# Treatment of surface intersections for gradient-based aerodynamic shape optimization


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## I. Introduction

THE gradient-based optimization strategy, combined with accurate flow simulations and the use of the adjoint formulation to efficiently calculate the gradients, has been proved a promising approach for the improvement of the aerodynamic performance or aircraft designs [1]. However, the deployment of this technology in an industrial environment still faces limitations as the difficulty to handle moving intersections of surface components during the optimization, such as wing-fuselage and wing-pylon-nacelle.

Non-Uniform Rational B-Splines (NURBS) surfaces are extensively used by Computer Aided Design (CAD) software and become a widespread standard representation of the geometry. This representation does not define a continuous surface for the whole geometry, so several NURBS patches are employed to assemble different sections and components.

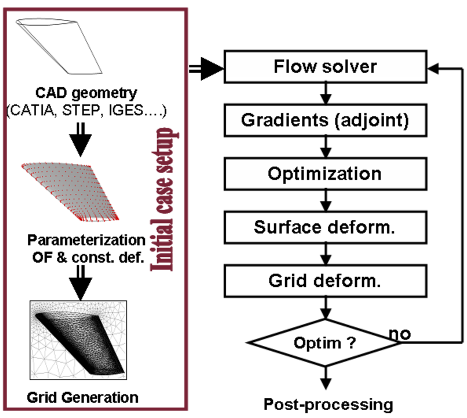


Fig. 1 Gradient-based shape optimization process.

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The employment of a gradient-based optimization of an aircraft, as shown in Fig. 1, is limited to individual components without a proper treatment of moving intersections between different surface patches. One possible solution is the employment of automatic grid regeneration combined with mesh refinement techniques [2], although could be time expensive. For small deformations, the solution proposed is to adapt the computational grid by employing the NURBS, directly extracted from the CAD representation file in IGES file format, to recalculate the intersection between surface patches and performs the necessary adaptations to propagate the boundary deformation to the volumetric grid.

The methodology developed comprises four steps: calculation of the NURBS parametric coordinates of the vertex of the computational surface grid; detection and recalculation of the moving intersection; deformation of the surface grid; and propagation to the volumetric grid.

## II. Intersections Handling

From the mathematical point of view, NURBS are b-splines parametric representations of the geometry; a surface is defined from the parametric coordinates $\{\xi, \eta\}$ as:

$$S(\xi,\eta) = \frac{\sum_{i}^{I}\sum_{j}^{J} U_{i,p}(\xi) V_{j,q}(\eta) w_{ij} C_{ij}}{\sum_{i}^{I}\sum_{j}^{J} U_{i,p}(\xi) V_{j,q}(\eta) w_{ij}} \quad (1)$$

In the equation above $p$ and $q$ are the polynomial order, $C$ are the control point's Cartesian coordinates, $w$ are the control point's weights, and $U$ and $V$ are the basis functions.

In order to efficiently deal with intersections, the parametric coordinates are required. Surface vertices of the computational grid may belong to more than one NURBS patch at joints and intersections, although they may correspond to the same spatial coordinates. The process to obtain the NURBS parametric coordinates from the spatial Cartesian coordinates $R^3\{x,y,z\}\rightarrow R^2\{\xi,\eta\}$ is usually referred as the "point inversion problem" [3]; in general, there is no known analytical solution. Alternatively, the parametric coordinates can be provided while the grid is generated.

Upon a perturbation, to identify a moving intersection, the parametric coordinates of both NURBS surfaces at the intersection no longer represents the same spatial coordinates and should be recalculated to verify:

$$S_a(\xi_1,\eta_1) - S_b(\xi_2,\eta_2) = 0 \tag{2}$$

The parametric coordinates at the intersection can be accurately and efficiently computed with a Newton-Raphson algorithm as:

$$\{\xi,\eta\}^{n+1} = \{\xi,\eta\}^{n} - \frac{f}{f'} \tag{3}$$

The derivatives are obtained as:

$$f' = \begin{bmatrix} f_\xi \\ f_\eta \end{bmatrix} = \begin{bmatrix} 2\dfrac{\partial S_a(\xi_1,\eta_1)}{\partial \xi}\Delta S \\ 2\dfrac{\partial S_a(\xi_1,\eta_1)}{\partial \eta}\Delta S \end{bmatrix} \tag{4}$$
$$\Delta S = S_a(\xi_1,\eta_1) - S_b(\xi_2,\eta_2)$$

Once the parametric coordinates of the surface vertex are recalculated, the surface grid should be adapted to match the moving intersection. This adaptation is performed in parametric coordinates. A simple and easy to implement elastic algorithm is suggested:

$$a' = \frac{\sum_i \left[x_i' - x_i^0\right]\left\|x_i, a\right\|}{\sum_i \left\|x_i, a\right\|} + a^0 \tag{5}$$

where $\left\|x_i, a\right\|$ is a suitable norm.

Then, the deformation is propagated into the volumetric grid with an advancing front algorithm, and finally returned for further flow evaluations within the optimization loop.

## III. Test Cases

The method has been applied to the DLR F6 configuration, a wing-fuselage-pylon-nacelle geometry which has been used in the past for validation of CFD codes at the second and third AIAA sponsored Drag Prediction Workshops [4].

### *A. Wing-fuselage intersection*

In this test case, a bump is applied to the upper side of the wing of a DLR's F6 configuration at the joint with the fuselage, which is held fixed. The deformation has been exaggerated in order to show the robustness of the methodology employed. In this case, the adaptation of the deformation is roughly normal to the moving surface, and the algorithm works perfectly well, even for large deformations.

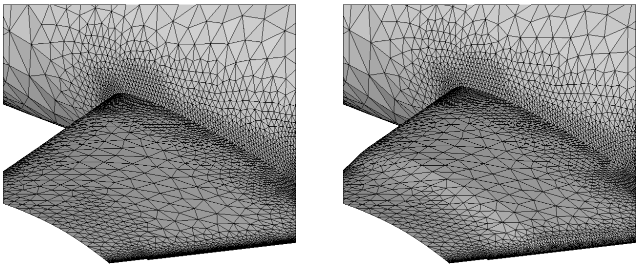

Fig. 2 Surface grid adaptation of the wing-fuselage intersection in the DLR's F6 configuration. Original (left), after the treatment of the deformation of the wing (right).

### *B. Wing-Pylon intersection*

In this case, the pylon and the nacelle have been rigidly moved to the left. The critical region is where the aerodynamic front of the pylon intersects the leading edge of the wing, where there is tangential deformation at the intersection.

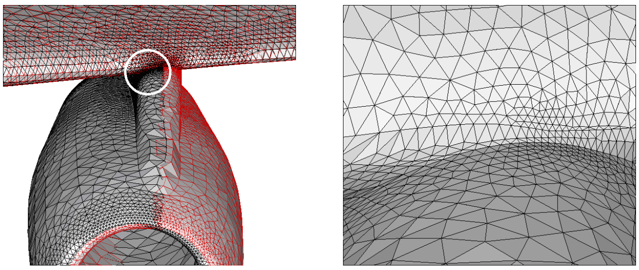

Fig. 3 Surface grid adaptation of the Wing-Pylon intersection of DLR's F6 after rigid movement of the pylon and the nacelle (left). Details of the intersection (right).

In the full paper, an optimization for a relevant three-dimensional case will be shown.

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