LOW-SPEED HIGH-LIFT PERFORMANCE IMPROVEMENTS OBTAINED AND VALIDATED BY THE EC-PROJECT EPISTLE

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Abstract

A new method for low-drag high-lift system design based on viscous flow solvers was developed for Supersonic Commercial Transport wings within the EC research project EPISTLE. Two high-lift systems were manufactured for a large-scale wind tunnel model. The numerically predicted drag reductions (20% compared to a datum system) were fully confirmed by high Reynolds number tests. These drag reductions lower the low-speed noise for future SCT configurations by more than 4 EPNDB.

1 Introduction

Increasing mobility of individuals and products in western countries is a main driver for their economy. Persons are demanding several transportation possibilities of varying speeds and comfort depending on their travel purpose. Since the end of Concorde's scheduled supersonic flights in 2003 the range of choice regarding the speed of air transportation is limited.

Nevertheless the generally increasing mobility demands for travel time reductions and implicitly for high-speed air transportation. The growing interest in supersonic business jets confirms this statement. But ecologic concerns regarding most kinds of transportation do also exist. These concerns will obviously impact the development of new air transportation solutions.

A future Supersonic Commercial Transport (SCT) may reduce travel times for a wider public by increasing the transport productivity. To achieve ecological acceptance and economic viability any future SCT requires major performance improvements of all contributing disciplines. Compliance with current and future community noise regulations near airports is the most critical design requirement.

Aerodynamics can help to reduce the aircraft noise at low-speeds. SCT configurations easily achieve the lift at low-speeds because of their relatively large wing area. The challenge is to reduce the drag and to improve the take-off, approach and landing performance for these aircraft. Increased low-speed performance enables reduced throttle settings (reduced engine noise) and enables better climb out characteristics also reducing community noise.

Current European SCT concepts feature wings with leading and trailing edge (LE & TE) flaps to optimize low-speed performance aiming at reduced noise emissions. These devices will optimize the wing for transonic cruise in addition.

Within the EC project EPISTLE the main focus is on low-speed noise reduction by aerodynamic means. The objective is to enable high-lift system designs for low-noise SCT configurations. A new aerodynamic high-lift system design method is developed and validated. The method obtained 20% performance improvement beyond a datum high-lift system or about 40% aerodynamic performance improvement compared to a clean wing.

2 EPISTLE project partners

The EPISTLE project (**E**uropean **P**roject for **I**mprovement of **S**upersonic **T**ransport **L**ow Speed **E**fficiency) run from March 2000 until

November 2003 with the following partners (in alphabetical order): Airbus (Germany, France, UK), BAE Systems and the research establishments: CIRA, DLR, INTA, NLR, ONERA as well as QinetiQ. The Helsinki University of Technology (HUT) contributed as a subcontractor. The project was co-ordinated by DLR. EPISTLE was sequentially organized with numerical, experimental and analytical activities and foresaw breakpoints in case technical milestones were not met.

3 Datum high-lift system

The low-speed experiment performed within the previous EC-project EUROSUP [1] on a datum high-lift system revealed that the measured flow topology on this small scale wind tunnel model was separated and complex. The flow developed several vortices around the design point. Due to a different emphasis in EUROSUP no further low-speed measurements were performed. The low-speed flow development from fully attached to open separations was therefore investigated in EPISTLE in more detail.

These new tests confirmed the findings of the previous campaign at the design point. Also a clean wing without deflected LE flaps was low-speed tested. The measured performances of both wings were compared, see **Fig. 1**. The

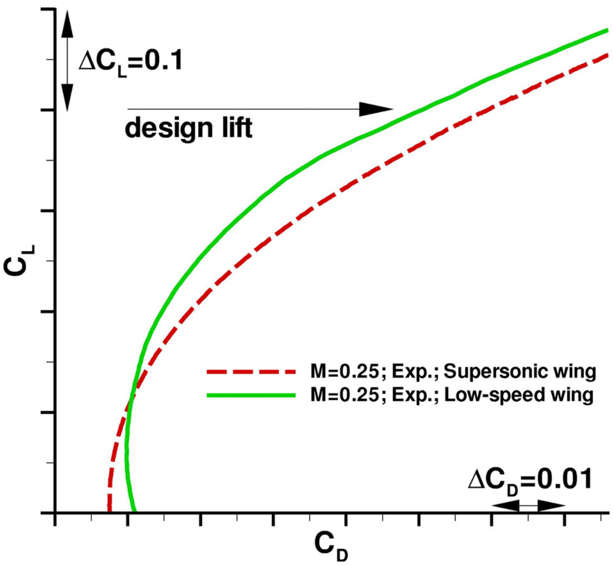

Fig. 1: Aerodynamic performance gain at M=0.25 due to the datum high-lift system.

aerodynamic performance is given as lift over drag. Although the onset of separations produced non-linearities in lift, drag and pitching moment the datum high-lift system recognizable improves the aerodynamic performance around the design lift ($\Delta C_L/C_D \approx 2.4$) compared to the clean wing.

In-depth analysis and topological sketches helped to explain the development of this

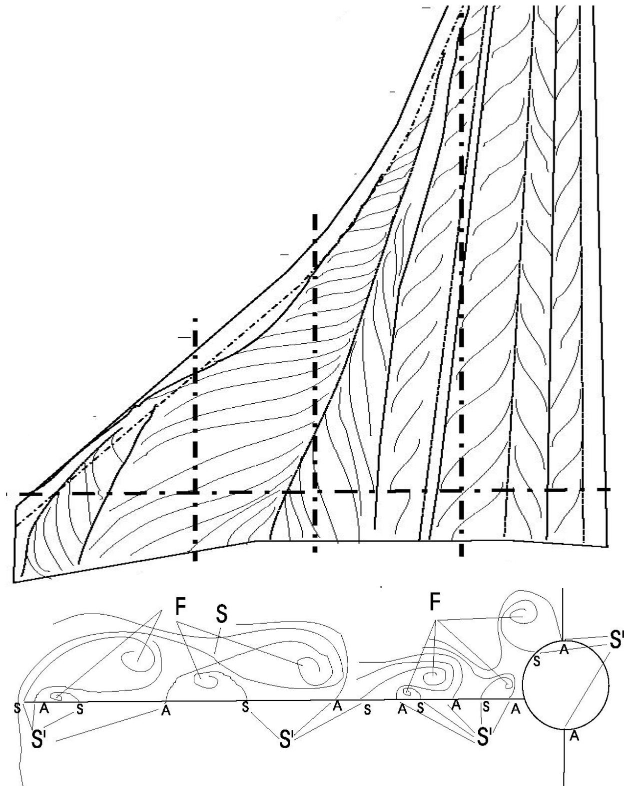

Fig. 2: Flow topology of the datum high-lift system wing at the design conditions, M=0.25, α=10.5°.

complex vortical flow structure, see **Fig. 2**. Several distinct vortices in spanwise direction run along the whole cord. Furthermore a large amount of cross flow is present on the outer wing. Partners published their detailed analysis results [2], [3] earlier on.

4 Assessment of numerical tools

Partner's numerical tools were assessed before the design of a new and improved high-lift system for the given SCT wing was started. This assessment was based on a realistic benchmark case orientated at previous experience [4] regarding necessary numerical prediction accuracy.

The available experimental data of the EUROSUP datum high-lift system was used. This datum high-lift system was designed as a droop nose along the complete LE with approximate methods. The flow on the datum high-lift system does not characterize preferable aerodynamic behavior. Nevertheless this geometry serves as an excellent test case. The CFD methods are requested to predict a complex flow. They are checked to accurately predict attached, separated and separation onset flows with sufficient accuracy.

Industrial partners translated their noise prediction accuracy needs into low-speed CFD prediction accuracy requirements. These CFD requirements were formulated assuming that significant drag reduction will be obtained by attached flow. This was the basic assumption during the definition of the EPISTLE project. Attached flow seemed preferable because vortices were viewed as severely drag increasing.

All partners computed the above described benchmark case. Numerical results in accordance with the accuracy limits passed the code acceptance test. Details can be found in the associated previous papers [5], [6]. All benchmark results were thoroughly analyzed to judge the separation onset prediction capabilities of the codes. As a range of different meshes (type and density) and turbulence models were used physical motivated correlation between the results of differing quality and associated numerical influences were extracted. This allowed formulating recommendations regarding local discretization requirements as well as turbulence model preferences for the design work.

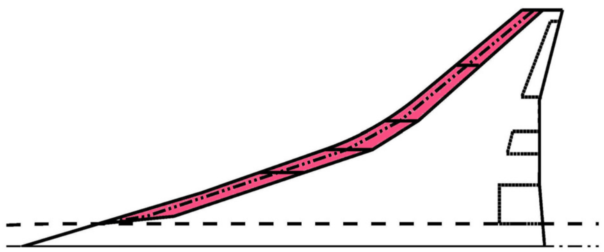

Fig. 3: Leading edge flap based high-lift system, five flaps in spanwise direction.

5 Design Variable Sensitivities

The target for the EPISTLE SCT high-lift system was to obtain 20% drag reduction compared to the datum high-lift system at a specified lift (C_L) at M=0.25. A single design point was the simplifying compromise between the design points for take-off, approach and landing and the validation requirements for the second large-scale experiment in the project. This C_L, angle of attack (AoA) and Mach combination simulated the noise sensitive flight envelope point: flyover noise. The AoA to reach the lift for this flight condition was constrained. Flows were computed using the wind tunnel Reynolds number to ease the validation work later on.

To obtain a reasonable high-lift system it was agreed to use only drooped LE-flaps and to restrict their chord due to structural constraints. It was agreed to use up to five flaps in spanwise direction, see **Fig. 3**. The planform of the generic SCT wing and the five LE-flaps are visible in this graph. The allowed maximal flap chord is colored. The datum flap chord is depicted as a dashed line. Freedom was given regarding the hinge geometry of these LE-flaps. Therefore virtual flap hinge lines (located even below the wing) were used to generate large radius of knuckle curvature to delay separation.

The geometry representation of the LE-part of the wing was simplified to ease the mesh generation. Instead of modeling the opening gap between adjacent but different deflected flap segments a “rubberized section” between flap segments was introduced. Furthermore the deflection of the LE-part was performed at the location of the hinge but around a rotation axis perpendicular to the fuselage axis.

To obtain comparable wing and high-lift system geometries a purpose specific routine (geometry engine) was written and distributed to partners early in the project.

The design variables for each of the five LE-flaps are depicted in **Fig. 4**: the flap deflection angle, the flap chord and the hinge line position (in vertical direction) defining the flap knuckle geometry. Further design variables are the local LE shape and the lateral side gaps between flap segments.

Estimating the design variable sensitivities was intended to support the later design work. Varying all design variables opened up a large matrix of cases to be computed. This workload

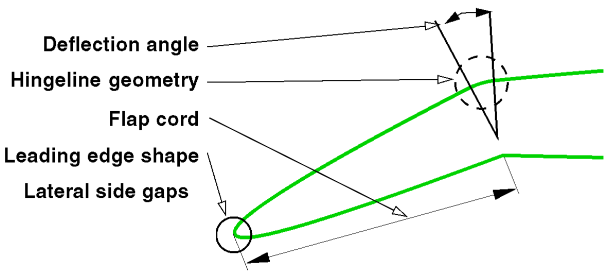

Fig. 4: Design variables of the LE flap high-lift system.

was shared among partners. In addition a common reference case was computed by all participants to enable cross comparison of the sensitivities.

To highlight one of many aspects a single design variable will be presented here.

As most technical contributions have been

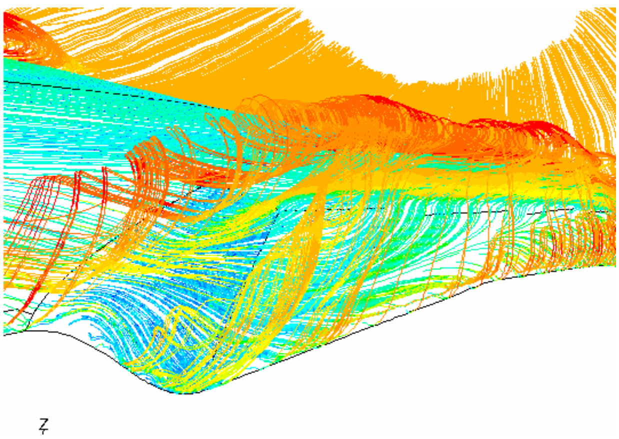

Fig. 5: Local flow (colored streamlines) over a rubberized section between two LE flap segments.

computed on structured meshes a geometric simplification regarding the lateral side gap between adjacent flap segments was required. A rubberized section between the flap segments was assumed and modeled. One partner in the project used an unstructured code to verify that this assumption was valid. The computed local flow topology on one of these rubberized sections is given in **Fig. 5**. A small vortex is moving downstream from the flap edge. The more deflected next flap segment triggers a new small vortex. The local flow change due to the

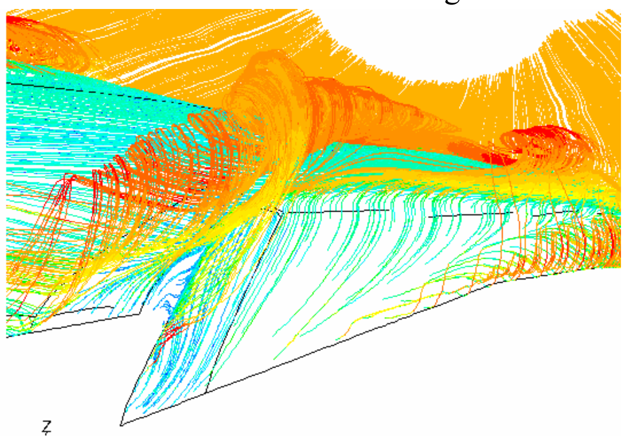

Fig. 6: Local flow (local streamlines) developing due to a gap between two adjacent flap segments.

presence of a real gap is depicted in **Fig. 6**. The overall topology does not change. This finding is also true for the associated aerodynamic coefficients. The gap presented in Fig. 6 is constructed parallel to the fuselage. Another gap type (flaps segmented normal to the flap hinge) has been analyzed too. For separated flow beyond the AoA limit some additional lift is found without increasing the drag compared to the rubberized geometry. Some pitching moment changes have been recognized indicating marginal vortex topology "modulation" without a predicted drag increase. The use of rubberized sections in structured meshes seems therefore fully valid.

This example shows what all partners observed during their investigations: there is hardly a linear correlation between the design variable and the resultant flow. The reason is that the flow at the design lift is near separation. Due to small changes (triggering presence of vortices) a highly three-dimensional flow is generated. This finding had significant impact on the project: The design sensitivity results experienced significant scatter because the partially separated flow was very sensitive to numerical influences.

The use of the sensitivity results to arrive at quantified design rules was not possible. Instead the most reliable results analyzed to formulate physically motivated design guidance. It became clear that the design would not be achievable with attached flow.

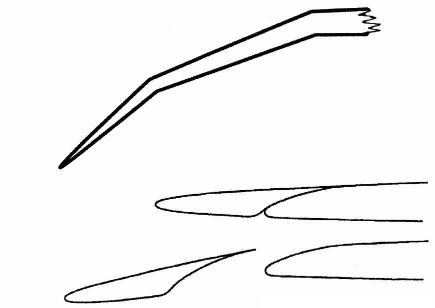

Fig. 7: Innovative high-lift system concepts for SCT wings: double hinge and slotted slat.

In parallel to the design variable sensitivity estimation alternate high-lift devices were found by an intense literature search. Three convincing concepts were named: sub-scale vortex generators, slotted slats and double hinge slats. The two most promising candidates, see **Fig. 7**, were selected and their performance potential was numerically estimated. The investigation of the sub-scale vortex generators was viewed as too difficult.

Although a slotted slat is a quite conventional device on transonic transport aircraft it is innovative on an SCT wing because of the high LE sweep and the associated structural uncertainties on very thin wings. The numerical investigation revealed that due to the LE sweep a channel flow between the slat and the main wing develops reducing drag due to a virtual span increase. The investigations revealed a L/D performance gain of 1.76.

The double hinge slat was investigated too and by adapting the deflections of the two slat parts a L/D improvement of about 1.8 was predicted.

6 High-lift system design

To maximized the probability to obtain a minimal drag high-lift system and to reach the 20% drag reduction objective the high-lift system design has been organized as a competition. During the estimation of the design sensitivities it became clear that obtaining the target lift requires releasing the AoA constraint for the EPISTLE high-lift system design. Furthermore it was found that the flow around the design lift is partially separated and more complex than originally assumed.

As a result of this it was decided to split the activities between two design philosophies in order to reduce the technical risk. Firstly to attempt an efficient separated flow design using plain LE flaps only to meet the original target lift, but with the incidence constraint relaxed. Secondly to seek an attached flow design for a reduced target lift. The reduced target lift was based on the assumption (made using industrial project level tools) that the trailing edge flaps could be deflected to produce the missing lift increment without causing separation.

As the project also aimed at estimating the performance and success of different design methodologies, the methods applied in EPISTLE covered a range of existing and also new methods: engineering tools based on suction analogy in combination with a vortex-lattice method, panel and Euler solvers coupled with optimizers and response surface methods respectively and manually applied Navier-Stokes solvers.

Six independent high-lift system designs - one for attached flow- were presented at the end of the design phase. Selection of two designs to be included on the large-scale wind tunnel model (in addition to the deflected datum) for validation purposes was carried out using a decision process defined and agreed earlier on. All partners presented designs and their design process. The key factors on which the selection decision was to be based were addressed.

The attached flow design (based on inviscid computations) turned out to produce most likely small separations and hardly showed performance increases compared to the datum high-lift system at the lower lift coefficient. From the remaining five designs the two best performing ones were selected.

The configuration entitled #1 resulted from the innovative concepts investigation (double hinge configuration). Configuration #2 showed second best overall performance and was the best result of a "method" called knowledge driven RANS computations that was applied by two partners independently.

Details regarding the drag reduction mechanism of the selected configuration will be given based on results for configuration #2.

Using something like a knowledge driven "method" mainly relies on three factors: 1) fast turn around times for the (structured) mesh generation, 2.) a highly efficient flow solver and 3) on sufficient understanding of the flow physics.

The structured mesh generation for the design work of configuration #2 was based on a rapid turnaround time scripting technique [7], [8]. A multi-block mesh with about $1.8*10^6$ cells was generated for each variant of the high-

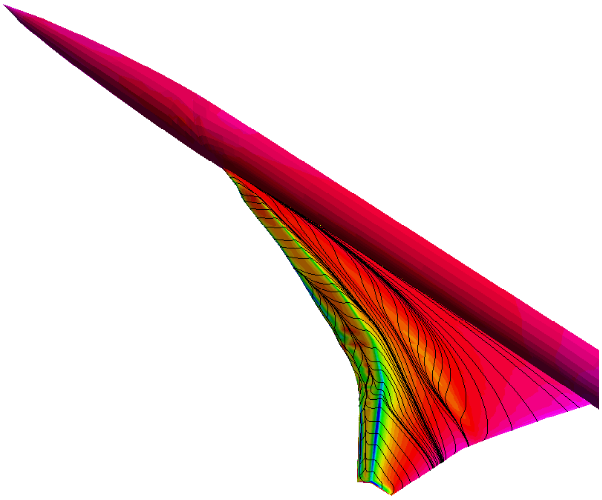

Fig. 8: Pressure distribution and vortices on the high-lift system #2 at the design lift condition

lift system geometry. The general mesh layout was orientated at the recommendations obtained earlier in the EPISTLE project. The recommended Baldwin-Lomax turbulence model [9] (with Degani-Schiff extension [10]) was used. Usually about 10 hours of CPU-time were needed for a converged numerical solution on a NEC SX-5 (2001 data).

The design process was driven by findings from the sensitivity study and further in-depth analysis of the flow topology of the computed geometries. Changes of the high-lift system geometry were decided based on the physical interpretation of the obtained flow topologies and the aerodynamic coefficients.

About thirty different high-lift system configurations were generated and computed (each at three different AoA) before the 20% performance improvement in comparison to the datum system was obtained.

The low drag configuration #2, **Fig. 8**, shows controlled separated flow. Nevertheless significant differences between the flow topology of the datum wing geometry and this design exist. The amount of cross flow on the outer wing is reduced significantly.

This low-drag flow was designed by reducing the inner wing LE-flap deflection to force the LE-flap vortex to develop as much inboard as possible. The appropriate span wise LE-flap depth and deflection distribution enables to keep two vortices on the deflected LE-flap and to reduce the cross flow on the wing. This prevents the vortices from merging and helps to reduce drag. The applied knuckle rounding prevents separation from the knuckle. Furthermore the strength of the LE-flap vortices is slightly increased and therefore the designs overall performance is pushed. These are the physical ingredients to obtain a low drag high-lift flow on this SCT wing at the required lift condition.

The flow topology obtained by the double hinge configuration (#1) showed similar physical mechanism, see **Fig. 9**. Due to the additional design variable –the second flap half- the adaptation of the wing camber to the onflow

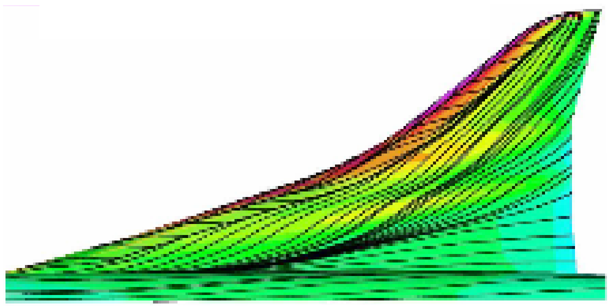

Fig. 9: Pressure distribution and surface streamlines on the high-lift system #1.

conditions is easier obtainable because high suction peaks –tiggering separations- at only one kink was prevented. On configuration #2 this suction peak was largely removed by dropping the hinge but the thin wing could easily prevent such a solution.

The assumption at the start of EPISTLE was that attached flow reduces drag. The weak performance increase of the attached flow design showed that this approach was inappropriate.

The two selected designs obtain significant drag reductions due to vortical flow topologies. The reason is that LE-flap vortices generate higher suction force than attached flow. It is obvious that the design of such a controlled separated flow is more demanding than an attached flow design.

7 Design validation experiment

The modular concept of the EPISTLE wind tunnel model enabled to reduce costs and a wider use beyond the EPISTLE project. The large scale (1:22) and the high geometric accuracy of this model -fitting in the major European low-speed tunnels- makes its further use quite likely. An important design requirement was to obtain short configuration change times as measurements in pressurized tunnels are quite expensive. Modularity was enabled by the fact that the differences between the three configurations (datum, design #1 and #2) only exist in the LE area. The main wing and the TE area were not affected.

The wind tunnel model was therefore constructed around a metal core wing housing the three strut mounting devices. The front strut could be fixed inside the wing being thick enough at that location. The two rear strut rotation axes were put in external pylons. Both the leading and TE flaps were screw mounted onto the core wing relying on a relative wide mechanical interface also serving to route pressure tubes. This interface can be seen on the left hand side of **Fig. 10** where no LE flaps are yet installed.

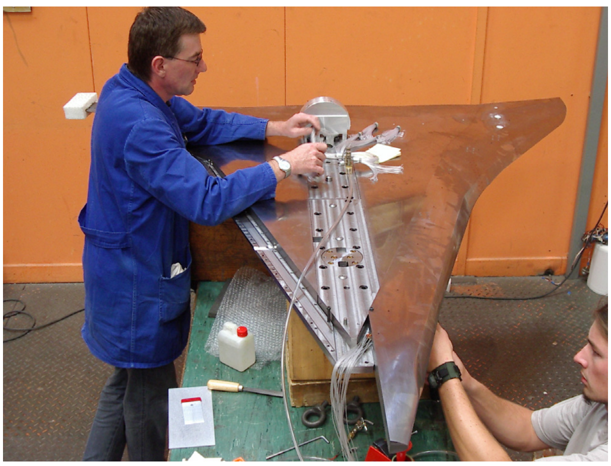

Fig. 10: Preparing the modular EPISTLE wind tunnel model for the validation test

As boundary-layer measurements near the rounded knuckle were planned the mechanical break between the deflected LE flap part and the main wing were located relative far back. This impacted the weight of the metal LE part. To enable reasonable mounting the LE part was split into three peaces of similar weight.

The fuselage was made from fiberglass consisting of a front and rear cone plus a central part. This central fuselage part covered the instrumentation and allowed fast access, as it can be easy removed (vertical).

The wind tunnel model was instrumented with pressure tabs at seven spanwise locations. Three sections were equipped with 25 pressure tabs only on the leading edge part.

Five miniaturized boundary-layer devices allow a calibrated three-whole probe to travel vertically through the boundary layer. These actuator devices with the probe pointing in upstream direction were flush mounted into the wing and allowed to measure boundary-layers up to 25 mm with a local resolution of about 0.1mm. At thinner areas of the wing some part of the actuator body was sticking out of the lower wing surface.

The first EPISTLE validation tests were conducted in September 2002. During these

Fig. 11: EPISTLE wind tunnel model mounted on three struts in the tunnel.

tests measurements of forces, pressures (215 pressure taps for each configuration) were performed for the three different configurations. **Fig. 11** shows one configuration strut mounted in the tunnel. Mach (0.2 - 0.3) and Reynolds number (7 to $22*10^6$) have been varied. In addition oil flow pictures have been taken for each of the three high-lift system configurations at the design conditions.

The main conclusion was that both

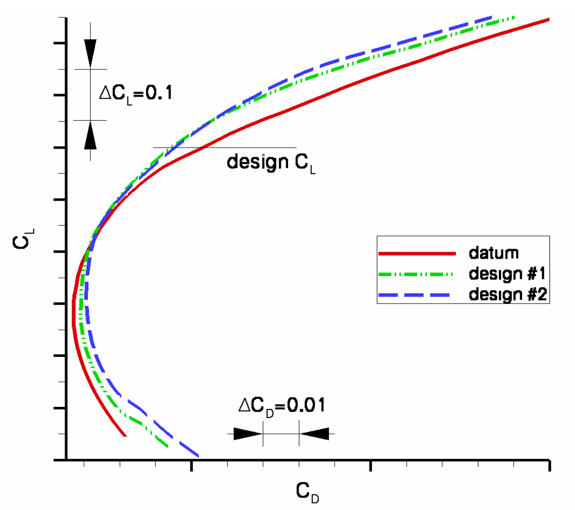

Fig. 12: Low-speed drag polars at M=0.25 of the high-lift systems.

designed high-lift systems reached the numerically predicted performance improvement while showing the designed flow topologies. The project objective to reach 20% aerodynamic performance improvement was also met by both systems, see **Fig. 12**. This figure compares the measured drag polars of the datum and the two new high-lift systems showing significant drag reduction. At higher lift conditions the configuration #2 produces less drag. This reverses at lower AoA.

The second EPISTLE validation test was conducted in December 2002. Detailed analysis of the double hinge configuration (#1) flow was performed. Boundary layer and wake measurements (two planes) were taken for a range of flow conditions.

8 Data analysis and extrapolation to flight

All tested high-lift system configurations have been numerically analyzed. Care has been taken to obtain geometric identity to the wind tunnel set-up. These computations showed very good agreement to the design results although the geometry used for the design was simplified (no up-swept fuselage, no rounded wing tip).

Due to initial experimental data correction problems significant absolute drag value differences between numerical predictions and the experiments were encountered. Nevertheless the predicted drag reductions were confirmed by the experiment. Therefore an unknown drag source was assumed in the experiment for which no tunnel correction was available.

It was decided to investigate potential drag adding sources. Not only the wing body high-lift configuration has been calculated but also configurations adding experimental devices, like: rear strut pylons, rear strut pylons plus the three struts and wind tunnel walls.

Adding the rear strut pylons revealed that no large drag increasing separation took place on these devices. This only confirmed the good aerodynamic design of theses added parts.

Numerically analyzing the effect of the wind tunnel walls mainly confirmed the wind tunnel corrections applied but did not point towards alarming differences.

Finally computing the wind tunnel model mounted on three struts including the rear strut pylons, see **Fig. 13**, gave some indication for additional drag. It was found that due to the relative high AoA and the large wing area the two rear struts operated in a cross flow field resulting in separations from these struts. Unfortunately the estimated drag amount did not fully explain the differences found.

A repeated review of the experimental data discovered a data correction problem. Fixing this resulted in good agreement between the reference computations (adding the drag increments found for the strut separations) for the two designs and the experiments for lower AoA.

Calculations at flight Reynolds number ($160*10^6$) have been achieved for all three high-lift systems. Increasing the Reynolds number from wind tunnel to flight conditions reduces the skin friction drag. The estimated reductions revealed that different pressure drag reductions were found for the two new high-lift system

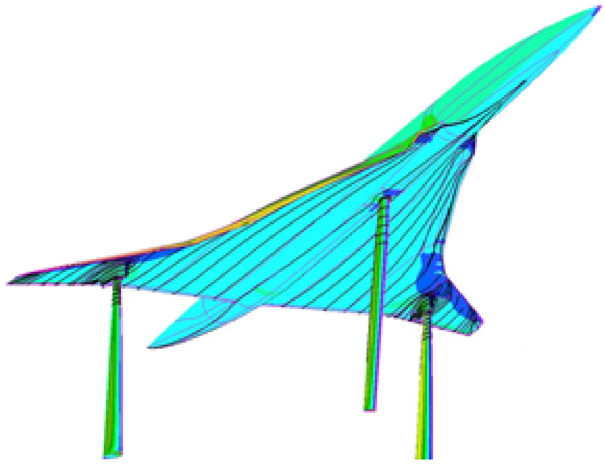

Fig. 13: Numerical rebuild of the EPISTLE experiment at M=0.25, Re=22*10^{6}, design lift AoA.

configurations. It seems that a smooth flap hinge shape seems more beneficial at flight conditions.

For lift coefficients around the design C_L the reference solutions are able to capture the onset and existence of vortices as well as their initial position. The vortices on the deflected leading edge flaps are very well captured too leading to good drag reduction estimation.

The reason for increasing deviation from the experiment at higher lift coefficients are relative high numerical dissipation levels in the reference solutions. Due to the unphysical dissipation the vortices seem to spread and merge depending on the mesh and CFD method used. An example of this is given in **Fig. 14**. The top figure shows a numerical solution obtained for identical onflow conditions. The difference between the experimental results and CFD exist for both, pressure distribution and flow topology. These differences are increasing with the distance from the wing apex.

The flight polar has been built based on the EPISTLE double hinge design (#1) and on the datum configuration. The data has been compiled from experimental results and from the numerically estimated Reynolds number effect. Some classical drag terms (antennas, production surface roughness, …) have been added as well as TE flap effects. The TE effect has been addressed using project office level methods and RANS computations.

To estimate the potential noise reduction of the EPISTLE high-lift system #1 a preliminary aircraft design and optimization tool used this flight polar. For both EPISTLE geometries (datum and configuration #1) an approximate weight increase and some fuel capacity reduction (increasing flap size) has been found.

To capture all aspects the aircraft needs to be resized to find the new balance between all design driving aspects. The resized configuration features the new EPISTLE high-lift system design as well as deflected trailing edges (+5°) to account for the associated lift losses. The resized aircraft shows an overall mass increase (MTOW, MLW, OWE) of about 1%. The wing area has to be increased by about 4.5% (compensation for fuel volume loss due to increased chord of the LE devices). The lower drag of the configuration helps to reduce the thrust by about 5% on approach. The approach speed can therefore be reduced by about 4%.

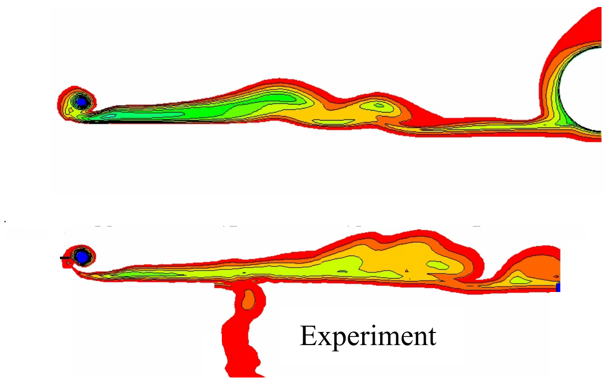

Fig. 14: Total pressure loss contours at the wing trailing edge, config. #1, design lift, M=0.25, Re=22*10^{6}.

As the climb rate of the aircraft is improved significantly a noise reduction (fly over point) of about 3 EPNDB is obtained. Furthermore noise on approach will reduce by about 1.2 EPNDB. These significant noise reductions only through aerodynamic means are the most convincing result obtained within EPISTLE.

9 Conclusion

The EC research project EPISTLE was able to design low-drag high-lift systems. These systems were tested and the numerically predicted 20% drag reduction (compared to a datum system) was confirmed at high Reynolds numbers. The drag reduction helps to reduce the low-speed noise for such aircraft considerable.

EPISTLE started by extending an experimental dataset in April 2000. The examined flow was analyzed and described in detail.

Based on new experimental data the capabilities of partner's flow solvers to predict partially separated flows were analyzed. The CFD codes were qualified for practical design work. This qualification was obtained by predicting the flow of a datum high-lift system against accuracy limits.

The computed flow solutions were used to assess the prediction capability of numerical and physical models. Recommendations regarding numerical aspects were formulated.

To understand the design driving "forces" the sensitivities of the design variables for a LE flap based high-lift system were estimated. The type of flow experienced around the design point of the high-lift system proved to be quite challenging to compute because partially separated flow was found. The detailed analysis of these sensitivities led to the formulation of design guidelines.

In parallel alternate high-lift system devices were screened in a literature review and two devices were assessed numerically.

With such preparation the 3D wing design was started. Six high-lift systems were designed and the two best performing systems were selected for wind tunnel testing.

High Reynolds number measurements investigated the datum and the two new configurations. The predicted performance increases as well as the designed flow topologies were fully confirmed.

CFD reference solutions were generated to validate the design methods and the designs. To support extrapolation to flight additional computations were performed to assess the influence of wind tunnel model mounting aspects.

Numerical and experimental analysis of the available data was performed and the estimation of the aerodynamic performance improvement on the overall aircraft noise revealed a noise reduction of about 1.2 EPNDB on approach but 3 EPNDB during climb out.

EPISTLE showed that large drag reductions of about 40% (compared to Concorde) requires to design a high-lift system with controlled separated flow on the deflected part of the leading edges. This level of drag reduction contributes to recognizable low-speed noise reductions for such aircraft.

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