

## SHAPING OF AIRCRAFT AND HELICOPTER CONFIGURATIONS WITH CAD

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**Key Words:** *Virtual Product, CAD, parameterisation, lofting, complex geometry generation.*

**Abstract.** Today the focus in industry is on virtual product design with CAD and virtual testing, with CAE. Since the use of CAD in aerodynamic design is still controversial the present study tries to give an overview about the possibilities a modern parametric CAD system, such as CATIA V5, provides to create super ellipses or conical curves, which are still classical curves in aerodynamic design. Furthermore the paper demonstrates that use of B-spline curves is more beneficial due to their special properties when compared to spline fit curves. In several examples curve parameter variations are performed and the influence on flow field and aerodynamic coefficients is presented.

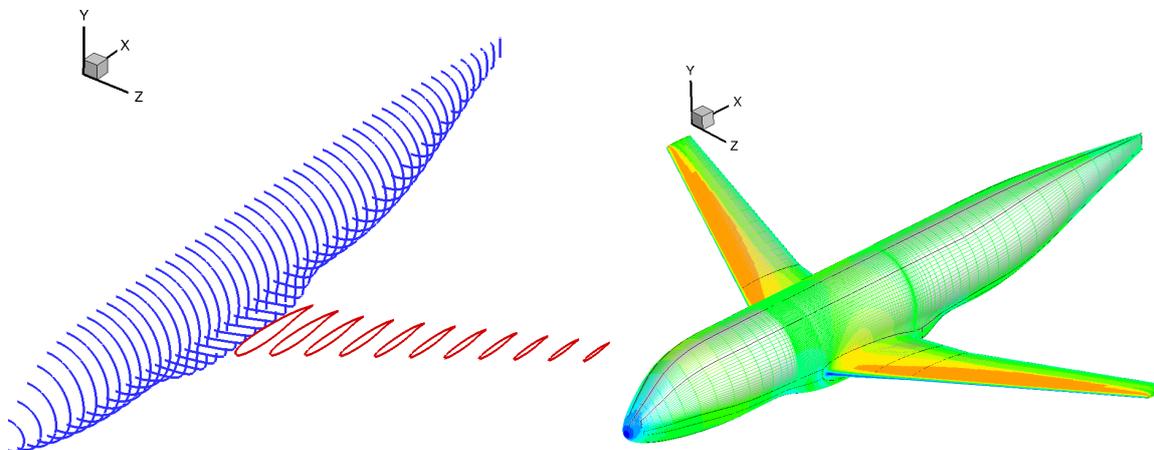
### 1 INTRODUCTION

In product design the focus is on robust and reliable simulation techniques to develop competitive and complex technical products almost completely virtually. Today the lifecycle of a product starts from a first pre-design concept and reaches a state where a virtual prototype is available to be used to generate the detailed programming of the numerical controlled machine to launch manufacturing, [1]. In order to mitigate the risk of unfeasible designs which cannot fulfill top level requirement, it is highly desirable to gain as much knowledge as possible of the product under development already in early design phases, [2]. Finally the tradeoff of virtual product development is at first a shortening of development time and ongoing with that a saving of development costs.

Computational fluid dynamics (CFD) has become state of the art in aerodynamic aircraft design, and meanwhile simulation based design (SBD) is going to replace the classical wind tunnel design methodology. Since many flow solution methods of the Navier-Stokes equations are based on the finite volume approach, a computational grid is required which encloses the fluid flow domain and finally a geometry is required around which the grid is generated. In any case the geometry can be a single airfoil section or even the outer mold line of a complete aircraft, which already exists or which is under development.

At DLR the focus was at first on the development and on the validation of CFD tools. Therefore geometry generation played only a minor role and a large amount of work was spent to develop grid generation software for dedicated wind tunnel models for the purpose of code validation, [3]. Geometry generation of these models was based on existing point coordinates and was merged together with grid generation in a single code. In many applications, the calculation of surface/surface intersections was the most critical part of the whole geometry/grid generation process.

Later, the development of an interactive grid generation tool for general configurations was started, having elementary CAD functionalities, i.e. projection onto surfaces and surface/surface intersections, [4]. For both approaches, which are still in use today, an initial geometry, defined by coordinate sections, as shown in Figure 1, is required. Bilinear interpolation routines, normally used to generate far field boundary grids or interface boundaries between grid blocks, are also used to generate elementary surfaces, as wings, bodies, pylons and nacelles.



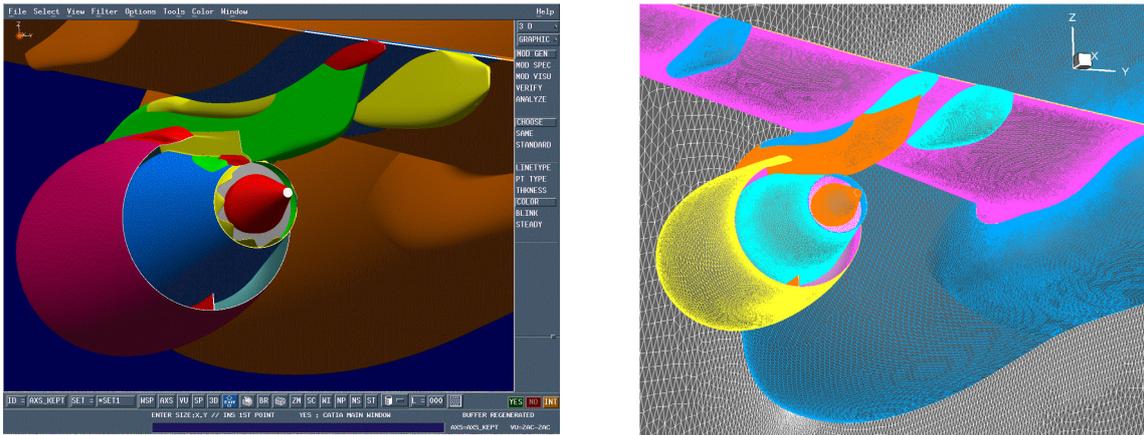
**Figure 1:** Input coordinate sections for grid generation and surface pressure pattern wing body geometry

In contrary to the previously described techniques, which require an initial geometry defined by coordinates, the method developed by Sobieczky, [5], was able to generate dedicated components of an aircraft with the help of coefficients controlling slope and curvature of analytical curves and surfaces. The software was used as automatic geometry preprocessor for either homemade grid generation software or it was used to create data for commercial CAD programs. This had become necessary since nearly all modern grid generation software tools had been tailored to process native or neutral CAD data. Particularly with the development of powerful grid generation software for unstructured meshes with nearly no limitations concerning the geometrical complexity the use of CAD systems became necessary to prepare and repair any complex geometry in front of grid generation, as it was shown in Figure 2.

This work flow using CAD systems as postprocessor for coordinates has not changed marginally until today. Despite the fact that CAD systems were developed first and foremost to generate geometry, they play only a minor role in conceptual or in preliminary design

phases. The intention of this study is to demonstrate and illustrate prospects of modern CAD-systems for geometry generation in aerodynamic design.

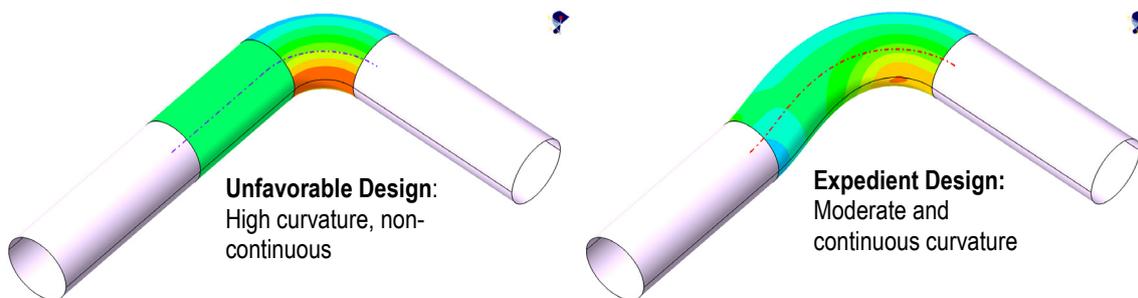
The use of CAD for geometry generation in early design phases has been depicted in several publications, [6], [7]. Particularly modern parametric CAD systems are predestinated to generate geometric variants in a very short time and which are ready for grid generation in front of CFD.



**Figure 2:** CAD geometry of Do 728 Jet and unstructured surface grid

## 2 PARAMETRIC CAD DESIGN

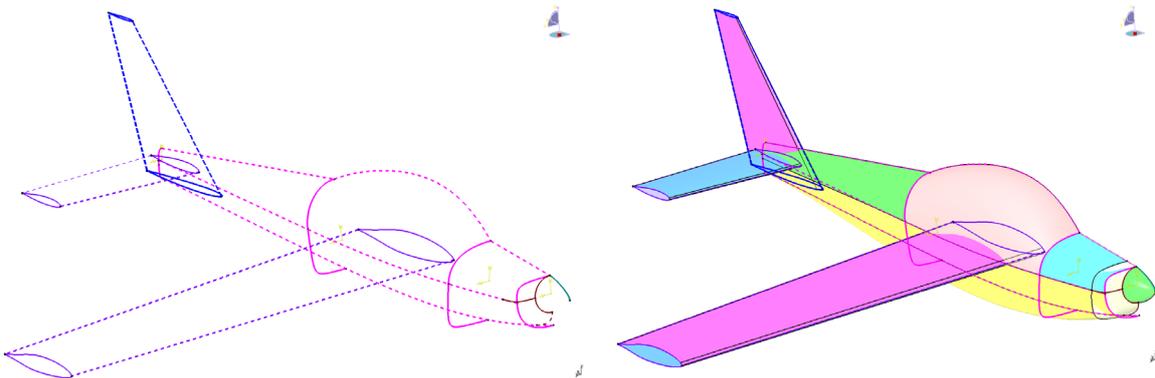
Today grid generation for CFD belongs to the most difficult and cumbersome tasks in the whole simulation process chain. Therefore, design work is often delegated to skilled CAD designers, which usually have less knowledge about fluid dynamics phenomena. If now the aerodynamic designer has less knowledge about CAD design, this may lead easily to improper designs. This is as illustrated in Figure 3 for two different elbow joints, which were constructed with CATIA V5 from Dassault Systemes, [8]. While the unfavorable design is based on lines and circles and is done in few minutes, the more expedient design requires the construction of an adequate freeform curve used as spine to sweep a circle from one segment to the other pipe segment.



**Figure 3:** Different joint designs between two perpendicular pipes with curvature analyses

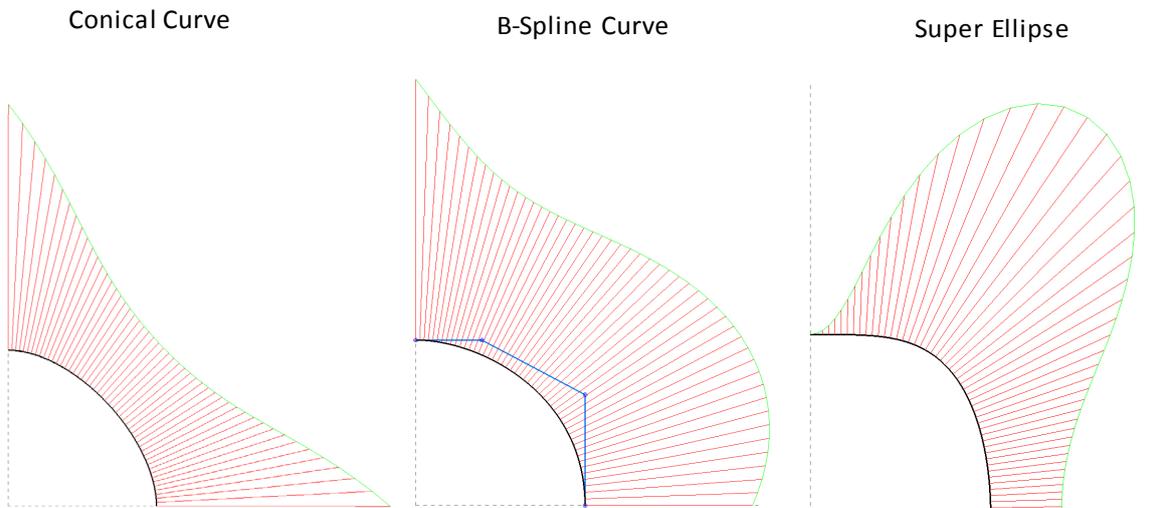
## 2.1 Wireframe Curves

This example demonstrates the importance of freeform curves in fluid dynamics and the basic procedure is to create a wireframe from curves to further create surfaces by sweeping, extruding, revolving, and lofting. For a simple propeller aircraft a wireframe model, generated with CATIA V5, is depicted in Figure 4. Most of the aircraft surfaces are generated with the loft function, which is available in any professional CAD system. Normally all curves having high and varying curvature are used as generating curves (solid curves), while lines or curves with less curvature are used as guiding curves (dashed curves).



**Figure 4:** Wireframe- and surface model of propeller aircraft

Guiding curves are mainly derived from sketches, which define side-view and top-view of the aircraft. In some cases surfaces are planar and some can be generated by sweeping or rotating a curve as this was done with the spinner surface. Beneath airfoil sections, whose generation was already described in [6], cross sections for the fuselage have to be provided. For this purpose various curve creation methods of freeform curves and also analytical curves are provided by most CAD systems. Some are shown in Figure 5 with a porcupine visualization of the curvature.



**Figure 5:** Curves generated in CAD with curvature analysis

The classical curve in aerodynamic design is the conical curve, [9]. It is normally defined by two planar tangent vectors which intersect in some point, shown in Figure 6. It has one parameter, the so called conic parameter. For certain parameters the conic curve may represent a circle, an ellipse, a parabola or a hyperbola. In the previously shown propeller aircraft example a conical curve is used to define the spinner. Among conical curves super-ellipses are preferred in aircraft design for fuselages and other barrel-type parts. A super-ellipse is derived from the ellipse but has arbitrary exponents. Some examples of super-ellipse curves are also shown in Figure 6 for different pairs of exponents. To construct super-ellipses in CATIA V5 the law function was utilized, which allows to type in analytical functions with any mathematical standard operator.

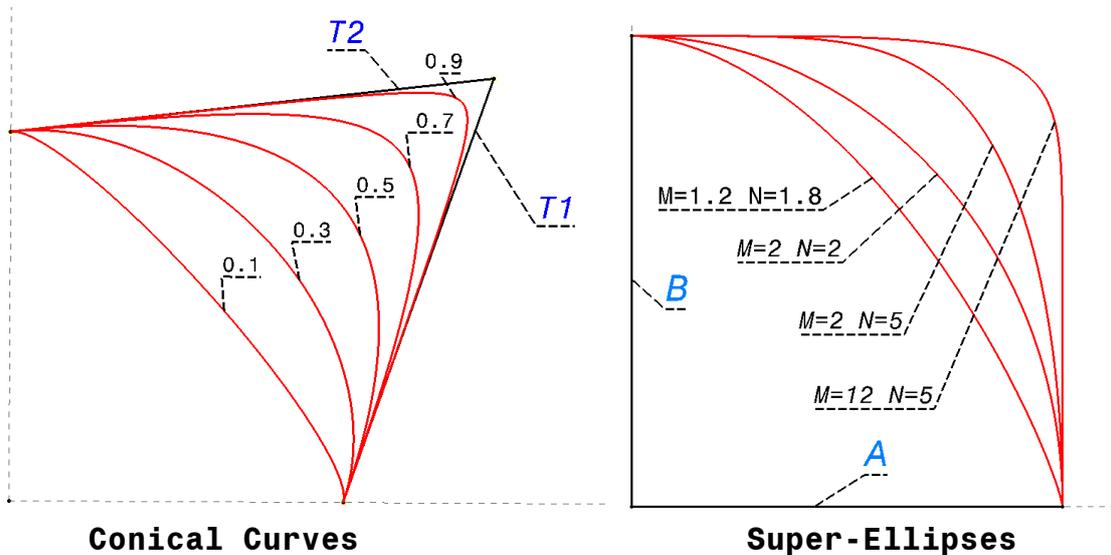
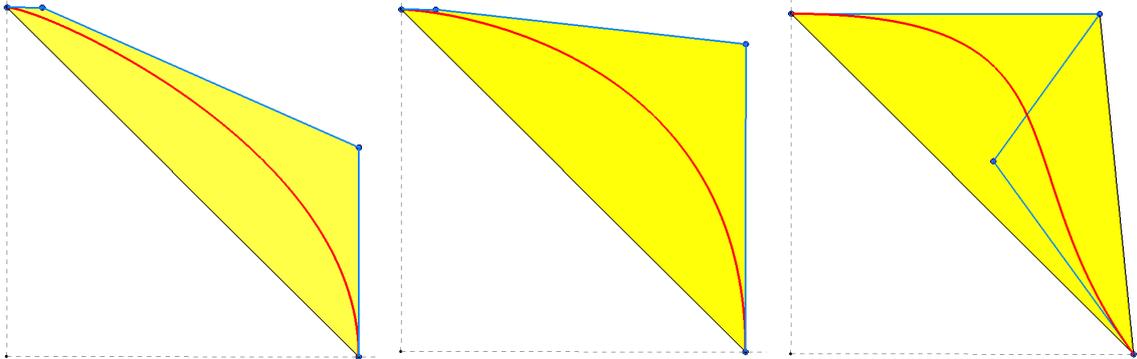


Figure 6: Analytical curves generated with CAD

Interpolation-splines are extensively used in aerodynamic design to create curves which fits through a given set of points. Even if the intended curve is a circle defined by the parameters center, support plane and radius, a spline-fit curve may require more than one hundred coordinate points to represent the circle. Furthermore, as nearly all CAD-kernels are based on non-uniform rational B-spline (NURBS) representations, an elaborate conversion is invoked inside the CAD-system if a spline fit curve is considered. Since this process is also very time-consuming, the conversion of a wing-body configuration defined by several coordinate sections with several hundred points per section, as shown in Figure 1, may take some hours. Therefore the use of CAD-systems in conceptual and preliminary design is still highly controversial as long as designers adhere on coordinate representations of curves.

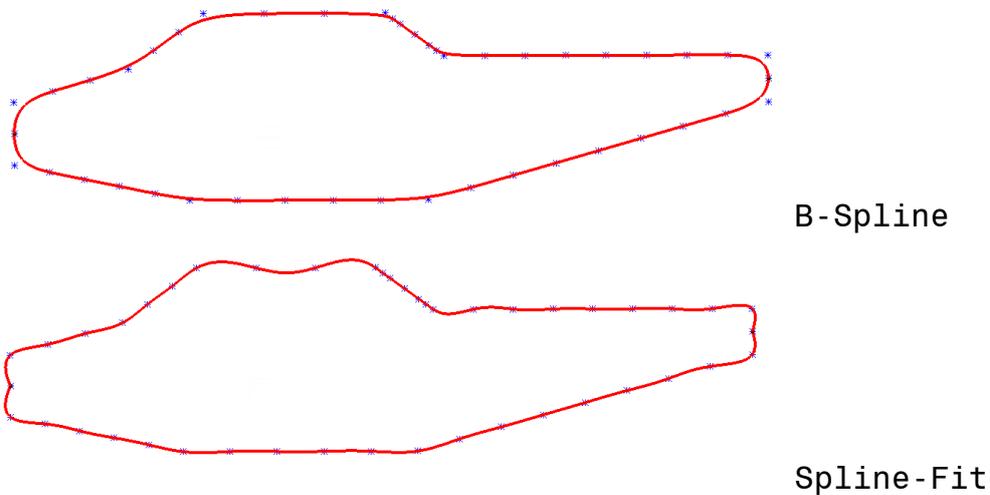
A viable and elegant way out of these difficulties is the use of B-spline curves, [10]. B-spline curves are defined by control points, which form a control polygon. Even though, the curve does not fit the control points, what is often depicted as disadvantage, it can be seen from Figure 7, that start and end point of the curve are identical with the control polygon, what is accomplished by the multiplicity of these points in the knot vector. Ongoing with the multiplicity, the curve is tangential with the control polygon of start and end segments.

At third, the lengths of these segments control the curvature of the curve at start and end point. Depending on the degree of the B-spline curve, each curve segments lies inside a convex hull defined by the corresponding control points.



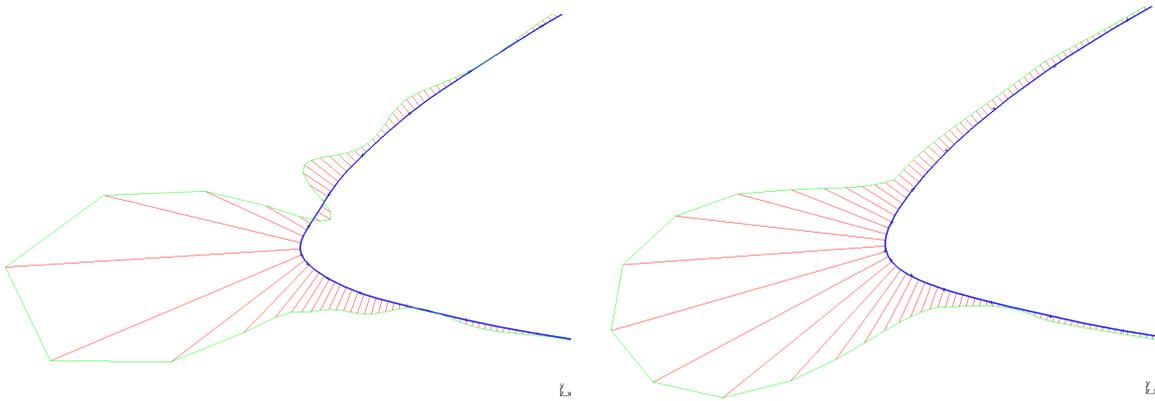
**Figure 7:** B-Spline curves with control polygons and convex hulls

This convex hull property prevents the curve to produce undesired wiggles or it can be utilized to define shapes with linear and curved parts in a single curve as shown in Figure 8. In this example more than four neighboring control points are linear. In these regions the B-spline curve segments have less or even zero curvature. In contrary, if instead of a B-spline curve a spline fit curve will lead to improper results.



**Figure 8:** Comparison of spline curves

However in some cases a spline fit is useful, as far as the number of points is small and it is sometimes unavoidable if the curve had to go through certain points to depict an airfoil from an airfoil coordinate database, [11]. Experience has shown that a manual smoothing of the curve is indispensable in front of further construction work. In Figure 9, this is demonstrated for a glider airfoil which was downloaded from the previously mentioned airfoil



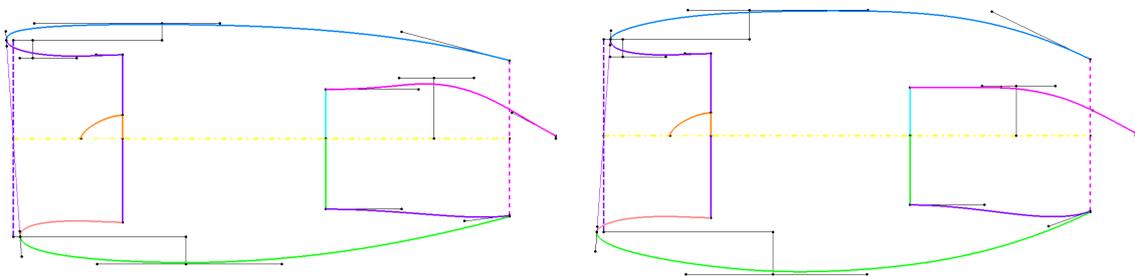
**Figure 9:** Spline fit (left) and spline approximation (right) of glider airfoil coordinates FX67K150

database. In case of the smoothed airfoil curve a deviation of 0.03% of the airfoil chord length was allowed for the spline curve, which now approximates the given coordinate points.

## 2.2 Design Parameter in Parametric CAD

Based on the previous considerations and findings, for parametric wireframe model, both types, analytical and B-spline curves are useful, and both types can be generated in modern high end parametric CAD-systems. In case of conic curve the shape controlling parameter is explicitly accessible, while in those cases in which the curve is defined via a law such as:  $y=B*(\text{abs}(1-x**M))**(1/N)$  for super ellipses, the parallel function is used. Though, the design parameters are indirectly accessible. In case of B-spline curves the design parameters are simply the coordinates of the knot points. If the endpoints of lines are used as knot points, as this is illustrated in Figure 10, the design parameters are the extensions at start or end of the corresponding line and also the angle which defines the direction of the line. This ingenious approach, which was presented for airfoil parameterizations in [12], was found to be ideal for the generation of nacelle shapes.

The most outstanding feature of a parametric CAD system is the ability to repeat a complete construction sequence automatically or manually invoked, if one or more parameters have been changed. This is also shown in Figure 10, where some start lengths and end line length were changed arbitrarily and some of the lines work as handles which control the shape of the curves. Also the tangent direction along the nacelle trailing edge can be controlled clearly and the scarf angle at the nacelle nose.

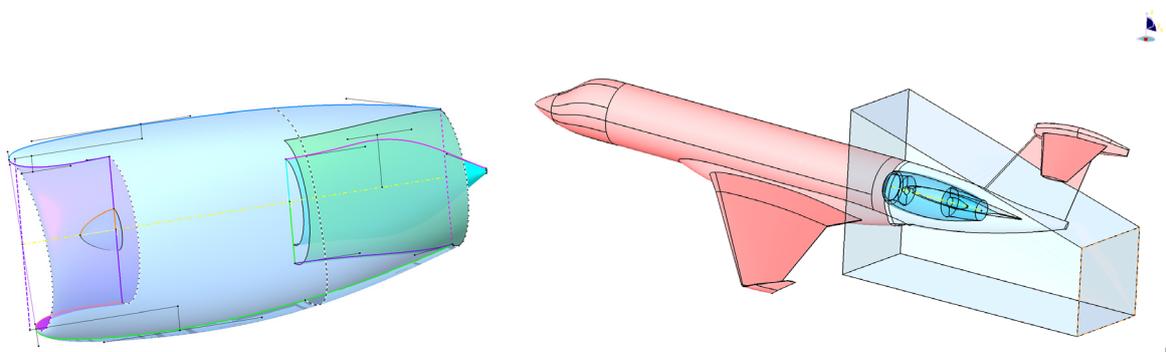


**Figure 10:** Line framework for B-spline curves of generic jet engine before and after parameter variation

### 3 APPLICATIONS

#### 3.1 Generic Business Jet Configuration

If the construction of the curve framework is almost completed, in the next step surfaces have to be generated, predominantly by lofting, some were extruded or swept or if these parts are axisymmetric they were created by revolving. This is shown in Figure 11 for the engine with inlet- and exhaust planes to simulate a jet with CFD. In this case guiding and also spine curves are mandatory for the lofting of the outer nacelle and the engine inlet. Here the spine curve is a circle with the engine axis as center-axis. Furthermore, to ensure a proper inlet shape, the guiding curve, connecting the nose points of upper and lower nacelle section, has to lie on a plane which incorporates the scarf angle as a further design parameter.

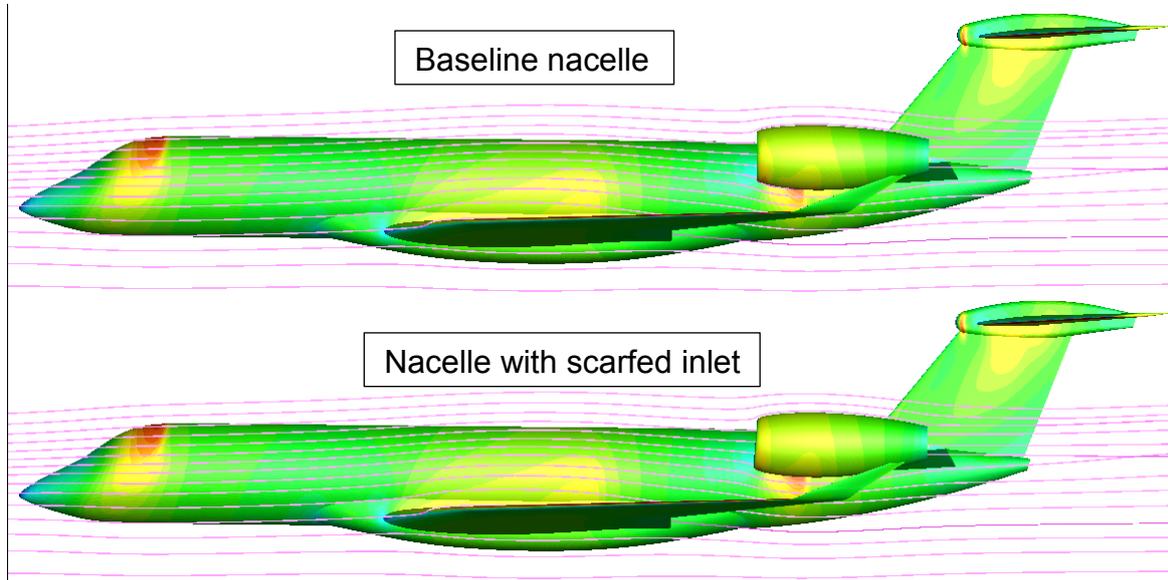


**Figure 11:** Generic engine half model from parametric wireframe (left), and mounted (right) on aircraft with box for modular grid generation

The next step is to mount the generic engine to business aircraft geometry, [13], to study for example the influence of the scarf angle on the engine installation drag with CFD. For this task the engine model is copied to a new CATIA part, which already contains a half of the airframe and after the engine is placed and mirrored, it is trimmed with the pylon. Additionally for the purpose of modular grid generation, which is used here, [14], a box is defined around the engine.

At first the baseline configuration is meshed and computed with CFD, and immediately after varying the scarf angle, the new geometry is available. This works also automatically if the aircraft model is linked with the engine model, and each time the engine shape has changed via the parameters which control the curve wireframe, these changes are propagated to the aircraft geometry, where all intersections between nacelle and pylon are updated. Due to the modular approach the grid generation for the new geometry is completed in a few minutes and normally requires no user interaction. However, the time to compute the flow field is still equivalent, but with the modular approach the grid quality is preserved in a large region of the flow field, which in turn leads to a constant numerical error.

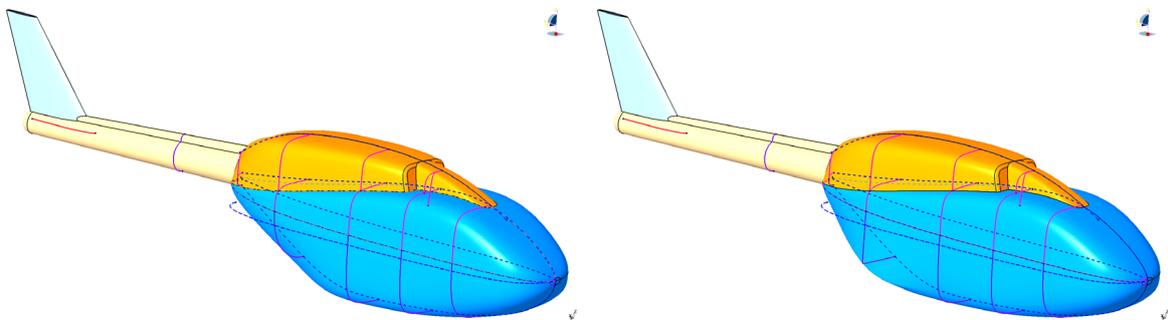
The effect of changing the scarf angle of the nacelle inlet on the flow field is depicted in Figure 12. It has been computed with the DLR flow solver TAU, [15], for a typical cruise condition with realistic engine jet simulation. With the scarfed inlet a drag reduction of about 1 drag count has been achieved.



**Figure 12:** Influence of engine inlet scarf angle on flowfield around generic business jet aircraft

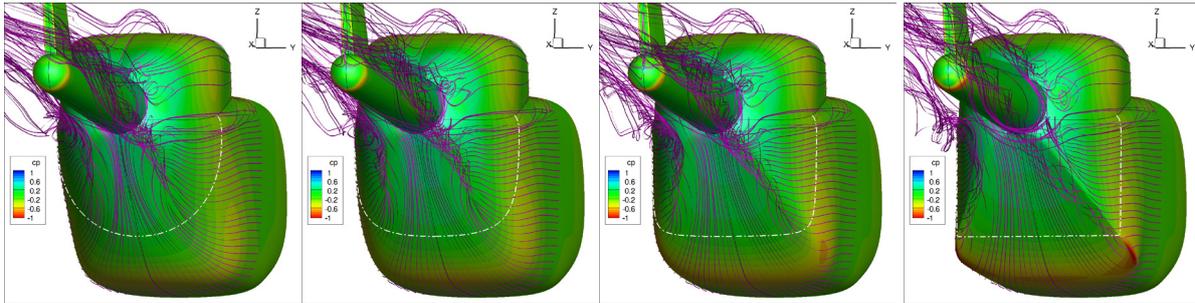
### 3.2 Helicopter Fuselage

In the previous example B-spline curves were used as generating curves and analytic curves such as circles were used as guiding curves. In case of a generic helicopter, which is shown in Figure 13, B-spline curves are used to define the silhouettes of the fuselage and represent now the guiding curves (dashed) for lofting of upper and lower fuselage and also the engine housing on top of the fuselage. The tail boom is generated by extruding a profile, which consists of two intersecting circles and in a similar way the fin was constructed. Finally, air intakes were modelled, but have been closed for this study, since the focus was on fuselage upsweep drag, which is mainly influenced by the shape of the fuselage tail with rear loading backdoors, [16].



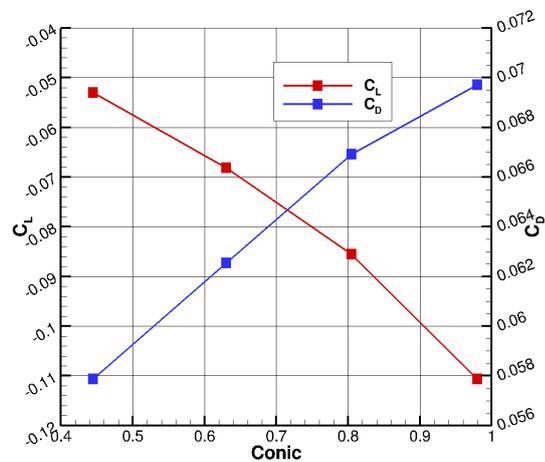
**Figure 13:** Helicopter fuselages with different conical curve parameters

For the relevant part of the fuselage conical curves were arranged for lofting the surface. For demonstration, the conic curve parameter of the next to last fuselage section was changed several times to generate shapes with more less sharpened edges, with the extreme cases shown already in Figure 13 . Several variations have been performed and were calculated with DLR TAU-Code for a typical forward flight condition of the helicopter. Horizontal tail plane and rotor flows have been neglected for this study. The differences of the flow field are visualized in Figure 14, showing volume streamlines, which form significant tail vortices.



**Figure 14:** Influence of conical parameter on helicopter tail-flow in forward flight

Depending on the curvature of the varied fuselage tail section curve, the position and also behavior of these vortices change considerably. This has also a direct influence on lift  $C_L$  and drag  $C_D$ , which are plotted in Figure 15 versus the conical parameter. The results show that an increase of the conical parameter leads to a nearly linear increase of the drag coefficient and a decrease of the lift.



**Figure 15:** Influence of conical parameter on helicopter lift and drag in forward flight

This example illustrates that with an increase of the conical parameter, on the one hand the pay load capacity is increased, but on the other hand the aerodynamic performance is deteriorated in the same degree.

### 3.3 Swept Wing Tips

For the reduction of induced drag of an aircraft wing, more and more aircraft have been supplied with winglets. This however implies that the wetted surface area increases and the root bending moment, which has a direct impact on the structural weight of a wing, also grows. The objective of the following short task was to investigate the influence of swept up or swept down wing tip shapes, as it was proposed in [17]. For this construction a wing of a small transport aircraft was cut off close to the wing tip. Here the problem came up, that some of the curves, which were created to define the loft, are non-planar curves, as shown in Figure 16. For the construction of the trailing edge B-spline curves, control points were derived from the former trailing edge and to fit the new surface lofts to wing nose intersection curves were generated. The most crucial curve, however, is a curve which is generated with the parallel curve function in CATIA V5. It is based on a conic curve and an S-type law, with a parameter defining the amplitude of the S-type offset. Finally, this curve is used as guiding curve for lofting the wing tip surface.

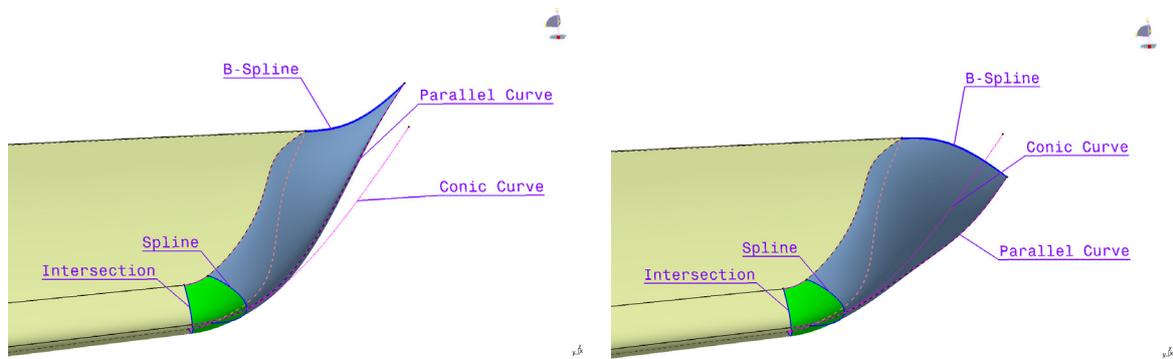


Figure 16: Curved wing tips (left: bend up, right bend down)

The parameter defining the amplitude has been varied several times and the flow field was computed for each variation. For the grid generation the modular approach was used again and the flow fields were calculated for a subsonic cruise condition. The pressure patterns of the each wing tip variation together with the corresponding tip vortices are shown in Figure 17.

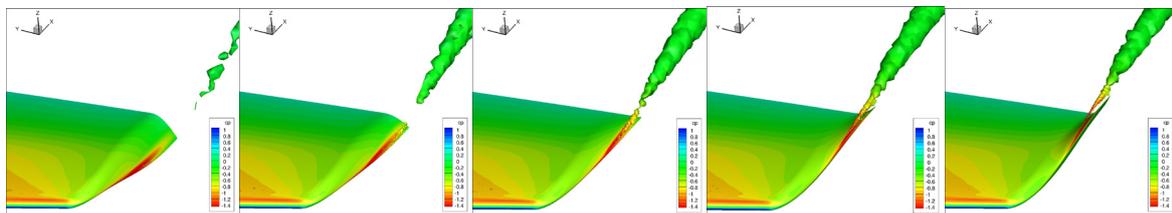


Figure 17: Flow field with vortex core for different wing tip shapes

The computed drag coefficients are shown in Figure 18. It turns out, that a bending down is more efficient than a bending up and secondly a drag saving of 1.5 drag counts could be achieved for this wing.

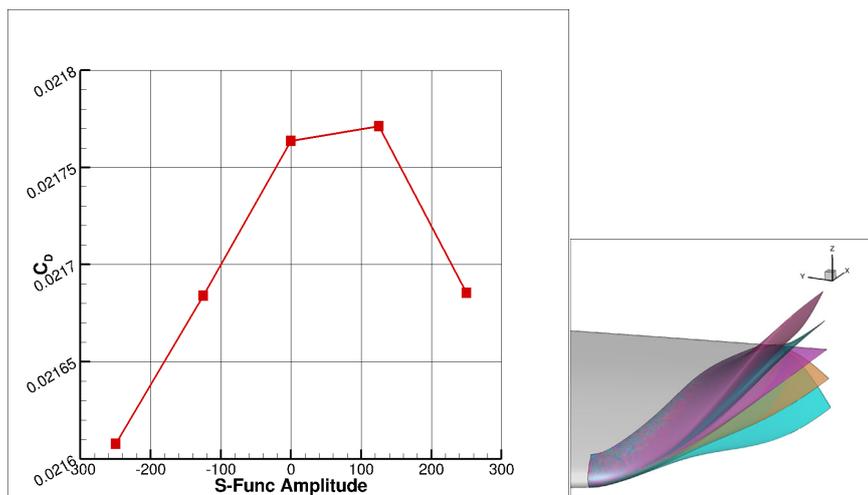


Figure 18: Drag coefficients versus amplitude of tip bending curve

#### 4 CONCLUSION

This paper addresses some aspects about the possibilities of parametric CAD in aerodynamic aircraft design. It was demonstrated, that the key function to generate nearly any part of the wetted surface of an aircraft is the loft function, which indeed requires section-, guide- and spine curves. For this issue a modern CAD system as CATIA provides a variety of curve creation functionalities. In the simplest case the design parameters are identical to curve parameters as for example the conic parameter of a conical curve. In other cases the design parameters define the coordinates of knot points of a B-spline curve.

Since parametric CAD systems are able to regenerate the whole construction of a CAD model after a parameter has been varied, their use became more and more indispensable in aerodynamic design. Variants can be generated on key press with the CAD system and if the grid generation process is also automated, CFD simulations can be performed with little or without any effort. This allows performing extensive parameter studies with realistic geometries to detect trends and finally to find a reliable and improved design. Finally, if a simulation process can be fully automated, simulation based shape optimization is enabled.

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