REALISTIC HIGH-LIFT DESIGN OF TRANSPORT AIRCRAFT BY APPLYING NUMERICAL OPTIMIZATION

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Abstract. The design activity within the EUROLIFT II project is targeted towards an improvement of the take-off performance of a generic transport aircraft configuration by a redesign of the trailing edge flap. The involved partners applied different optimization strategies as well as different types of flow solvers in order to cover a wide range of possible approaches for aerodynamic design optimization. The optimization results obtained by the different partners have been cross-checked in order to eliminate solver dependencies and to identify the best obtained design. The final selected design has been applied to the wind tunnel model and the test in the European Transonic Wind Tunnel (ETW) at high Reynolds number confirms the predicted improvements.
1 INTRODUCTION

The EUROLIFT II project, funded by the European Commission within the 6th framework programme, is dedicated to the investigation of transport aircraft in high-lift configuration. It covers both numerical and experimental studies, mainly targeted towards validation of CFD for maximum lift prediction of such configurations. It is a follow up to the EUROLIFT project of the 5th framework program [1]. While in the former project a simplified wing-body high-lift configuration was investigated, the new project focuses on a more realistic configuration including engine nacelles, pylons, tracks and brackets. Additionally the next step is undertaken coming from analysis to design. Since it is a main aim of the project to deal with realistic configurations, this design will be done at a Reynolds number comparable to flight conditions of a real transport aircraft.

The design activity within the project is targeted towards an improvement of the aerodynamic properties of the DLR-F11 model already used in EUROLIFT. The investigations mainly focus on an increased take-off performance by modifying the trailing edge flap both in shape and position. The design is mainly performed using numerical optimization methods for optimization of a specific wing section. The involved partners apply different optimization strategies as well as different types of flow solvers in order to cover a wide range of possible approaches for aerodynamic design optimization. The flow calculation methods range from an Euler-Boundary layer code to structured and unstructured RANS solvers either in 2D or 2.5D. For optimization also a lot of different strategies are used, including gradient based methods, simplex strategies, simulated annealing, evolutionary algorithms and last but not least an industrial best practice approach.

The design activity is split up in three phases related to verification, design and validation. At the beginning a verification phase is scheduled where a mandatory test case has been defined and optimized applying the available design strategies in order to assess the reliability and the limitations of the design process. In a next phase the design specification has been formulated taking into the account the results of the verification phase [2]. This case is now optimized by the different partners by using their numerical optimization processes. Afterwards the different optimization results are cross-checked in order to identify the best obtained design. In the validation phase in the further proceeding of the project, the best design is applied to the three-dimensional wind-tunnel model and is measured in ETW at high Reynolds numbers close to real flight conditions.

The work share between the partners within the design task was constructed in order to assess as many different strategies as possible. For this reason the different partners apply different optimization strategies as well as different levels of flow simulation accuracy. The optimization strategies applied include gradient based methods, simplex strategies and evolutionary algorithms. For the flow calculations Euler-BL methods, RANS methods and additionally PSE methods for transition prediction are used.

In addition to the aforementioned numerical optimization strategies that are based on numerical optimization approaches an industrial best practice strategy was applied by Airbus Germany. Best practice can be described as an engineering step-by-step “optimization” that is not only driven by evaluating the objective function but also by varying parameters based on
examination of the flow physics and judgments incorporating aerodynamic expertise. A
general work flow comprises shape and setting modifications, grid generation, flow solution
and most important the analysis of the obtained results. Since the high lift components of the
targeted configuration were already designed with best practice an improved flap shape and
setting according to the given guidelines of the specification couldn’t be achieved by this
engineering approach. Either the objective function was improved but the constraints couldn’t
be kept or vice versa.

2 THE TAKE-OFF DESIGN CASE

One major issue for the realistic design of a high-lift system using only the 2D wing
section is the formulation of the design target. Two different problems arise, the first one is to
define realistic design targets and the second is a proper transformation from the 2D
calculations to 3D behavior. For the specification of the optimization cases the wind tunnel
tests performed in the EUROLIFT project were examined in detail to define proper design
targets. The design is performed for the specific wing section called DV06 shown in Figure 1.
This wing section is equipped with a row of pressure probes on all three wing elements of the
corresponding wind tunnel model DLR F11.

2.1 Objective function

Since the design focuses on an increased take-off performance the corresponding flight
regime was evaluated. As it is shown in Figure 2 the design range for the specific
configuration take-off 22/20 is limited by an upper lift coefficient, where the minimum flight
speed at 1.13 times the stall speed is reached [3]. The lower limit is the minimum flight speed
of the next more retracted configuration take-off 16/8. The definition of the objective function
is based on the climb index

\[ F_{obj}(\bar{x}) = \sum_{i=1}^{3} -\frac{C_{L}^3}{C_{D}^2} \]

at the limits of the design range. This performance indicator is better suited for high-lift
performance improvement than the lift to drag ratio because it has an additional weighting on
the lift coefficient. The climb index itself is derived form the climb speed which is
approximately

\[ \frac{w}{V} \approx \frac{T}{G} - \frac{C_{p}}{C_{L}} \Rightarrow w \approx \frac{1}{\sqrt{C_{L}}} \frac{T}{G} \frac{C_{D}}{C_{L}^{1/2}}. \]

Constraints are applied in order to retain the initial lift coefficients and to not increase the
pitching nose down moment. A geometric constraint is applied on an increased horizontal
deflection in order to account for increasing track weights of the high-lift system kinematics.

2.2 Design Variables

The parameters used for the design include the three degrees of freedom for the rigid body
motion of the 2D flap section and part of the flap shape. Since for a realistic application the shape of the clean airfoil with retracted high-lift system must be retained in order to not affect the cruise performance of the aircraft, only the part of the flap shape that is invisible in retracted position is free for design. Limitations apply due to the request, that even the free flap shape must fit into the clean wing and at the shroud railing edge a minimum thickness must be retained. For this purpose a geometric box has been specified, depicted in Figure 3, that has to enclose the designed flap shape. For the edges of the designable shape at least a tangential continuity to the fixed shape had to be achieved.

2.3 Swept wing analogy

For the application to transonic transport aircraft the infinite swept wing analogy (Figure 4) is used together with a systematic scaling based on the 3D planform to transfer the 2D section data to 3D wing performance. The infinite swept wing analogy divides the flow into two parts, the first governing the flow in a plane normal to the sweep direction and the second into the direction of the sweep. Since in the second part all geometry is parallel to the direction of sweep, no gradients of the flow quantities in this direction occur. The applied transformation results in a scaling of the wing section geometry

\[ y_{2D} = z_{3D} \cos \varphi \]  

and the nominal flow conditions

\[ M_{2D} = M_{3D} \cos \varphi \]  
\[ Re_{2D} = Re_{3D} \cos^2 \varphi \]  
\[ \alpha_{2D} = \tan^{-1} \left( \frac{\tan \alpha_{3D}}{\cos \varphi} \right) \]

For the reverse transformation first the computed pressure distribution has to be scaled according to the reduction of the reference Mach number

\[ c_{p_{3D}} = c_{p_{2D}} \cos^2 \varphi \]

This pressure distribution is then matched to data of the 3D wing by varying the angle of attack. This is necessary since the local effective angle of attack at the design section is unknown because it is a function of the circulation distribution and the angle of attack of the 3D wing. Figure 5 shows a comparison of 2D scaled calculated pressure distributions matched to wind tunnel data of the corresponding 3D half model wing at the both design points.

The second step of the reverse transformation includes some assumptions on the 3D wing behavior. One assumption is that the characteristic shape of the spanwise distribution of lift and drag is at a first glance a function of planform and twist distribution. It is further assumed that only the level of the distribution is changed by the flap modifications. By this we can assume a scaling between 2D and 3D for the lift coefficient by

\[ C_{l_{2D}} = \gamma_c C_{l_{3D}} \cos^2 \varphi \]
where the correlation factor is evaluated from comparing the lift coefficients for 2D and 3D at the points matched by the pressure distribution for a number of angles of attack.

For the correlation of the drag coefficient first the induced drag has to be separated, since it cannot be accounted for in 2D. We do this by assuming the induced drag of an elliptical wing of the same aspect ratio as the 3D wing. Better results can be obtained if more detailed information about the reference wing is accessible. After extracting the induced drag, the correlation of the remaining 3D pressure drag to the 2D computed drag values leads to a correlation factor similar the above described factor for the lift coefficient. To obtain at least 3D values for the drag the induced drag part has to be reintroduced leading to

\[
C_{D_{\text{ind}}} = \gamma_{C_c} C_{D_{\text{ind}}} \cos^2 \varphi + \frac{1}{\pi \lambda} \left( \gamma_{C_c} C_{\rho_{\text{ind}}} \cos^2 \varphi \right)^2
\]  

(9)

The result of this approximation for the DLR-F11 configuration is shown in Figure 6. The figure shows the 2D computed values of the design wing section, the 3D experimental values of the 3D wing together with the result approximation. Together with the correlation of the angles of attack a good match of approximated 3D behavior based on 2D calculations with the 3D wind tunnel data is obtained.

3 APPLIED METHODS

A key issue for the design work has been that every partner uses his own methods in which he trusts and applied with the best practice available. This approach offers the possibility to examine shortcomings and advantages of the different methods for the high-lift design by the comparison of the results.

3.1 CFD-solver

Most of the partners applied Finite Volume Methods based on the Reynolds-averaged Navier-Stokes (RANS) equations. The equations are solved by a time-integration scheme. One partner applied within the optimization loop an Euler-boundary layer coupling method.

CIRA had two different tools available, namely the MSES Euler+B.L. flow solver [4], and the in-house developed ZEN 3D RANS-code. Based on the experience of previous design problems [5] the first decision was to work with the RANS-code. A k-ω turbulence model was adopted, and the flow was considered fully turbulent. A parametric grid generation procedure was developed, capable of generating a multi-block grid with 96384 cells around three component airfoils of the class of those used for the optimization problem. The subsequent step was the tuning of grid and solution. A 5 stage Runge-Kutta scheme was used in the solver, and a fully converged solution was obtained after about 40000 explicit iterations that required 4 hours of vector CPU (NEC SX-6) using the ZEN RANS-code. The obtained results were then very consistent with those obtained using Euler+B.L. (both in fully turbulent and free transition mode) and it was therefore decided to use the Euler+B.L. solver in free transition mode in the optimization process, while the RANS-code with the fine grid would have been used for verification and validation of the obtained results.

DLR used its in-house developed FLOWer code [6], which is a structured finite-volume
RANS solver. For the discretization of the governing equations a central scheme of second order accuracy in space is used. From several algebraic and transport turbulence equation models, the Spalart-Allmaras model with Edwards modification is preferred for its accuracy and robustness. The steady RANS equations are integrated in time using a time-marching 5-stage Runge-Kutta scheme and typical convergence acceleration techniques, like multigrid, implicit residual smoothing and local time stepping are applied. Since the quality of the computational grid plays a crucial role for the correct resolution of the complex flow which occurs around the 3-element airfoil, it was decided to generate new meshes at each optimization step instead of applying mesh deformation. For this purpose the parametric grid generator MegaCads [7] developed at DLR has been used. This approach offers the generation of grids of constant quality, in terms of smoothness and boundary layer resolution, around changing geometries in an automatic way using algebraic, elliptic and hyperbolic techniques. All meshes are based on the same topology, a multi-block type mesh with 9 blocks, 90,065 points and designed for 3 levels of multigrid. Special care is taken to discretize the boundary layer and the wake of each element.

**FOI** applied the flow solver EDGE [8], developed at FOI, which solves the Reynolds-averaged Navier-Stokes equations on unstructured grids, using a vertex centered finite volume discretization of the mass, momentum, energy and turbulence equations. The Spalart-Allmaras one-equation turbulence model is used here. Convergence is accelerated by local time stepping, multigrid, and implicit residual smoothing. Additionally, in order to account for natural transition a linear stability analysis is applied [9].

**ONERA** used for the calculation of the aerodynamic coefficients the ONERA elsA software [11], which solves the compressible three-dimensional RANS equations by using a cell-centred finite volume spatial discretization on structured multi-block meshes. Computations have been carried out using an uncoupled approach between the RANS system and the turbulence model transport equations [12]. For the explicit scheme, a 4-step Runge-Kutta space centred type scheme, as proposed by Jameson, is used for the conservative variables. A fourth order linear dissipation is generally used, with added second order dissipation terms for treatment of flow discontinuities. For the implicit stage, a LUsor scheme is associated with an Euler backward time integration scheme. For the turbulent variables, the Roe numerical scheme is used. Different multi-grid techniques are available for convergence acceleration (V or W cycles), as well as low-speed preconditioning [13]. A number of turbulent models are available. The two-equation k-ω model from Wilcox [14] has been selected for the optimization work. A wall function formulation [15], allowing Y+ values around 100 and more regular cells is applied, since such modifications increase robustness and make high Reynolds number computations less mesh dependent. During the EUROLIFT I program, a comparison was made between classical structured multiblock, unstructured and structured chimera grids on the same configuration did not show dramatic differences [16].

### 3.2 Optimization methods

The applied optimization strategies cover the complete range of approaches that exist...
today. Gradient-based, gradient-free and stochastic methods have been used.

**CIRA** used a multi-objective genetic algorithm [17][18] for the optimization, with a crossover rate of 100%, a mutation rate of 1.5% and local random walk as selection method for choosing the mating parents.

**DLR** made some preliminary tests on this design case applying gradient-based, gradient free as well as stochastic methods. The final design was obtained using a differential evolutionary algorithm (DE) [19]. In contrast to standard evolutionary algorithms, DE combines the mutation and recombination phases to one operation. The main idea is to use vector differences (mutation) and a variant of uniform crossover (recombination) for the creation of the children. The last phase (selection) is straightforward and very simple: the child replaces his parent if it is better. DE has been tested both on benchmark problems [20] and on real problems [21] and it often appears to be the best performing algorithm for finding the global optimum.

**FOI** used a quasi-Newton method (BFGS update) to calculate descent directions in combination with a line search algorithm using Goldstein conditions [22]. The gradient of the objective function is estimated by a finite difference approximation, requiring in the present case 12 CFD solution for one gradient.

**ONERA** applied the conjugate gradient method CONMIN of Vanderplaats [23]. In the present methodology, the gradients are determined by finite differences at each iteration. For the accounting of the constraints, the feasible direction method of Zoutendijk is applied. The conjugation of the gradient is done according to Fletcher and Reeves. At each optimization iteration, three steps are performed to search for the objective function minimum along the search direction and to respect the constraints. The process for gradient computation has been parallelized, which means that in term of restitution time, the time requested of one optimization process is nearly equivalent to the number of iterations times the time needed for the flow solution.

### 4 OPTIMIZATION RESULTS AND CROSS-CHECK

As stated earlier every partner used different approaches for the design optimization work. Additionally a work share was established in order to get also answers on the usability of the different approaches as well as some distinction about the influence of setting variation and shape variation. For this purpose some partners performed pure setting optimization while others performed shape and setting optimization. One big question when designing with 2D methods for a 3D configuration is of course the influence of the neglected cross flow effects. For this reason some optimizations have been run in 2D mode while others were done in 2.5D swept wing mode accounting for cross flow. Table 1 summarizes the agreed work share.

After the optimizations an essential part of the evaluation of the concurrent designs has been the implementation of a cross-checking phase in the work program. In this phase each partner calculated all optimization results obtained by the different partners. By this the dependencies on the methods used for the design should be discovered and eliminated.
4.1 Setting optimizations

The resulting flap positions of the setting optimizations performed by CIRA and ONERA are depicted in Figure 7. The result of CIRA shows a downstream movement of the flap at a nearly constant gap with a slight reduction of the flap angle, resulting in a 0.8% improvement of the objective based on CIRAs calculation method. ONERAs results show in contrast a reduction of the flap gap at nearly the same overlap without changes of the flap angle, claiming a reduction of the objective of 5.6% in 2D and 7.5% in 2.5D. One result to be highlighted is that the two optimizations run by ONERA in 2D and 2.5D mode show only a slight variation of the overlap. This indicates that cross flow is not affecting the design critically in this type of application.

4.2 Setting and shape optimizations

For the combined setting and shape design three solutions have been obtained that are shown in Figure 8. CIRAs design is characterized by a reduction of the leading edge radius with a following flat section. Downstream the trailing edge of the main wing a local curvature increase is observed. The flap position is moved downstream and the gap is considerably closed. The predicted improvement of the objective function by this design is stated by CIRA to be only 0.1%, which results mainly from a heavy penalty on the downstream movement of the flap. A further reason for the improvement being less than for the pure setting optimization above is related to the use of the EULER-BL solver in the optimization while the assessment of improvements is evaluated using the RANS method (the improvement in the objective function obtained using the EULER-BL solver with free transition is equal to 2.4% [24]). DLRs shape shows a significant high curvature at the nose that is additionally moved close to the lower side of the flap. The following shape on the upper flap side is characterized by two regions of high curvature connected with relatively flat surface parts in between. As for the CIRA design the second region of increased curvature is located right behind the main wing trailing edge. The flap is moved downstream and upwards as in the CIRA result but to a smaller extent. DLR stated an improvement of the objective function of 2.0% for their design. The result of FOI obtained in 2.5D mode shows only a minor change of the flap shape. The positioning of the flap is similar to the result of CIRA for the pure setting optimization. FOI claimed an objective function improvement of 1.0%. A reason for the low significance of the flap shape for this optimization has been discovered in the typical problem of scaling gradients for variables with large differences in range and sensitivity.

A remarkable outcome at this point has been that the differences in the obtained optimum flap positions are much larger than for the pure setting optimization itself, although the proposed benefits are closer to each other. Looking onto the geometries it shows up that all three results are some kind of lined up at the flap leading edge. An assumption based on this result has been that the combination of leading edge modification, gap closing and the constraint of downstream movement act dependently on the objective function.

4.3 Cross-checking results and selection of final design

The above stated improvements of the obtained designs are not well comparable, since
they include all kinds of dependencies on the flow solver. To overcome this, the cross-checking has been implemented into the work plan. In essence, all obtained designs have been calculated with most of the different methods. This procedure has the best chance to detect the configuration that improves the performance independent on the flow calculation procedure.

Figure 9 summarizes the predicted improvements of the objective functions based on these cross-checking calculations. The rows of the included table correspond to the partner’s optimization result, while the columns correspond to the calculating partner. The graph shows that the assessed improvements of CIRA, DLR and FOI are of the same order and show more or less similar trends. ONERAs computations show significantly larger differences between the configurations and different trends. For some combinations the situation occurs that some partners are detecting improvements while others predict a worsening of the objective function.

Based on these calculations a decision has to be made concerning the selection of a shape to apply to the wind tunnel model. To be as confident as possible it was decided to use the shape that was predicted by all partners to gain improvements, which is the DLR design. Detailed analysis showed that the disadvantage of CIRAs design is mainly related to a higher penalty due to the upstream position, while the aerodynamic performance itself is predicted to be slightly better than for the DLR design. Nevertheless it was not expected that the aerodynamic performance improvements of the CIRA and DLR designs are as similar as they are computed, since the flap setting is completely different. To verify this result additional calculations have been performed by DLR with the DLR flap shape positioned at the CIRA result and vice versa (Figure 10), showing that the minor dependence on the setting is also present using one single calculation method. This is also visible looking at the flap pressure distributions of both flap shapes at the same flap setting (Figure 11), which show no significant differences. To verify this insensitivity to the setting variation, it has been decided to test the new DLR shape at both the DLR and CIRA setting.

5 VERIFICATION WIND TUNNEL TEST

5.1 Implementation of selected flap shape to wind tunnel model

The first step towards the verification of the performed design is the modeling of the 3D flap of the wind tunnel model based on the 2D section design. For this purpose the CAD system CATIA V4 has been used. The original flap surface has been divided at the upper and lower retraction edges. The loft of the new flap shape was generated by an affine translation of the design section along the flap span.

The setting values obtained by the optimizations have been transformed according to the local flap chord. The outboard flap has got a constant relative chord, while the inboard flap has a constant absolute chord. Respecting this the setting values were applied with constant percentage of local wing chord to the outboard flap and held constant for the inboard flap.

5.2 High Reynolds number test in ETW

Wind tunnel tests with the reference flap and the new designed flap at the settings
proposed by DLR and CIRA have been conducted in the European Transonic Wind Tunnel facility in Cologne, Germany. The experiments were performed in a cryogenic and pressurized environment, allowing for Reynolds numbers of up to \( Re = 25 \times 10^6 \) at a temperature of \( T = 115K \). All configurations have been measured at a Mach number of \( M_\infty = 0.2 \) for the Reynolds numbers \( Re = 15 \times 10^6 \) and \( Re = 20 \times 10^6 \). The higher Reynolds number has been measured with two different conditions of temperature and pressure in order to assess dependencies on the model deformation.

5.3 Comparison of measurements to predictions

Out of the amount of data obtained in the wind tunnel comparisons of the predictions towards the experimental data will be made for the higher Reynolds number \( Re = 20 \times 10^6 \) at \( T = 115K \), since this was the design condition. First, a comparison of the improvements of the climb index \( \frac{C_l}{C_D} \) is shown in Figure 12. The lines without symbols represent the experimental data. The symbols refer to the scaled values at the two design points as predicted by the different partners. It is observed that the order of magnitude of the predicted improvements match well for most of the partners. Also the tendency of one design point to the other is well captured. Only ONERAs calculations show too large differences between the reference and the designed flap. It is now part of further investigations to evaluate the reasons for this misbehavior.

The experimental data for the two applied settings for the new flap also show fewer differences to each other than the general improvement related to the baseline flap. Nevertheless, the predicted slight advantage of the CIRA setting over the DLR setting regarding the aerodynamics only is not verified by the measurements. A look at the flap pressure distributions in Figure 13 shows that the suction on the flap upper side is predicted slightly too low. This may result from the fully turbulent calculation method compared to wind tunnel experiments with natural transition.

12 CONCLUSIONS

Numerical optimization methods have been applied for the design of a new flap for a high-lift wing-body configuration at realistic high Reynolds number conditions. A new method has been applied that allows for a proper prediction of the behavior of the three-dimensional configuration based on two-dimensional calculations. A two-point design has been performed where the design conditions have been derived from realistic flight conditions based on regulations.

A concurrent design work has been performed by the partners. The final designs have been evaluated by a cross-checking in order to assess solver dependencies. From this data a final design has been selected and applied to the three-dimensional half-model. Wind tunnel tests have been carried out under a cryogenic and pressurized environment in order to achieve realistic Reynolds number. These tests show a good agreement between the predicted and the experimental obtained performance improvements. The predicted improvement of about 2% in terms of the climb index has been verified.
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REFERENCES


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Table 1 : Work share of performed optimizations
Figure 1: DLR-F11 high-lift model and selected wing section for the design of a new flap

Figure 2: Design range for the DLR-F11 model

Figure 3: Constraint on flap shape modification: Only the blue part is free for design, the flap shape must be contained in the red box.

Figure 4: Transformation of the design section (red line) into the leading edge coordinate system (blue line) by use of the infinite swept wing (yellow) analogy
Figure 5: Comparison of the pressure distributions of the measured 3D wing and the calculated normalized 2D wing section for both design points.

Figure 6: Approximation of three-dimensional aerodynamic coefficients based on two-dimensional calculations.

Figure 7: Comparison of designed flap setting positions resulting from the numerical optimizations of different partners.

Figure 8: Comparison of designed flap shapes and setting positions resulting from the numerical optimizations of different partners.
Figure 9: Improvements of the objective function for the different designs assessed by cross-check calculations by the different partners.

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Figure 10: Comparison of predicted improvements of the shape designs distinguished between setting and shape influence.

Figure 11: Comparison of the pressure distribution of the designed flap shapes at an identical position.
Figure 12: Comparison of predicted improvements of the climb index towards experimental data obtained in ETW wind tunnel

Figure 13: Comparison of calculated (lines) and measured (dots) flap pressure distribution for the designed flap shape at two different settings compared to the reference configuration