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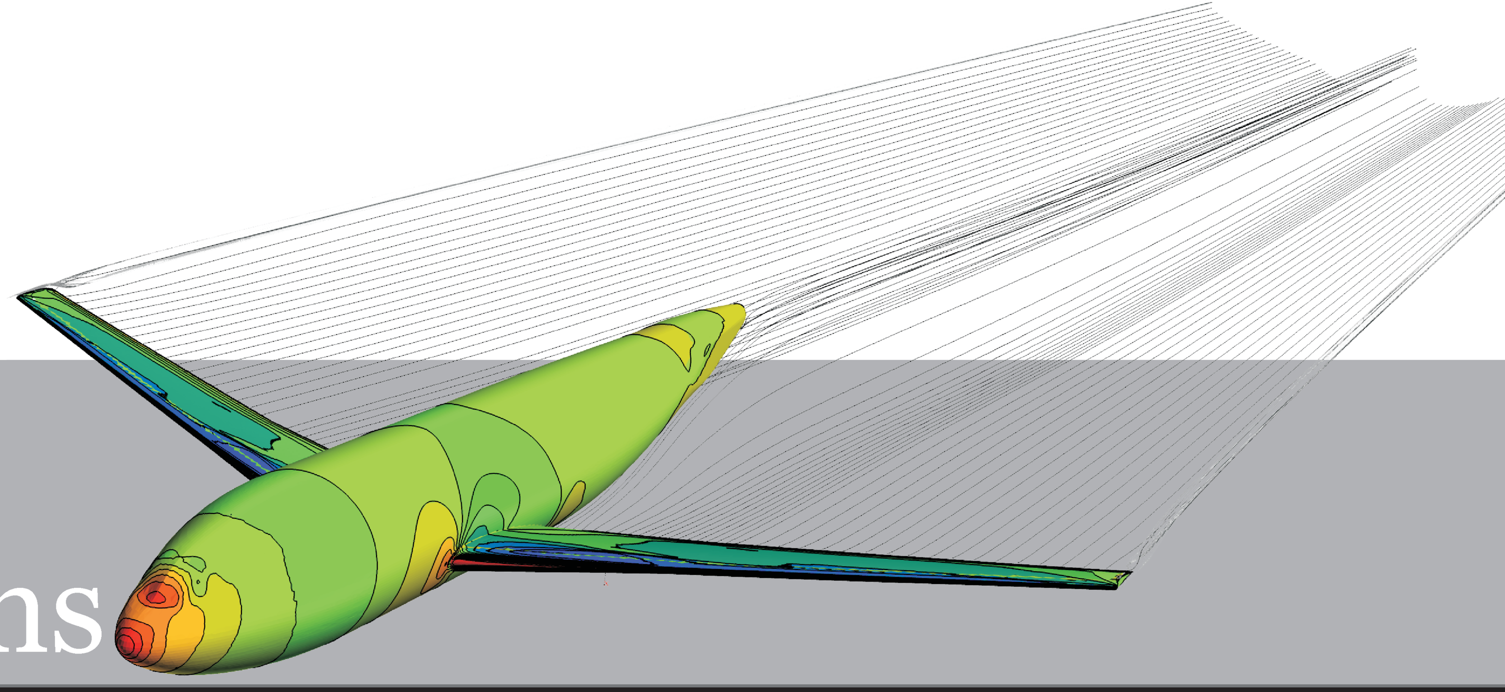

Shape optimisation using CAD linked Free Form Deformations

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Over recent years the advancements made in computing power have revolutionised the design process. The traditional trial and error methods have been replaced by automated optimisation routines that use computer modelling techniques to asses the performance of new designs. It is now common place for optimisation studies to utilise Computational Fluid Dynamics (CFD), a traditionally computationally expensive method, to optimise aerodynamic surfaces. Within such a study, the method of parameterisation, (how the designs are described), is critical to the overall success of the optimisation process. The parameterisation technique defines the design space and hence determines the possible designs the optimisation process can produce. The suitability of a parameterisation technique is based on it's ability to strike a balance between the flexibility of the representation and the number of design variables it requires.

A method that appears to fulfil this balance is Free Form Deformation (FFD)[1]. At present this technique has been successfully implemented as a parameterisation method for aerodynamic surfaces by deforming the CFD analysis grids. Whilst this has proven to be successful if the results of the optimisation process are to be manufactured a computer aided design (CAD) model is essential. With the current usage of FFD complicated reverse engineering techniques would be required to generate a CAD model for the optimisation results.

This piece of work aims to develop a methodology to utilise the FFD techniques within a CFD-based optimisation framework while maintaining a CAD geometry. The proposed method employs FFD, CAD integration, Response Surface Optimisation and CFD. The application of this process is assessed via the optimisation of the shape of a wing-fuselage junction for a typical passenger aircraft.

Free Form Deformation

Free Form Deformation (FFD) is a technique introduced within the graphics industry that enables deformation of geometric models in a free-form manner[2]. The method is best described using the following physical analogy. Imagine that the geometry to be deformed is manufactured from a flexible material, for example a rubber ball. The rubber ball is then embedded within a clear flexible plastic block. If the block is now deformed, the embedded geometry is forced to deform in a similar fashion. Figure 1 shows a example of this process in action. The sphere is embedded within a deformable volume represented by the black lattice. As the lattice is stretched the sphere inside also stretches to form an elliptical profile.

The method uses an R^3 to R^3 mapping of a deformable space to the global Cartesian space to produce the geometry deformation. In this case the deformable volume is a Bézier volume, which is defined by a regular parallelepiped lattice of control points. The embedded sphere is mapped to this volume such that the position of each point can be described as a position within the Bézier volume. If the control points are subsequently perturbed the underlying Bézier volume is deformed. Using the previous mapping and the new perturbed Bézier volume, it is now possible to determine the location of the deformed sphere.

FFD is independent of embedded geometry definition. It can therefore be used within an optimisation process to deform complex geometries to form new designs. In this case the lattice control point coordinates are used as the design variables. Thus, FFD allows complex geometry manipulations to be defined by a relatively small number of design variables.

Considerable research has already been undertaken to improve the basic FFD technique presented above. Two of the major advances are Extended FFD (EFFD), which allows the control volume to have a non-uniform shape[3], and Directly Manipulated FFD, which uses a direct manipulation scheme to improve control over the deformations achieved[4].

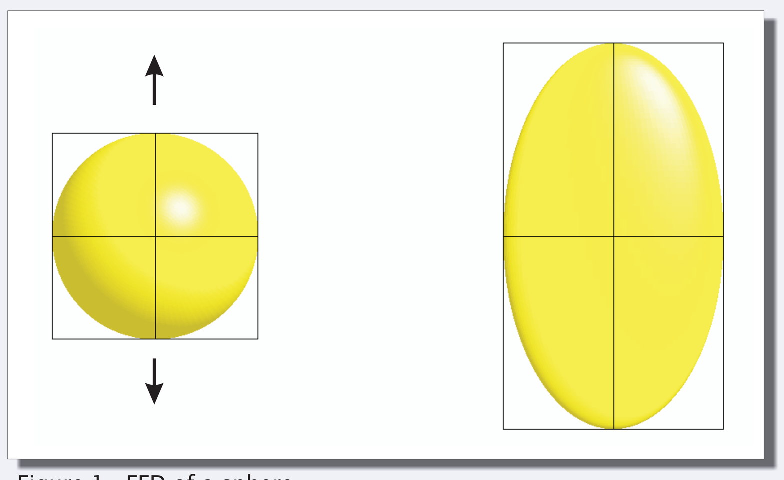

Figure 1. FFD of a sphere.

CAD integration

The CAD software used throughout this study is CATIA V5, although the methodologies presented should be applicable to any of the major CAD packages. In order to integrate the FFD techniques with a CAD package it is necessary for the techniques to be able to manipulate surface construction points. However, within the CATIA package once a surface has been created the construction points are not directly accessible. It is therefore necessary to identify alternative methods of CAD integration. If the surface is created through lofting spline profiles, CATIA design tables can be used to gain access to the spline construction points.

CATIA design tables allow the values of CATIA geometry constraints to be linked with an external design table. This could take the form of an Excel sheet or a tab delimited text file. The design table can be edited externally and then the CATIA geometry can be updated via a macro with the new values.

FFD can then be used to parameterise the spline construction points, thus indirectly parameterising the surface. This is achieved by placing either a three-dimensional or a two-dimensional lattice around the points. As the FFD lattice nodes are deformed the construction points are perturbed. The new position of the construction points are fed back to CATIA via the design table and hence creates a new surface, see figure 2.

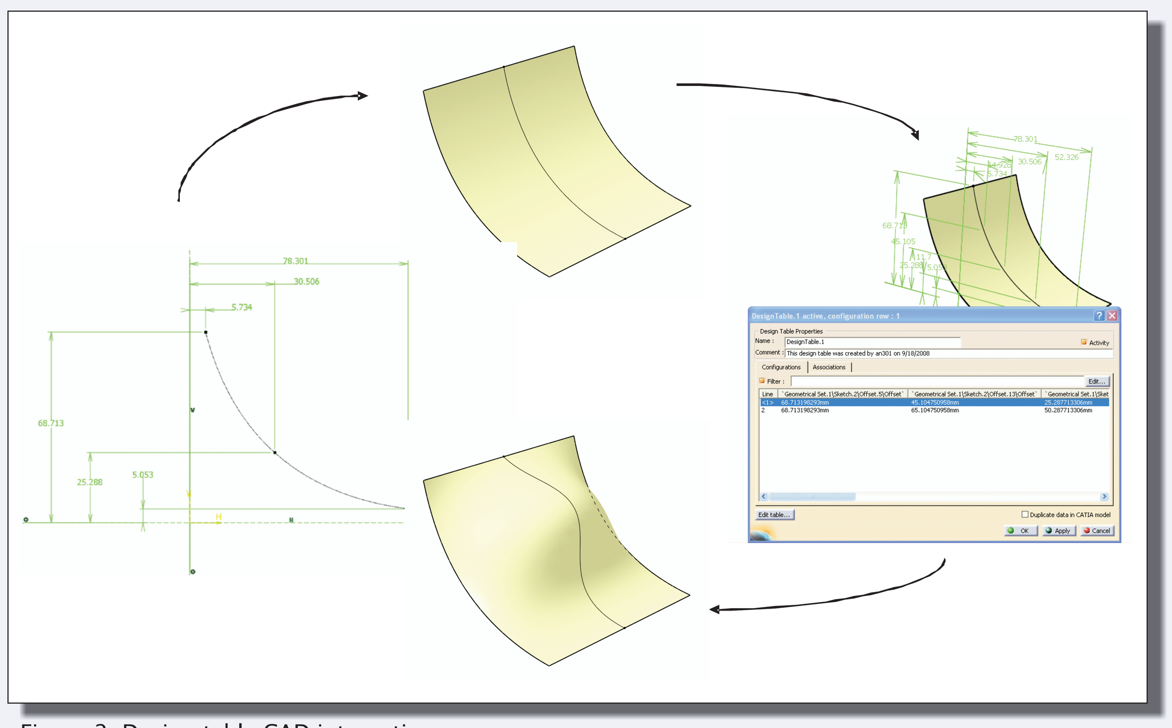

Figure 2. Design table CAD integration.

Optimisation framework

The FFD techniques are integrated into an optimisation framework. The framework used is provided by the optimisation package OPTIONS MATLAB that has been developed within the CED group.

Within the MATLAB environment the spline construction points are recreated and embedded within an FFD lattice. During the optimisation process OPTIONS passes a MATLAB function a vector of normalised design variables. This function converts the design variables into lattice point displacements and uses FFD to deform the spline construction points. The CATIA model is subsequently updated to form the new geometry. With the case of aerodynamic design the MATLAB would now continue to create a mesh for the design and evaluates the design using CFD.

An illustration of the optimisation framework used for this study can be seen in figure 3. A response surface[5] (RS) methodology has been utilised as the computational expensive nature of CFD inhibits the use of a direct search strategy. The RS procedure entails evaluating a few designs using CFD and then fitting a surface to the results. This surface is then used to estimate the design space of the optimisation problem. By substituting the CFD analysis with an evaluation of this surface the optimisation routines can be used to find areas where potentially good designs may reside. The predicted best designs within these areas are then evaluated using CFD. This method of locating promising designs requires far fewer design evaluations than a direct search. However, the ability of the response surface to estimate the design space is critical to the success of the optimisation process.

To aid the initial accuracy of the RS a design of experiments (DoE) is used to select the initial population of designs. A DoE uses space filling patterns to select initial designs.

On top of this, an update cycle is used to increase the accuracy of the RS. After a set of promising designs has been evaluated the accuracy of the response surface is tested. If the accuracy is below a predefined level these points are appended to the initial DoE database and a new RS is created. If the RS is of sufficient quality it is searched for a final optimum design.

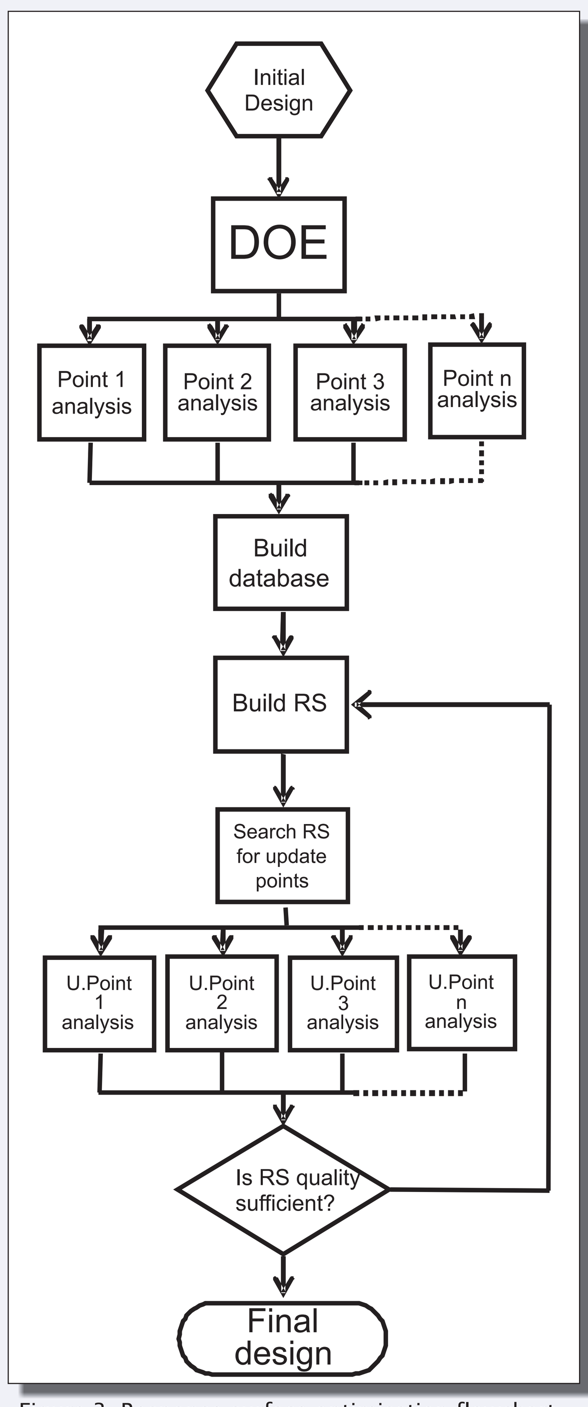

Figure 3. Response surface optimisation flowchart.

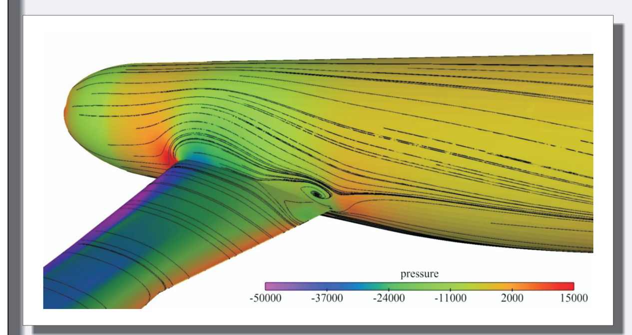

Figure 4. CFD analysis of the DLR-F6 geometry. Pressure contours and surface restricted flow line showing separation bubble at the trailing edge.

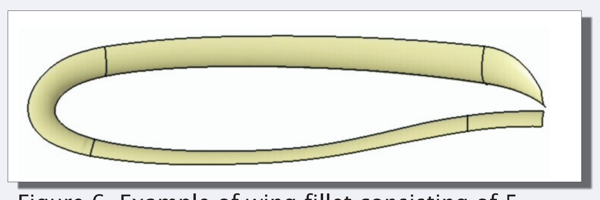

Figure 6. Example of wing-fillet consisting of 5 surface patches.

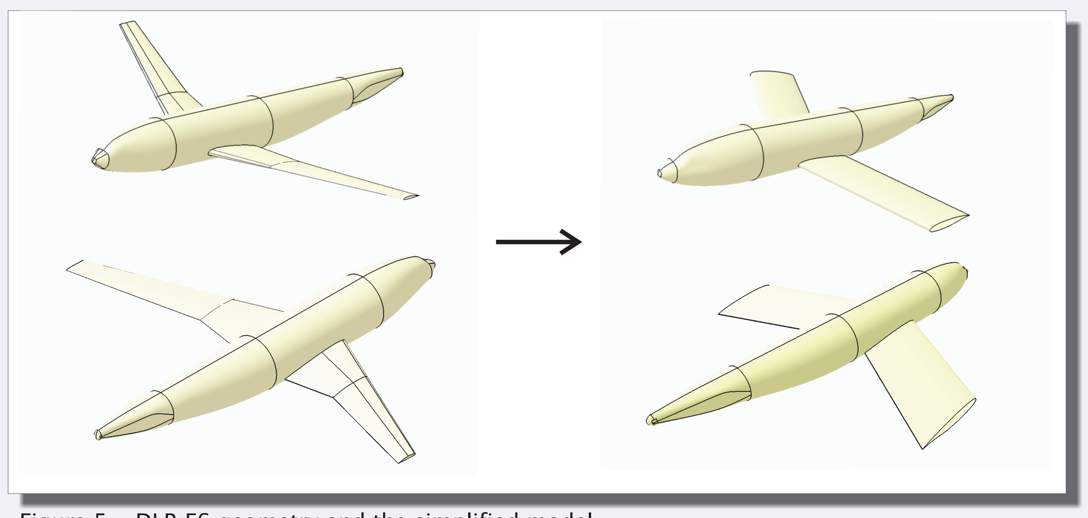

Figure 5. - DLR-F6 geometry and the simplified model.

Case study

To examine the practicalities of implementing the proposed methods, this study attempts to optimise a faring placed around the wing-fuselage junction (termed "wing-fillet") of a typical transonic passenger aircraft. This case study has been chosen as it requires the manipulation of a complex geometry with numerous geometrical constraints to test the proposed methodology. It is also an area of the flow field within which improvements may be possible. Figure 3 shows the pressure contours and flow lines resulting from CFD analysis of the base geometry. It is clear from the flow lines that there is a separation bubble on the wing-fuselage junction towards the trailing edge of the wing. This case study aims to minimise the total drag experienced by the aircraft by only manipulating the shape of a wing-fillet. It is thought that reducing this separation will lead to the greatest drag recovery possible. Each design is subject to the following aerodynamic constraints:

1. Angle of attack ,1 degree
2. Mach number, M = 0.75.

These constraints are the design cruise conditions for the unfaired configuration of the selected geometry. CD and CL estimates are achieved via a Reynolds-Averaged-Navier-Stokes (RANS) solution of the problem with the use of the commercial CFD analysis code Fluent. In addition to minimising the total drag the optimisation process also attempts to match the coefficient of lift experienced by the base geometry at cruise conditions.

The base geometry selected for this study is the wing-body configuration of the DLR-F6 as used in the AIAA second drag prediction workshop. The DLR-F6 geometry is simplified to reduce the computational time needed to converge the CFD analysis. The simplified geometry uses the DLR-F6 fuselage but a shorter, simplified wing has been created with no twist, taper or dihedral (see Figure 5). The wing-fillet is constructed from five separate surface patches, each consisting of a lofted surface with splines profiles, see figure 6.

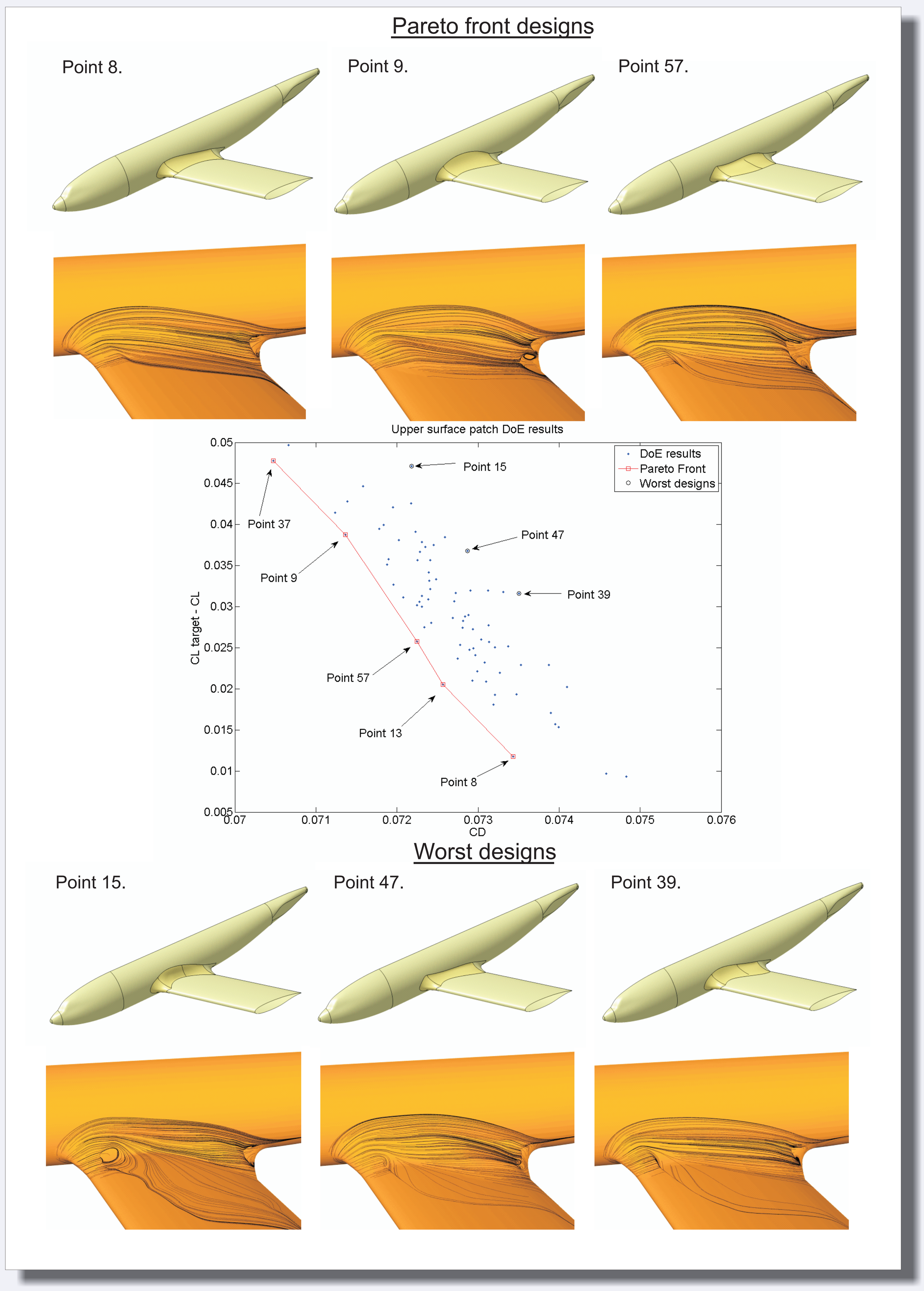

Figure 7. Results of the DoE on the upper surface patch with examples of good and poor preforming designs.

The initial study is limited to optimise only the upper surface patch of the wing-fillet. This enables the methods to be analyses before the addition of complex geometrical constraints present in the other surface patches. The results of the eighty point DoE for this initial study can be seen in figure 7. The central plot illustrates the distribution of the results against the optimisation criterion. The results display a relatively significant variation in CD of approximately five drag counts, as well as a maximum distance of 0.05 from the target lift coefficient. This distribution contains a Pareto-like front upon which the best performing designs reside. There is an obvious trade off between minimising the CD value and matching the CL value of the base geometry. Designs such as point nine perform the best with respect to the drag values achieved, however perform the worst when assessing its lift coefficient compared to the target value. Whilst the exact opposite is true of design eight, both of these designs lie on the Pareto front.

Figure 7 also shows the surface restricted flow-lines within the wing-fillet region. By examining these it is clear that the dominating flow features are the separation bubbles at the tailing edge and on the upper surface. The lower surface shows no significant flow features on any of the designs explored. The designs located on the Pareto front do not exhibit the separation on the upper surface that is seen on the designs away from the front. It is also clear that the flow spread is significantly larger for the worse performing designs than those situated on the front. It appears that the development of this separation bubble increases the drag and so moves the designs away from the Pareto front. The CATIA models for each of the designs that exhibit this behaviour display a concave junction line at the wing surface, which is not present on the front designs. It is therefore likely that the high degree of curvature change within this region produces the aforementioned undesirable flow feature. It would be expected that any subsequent optimisation process would select designs with gradual changes in curvature.
Although none of the designs eliminated the flow separation at the trailing edge it hoped that when the trailing edge patch is optimised this will be achieved.

Ongoing work

Presently the optimisation process based on the above DoE is being analysed. Upon completion of this the methods will be extended to all the surface patches and then ultimately applied to a wing-fillet on the DLR-F6 geometry. It is hoped that significant reduction in drag can be achieved by the final optimisation process as well as generation of some radical fillet designs.
It is thought that the most appropriate use for the parameterisation and optimisation methods displayed would be during the initial design phase working on novel aircraft configurations, in the interface between conceptual design (future projects office) and the single disciplines and potentially, in multi-disciplinary optimisation.

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3. Coquillart, S., Extended Free-Form Deformation: A Sculpturing Tool for 3D Geometric Modeling," *SIGGRAPH'90*, Vol. 24, ACM, Aug. 1990, pp. 187.
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