Applications of a discrete viscous adjoint method for aerodynamic shape optimisation of 3D configurations

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Abstract Within the next few years, numerical shape optimisation based on high-fidelity methods is likely to play a strategic role in future aircraft design. In this context, suitable tools have to be developed for solving aerodynamic shape optimisation problems, and the adjoint approach—which allows fast and accurate evaluations of the gradients with respect to the design parameters—is proved to be very efficient to eliminate the shock on aircraft wing in transonic flow. However, few applications were presented so far considering other design problems involving 3D viscous flows. This paper describes how the adjoint approach can also help the designer to efficiently reduce the flow separation onset at wing–fuselage intersection and to optimise the slat and flap positions of a 3D high-lift configuration. On all these cases, the optimisations were successfully performed within a limited number of flow evaluations, emphasising the benefit of the adjoint approach in aircraft shape design.

Keywords Optimisation · Adjoint method · Aerodynamics · Wing design · High lift

1 Introduction

Numerical shape optimisation is playing an increasing strategic role in aerodynamic aircraft design. It offers the possibility of designing or improving aircraft components with respect to a given objective, subject to geometrical and physical constraints. However, computational fluid dynamics (CFD) still suffers from high computational effort for flow simulations around realistic 3D configurations which limits its use in design process. Consequently, worldwide a large effort is being devoted to developing efficient optimisation strategies for industrial aerodynamic aircraft design.

One of the most promising design strategies is the use of the adjoint formulation [1–4] of the CFD solver for efficient and accurate computation of gradients in high-dimensional design spaces, which can then be applied within, among other, gradient-based optimisers. In the late 90's, the adjoint approach was matured enough to consider 3D viscous flows, both on structured [5] and unstructured meshes [6]. Few years later, the adjoint approach was used by the industries for solving more realistic 3D design problems [7–9], confirming the potential of the methods. Ironically, the viscous adjoint approach was almost exclusively applied to reduce the shock strength on the wing in transonic flows, see also [10, 11], but few applications consider other 3D viscous problems, like the wing–engine integration [12]. More surprisingly, the reduction of the flow separation onset at wing–fuselage intersection or the optimisation of the 3D high-lift devices was not investigated so far.

At the DLR, activities focus on developing several key technologies relating to the establishment of an efficient and flexible numerical optimisation capability based on high-fidelity methods. These include suitable techniques

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for geometry parameterization, meshing and mesh movement methods, efficiency and accuracy improvements of the flow solvers, as well as robust and efficient optimisers.

The paper gives an overview of the work performed at the German Aerospace Center's Institute of Aerodynamics and Flow Technology, on the application of the discrete adjoint approach for solving various aerodynamic shape optimisation problems. The paper introduces first the strategy developed in the unstructured *TAU* code [13–15] to solve the adjoint problem and to compute the gradients. In the second part, the paper focuses on the application to 3D design in cruise and take-off conditions.

2 Gradients via adjoint approach

2.1 Primal approach

Let the optimisation problem be stated as:

$$\min_{w.r.t. D} I(W, X, D), \quad (1)$$

subject to the constraint

$$R(W, X, D) = 0, \quad (2)$$

where I is a cost function such as lift or drag, D is a vector of design variables that control the shape of aircraft subject to aerodynamic design, $W(X, D)$ the vector of flow variables, $X(D)$ the computational mesh and $R(W, X, D)$ the residuals of the Reynolds-averaged Navier-Stokes equations completed by the Spalart-Allmaras turbulence model.

For a gradient-based optimisation strategy, the search for the minimum requires the sensitivity vector of the cost function I with respect to the design variables D . This vector can be written as

$$\frac{dI}{dD} = \frac{\partial I}{\partial X} \frac{dX}{dD} + \frac{\partial I}{\partial W} \frac{dW}{dD}. \quad (3)$$

The first and second terms in (3) give the direct effect of the geometry perturbation on the cost function I and the impact of the flow alteration caused by the geometry perturbation, respectively. Solving the above equation can be done by applying finite differences which requires evaluations of the flow solver on additional n perturbed geometries, with n the number of design parameter. Alternatively, the adjoint approach allows a rapid evaluation of dI/dD for a large number of design variables D , without computing the flow solution on any perturbed geometry.

2.2 Dual approach

Instead of applying the chain rule to I , apply it to the Lagrangian gives

$$L(W, X, D, \Lambda) = I(W, X, D) + \Lambda^T R(W, X, D) \quad (4)$$

where Λ are known as the adjoint variables. Since (2) holds for all D , $L = I$ for all Λ and all D . Hence,

$$\frac{dL}{dD} = \frac{dI}{dD} \quad \forall \Lambda, D. \quad (5)$$

and so, applying the chain rule to L , the sensitivity vector of I becomes:

$$\begin{aligned} \frac{dL}{dD} &= \left\{ \frac{\partial I}{\partial X} \frac{dX}{dD} + \frac{\partial I}{\partial W} \frac{dW}{dD} \right\} + \Lambda^T \left\{ \frac{\partial R}{\partial X} \frac{dX}{dD} + \frac{\partial R}{\partial W} \frac{dW}{dD} \right\}, \\ &= \left\{ \frac{\partial I}{\partial X} + \Lambda^T \frac{\partial R}{\partial X} \right\} \frac{dX}{dD} + \left\{ \frac{\partial I}{\partial W} + \Lambda^T \frac{\partial R}{\partial W} \right\} \frac{dW}{dD}. \end{aligned} \quad (6)$$

The unknown quantity dW/dD may be eliminated by choosing Λ such that

$$\left(\frac{\partial R}{\partial W} \right)^T \Lambda = - \left(\frac{\partial I}{\partial W} \right)^T. \quad (7)$$

This is the adjoint equation, and must be solved only once to evaluate the gradient of a single I with respect to any number of design variables. The resulting Λ allows rapidly computing the derivative using:

$$\frac{dI}{dD} = \left\{ \frac{\partial I}{\partial X} + \Lambda^T \frac{\partial R}{\partial X} \right\} \frac{dX}{dD}. \quad (8)$$

2.3 Implementation of the discrete adjoint approach

The discrete variant of the adjoint equation (7) is now considered. Its implementation requires the ability to evaluate the quantities $\Lambda^T (\partial R / \partial W)$ —the adjoint residual—and $\partial I / \partial W$.

The Jacobian $(\partial R / \partial W)$ is evaluated by hand, which is a straightforward exercise as R may be written explicitly in terms of W , while being time-consuming as R is often extremely complex. As R is a sum of convective fluxes, viscous fluxes, boundary conditions etc., each of these may be handled independently, and by application of the chain rule may be further subdivided into manageable chunks. The derivatives are further simplified by choosing primitive variables as working variables. Because the equations remain in conservative form this choice has no effect on the final solution. A more detailed description of the implementation in the *TAU* code can be found in [16]. A wide range of the spatial discretizations available in *TAU* have been differentiated, including the Spalart-Allmaras-Edwards one-equation turbulence model. The effect of various approximations of the Jacobian was investigated and their impacts on the optimisation were analysed on several 2D optimisation problems [16, 17]. It has been seen that approximating the adjoint by freezing turbulent

quantities leads to gradients that are accurate in low-speed case, but exceptionally poor on configurations involving a strong shock. In the present study, the viscous 3D adjoint computations have been performed by freezing turbulent quantities—i.e. assuming they are invariant with respect to the linearization. This is necessary because incorporating the linearization of the turbulence equations resulting in an exceptionally poorly conditioned Jacobian matrix, which is not amenable to solution with conventional iterative methods.

Despite the guarantees regarding convergence provided by the theory of adjointed fixed-point iterations (FPIs) [18] there are regularly situations in which it is possible to obtain a reasonably converged solution of the non-linear equations, but not of the corresponding adjoint equations. This can occur for three reasons: either (a) the non-linear solution is not sufficiently converged, or (b) there is a discrepancy between the linear and non-linear problem due to some approximation of the Jacobian, or (c) the FPI applied to the non-linear problem does not converge asymptotically itself. All three cases appear regularly in practice. An engineer may reasonably consider a computation converged when the integrated forces that interest her no longer vary significantly, though this may occur prior to the asymptotic regime.

In an effort to understand and mitigate these phenomena, we consider the recursive projection method (RPM), originally developed by Schroff and Keller in 1993 [19], as a means of stabilizing unstable procedures. A detail description of the effort can be found in [18] and here only the main idea is outlined: let the (linear) adjoint system be written $Ax = b$, and regard the transient solution of the linear problem as a sum of eigenvectors of the relaxation operator $\Phi = (I - M^{-1}A)$ where M is some iteration operator, e.g. LU-SGS with multigrid. The application of Φ to an approximate solution then corresponds to a product of each eigenvector with its corresponding eigenvalue. Divergence of the iteration implies that there is at least one eigenvalue of Φ with modulus greater than unity. Assuming that the number of such eigenvalues is small, and that the space spanned by their eigenvectors is known, call it P , then it must be possible to solve the projection of the problem onto this low-dimensional subspace using some expensive but stable method, while solving the projection onto the complementary subspace Q using the original FPI iteration, which is known to be stable there. Newton–Raphson is therefore used on P . The space of dominant eigenvectors is determined as the calculation progresses, by applying the principle that the difference between successive applications of the FPI on Q form power iteration on the dominant eigenvalues of Φ restricted to Q .

This procedure has been successfully applied for the design of DLR-F6 configuration that features flow separation in the junction between the upper surface of the wing and the fuselage, see Sect. 3.

Further investigations revealed that the robustness of RPM for the viscous adjoint problem was limited in the case that the base iteration diverges too rapidly for P to be well approximated. In this case applying the well-known generalised minimum residual (GMRes) method in its restarted form [20], with 10–50 iterations of LU-SGS with multigrid as a preconditioner has been seen to be an exceptionally robust alternative (although still not robust enough to solve systems including full turbulence model linearization in general) [21]. This was the stabilization used to converge the adjoint problem for the high-lift configuration in Sect. 4.

2.4 The metric terms

In order to compute the sensitivity vector of the cost function I as given in (8), the metric term variation is computed by using finite differences, which in case of R leads to:

$$\frac{\partial R}{\partial X} \frac{dX}{dD_k} \approx \frac{R(W, X(D + \Delta D_k)) - R(W, X)}{\Delta D_k} = \frac{\Delta R}{\Delta D_k}. \quad (9)$$

After obtaining Λ , the sensitivities can be evaluated with a single point deformation and yields for each design variable D_k to a variation of the cost function due to the perturbed geometry and we get a scalar difference for the direct variation and a matrix-vector product for the dependency of the residual,

$$\frac{dI}{dD_k} \approx \frac{\Delta I}{\Delta D_k} + \Lambda^T \frac{\Delta R}{\Delta D_k}. \quad (10)$$

The sensitivity vector requires here n perturbed meshes and the procedure is therefore not anymore strictly independent to the number of design variables since the mesh generation can take some minutes on complex 3D configuration. Alternatively, one can introduce an additional adjoint computation based on the volume mesh deformation to eliminate the mesh sensitivities as proposed by Nielsen and Park [10]. Such alternative is currently under development at DLR and promising results have already been obtained on 2D viscous flows [22]. In the 3D applications presented here, the metric terms are approximated using finite differences and the perturbed meshes are first generated (and stored) during the flow and adjoint computations. Once all perturbed meshes, the flow and the adjoint fields are available, the computations of the residual as in (9) take few seconds and the sensitivity

vector following (10) is obtained after few minutes. Such approach was successfully applied on design problems with up to 96 design parameters without penalty on efficiency. It is however clear that such method is hardly usable on larger design problems involving thousands of design variables and an alternative strategy like the mesh adjoint is mandatory.

2.5 Drag reduction at constant lift by adapting the angle of incidence

A major goal in aerodynamic shape optimisation is to improve the drag coefficient without loss on the lift. In some cases, the lift constraint can be enforced explicitly by varying the angle of attack during the evaluation of the drag in the non-linear RANS solver, the so-called target-lift mode. In this case, the angle of attack is not controlled by the optimiser, but will change during the optimisation. The computation of the gradients has to be accordingly adapted and following the work of Reuther et al. [23], we first consider the variation of the drag and the lift with respect to the shape and the angle of attack:

$$\delta C_D \approx \frac{\partial C_D}{\partial D} \delta D + \frac{\partial C_D}{\partial \alpha} \delta \alpha \quad (11)$$

$$\delta C_L \approx \frac{\partial C_L}{\partial D} \delta D + \frac{\partial C_L}{\partial \alpha} \delta \alpha \quad (12)$$

In order to ensure a constant lift during the optimisation, i.e. $\delta C_L = 0$, the change of the angle of attack is then set to compensate exactly the variation of the lift coefficient due to the change of the shape:

$$\delta \alpha = - \left(\frac{\partial C_L}{\partial \alpha} \right)^{-1} \frac{\partial C_L}{\partial D} \delta D \quad (13)$$

Finally, by introducing (13) in (11), we end up with the variation of drag at constant lift by adapting the angle of attack:

$$\delta C_D|_{\delta C_L=0} \approx \frac{\partial C_D}{\partial D} \delta D - \left(\frac{\partial C_L}{\partial \alpha} / \frac{\partial C_D}{\partial \alpha} \right) \frac{\partial C_L}{\partial D} \delta D \quad (14)$$

The sensitivities to design variables D are obtained as described in Sect. 2.4 while the sensitivities to the angle of attack have been differentiated exactly per hand and are provided at the end of the computation of the adjoint flows.

3 Shape optimisations of the DLR-F6 configuration

The adjoint method is first applied to the drag minimization of the DLR-F6 wing-body configuration at Mach 0.75, a Reynolds number of 3×10^6 , and lift coefficient 0.5. At this condition, the baseline configuration has a large region of separated flow in the junction between the upper

surface of the wing and the fuselage. The focus of the shape optimisation is on the reduction of the separation area through drag minimization at constant lift.

The optimisation algorithm is the conjugate gradient (CG), as in [24], where the angle of attack is automatically set by TAU to maintain the lift constant. The computational grid is made of structured meshes with highly stretched hexahedral cells for the boundary layer around the wing and fuselage and tetrahedral elements for the outer flow field, see Fig. 1. This mesh technique can greatly speed up Navier–Stokes flow computations without losing solution accuracy, thanks to the reduced number of points [25]. The mesh used here has 118,911 points but gives more accurate solution than a hybrid mesh—consisting of prismatic, pyramidal, and tetrahedral elements—with 867,266 points [24]. The mesh used is far too coarse to adequately resolve all flow physics details—like the shock strength—but is sufficient to capture the separated flow, the purposes of the current demonstration. For each new configuration, the structured meshes are generated each time to ensure a constant mesh quality while the tetrahedral elements are accordingly deformed. Such approach ensures a constant number of mesh points which is a necessary condition for computing (9). The geometry is parametrised by the coordinates of the lattice box points controlling the free-form deformation (FFD) [26–28]. The FFD technique allows a broad range of deformations with a low number of parameters and ensures a smooth deformation. The lattice boxes are generated with DLR's parametric grid generator MegaCads [29]. Note that since the bounding box passes inside the fuselage, the wing-body junction also varies, and this is accounted for by the geometry and grid generation process.

Fig. 1 Mixed structured/unstructured Navier–Stokes meshes of the DLR-F6 configuration

Fig. 2 Parameterization of the wing with a free-form deformation box with 84 paired nodes

3.1 Wing shape optimisation

For the wing optimisation, the vertical positions of 84 paired nodes of the FFD bounding box as well as 12 additional wing twist variables are used as design parameters, see Fig. 2. In total the wing is parametrised with 96 variables and the pairing of nodes ensures that the wing thickness remains unchanged during the optimisation. With such a large number of design variables only gradient-based optimisation is viable, and only the adjoint method can deliver the gradient efficiently. The standard method of adjointed LU-SGS with multigrid alone was unconditionally unstable and applying RPM is necessary to obtain a converged solution. The metric sensitivities needed in the gradient calculation are evaluated by central finite differences.

The convergence of the optimisation is shown in Fig. 3, the horizontal axis shows the number of calls to the flow solver (both linear and non-linear), thereby approximately

Fig. 3 Convergence of the DLR-F6 wing shape drag-minimisation optimisation

Table 1 Angle of attack, drag, lift and pitching moment coefficient on the baseline and wing designs configurations

Configuration	AoA (deg.)	Drag (CNTS)	Lift	Pitching moment
Baseline	0.66	401.2	0.5	−0.688
Wing design with 42 DV	0.46	393.2	0.5	−0.696
Wing design with 96 DV	0.38	391.1	0.5	−0.701

representing computational effort. Symbols indicate gradient evaluations. After 32 solver calls CG is unable to reduce the drag further giving a final reduction of about ten drag counts (1 drag count equal to 0.0001), without change on lift and limited variation on pitching moment, see Table 1. At the end of the optimisation, the norm of the gradient is only divided by a factor of 3, which indicates that the drag could be further improved. The optimisation here stalled probably due to the accuracy of the gradient—the adjoint flow did not take into account the linearization of the turbulence model—and/or the parametrisation. A similar optimisation with 42 parameters produced a reduction of only eight counts on this mesh (in a similar CPU time), emphasising the need for a comprehensive parameterization. The optimisation reduced the region of corner separation considerably, Fig. 4, while not completely eliminating it, which is unlikely to be possible within the design space considered, as it does not allow deformation of the fuselage. As expected the change of the wing shape is rather limited, and mainly concentrated at the wing leading edge to decrease the maximum overpressure, see Fig. 5, and at the trailing edge angle to increase the lift close to the wing-body intersection line Fig. 6.

Fig. 4 Comparison of the region of corner separation before (presented with the dashed line) and after wing shape optimisation

Fig. 5 Geometry and pressure distribution at sections $\eta = 0.331$

Fig. 6 Lift distribution along the span-wise direction on the baseline and optimised configurations

3.2 Fuselage shape optimisation

As second demonstration, the fuselage shape is now optimised by considering the wing shape constant. This exercise intends to demonstrate the possibility of removing the flow separation by shaping the fuselage. Here also, the FFD is employed and a representation of the bounding box around the fuselage is given in Fig. 7. The horizontal

Fig. 7 Parameterization of the fuselage with a free-form deformation box with 25 active nodes (red spheres)

displacements of 25 nodes, concentrated around the intersection line, are selected as design variables. The node displacement is not restricted to any direction and can lead to an increase or a decrease of the volume of the fuselage. After deformation, the intersection line is recomputed with the in-house tool MegaCads.

After 46 flow and 7 gradient evaluations, the optimisation process converges to a final configuration by keeping constant the lift coefficient, see Fig. 8. The new optimised configuration has almost 20 drag counts less than the baseline configuration. The norm of the gradient has been reduced by more than one order of magnitude with a final value close to zero: the optimisation here converges to the optimal solution. In fact, the gradients are more accurate than in the previous case since the design variables control parts where no shock occurs. It was indeed observed on 2D cases [17] that the adjoint computations based on frozen turbulence model gives gradients of good quality on flow without shock.

Figure 9 shows a comparison of the region of corner separation before and after optimisation of fuselage shape. In fact the optimisation procedure is able to completely remove the flow separation. Close to the trailing edge of the wing, the new fuselage presents a shape similar to a fairing as observed on modern aircraft. A side view of the optimised wing-body intersection shows a more complex 3D shape, with parts going into the fuselage, Fig. 10. The optimisation process perfectly adapts the shape to the flow to avoid separation. This result confirms the accuracy of the adjoint approach for computing gradients and demonstrates the flexibility of the optimisation process to handle complex 3D aerodynamic flows.

Fig. 8 Convergence of the DLR-F6 fuselage drag-minimisation optimisation

Fig. 9 Comparison of the region of corner separation before and after fuselage shape optimisation (*dashed line* represents the limit of flow separation on baseline configuration)

Fig. 10 Close view of the wing-body intersection after optimisation of the fuselage shape

4 Flap and slat settings optimisation of the DLR-F11 aircraft

The last configuration optimised is the so called DLR-F11 model with full span flap and slat in take-off configuration, see Fig. 11. This model is a wide-body Airbus-type research configuration with a half span of 1.4 m that can feature different degrees of complexity [30]. Here six design variables are selected to modify the deflections, the horizontal and the vertical positions of the flap and the slat. The geometric changes are propagated homogeneously

Fig. 11 Mesh around the DLR-F11 model in full span flap and slat configuration

along the span. The goal is to maximise at a single take-off condition (Mach = 0.2; $Re = 20 \times 10^6$; AoA = 8°) a derived expression of the lift to drag ratio:

$$Obj = \frac{C_L^3}{C_D^2}. \quad (15)$$

This performance indicator, based on the climb index, has already been successfully employed for flap design based on 2D computations and turned to be better suited than the lift to drag ratio [31]. Additionally, the lift has to be maintained constant and the angle of attack is kept fixed. In order to make a more realistic optimisation the weight of the high-lift system kinematics, which depends on the horizontal deployment capability, is taken into account by penalising the objective function to avoid too heavy a mechanism. The relation between the horizontal displacement Δx , with $\Delta x > 0$ for flap or slat deployment, and the penalty is set according to industrial specifications [31]:

$$P(\Delta X) = \begin{cases} 0 & \forall \Delta X \leq 0 \\ 200 \times Obj_{ini} \times (\Delta X)^2 & \forall \Delta X > 0 \end{cases}. \quad (16)$$

An ICEM-CFD macro has been developed to handle both the parameterization and the mesh procedure. This macro first sets the position of the elements according to the design variables and computes automatically the flap and slat intersection lines with the body. Once the CAD geometry is ready, the meshing part starts and automatically projects the mesh on the moving part and on the updated intersections lines, sets the position and size of the O blocks surrounding the elements. The resulting mesh has in total 2.5 millions points, see Fig. 11. The complete process, from reading the design variables to writing the mesh in unstructured formats takes about 1 min on a single AMD Opteron 2.5 GHz processor.

The numerical simulations are based on the RANS equations and the Spalart–Allmaras–Edwards turbulence model. For fast convergence, the low Mach number

Fig. 12 Evolution of the objective and lift coefficient according to the wall clock time

preconditioning approach is adopted and the steady state is reached by a Runge–Kutta scheme using multigrid W-cycles on 3 levels. A fully converged solution with almost 5 orders of density residual decrease is obtained after 5,000 TAU cycles.

In order to exploit the parallel capability of the TAU code, the aerodynamic flow is computed on a cluster of 32 AMD Opteron 2.4 GHz processors and the drag and lift adjoints are computed simultaneously on 2 clusters of 16 processors each. Each solution is fully converged after 3 h wall clock time.

Figure 12 presents the evolution of the optimisation process obtained with the NLPQLP optimisation strategy [32] available in modeFRONTIER [33] coupled to the adjoint approach for the computations of the gradients. After 13 evaluations and 78 h of simulations the optimisation converged to a maximum with a limited deviation on the lift coefficient. The performance improvement is made evident by plotting the drag distribution in span-wise direction for each element, see Figs. 13, 14: the

Fig. 13 Drag distribution along the span-wise direction on the baseline and optimised configurations

Fig. 14 Lift distribution along the span-wise direction on the baseline and optimised configurations

optimisation has almost no influence on the lift and drag of the body and the flap but permits to make further negative the drag on the slat by increasing the lift. This improvement has to be paid by a drag increase and lift loss on the main wing. Finally, the optimised configuration has in total 17.8 counts less drag than on the baseline configuration by same lift coefficient and a slight increase of nose-down pitching moment ($\Delta C_m = 1.3\%$). Figures 15, 16 present a comparison of the slat and flap positions at a given span-wise position and confirm the trends already observed. The slat trailing edge move closer to the main wing to produce higher lift and thereof larger negative drag. As a consequence, the gap of the flap has to be increased to keep the total lift constant.

Similar optimisations were performed with other optimisation strategies ranking from a differential evolution to gradient free approach [34]. All optimisations end up with very similar flap and slat positions after more than 1 week of computations. It can be guessed that the design space is rather shallow close to the optimum and only the gradient-based strategy using the adjoint approach is able to find the minimum in a reasonable turn-around time and reduced

Fig. 15 Slat setting for the baseline and optimised configuration at the middle of the outer wing

Fig. 16 Flap setting for the baseline and optimised configuration at the middle of the outer wing

computation power. Furthermore the process is almost independent to the number of design variables and makes a more detailed design possible at similar turn-around time.

5 Conclusion

This article presented activities carried out at the DLR for the development of the discrete adjoint approaches in the unstructured RANS solver TAU code and its application for solving viscous dominated aerodynamic shape design problems.

The capability of the adjoint approach to handle problems with large number of design parameters has been first demonstrated for the optimisation of the DLR-F6 configuration. It has been observed that the region of separation is considerably reduced thanks to the fine parameterization of the wing. When the fuselage is parametrised, the optimisation process is able to remove the flow separation within a limited number of flow computations. It can be pointed out that the FFD is here a key technology for the parametrisation of critical area. This successful optimisation confirms the accuracy of the developed adjoint based procedure for computing the gradients.

The method has been then applied to optimise the settings of a 3D high-lift configuration. Thanks to the adjoint approach, only a few flow computations are required to converge the optimisation problem. The inclusion of the adjoint approach gives new opportunities to treat more complex optimisation problems in limited turn-around time.

Near future activities will focus on improvement of the evaluation of the metric terms to compute more efficiently the gradients. From the applications point of view, future work will deal with multi-points problems for robust design and on other complex configurations, such as engine integration problems.

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