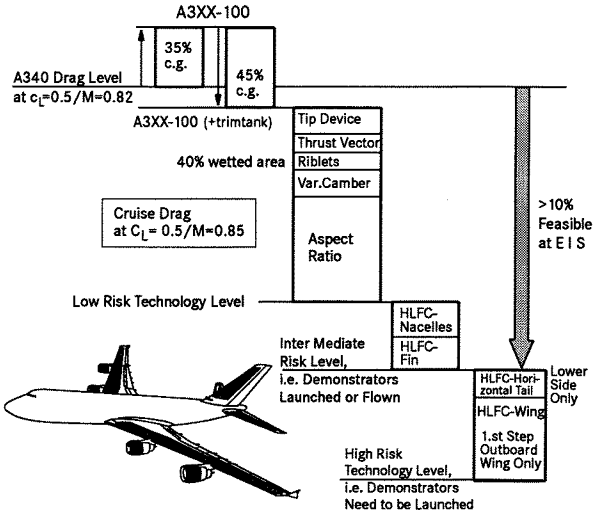
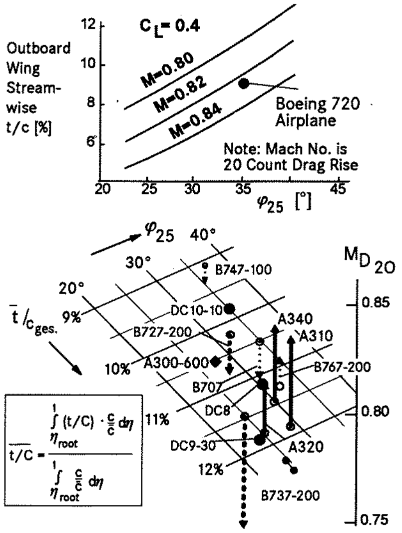


Fig. 7 Improvement Potentials through Aero-Technology



$$\overline{t/C} = \frac{\int_{\eta_{root}}^{1} (t/C) \cdot \frac{c}{\bar{c}}\, d\eta}{\int_{\eta_{root}}^{1} \frac{c}{\bar{c}}\, d\eta}$$

$$\frac{\partial M_{D_{20}}}{\partial t/_c} = \frac{0.0114}{1\%}$$

$$\frac{\partial M_{D_{20}}}{\partial \varphi_{25}} = \frac{0.0033}{1°}$$

Wing Sweep-Thickness Trades 1960
From: AIAA Case Study
A/C Design Boeing 727

$$\frac{\partial M_{D_{20}}}{\partial t/_c} = \frac{0.025}{1\%}$$

$$\frac{\partial M_{D_{20}}}{\partial \varphi_{25}} = \frac{0.00125}{1°}$$

Wing Sweep-Thickness Trades of State-of-the-art Wing Designs

Note: A Flag Up/Down Means a Higher/Lower Divergence Machnumber Than Expected From φ_{25}/t/c
⇒ Technology Level

Fig. 8 Wing Sweep/Thickness-Trades

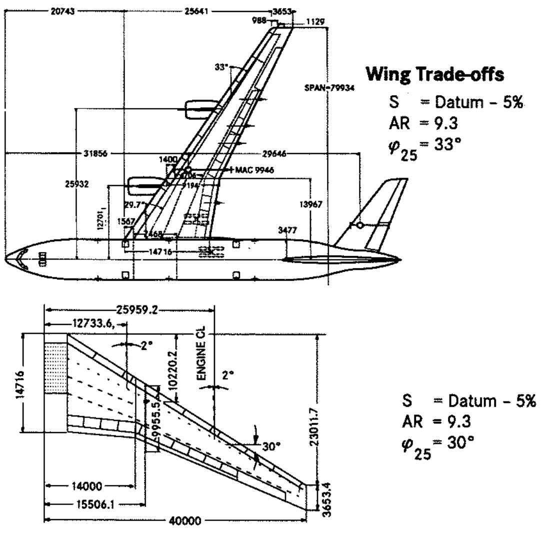


Fig. 9 Alternative Wing Layouts

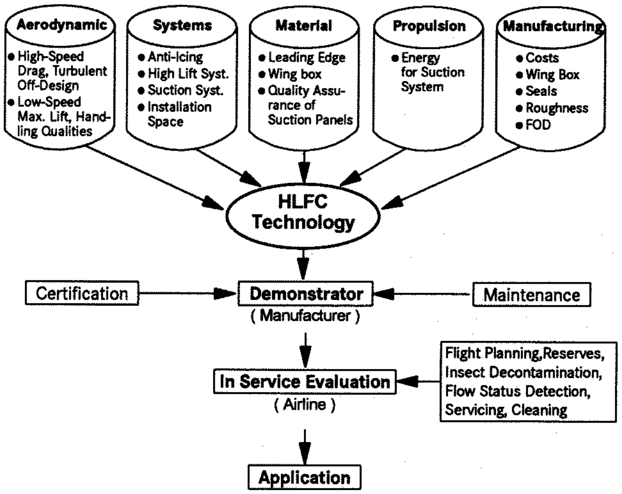


Fig. 12 HLFC - A Multidisciplinary Technology

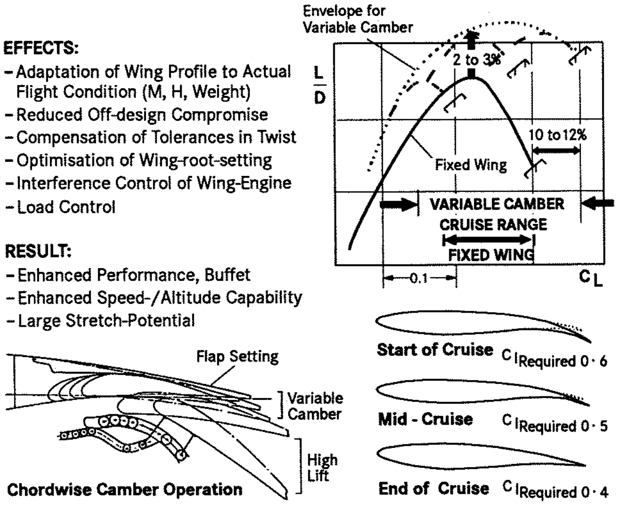


Fig. 10 Principle of Variable Camber Operation

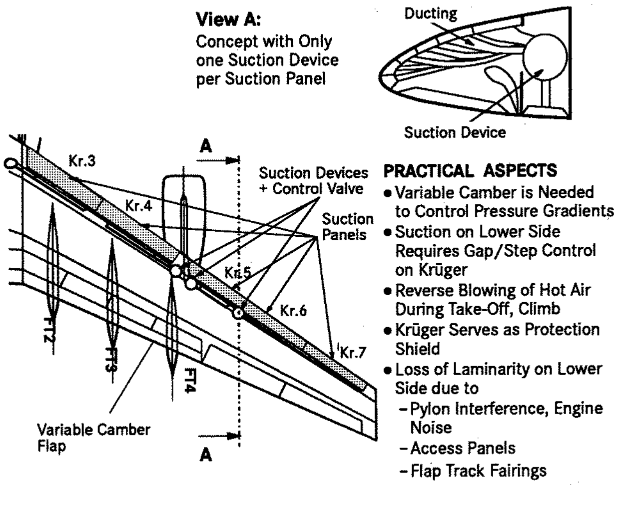


Fig. 13 Practical Aspects of HLFC-System Layout

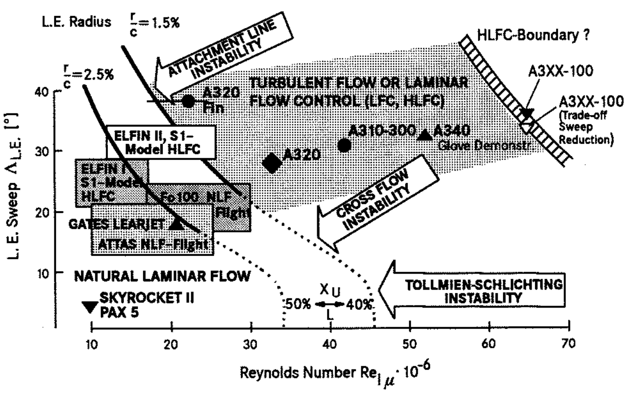


Fig. 11 Boundaries for Laminarization

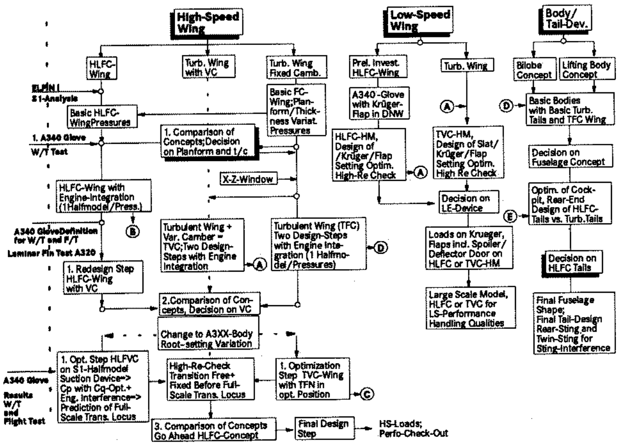


Fig. 14 Aerodynamic Development Concept

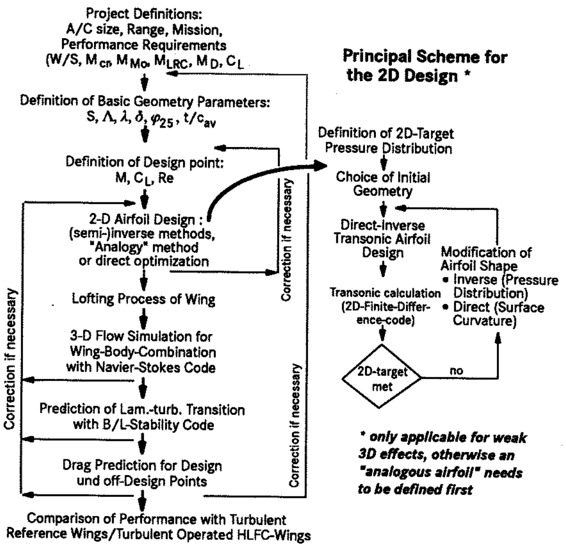


Fig. 15 Aerodynamic Design Cycle

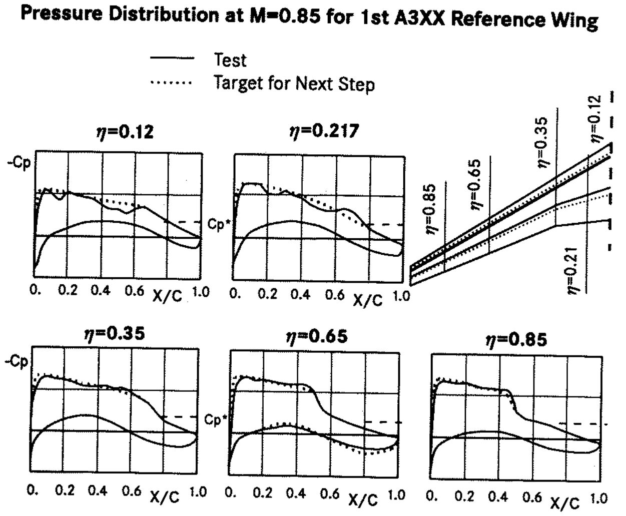


Fig. 16 Pressure Distribution for Turbulent Reference Wing

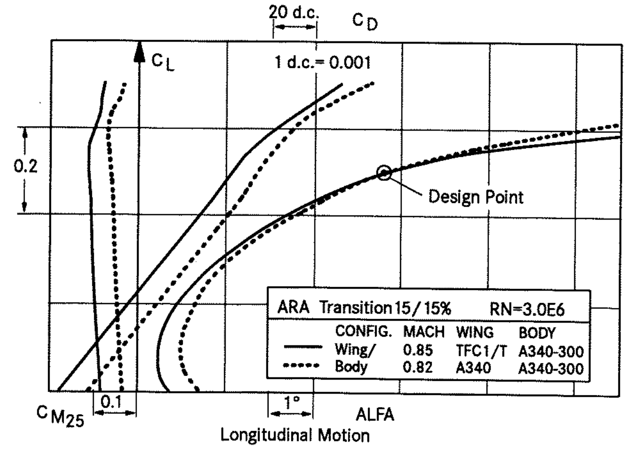


Fig. 17 Longitudinal Motion of Turbulent Reference Wing

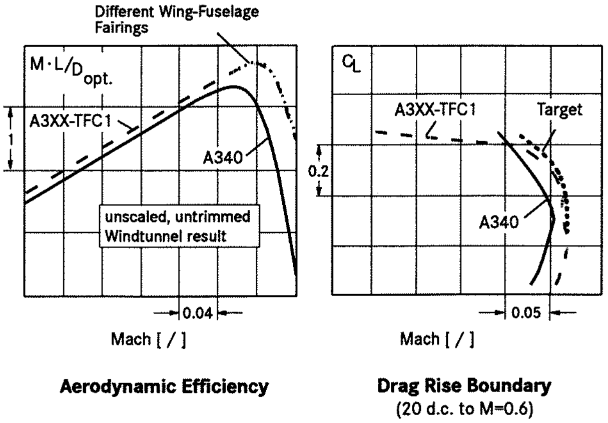


Fig. 18 Aerodynamic Properties of Turbulent Reference Wing

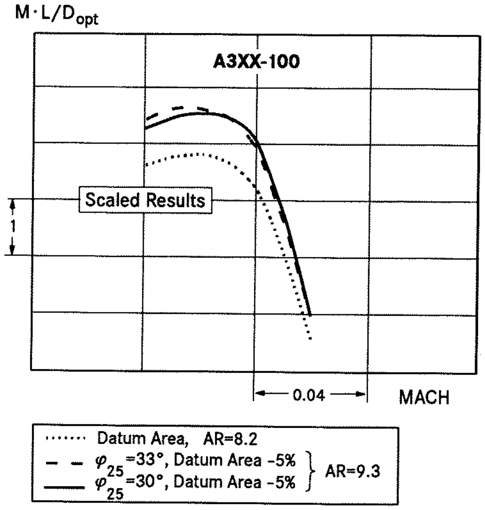


Fig. 19 Scaled Aerodynamic Efficiency of Alternative Wings

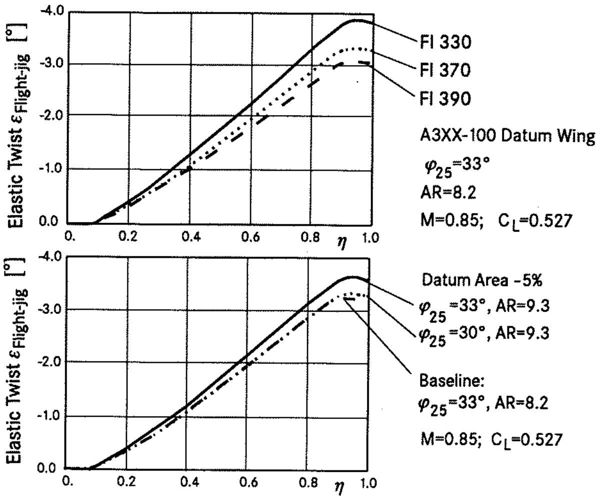


Fig. 20 Aeroelastic Twist Jig-to-Flight

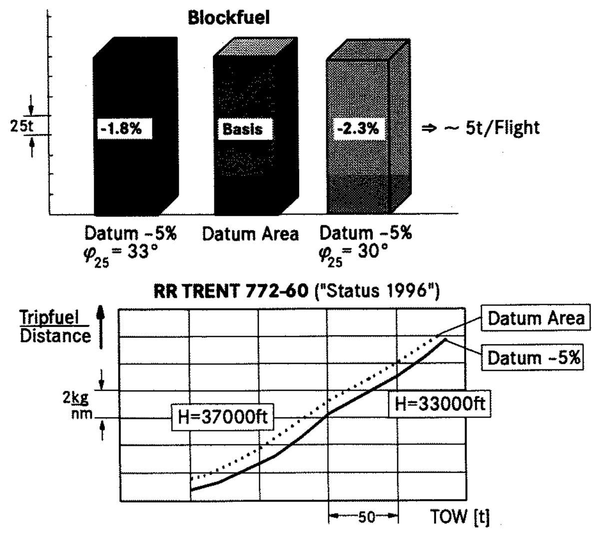


Fig. 21 Comparison of Cruise Performance

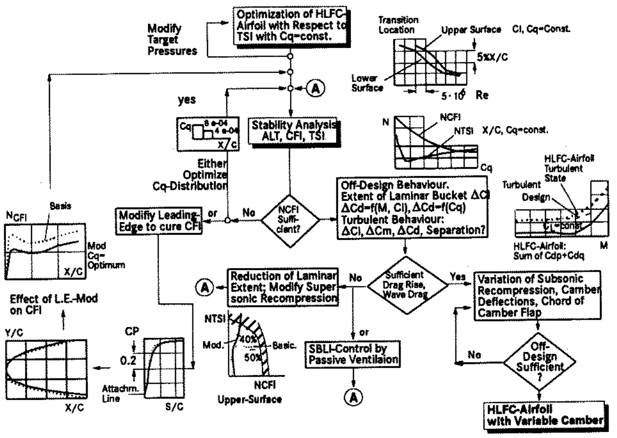


Fig. 24 Design Process of a HLFC Airfoil

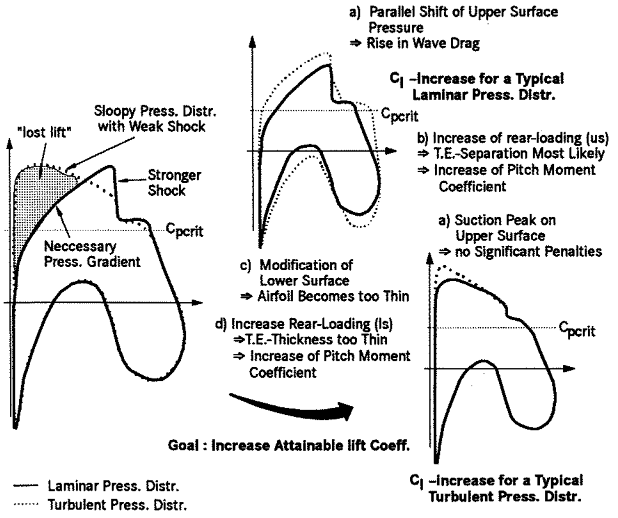


Fig. 22 Basic Design Differences between Laminar vs. Turbulent Design

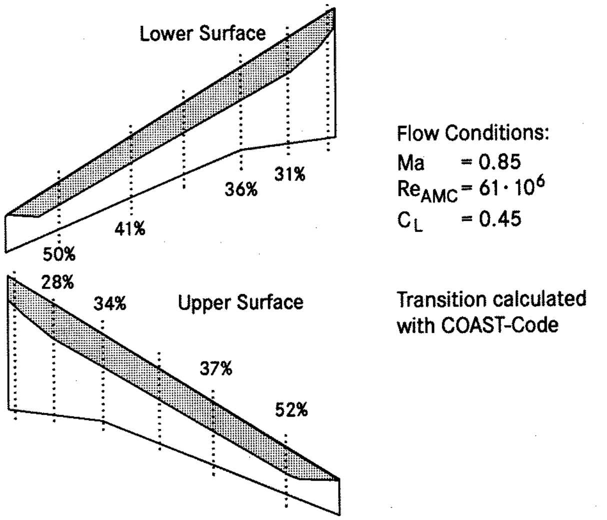


Fig. 25 Calculated Transition Lines for HLFC Wing with COAST

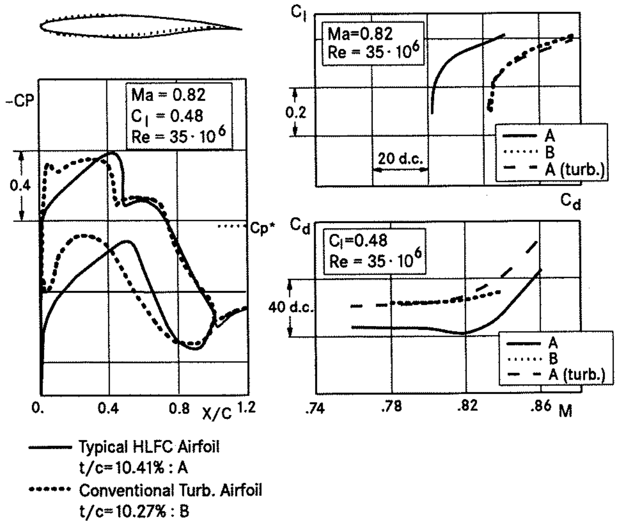


Fig. 23 Comparison of Turbulent and HLFC Airfoil

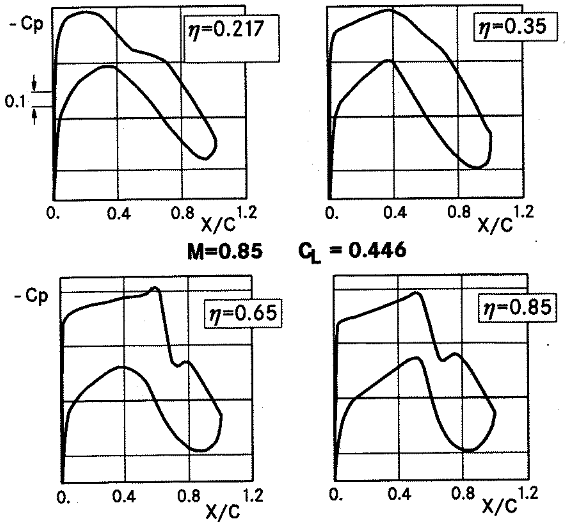


Fig. 26 Navier-Stokes Calculation on HLFC Wing

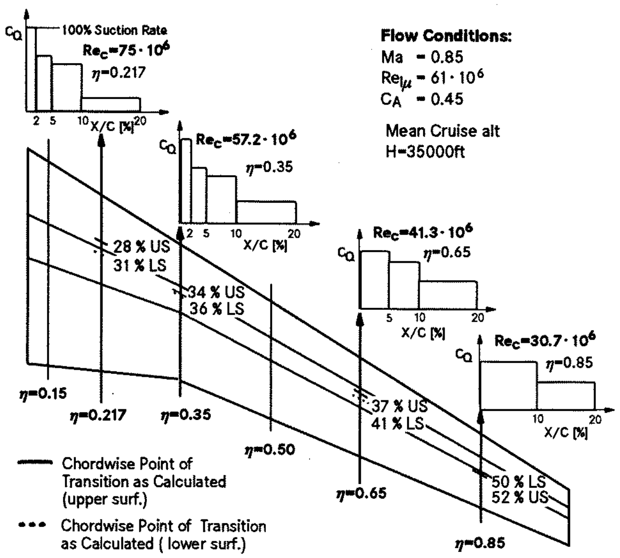


Fig. 27 Estimation of Suction Requirements

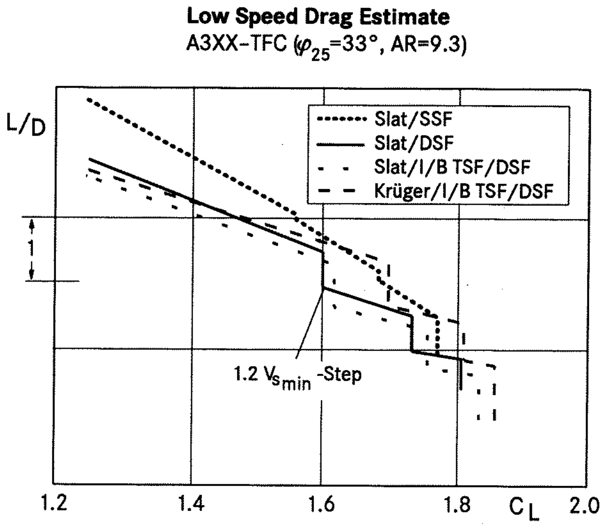
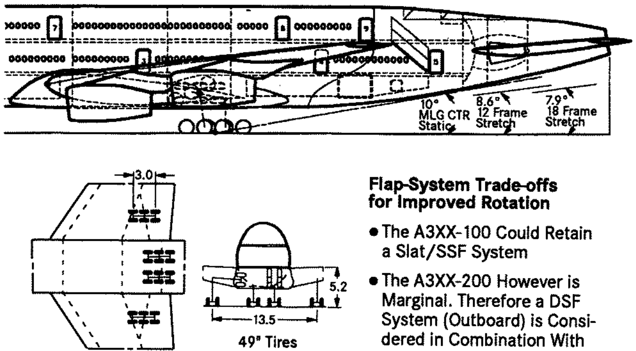


Fig. 30 Low-Speed L/D Estimates



- 4 Leg Design
- 4 × 6 Wheels
  ⇒ Improved Growth Capability

Flap-System Trade-offs for Improved Rotation

- The A3XX-100 Could Retain a Slat/SSF System
- The A3XX-200 However is Marginal. Therefore a DSF System (Outboard) is Considered in Combination With a TSF Inboard
- A Krüger Flap Can Compensate The Drag Penalty at Take-off While Maintaining the Max. Lift.

Fig. 28 Landing Gear Design and Flap System Trade-offs

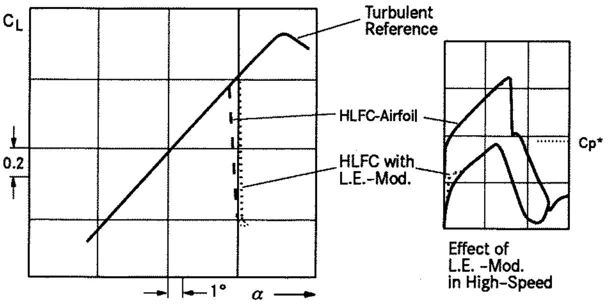
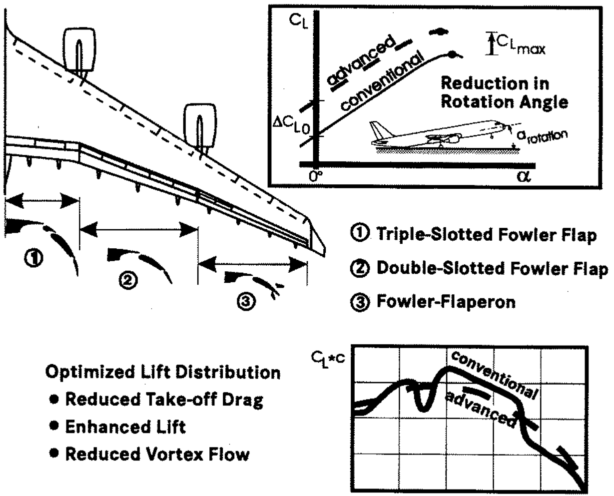


Fig. 31 Stall Behaviour of HLFC Airfoil



Optimized Lift Distribution

- **Reduced Take-off Drag**
- **Enhanced Lift**
- **Reduced Vortex Flow**

Fig. 29 Improved High-lift System Concepts

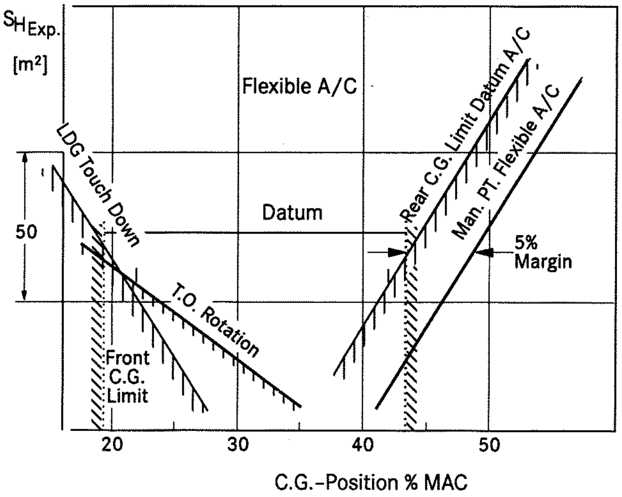


Fig. 32 A3XX Horizontal Tailplane Sizing

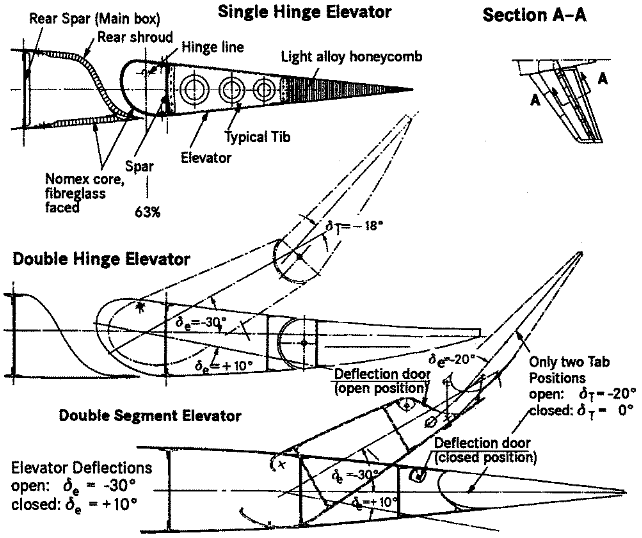
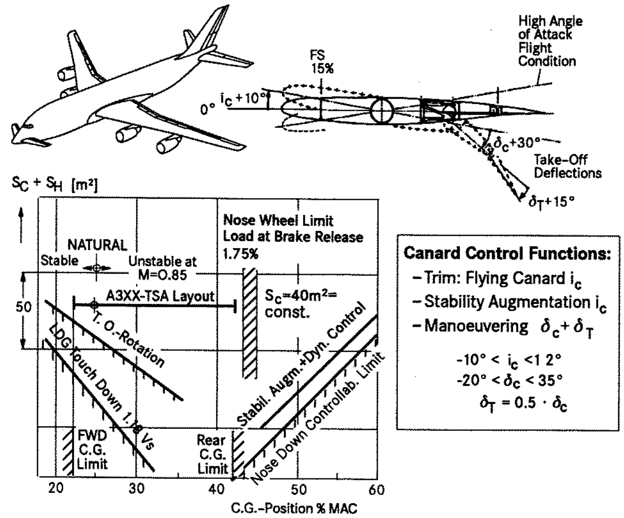


Fig. 33 Alternative Elevator Concepts for Fixed Tail



Canard Control Functions:

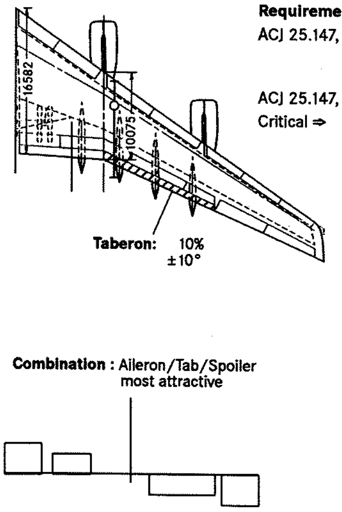
- Trim: Flying Canard i_c
- Stability Augmentation i_c
- Manoeuvering $\delta_c + \delta_T$

$-10° < i_c < 12°$

$-20° < \delta_c < 35°$

$\delta_T = 0.5 \cdot \delta_c$

Fig. 34 Three-Surface Configuration



Requirements :

ACJ 25.147, (c) (2) : 60 deg. bank 11 seconds,
one engine inoperative,
Airspeed: V2

ACJ 25.147, (e) : 60 deg. bank 7 seconds,
Critical ⇒ all engines operative,
Airspeed : V2 => VMO/MMO

Maximum Control Deflections :

Ma = 0.20 (Low Speed, Clean)

Ailerons:	± 25 deg.
Spoilers:	35 deg.
Tabs:	± 10 deg.

Combination : Aileron/Tab/Spoiler most attractive

Ailerons/Spoiler Arrangement is marginal taking acceleration into account
⇒ Improvement of
~13% in roll rate possible

Fig. 35 Roll Control Concept