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AERODYNAMIC DESIGN OF AIRBUS HIGH-LIFT WINGS IN A MULTIDISCIPLINARY ENVIRONMENT

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***Abstract**: Aerodynamic design plays an important role in this process as the concept selection, layout definition and major constraints for the following disciplines as systems, structures and manufacturing are heavily influenced by aero design considerations. Knowledge based engineering shape design tools and fast & advanced computational methods (CFD) are besides the windtunnel the major tools in use for design definition & verification. Fast and reliable CFD-methods allowing a quick evaluation of numerous design modifications as well as advanced methods capable to predict the complex flow around a complete aircraft in high-lift configuration are part of the design process. The ongoing development in grid-generators' and CFD-codes' capabilities to cope with complex configurations in combination with available computing power is currently leading to a significantly increased use of CFD as a tool for high-lift design tasks. As example for the multidisciplinary aerodynamic design process an extensive overview of the aerodynamic design work conducted for a "Megaliner" aircraft is given.*

0 NOMENCLATURE

c	Wing element chord
C_D	Drag coefficient
$C_{L,max}$	Maximum lift coefficient
CFD	Computational fluid dynamics
DOC	Direct operational cost
DSF	Double slotted flap
FAR	Federal airworthiness requirements
L/D	Lift to drag ratio
Ma	Mach-number
SSF	Single slotted flap
t	Wing element thickness
T/W	Thrust to weight ratio

T_{rev}	Reverse thrust
W/S	Wing-loading
α	Aircraft angle of attack
μ	Ground roll friction coefficient

1 INTRODUCTION: HIGH-LIFT DEVICES FOR TRANSPORT AIRCRAFT WINGS

For every wing design of modern transport aircraft the need for a high-lift system exists. With such a solution a design best adapted to cruise performance requirements but also capable to meet the airfield requirements is possible. Various concepts and approaches for high-lift systems are possible. On modern transport aircraft the use of mechanically moveable high-lift devices is common practise.

An example for the design of the high-lift-system of a modern transport aircraft with leading and trailing edge devices is shown in Figure 1. The shown A319 wing uses slats as leading edge devices and single slotted Fowler flaps as trailing edge devices.

Figure 1: Airbus A319 wing in high-lift configuration

For swept wing aircraft operating with transonic speed the combination of a leading edge device and a trailing edge device is the common solution. However, the high-lift systems on existing aircraft types include different approaches (figure 2 and 3).

As leading edge devices slats and Krueger-flaps (or a combination) are common. The slat is normally deployed on circular tracks and opens up a slot to the main wing. The Krueger-flap is folded out of the lower part of the wing and moved in front of its leading edge. An other possible solution is a hinged nose or droop-nose device which deploys similar to a slat but does not open up a slot to the main wing. All leading edge devices act in a similar way; maximum lift is increased by an extension of the flyable angle of attack region.

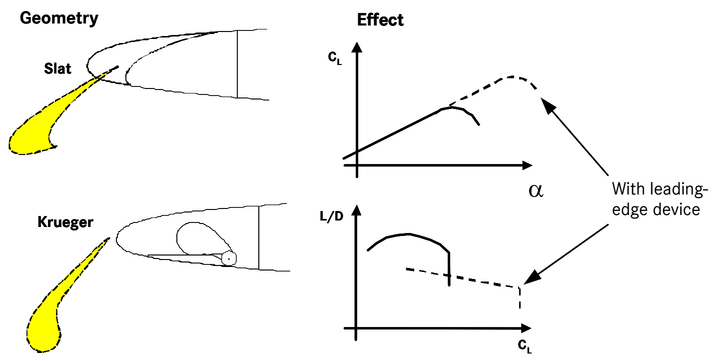

Figure.2: Leading edge devices

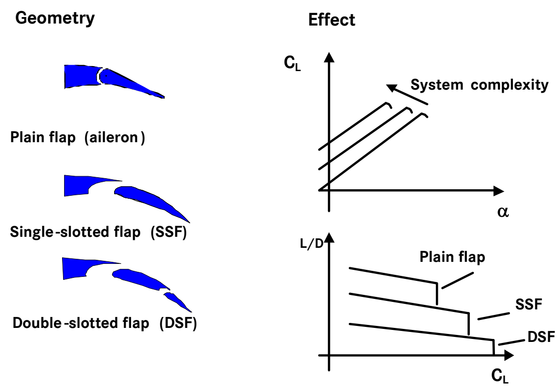

Figure 3: Trailing edge devices

As trailing edge devices Fowler-flaps are the common solution. The Fowler-motion, i.e. the rearward movement when deflecting the flap, leads to an increase of the effective wing area. Fowler-flaps are designed as slotted flaps. The interaction between such close arranged elements leads to an effective increase of lift compared to a profile with a plain flap without slot. With double-slotted or triple-slotted flaps further lift improvement is possible but for the price of higher system complexity. A flap deflection increases lift in the linear region of the lift polar and the maximum lift. Various possibilities in system to provide the Fowler-motion when deflecting the flap are possible. A 'dropped hinge' providing a circular deployment of the flap demands only low system complexity but also only limited Fowler-motion. Solutions with large Fowler-motion are possible when moving the flap with a carriage on a track with a rear linkage steering the deflection. These solutions are common for modern aircraft but demand a high system complexity and weight.

Powered high-lift systems (e.g. externally blown flaps), designed especially for military transport aircraft, showed an impressive maximum lift potential beyond the performance of the familiar conventional high-lift systems. However, for civil transport aircraft the passive high-lift systems remain standard mainly because of complexity, weight and cost reasons, but also because of sufficient existing runway lengths and certification rules for high lift systems on civil transport aircraft (i.e. the aerodynamic performance has to be maintained without engine power).

2 CONSTRAINTS FOR THE DESIGN OF HIGH-LIFT WINGS FOR TRANSPORT AIRCRAFT

The request for maximum efficiency measured by the direct operating costs (DOC) drives the layout of a transport aircraft. Target aerodynamic requirements as cruise speed, range, cruise altitude, climb capability and buffet boundaries directly influence the wing design parameters such as sweep, area, aspect ratio, span loading, thickness and twist. But also structural constraints like weight and manufacturability have to be taken into account. The chosen wing layout directly influences the necessary high-lift system to meet the required airfield performance. E.g. a small wing area is beneficial for cruise performance but requires a complex high-lift system to deliver sufficient maximum lift. As another example the sweep angle directly influences the maximum performance of the high-lift system and therefore again its complexity. High-lift wing aerodynamics is strongly influenced by the effects on and requirements of other disciplines, mainly systems and structures. The final wing solution therefore is to be understood as the best achievable compromise between the requirements from all interacting disciplines, which has to be developed in an iterative design process.

Decisive for the needed aerodynamic characteristics (i.e. maximum lift, lift at zero incidence, drag, pitching moment) of the wing in its different high-lift configurations is the requested flight performance for take-off and landing. The performance requirements are defined by different constraints, such as take-off and landing weight, runway length, climb gradient and approach and landing speed [1].

For the different flight conditions with wing in high-lift configuration the following correlations exist:

Take-off-performance:

$$\text{Acceleration distance on ground} = f\left(\frac{T}{W}, \frac{W}{S}, C_{L_{Max}}, C_D, \mu\right) \quad (1)$$

$$\text{Climb rate in 1st and 2nd segment} = f\left(\frac{T}{W}, \frac{L}{D}\right) \quad (2)$$

The FAR rules state that a minimum climb gradient must be maintained even in the case of an engine failure (2 engine configurations: 2.4°, 4 engine configurations: 3.0°)

For a reduction of the total take-off distance the ground acceleration distance has to be minimised whereas the climb rate has to be maximised. The acceleration distance on ground is influenced by thrust to weight ratio (T/W), wing loading W/S, maximum lift CL,max, aerodynamic drag CD, and friction drag μ from ground rolling.. For the climb gradient in the

1st climb segment and 2nd climb segment (after retraction of the landing gear) from these former parameters only the influence of the thrust to weight ratio remains of importance. The influence of the aerodynamic characteristics of the configuration is now described by the lift to drag ratio (L/D). For a minimum take-off distance it follows for the aerodynamic parameters that the lift to drag ratio and maximum lift have to be maximised while the drag and the wing loading have to be minimised.

Landing performance:

$$\text{Approach angle} = f\left(C_{L_{Max}}, \frac{W}{S}, \frac{L}{D}\right) \quad (3)$$

$$\text{Deceleration distance on ground} = f\left(C_{L_{Max}}, \frac{W}{S}, C_D, \mu, T_{REV}\right) \quad (4)$$

$$\text{Climb rate for go around} = f\left(\frac{T}{W}, \frac{L}{D}\right) \quad (5)$$

For a minimum total landing distance the approach angle has to be maximised and the deceleration distance on ground has to be minimised. In landing configuration the approach angle is influenced by maximum lift, lift to drag ratio and wing loading. For a steep glide path the approach angle should be large. The minimum required by FAR-rules is 3.0°. Therefore the lift to drag ratio in contrast to the take-off configuration has to be low. As the typical approach speed is fixed between 130 and 150 kts, the required maximum lift is also a constraint, i.e. the drag has to be increased for a larger approach angle. Further the wing loading should be low in landing configuration, which is opposed to the requirement for a high wing loading in cruise. The deceleration portion of the total landing distance can be minimized by utilizing effective brakes (friction drag μ) and reversed thrust (Trev). However the demand for high drag in landing configuration is in conflict with the FAR-requirement for the go around case, which is comparable to the required climb gradient for a high lift to drag ratio in the take-off 2nd segment climb (here 3.2° with all engines operative).

Following dependencies were found in [2] for the impact of the high-lift performance of the total aircraft performance for a typical twin-engine jet transport aircraft:

- 5% increase in maximum lift leads to 12-15% increase of payload
- 5% increase of take-off L/D leads to 20% increase of payload
- 5% increase of maximum lift in landing configuration lead to 25% increase of payload

Such relations are strongly dependant from the aircraft configuration. In many cases an improvement in aerodynamic wing performance cannot work beneficially for aircraft performance improvement the because of existing limitations.

E.g. the existing clearance angle of the tail could limit the maximum useable incidence by the danger of tailstrike on ground. This incidence limits then the maximum incidence of the wing in operation and therefore also the maximum useable lift of the wing. If the maximum angle of attack of the wing before flow separation occurs is higher the associated additional maximum lift potential could only be used by a taller landing gear. This on the other hand could compromise an improvement in payload by its higher weight.

In another example it could be possible that a solution provides a needed maximum lift improvement but increases also the take-off drag. Because the climb angle is dependant on lift to drag ratio this drag increase could now lead to not fulfilling the minimum climb rate requirement any more. In such a case although maximum lift was increased, the lift performance improvement would not lead to an overall improvement because other requirements, like low drag for a required minimum L/D, are now limiting the useable performance potential.

Besides providing the needed performance the wing in high-lift configuration also has to fulfil the handling quality requirements. For all configurations an acceptable controllability when encountering the flow separation in maximum lift must be maintained. For this reason no flow separation in the outboard region should occur on the wing at high angles of attack. Otherwise a loss of aileron efficiency and an additional pitch up moment, leading then to even stronger separation, would cause unacceptable behaviour of the configuration. The design of the high-lift wing must ensure that the maximum lift limiting separation occurs in the inner or mid region of the wing.

System complexity is a further field of importance, which is a very strong driver for weight and cost. E.g. a triple-slotted trailing edge flap (three single supported and driven elements) provides very good lift performance but leads to a high weight and also high system complexity, from which expensive manufacture and intensive maintenance needs with the resulting high costs follow. In many cases it could be more attractive for a well-balanced overall solution to choose a less complex system (e.g. a single slotted flap). This can result in an overall advantage for the aircraft coming from its weight and cost benefits although its aerodynamic performance is worse.

3 HIGH-LIFT WING DESIGN AT AIRBUS

3.1 Tendencies and experiences

Figure 4 shows the evolution of Boeing, Douglas and Airbus high-lift wing trailing edge concepts from B707 until today [3]. The effort is visible to reach a design fulfilling the aerodynamic requirements with minimum system complexity. While B727, B737 and B747 designs contained triple slotted flaps, double slotted flaps are applied on B757. B767 and B777 have a combination of double slotted and single slotted flaps. The Airbus wings contain double slotted flaps on A300 and A310 while the later designs A300-600, the A320-family (with the exception of the stretched A321) and A330/A340 work with full span single slotted flaps.

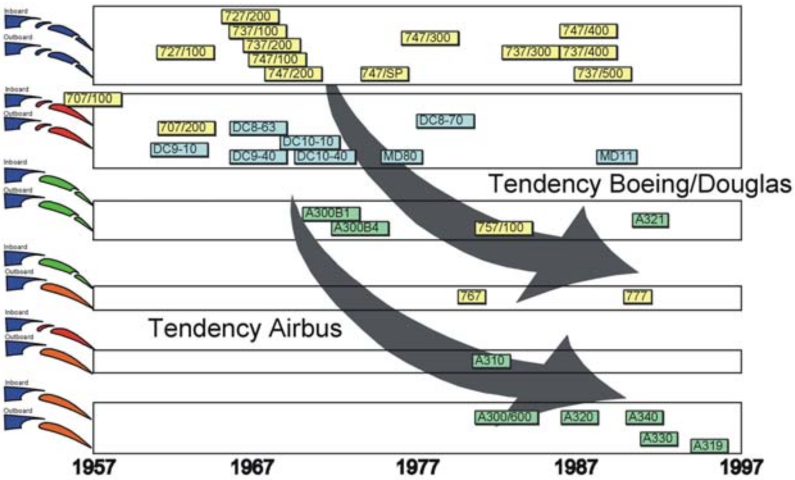

Figure 4: Design evolution of high-lift wing trailing edge systems [3]

One reason for the sufficient performance of the full span single slotted flaps on Airbus high-lift wings can be linked to the high-lift wing planform layout [4]. The wing layout may require a high-speed aileron in the inner wing region behind the engine in addition to the outboard aileron [5], [6]. This results in a discontinuity in the deployed trailing edge flap. This gap has a ‘thrust gate’ effect, minimising the interference between flap and engine flow but also heavily degrading the effectiveness of the trailing edge devices. The occurring lift loss has then to be compensated by a more effective but therefore also more complex trailing edge system.

The newer Airbus designs do not include such a high-speed aileron any more. Therefore a continuous flap is possible and a less complex system delivers sufficient performance. But the deletion of the inner aileron requires the outboard aileron to have sufficient effectiveness for roll control and trim in high-speed flight without any aileron reversal tendency due to the elasticity of the wing structure. Therefore the needed span of the outboard aileron limits now the maximum flap span. Further, without the thrust gate in the flap system, higher jet interference drag can result when engine flow interferes with the flap in the go around case with the landing configuration when flaps are still fully deployed. This additional drag could lead to problems in maintaining the necessary climb gradient in go around cases. The Airbus experience in high-lift design work confirmed these problems being controllable.

Introducing a stretched version of an existing aircraft (e.g. the A321 derived from the A320) may lead to problems fulfilling the performance requirements (runway length, take-off and landing speed) with the given high-lift wing. The stretched fuselage leads to a reduced tail clearance angle while the maximum take-off while landing weight is increased. In order to avoid an increase of the landing gear height the need for a modification of the layout of the high-lift wing can arise. On the A321 a double slotted flap replaced the A320 single slotted flap with only minor changes to the cruise wing planform and the wing box structure. For a shortened version (like A319 and A318) the baseline high-lift wing is 'over-designed', which could lead to a reduction of the maximum needed flap setting. A possible simplification of the system (e.g. less complex actuation mechanism or reduced flap span) could also be possible but is not beneficial from the family concept point of view in wing manufacture. It must be highlighted that a 'too targeted design' of the high-lift wing is not attractive when considering the wing as being a basis for an aircraft family. The initial design should enable a stretched version without system change but should not lead to an extremely over-dimensioned system for a shortened version.

The slat has found broad application especially on newer high-lift wings as a leading edge device with low complexity. Although the Krueger-flap has aerodynamic advantages, mainly in drag, the complex linkage mechanism enabling the folding of this device out of the lower surface of the cruise wing makes it unattractive. The slat solution therefore became standard for all Airbus high-lift wings.

With the increasing bypass ratio of modern turbofan engines the nacelle has to be placed closer to the wing as a tall landing gear with its large weight impact has to be avoided. Therefore a continuous slat as on the A300 and A310 was not possible on the A320 and A330/A340. The necessary gap in the leading edge device in the region of the wing-pylon junction in addition with the local effect of the flow around the nacelle may affect the maximum lift. Modifying the pylon shape to minimize the gap between the extended slat and the pylon can be necessary. Another solution to bridge the gap in the slats across the pylon may be a small Krueger-flap.

3.2 Tools for the design process

Based on the cruise wing geometry the high-lift wing is designed for meeting the performance requirements. Figure 5 shows the variety of effects occurring on a high-lift wing and limiting its performance. Viscous effects play the dominating role. The maximum lift of a well-designed high-lift profile is always limited by the onset of flow separation on the main wing or the leading edge device. However, on a realistic wing in most cases local disturbances cause the maximum lift limiting separation even before the maximum lift capability of the wing profiles is reached. The optimum setting of the high-lift elements is also strongly dominated by viscous effects. The thickness of the shear layers determine the effective gap between the elements, wherein a confluence of the wake of a leading element with the boundary layer of a following element may lead to a strong degradation of the ability of the boundary layer to withstand separation. The location of transition on the elements with its impact of the development of the boundary layer may play therefore also an important role.

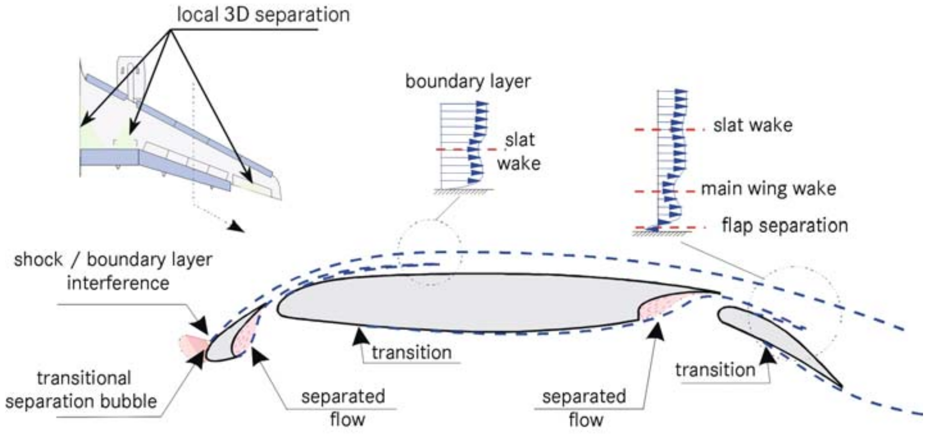

Figure 5: Flow phenomena on a high-lift wing

In the development of previous Airbus high-lift wings the major work was based on windtunnel experiments. Theoretical methods suited for the use under the tight time constraints of the design process were only available for 2D-section design in the past. The assessment and optimisation of the 3D-wing was then performed on experimental basis.

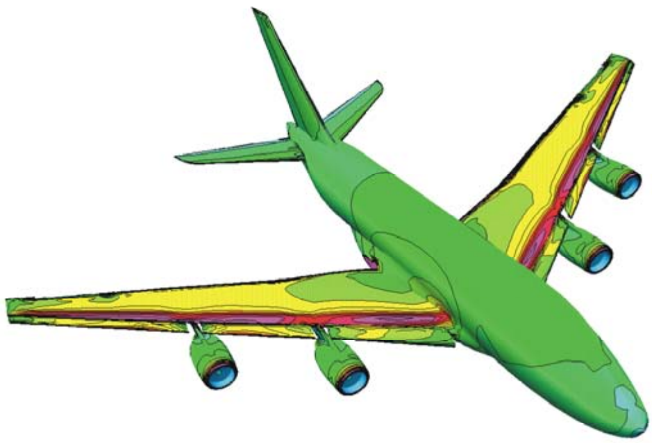

Figure 6: Flow analysis for the complete high-lift-configuration

At the Airbus aerodynamic design department a CFD infrastructure was established in the last years for being capable of capturing the task of the Megaliner high-lift wing design [7]. The principle for CFD-based design is the use and combination of methods with complexity end expense appropriate to the momentary design task in a 'chain of methods'. According to the advance in the definition of the high-lift wing, 2D-calculations for section design are complemented with quasi-3D calculations (coupling of a 2D-method with a lifting surface method) for assessment of the complete wing performance and finally with full 3D-calculations for the evaluation of the complete aircraft in high-lift configuration (figure 6).

Several methods were established in the last years including an advanced 3D panel-method, and a 2D Navier-Stokes method. Also successful applications of automated optimisation tools coupled with a 2D-Navier-Stokes code were made.

Besides the CFD methods, wind tunnel experiments are of critical importance to assess the performance characteristics of the theoretically designed high-lift wings as well as the final configuration selection. In Airbus high-lift wing design several windtunnels are used. The Airbus low speed windtunnels in Bremen/Germany and in Filton/UK serve for configuration evaluation and selection. The high-lift configuration can be tested in Bremen with powered turbine or propeller simulation as half model (figure 7) while in Filton the assessment of the configuration as complete model is conducted. In the German-Dutch Windtunnel DNW in Emmeloord/NL tests follow on a large complete model. Powered turbine simulation is also possible as well as tests with empennage and tests under sideslip conditions and in ground effect (figure 9). With flow physics being especially on high-lift configurations very sensitive to the Reynolds-number as flow similarity parameter further experiments have to be conducted for verification tasks at high Reynolds-number conditions. For those far more expensive high-Re tests pressurised (e.g. F1 in Toulouse/France or Qinetiq-5m in Farnborough/GB) or cryogenic windtunnels (KKK in Cologne/Germany) or a combination of both (ETW in Cologne/Germany) are used.

Figure 7: Megaliner complete-model in the DNW-LLF windtunnel

4 EXAMPLE: THE MEGALINER HIGH-LIFT WING

4.1 Requirements

The Megaliner-configuration Airbus A380 (figure 8) is designed to become the worlds largest civil transport aircraft. It represents a complete new aircraft development. Different to the new Airbus A340-600 it is not based on an already existing aircraft design and therefore is not fixed on the use of existing parts of the basic version. The A380 with its planned derivatives rather represents an own aircraft family, which will serve the market for aircraft larger than 450 seats. The basic version A380-800 will have a take-off weight of 560 tons and a typical payload of 66 tons (according to 555 passengers) can be carried over a range of up to 14800 km. The cruise speed is defined with a design-Mach-number of Ma=0.85. The stretched version A380-900 and the freighter A380-800F will have an increased maximum take-off weight of 590 tons.

Figure 8: 'Megaliner'-configuration Airbus A380

To be compatible with the existing major airport infrastructure the A380-wing has to be equipped with a high-lift system, which enables service on available runway length (i.e. with a take-off distance target of < 3350m) and operation in the given air traffic control requirements.

For the first time a limitation of the wingspan to 80m as a wing design constraint was given for keeping the ability to operate on the existing airport infrastructure. The design of the cruise wing had to be adapted to those constraints. The necessary wing area of the developed design is 845m^2. However, because of the span limitation the resulting aspect ratio is with 7.5 lower than on previous Airbus wing designs (aspect ratio of A340-300: 9.3).

Compared to the existing Airbus wings the high design-Mach-number of Ma=0.85 required a higher sweep angle. The maximum quarter-chord sweep on the Megaliner wing is 35.7° while on the A340-300 wing (designed for Ma=0.82) it is only 29.8°. Further, especially in the outboard region of the wing, a very low relative thickness of the profiles was necessary while using a pronounced rear loading on the lower surface trailing edge. Thereby the design constraints for the integration of the high-lift system in the given cruise wing shape became more critical.

4.2 The aerodynamic design work for the Megaliner high-lift wing

The Megaliner high-lift design was performed under the previously discussed requirements and had to result in a simple layout with sufficient performance for all members of an aircraft family [9]. This means the design was always considering also the geometrical and weight constraints of a stretched version of the aircraft. Based on the experience gained especially on the A340 wing a slat as leading edge device and a single slotted Fowler flap as trailing edge device were selected in the pre-design of the configuration as the baseline solution.

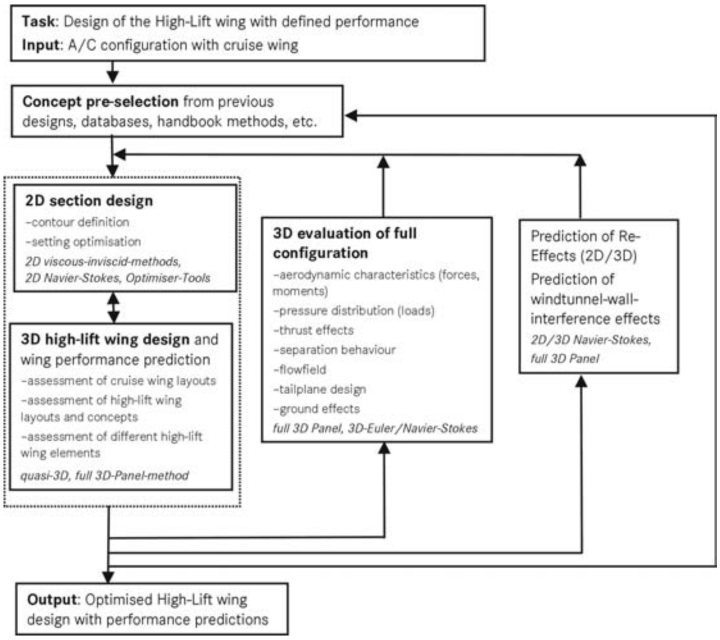

Figure 9: Sequence of the CFD-based high-lift design process

The sequence of the CFD-based high-lift design process is sketched in figure 9. Especially the availability of the quasi-3D-method allowed the evaluation of a large number of high-lift wing concepts and variations without any experimental work. With this approach far more studies and comparisons have been performed, as the previous design infrastructure with use of mainly only 2D-CFD for contour design verification would have allowed to. CFD helped to start testing with an already pre-optimised design, which reduced the expense in testing, respectively allowed a deeper and more targeted optimisation in windtunnel. Parallel to the windtunnel based work-studies of alternative designs and design variations were performed in order to ensure ‘being in the right track’.

For a selected high-lift wing design the evaluation of the complete aircraft followed. A fast commercial 3D-viscous-panel method (VSAERO) with ‘in house’-developed extensions was used. These extensions contain various ways for predicting the strong viscous effects like flow separation a panel method by basic definition cannot capture. 'Fast' empirical criteria as [10] but also extensions for the prediction of separated flow effects with the modelling of the separated wake and its interaction on the flowfield were used. A fast input geometry generation for high-lift wings was developed and enabled the quick assessment of the aircraft, e.g. for the prediction of the complete aircraft aerodynamic performance, aerodynamic loads, stalling behaviour, ground effects and the flowfield around the configuration. In support of the windtunnel tests windtunnel-wall interferences were studied and also the scaling of the experimental results to full-scale conditions was backed up with the comparison of calculated flow conditions at windtunnel and flight conditions.

While the 3D-methods were established as standard-tools for the Megaliner design process advanced 2D-Navier-Stokes solvers on structured and on hybrid meshes (DLR-methods Flower and TAU) have also been introduced. Especially for the understanding of flow physics and for the prediction of complex flow conditions they complete the capabilities of the fast viscous-inviscid coupled panel-methods which are used in shape definition. The coupling of CFD-methods with automated optimisation routines [11] was already successfully used in the Megaliner high-lift wing design. Evaluating the possibilities of those methods it is clear that they will gain a great importance already in near future.

4.3 Concept, layout and devices of the Megaliner high-lift wing

The design work was characterised and limited by the cruise wing shape. Because of the high design-Mach-number the outer wing profiles have a small relative thickness resulting in a small leading edge radius (figure 10). Furthermore a significant rear loading was applied, which results in a small trailing edge thickness. This limits more extreme as on previous Airbus wing designs the maximum thickness of the flap elements. For the possible flap contour a smaller leading edge radius follows and results in a pressure distribution with a dramatically higher suction peak on the flap nose. Compared to an A340-type flap a higher boundary layer loading and a worsened separation tendency is caused and leads to earlier decrease of flap efficiency with deflection angle due to earlier separation.

This effect could be compensated by invention of a more effective flap system. A double-slotted flap design was therefore studied. A strong disadvantage however would have resulted for the weight of the support and actuation system.

The flap thickness can be increased with a thinner spoiler. The suction peak and the boundary layer load are then lowered and lead to improved separation behaviour on the flap. Also a beneficial effect on flap weight follows from the increased thickness. However, the reduction of the spoiler thickness increases the deformation tendency of the spoiler and the necessary higher stiffness would then result in higher weight of the spoiler parts. This effect could partially compensate the weight advantage from the increased flap thickness.

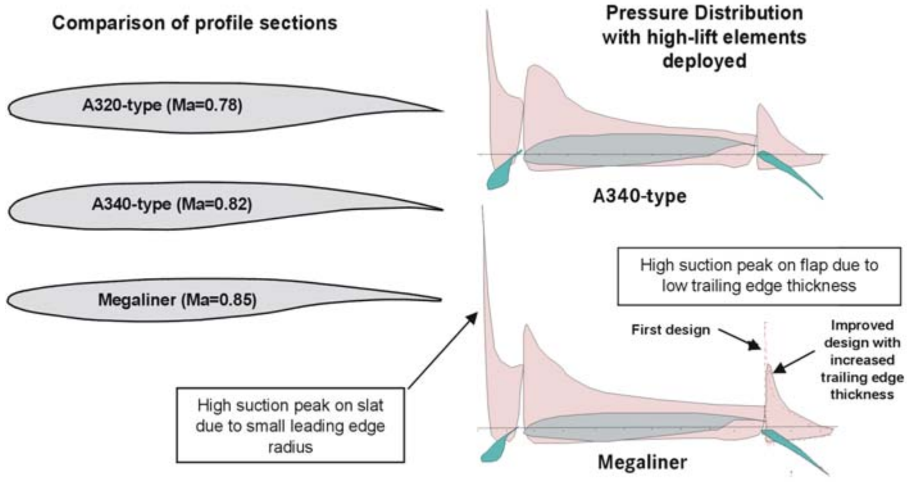

Figure 10: Comparison of Airbus profile sections and problem areas on the Megaliner high-lift wing profiles

Due to the problems mentioned above the early designs of the Megaliner cruise wing shape had to be modified to enable the integration of a feasible high-lift system with acceptable complexity. The trailing edge region of the cruise wing profile shapes was significantly thickened which required a reduction of the favourable effect on lift by the applied rear loading (figure 10). The outcome for the flap system was the required space for increased flap thickness with the resulting positive influence on flow quality, deformation and weight. With regard to a multidisciplinary optimum a part of the additional space was used also for a thickening of the spoiler in order to improve also spoiler weight and deformation.

On the leading edge a similar problem linked to the sharp leading edge radius following from the low profile thickness had to be solved. The suction peak on the initially designed slat appeared considerably higher than on an A340-type slat. As explained before, this results in a higher boundary layer loading and separation tendency. As a severe separation on the slat lead to the stalling of the wing in this area the obtainable maximum lift was limited to an unsatisfying level. For maximum lift improvement a further deflection of the slat could have been applied. A larger deflection then would have required longer tracks with the resulting higher weight and the difficulty stowing them in retracted position in the thin cruise wing shape. Therefore the maximum slat angle had to be limited.

Also the clean wing stalling behaviour was predicted as only marginally acceptable due to the separation onset in the outer wing region caused by the high boundary layer loading from the sharp leading edge in this region.

For these reasons the cruise wing leading edge had to be redesigned considering the high-lift performance. An increase of the outer wing profiles leading edge radius lowered the slat suction peak and resulted in an acceptable solution for the aircraft with regard to the limited maximum deflection. The demand of a large leading edge radius however stands in direct contrast to engine integration requirements for the high-speed flight. Especially in the inboard regions of the pylons a small leading edge radius helps to avoid unsteady shock induced separations on the pylon and the wing lower surface which can excite oscillations of the wing structure at high Mach-numbers and low incidences. A best compromise solution, which is providing acceptable flow conditions for both flight regimes, had to be found.

While the preceding described optimisations of the design were performed based mainly on CFD, the windtunnel represents the central tool for design verification and performance determination of the realistic complete 3D aircraft design. Various windtunnel models on selected design stages were specified, manufactured and tested. Based on these results the final layout of the high-lift wing was decided. Today, still only the windtunnel offers the possibility for the check of a large amount of variations on the high-lift configuration. Although model design, manufacture and testing is very expensive and time consuming, the windtunnel represents the tool far best suited for the production of the database for the aircraft and also for the detailed optimisation of the configuration with reliable results.

The conducted windtunnel experiments led to the selection of the high-lift elements of the Megaliner wing. In parallel to the design of the baseline solution alternative devices were designed and checked with CFD and verified in windtunnel tests. Especially for the reduction of the take-off drag Krueger-flaps and an inboard droop-nose device for the inboard wing appeared to be promising alternatives. But even with an aerodynamic advantage the impact on the complete design had always to be evaluated.

These considerations confirmed the selection of slats for the mid and outer wing. However, for the inboard wing a droop-nose device delivered advantages concerning take off drag improvement for 2nd segment climb performance (about 3% improvement versus the slat) while the adverse effect on maximum lift was still acceptable (about 5% loss versus the slat). For the droop-nose device a completely new aerodynamic design and system layout had to be developed, e.g. the requirements for sealing of the device in order to avoid leakage flow.

The extension of the inboard wing leading edge device was also optimised for a least weight solution. In windtunnel testing it was found that the wing still provided the necessary maximum lift performance with a cutback of the inboard leading edge device in the region near to the fuselage. This resulted in a possible reduction of 3.8m of the inboard span of the droop-nose device and the associated weight benefit.

Also for the trailing edge system intensive concept variations were performed. The problem of maintaining sufficient aileron effectiveness with the flexible wing structure in high-speed flight (‘aileron reversal tendency’) initiated studies on a layout change with an additional inboard aileron (figure 11). The outer flap span was extended here for maintaining the flap system performance and the outer aileron span was reduced, as this device was not required for high-speed flight any more. Not yet providing the necessary high-lift performance due to the spanwise gap in the trailing edge by the aileron this configuration was also examined with a double slotted flap on the inboard wing. As another alternative for avoiding the negative impact on cost and weight by the double-slotted flap a 'taberon' on the inner flap was studied. The taberon would work as a high-speed roll-control device without compromising the performance of the high-lift wing by avoiding the large spanwise gap in the deployed trailing edge.

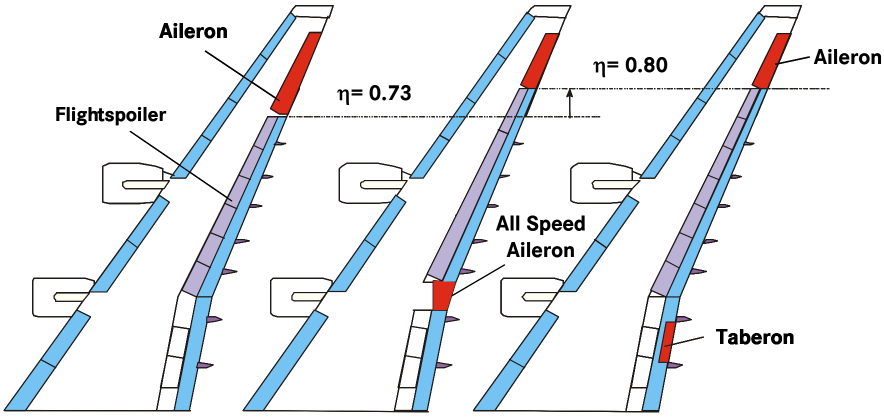

Figure 11: Variation of the trailing edge and roll control concept

The need for a best-balanced solution between the disciplines led to a trailing edge solution with a flap three-divided in spanwise direction. Although additional track locations with the resulting fairings and an additional flap-split with the related sealing problems are caused, this solution was still the most beneficial one for the aircraft due to advantages in structural and systems layout – but also due to manufacturability constraints of such large parts.

In the evolution of the aircraft layout the high-lift system had to be adapted continuously to the requirements of the actual aircraft performance status. The initial high-lift system design delivered more aerodynamic performance than needed. On one hand this was caused by the change of requirements but on the other hand also from the satisfying performance of the design itself. This allowed several steps of downsizing of the trailing edge system. The flap chord relative to the cruise wing profile chord could be reduced from initial 28% to 24%. At the same time also the shroud position (i.e. spoiler length) could be adapted from 88% to 86%. Also the flap span could be downsized from 73% to 65% of wingspan (figure 12). With this flap span reduction and a corresponding extension of the aileron inwards sufficient roll control efficiency in high-speed flight is maintained. A trailing edge solution with an additional inboard aileron could be avoided. Similar downsizing was applied also to the chord and the extension of the leading edge devices of the mid and outer wing. These adaptations of the high-lift wing to only the needed aerodynamic performance resulted in a large benefit to the wing-weight and therefore in the aircraft performance.

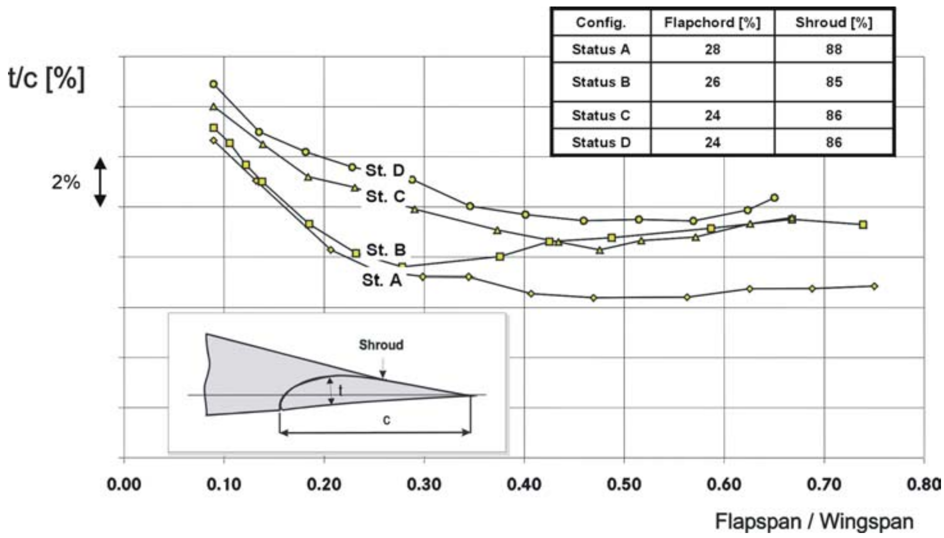

Figure 12: Evolution of the trailing edge device layout

It has to be remarked, that in the design process the ‘critical performance’ target changed. E.g. the maximum lift performance was limiting in the earlier design phase. Later the take off climb performance turned out to be limiting while maximum lift performance was not critical any more due to the geometrical limitation of the fuselage when rotating on the runway. The design therefore had to be continuously adjusted to meet the required ‘limiting’ performance target. Such continuous change of the critical design-target in the late design phase can be taken as an indication that a balanced layout is reached and the system not over-performing in uncritical fields with a resulting unnecessary system expense.

Intensive work was conducted by windtunnel tests for the optimisation of detailed solutions for local regions on the wing, especially the junction of the deployed slat respectively the droop-nose with the pylon. As the slat is deployed normal to the leading edge a gap between the slat end and the pylon remains. The effect of this gap was found to be nearly neutral on the outboard side of the pylon but very adverse on the inboard side. Several devices to close this gap have been invented and checked. But finally such a device with its necessary actuation system and the unwanted effect on weight and cost could be avoided. Shaping the pylon in a way to minimise the adverse effect maintained the needed maximum lift without additional expense while it was also used for improvement of the wing-pylon integration in high-speed flight.

The large amount of detailed work for the selection of the high-lift concept was performed in the accessible atmospheric windtunnels (e.g. the Airbus low speed windtunnels in Bremen and Filton). But especially the experience gained in the design work for the Megaliner underlines the necessity for the check of the design for high Reynolds-numbers already at an early design phase. It is well known that e.g. the maximum lift changes significantly with Reynolds-number [12]. Therefore high Reynolds-number checks, e.g. of the flap flow quality and the separation behaviour, were performed already in the design phase. The results helped to better adjust the configuration for flight conditions at a phase where this was still possible without dramatic impact on time schedule and cost. Also the reliability in scaling the windtunnel data to flight conditions and the performance prediction for the aircraft was improved and assured.

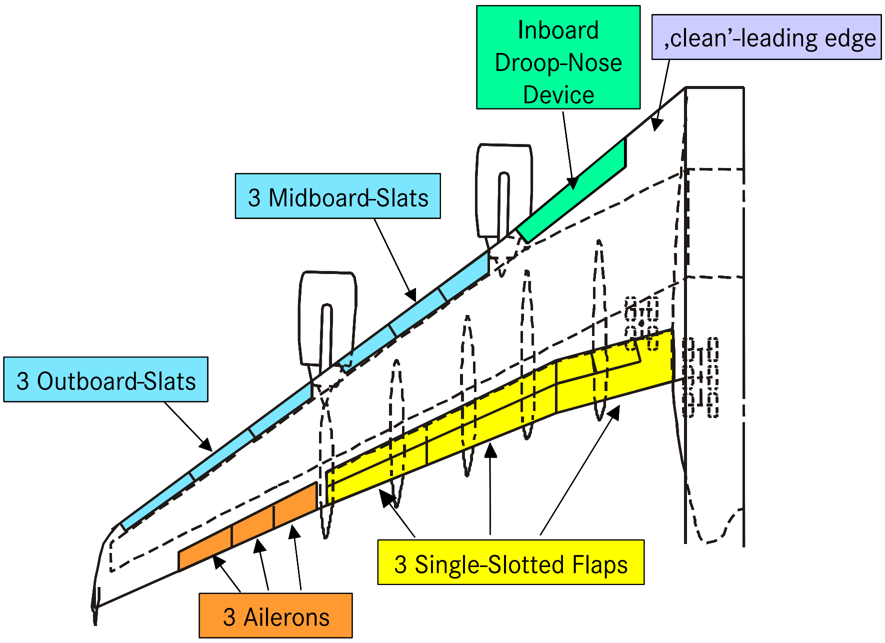

Figure 13: The Megaliner high-lift wing layout

5 CONCLUSIONS

- The aerodynamic design work for a high-lift wing represents a complex task influenced from multidisciplinary constraints, in which aerodynamics could not be considered independently of the complete aircraft design process.
- The design results in a high-lift wing providing the necessary performance with least possible system complexity. The intensive use of CFD enables to design and pre-select promising concepts before entering the windtunnel.
- An effective combination of CFD and windtunnel testing results in a best-possible balanced design.

REFERENCES

[1] Flaig A., Hilbig R., *High-Lift Design for Large Civil Aircraft*, AGARD-CP-515, 1992

[2] Butter D. J., *Recent Progress on Development and Understanding of High-Lift-Systems*, AGARD-CP 365, 1984

[3] Rudolph P., *High-Lift Systems on Commercial Subsonic Airliners*, NASA-CR 4746, Sept. 1996

[4] Wedderspoon J. R., *The High-Lift Development of the A320 Aircraft*, ICAS-86-2.3.2, 1986

[5] Olason M.L., Norton D.A.: *Aerodynamic Design Philosophy of the Boeing 737*, J. Aircraft Vol.3, No.6, Nov.-Dec. 1966

[6] Nield B.N., *An Overview of the Boeing 777 High-Lift Aerodynamic Design*, Aeronautical Journal Nov. 1995

[7] Reckzeh D., *CFD-Methods for the Design Process of High-Lift Configurations* (11th AG-STAB -DGLR Symposium 1998), New Results on Numerical and Experimental Fluid Mechnics Volume 72, pp 347-354, Vieweg Verlag, 1999

[8] Hansen H., *Überblick über das Technologieprogramm Hochauftriebskonzepte (HAK)*, DGLR-Jahrestagung 1998, DGLR-JT98-042

[9] Dreßler U., *Flugphysikalische Auslegung der Hochauftriebskonfiguration A380, Vortragsreihe Start+Landekonfiguration*, DaimerChrysler Aerospace Airbus, Bremen, 1999

[10] Valarezo W., Chin V.D., *A Method for the Prediction of Wing Maximum Lift*, Journal of Aircraft, Vol. 31, No. 1, Jan.-Feb. 1994

[11] Wild J., *Numerische Optimierung von zweidimensionalen Hochauftriebskonfigurationen durch Lösung der Navier-Stokes-Gleichungen*, DLR-Forschungsbericht 2001-11

[12] Haines A. B.: *Scale Effects on Aircraft and Weapon Aerodynamics*, AGARDOgraph 323, 1994