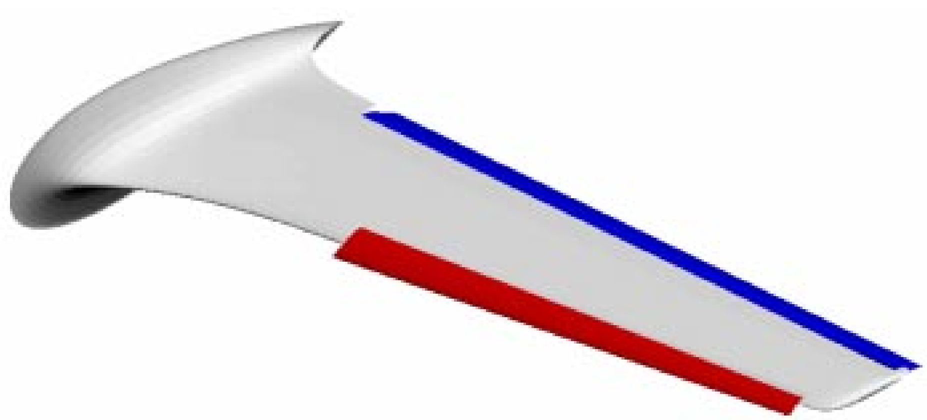
Reprint

Helmut Sobieczky

DLR , Göttingen

Parametric Airfoils and Wings



published in

K. Fujii, G. S. Dulikravich (Ed.):

Notes on Numerical Fluid Mechanics, Vol. 68, Vieweg Verlag

pp 71 - 88

(This page is left empty)

Parametric Airfoils and Wings

Helmut Sobieczky

DLR German Aerospace Research Establishment
Bunsenstr. 10, D-37073 Göttingen
e-mail: Helmut.Sobieczky@dlr.de

Abstract

Explicit mathematical functions are used for 2D curve definition for airfoil design. Flowphenomena-oriented parameters control geometrical and aerodynamic properties. Airfoil shapes are blended with known analytical section formulae. Generic variable camber wing sections and multicomponent airfoils are generated. For 3D wing definition all parameters are made functions of a third spanwise coordinate. High lift systems are defined kinematically by modelled track gear geometries, translation and rotation in 3D space. Examples for parameter variation in numerical optimization, mechanical adaptation and for unsteady coupling of flow and configuration are presented.

Introduction

Airfoil and wing design methodologies have made large steps forward through the availability of rapid computational tools which allow for specification of goals in aerodynamic performance. These goals are mainly to increase a measure of efficiency, like the ratio of lift over drag, or, in the higher speed regimes, its product with flight Mach number. The need for increased lift at higher flight speed, with drag kept low, has led to the development of knowledge bases for aerodynamic design: The art of shaping lift generating devices like aircraft wings is based on geometric, mechanical and fluid dynamic modelling, carried out with the help of mathematical tools on rapid computers. Given a designer's refined knowledge about the occurring flow phenomena, his goal may be to obtain certain pressure distributions on wing surfaces: This may be reached by inverse approaches with a shape resulting from the effort, or by applying optimization strategies to drive results toward ideal values.
With such methods we have refined tools available for extending our practical knowledge how the geometries of airfoils and wings are related to pressure distributions and aerodynamic performance. Certain details of desirable pressure distributions require a modelling of details in the boundary condition, usually a special feature of the curvature distribution. This is true especially in the transonic flow regime, where favorable as well as undesirable aerodynamic phenomena are correctly modelled by certain weak or strong singularities in the local mathematical flow structure including the flow boundary. Numerical optimization methods iteratively adjusting the resulting 2D or 3D shapes usually employ smoothing algorithms based on polynomials, splines and similar algebraic functions. These functions may be ignoring local properties of the shape being compatible to the inverse input, while they should accomodate the results from analytical inverse methodology using hodograph formulations of the governing equations. Hodograph-type methods, though not practical tools, have led to a deeper understanding about the relations between surface geometry and the structure of recompression shocks. These methods are most usefully applied to designing nearly shock-free airfoils and wings with favorable off-

design behavior. Understanding the resulting refined shapes and modelling them in a direct approach with a suitable geometry generator is a continuing challenge for more complex 3D configurations like complete aircraft, turbomachinery components and models for interdisciplinary design.

The present contribution is aimed at using explicit mathematical functions with a set of free parameters to define wing surfaces of practical interest for realistic aircraft applications, with a potential to arrive at optimum values of objective functions like aerodynamic efficiency, with a minimum of parameters having to be varied, because these parameters are defined from application of the fluid mechanic and gasdynamic knowledge base or prescribed by modelling kinematic models of a mechanical adaptation device.

Geometry generator

In the series of Notes on Numerical Fluid Mechanics the author has had the chance to present concepts, tools and examples of shape definition for aerodynamic components, with a strong emphasis on using mathematical functions which are drawn from analytical modelling of flow phenomena as they occur in the transonic regime. The need for reduction of shock losses has sparked an inverse procedure to find shock-free airfoils and wings, with the additional option to adapt wing geometries to varying operating conditions [1]. The increased need for creating test cases for numerical flow simulation (CFD), along with the requirements for precise definition of boundary conditions has then inspired the presentation of a wing within a transonic wind tunnel, with all boundaries including the tunnel and the inlet and exit flow conditions given [2], to be simulated and compared with experiments [3]. Later, the mathematical tools for defining such boundary conditions were further developed to model real aircraft components: wings, fuselages, propulsion components and their integration to complete configurations [4]. Since then, various applications have been studied and more recent refinements led to several versions of “geometry preprocessor software tools”. These support modern developments in a multidisciplinary design environment for aerospace components and not restricted to aerodynamic optimization.

Aircraft wings are the primary subject to optimization efforts, progress in aerodynamic design methodology is mostly influenced by new ideas to improve the lift-generating devices. Airfoils are the basic elements of wing geometry, they determine a large share of wing flow phenomena though they are just two-dimensional (2D) sections of the physical wing surface. Well-known aspects of wing theory are the reason for options of such idealization, with a large accumulated knowledge base resulting for 2D airfoil theory. It has, therefore, been well founded to use airfoil shapes with documented performance results from wind tunnel tests for the design of wing shapes. These airfoils are usually contained in published or proprietary data bases, we use them as dense data sets to describe the sections of wings with planform, twist and dihedral given by analytical model functions. Properties relevant for flow quality, for instance curvature, of these latter functions are simple and easily controlled by parameters while the airfoil input data are to be spline-interpolated to obtain a required distribution of surface data. With all the experience gained by using our shape-generating tools and updating them with recent developments in designing high speed flow examples, an effort is made to generate 2D wing sections in the same way the 3D shape parameters are already defined. Suitable functions should replace the hitherto required airfoil data sets. The goal is to propose functions with a minimum set of input parameters for shape variation, function structure and their parameters chosen to address special aerodynamic or fluid mechanic phenomena. This desirably relatively small number of control parameters will then effectively support optimization procedures.

Airfoil functions

With airfoil theory and airfoil data bases being well established components of applied aerodynamics on the ground of lifting wing theory, it is necessary to allow for using such data as a direct input in any wing geometry definition program. This fact was the motivation to provide spline interpolation for such given airfoil data in a first version of our geometry code, which has been described in various papers and publications. Recently these developments have been summarized in [5], here we focus on continuing this activity in the area of describing airfoils with more a sophisticated method than providing a set of spline supports.

Functions to describe airfoil sections are known for many applications, like the NACA 4 and 5 digit airfoils and other standard sections. Aircraft and turbomachinery industry have developed their own mathematical tools to create specific wing and blade sections, suitably allowing parametric variation within certain boundaries. We define such functions for airfoil coordinates in coordinates X, Z non-dimensionalized with wing chord therefore quite generally

$$Z = F_j(\boldsymbol{p}, X)$$

with $\mathbf{p} = (p_1, p_2, ..., p_k)$ a parameter vector with k components and F_j a special function using these parameters in a way determined by a switch j. The goal is to try to keep the number k of needed parameters as low as possible while controlling the important aerodynamic features effectively.

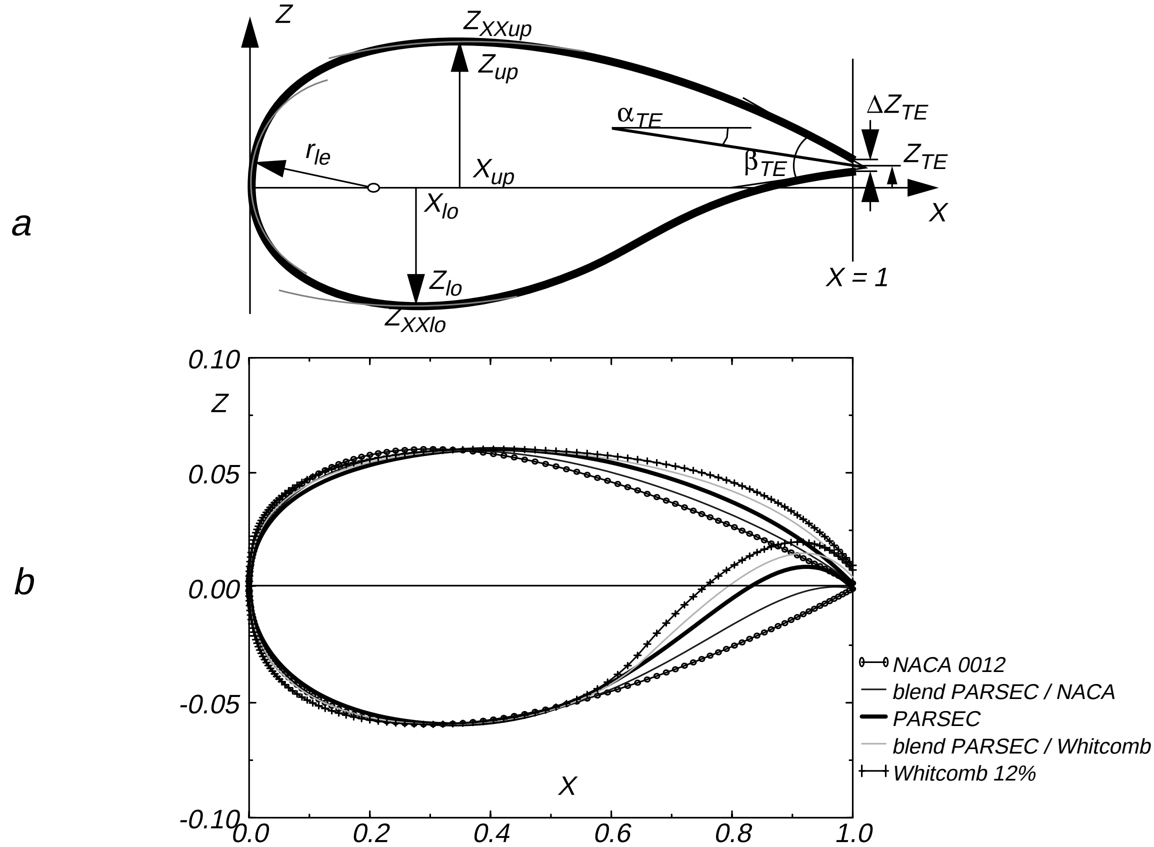


Fig. 1: "PARSEC" airfoil geometry defined by 11 basic parameters: leading edge radius, upper and lower crest location including curvature there, trailing edge coordinate (at X = 1), thickness, direction and wedge angle, (a).
Example: Variations of PARSEC airfoil by blending with NACA or Whitcomb airfoil (b)

Figure 1 illustrates 11 basic parameters for an airfoil family “PARSEC” which we found quite useful for applications. There is strong control over curvature by prescribing leading edge radius and upper and lower crest curvatures. Similar to 4Digit NACA series we choose a polynomial, though of a higher (6th) order:

$$Z_{PARSEC} = \sum_{n=1}^{6} a_n(\mathbf{p}) \cdot X^{n-1/2}$$

for upper and lower surface independently, the coefficients a_n determined from the given geometric parameters as illustrated in Fig.1. Comparison with other new or well known airfoil generator functions is made possible by including those functions in the software, a combination of individual features is then straightforward:

Blending of different airfoil generator functions

With an additional blending parameter p_{mix}, some known airfoils are included in this geometry tool as basic default functions, like NACA series airfoils as coded by Ladson [6]and Whitcomb’s supercritical wing sections as coded by Eberle [7]. These known sections require input of a subgroup of the above 11 basic parameters and they can be blended in with the more refined geometries.
Figure 1b shows an example of an airfoil series whith the 11 basic parameters kept fixed and using only the blending parameter, resulting in two different variations of the special choice PARSEC airfoil: Blending with an NACA 4Digit section for -1 < p_{mix} < 0 and blending with a 12% thick Whitcomb airfoil for 0 < p_{mix} < 1.

Example: Transonic airfoils

The 11 basic parameters in Fig. 1b are selected to re-model an efficient wing section from a previous study using the above mentioned spline support airfoil definition technique. A 30^{o}swept wing with a 12% thick main section had been designed for Mach = 0.85 and Re = 40 Mill. First favorable results of CFD analysis suggested a more detailed development of this wing and its main section. The PARSEC routine is applied here by choosing the 11 basic parameters directly from analysis of the spline support section. Application of swept wing theory requires a thickening by a factor of 1.1547 resulting in the airfoil to be investigated in Mach = 0.74. Here and in the following the Drela-Zores airfoil expert system software [8] is used for fast viscous transonic flow analysis, with pressure distributions, dragrise and polars resulting, Fig. 2.

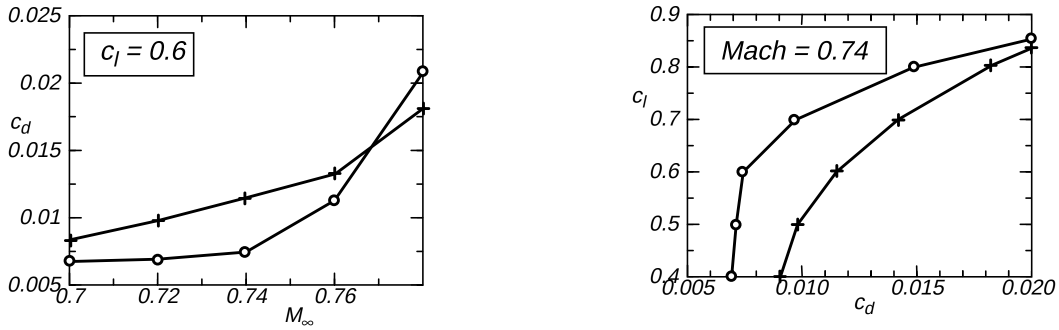


Fig. 2: Dragrise and lift/drag polar for Re = 40 Mill. transonic flow past PARSEC airfoil (symbol o) and Whitcomb airfoil (symbol +) using 6 of the 11 basic parameters. Design conditions at Mach = 0.74, c_l = 0.6.

Comparative Whitcomb section results are shown, too, indicating that for the relatively low transonic design Mach number 0.74 the PARSEC airfoil seems well suited, (ratio lift/drag = 80), while the use in higher design Mach numbers a blending with a Whitcomb section - or a variation of the basic PARSEC parameters guided by the Whitcomb airfoil geometry - will be a way to optimize the wing section with a relatively modest effort.

Parameter variations

The parametric airfoil generator PARSEC allows for control of curvature at the nose, at the upper and at the lower crest. With these additional degrees of freedom - compared to airfoil functions without curvature control - we may vary aerodynamic performance and shift the optimum conditions to desired operation conditions. The example illustrated in Fig. 3 shows a variation of the above PARSEC airfoil by, first, only increasing the leading edge radius and, second, also decreasing the upper crest curvature, which is suggested by the analyzed curvature values for the Whitcomb airfoil. We see a shift of the drag rise toward higher Mach numbers. Other parameter variations give similar substantial changes in performance. Here we stress the observed fact that for the PARSEC airfoil model function some *single* parameter changes may already improve a given section for selected operating conditions.

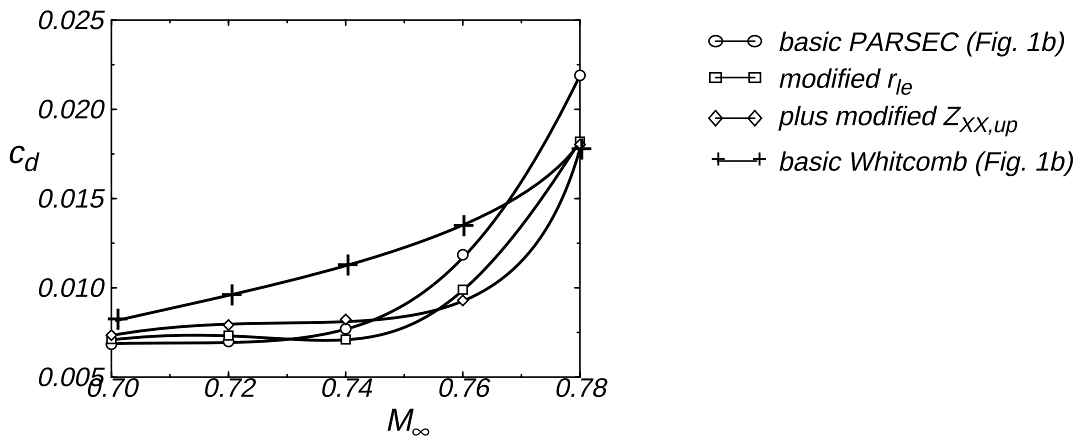


Fig. 3: Shifting drag rise to higher Mach numbers by changing single parameters

Trailing edge (TE) variations

Refined control of viscous flow parameters near the wing trailing edge may influence circulation and hence aerodynamic efficiency quite remarkably. In the past this has led to specially designed airfoil and wing TE shapes: Special solutions to the outer inviscid flow model equations were proposed to create a flow field in the vicinity of the TE which has a favorable pressure gradient on the airfoil surface. One little known theoretical base for the shaping of high performance airfoils has been presented by Garabedian [9]. Based on a complex hodograph analysis, the principle can be modelled by increased curvature only quite closely at the TE, to counteract the boundary layer's de-cambering effect.

This occurs on the upper surface more locally than on the lower surface. The practical consequence for physically relevant airfoils which are not having negative thickness or too thin TE's, is a blunt TE base, a convex upper surface contour shaping with curvature increasing toward the TE and a more evenly distributed curvature on the concave lower surface, resulting in a minimum thickness of the airfoil a few percent upstream of the TE. Such TE refinements have been studied on practical wing sections and have been termed 'Divergent Trailing Edge - DTE' airfoils [10],[11]. Modifications based on the hodograph analysis are added to the basic PARSEC shape: In the simplest case a single additional parameter $\Delta\alpha$ controls the functions added to airfoil upper and lower surface to become a DTE wing section, see Figure 4. Based on our hitherto quite limited experience with case studies, modification lengths $L_{1,2}$ range between 20 and 50 % of airfoil chord, for the exponents values we use n = 3 and 1.8 > μ > 1.3 (Garabedian's hodograph solutions suggest μ = 4/3).

$$\Delta Z = \frac{L \cdot \tan\Delta\alpha}{\mu \cdot n} \cdot [1 - \mu\xi^n - (1-\xi^n)^{\mu}]$$

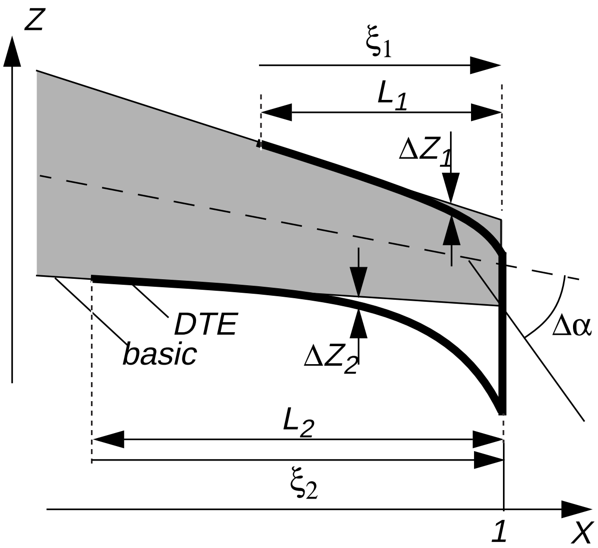


Fig. 4: Local airfoil geometry modifications to model a divergent trailing edge.

Local surface bumps

Transonic airfoils of high efficiency differ from classical low speed airfoils mainly due to their delicate curvature distribution on the upper (lifting) surface where supersonic flow conditions occur. In the case of exactly shock-free flow we observe distinct curvature maxima close to where local Mach number unity flow is found; these shape details can be understood from locally valid model solutions to the inviscid basic equations which have led to systematic design methods based on operational CFD analysis codes; a review of this concept with a more detailed discussion of the interaction of transonic gasdynamics with geometrical boundaries is given by the author in [12]. It is shown that the addition of two suitable bumps to a given conventional airfoil can convert the flow to be shock-free in high subsonic Mach numbers. This is done by a first bump near the leading edge which triggers a cluster of expansion waves, and a second one absorbs recompression waves which coalesce near the sonic recompression.

Based on this established knowledge for the design of transonic airfoils with high aerodynamic efficiency it has been found useful to influence local curvature of given airfoils in critical regions by surface bumps of varying shape and size, which can be built in an aircraft wing as a flow control device. Even reducing this effort to only adding a very small bump, extending to 2 - 3 % of chord near the location of a recompression shock, has been claimed to improve aerodynamic performance by dispersing the shock at the foot point on the airfoil, thus favorably influencing shock - boundary layer interaction [13].

$$\Delta Z = Z_m \cdot \sin(f(\xi))^{g(\xi)}$$

$$f(\xi) = a\xi + b\xi^2$$

$$g(\xi) = (P - Q\xi) \cdot (1 - (1 - c) \cdot \sin\xi)$$

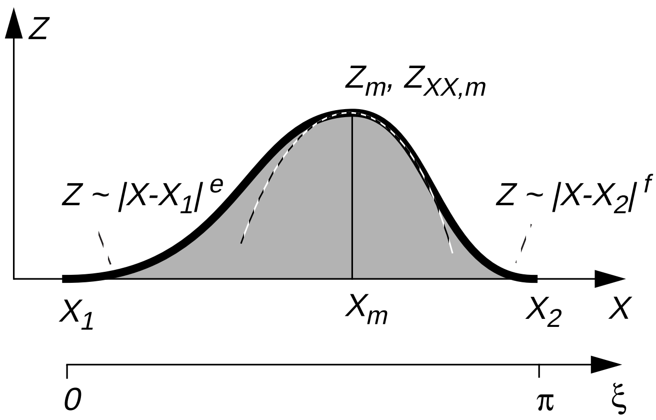


Fig. 5: Local airfoil geometry modifications to model a bump with strong shape control.

A function for arbitrary bumps has been added therefore to the airfoil generator program which generates bumps (Fig. 5) with strong local curvature control. Chordwise extent (X_1, X_2) is defined by choice of the local variable ξ . Possible requirement of an unsymmetrical bump crest location (X_m, Z_m) will be taken care for by coefficients a and b, crest curvature (Z_{XXm}) and curvature control at the bump ramps (e, f) are controlled by the coefficients P, Q and c in the equation for g(x) as can easily be verified.

Variable camber models

Flexible parts for a wing geometry may be used for widening the range of optimum efficiency in variable operating conditions. Structural constraints restrict the use of such parts to the areas of trailing and leading edges. For ensuring acceptable flow quality, sealed flaps at the TE and sealed slats at the leading edge (LE) maintain the smooth contour without gaps or corners. Setting up a geometrical model for realistic wings or wing sections of course depends on knowledge of the mechanical device putting the concept to reality. For rapid predesign studies, the task to geometrically model such contour variations is to define only the deflection angle ω as a single input parameter, for a given kinematics (in the simplest case the hinge point H coordinates) and fixed domain (ΔX) of some elastic surface modification. The sketch Figure 6 illustrates this for both a sealed slat and a sealed flap.
Without further specification of the elastic surface mechanics a simple analytic function provides a smooth connection between the original airfoil and its rotated nose or tail portion. For a specified mechanism solving the problem of connecting the solid parts with an elastic and sealed contour the model function needs to be adapted to the hardware data.

:

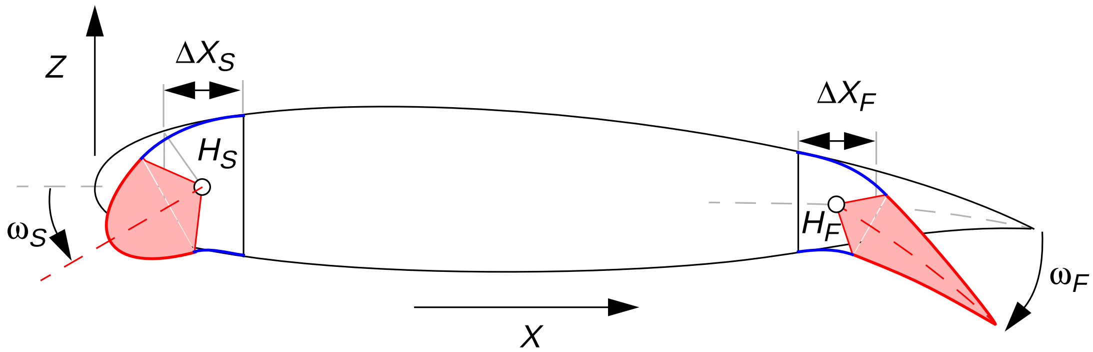


Fig. 6: Local geometry variation at leading and trailing edges by sealed slat and flap model

Multicomponent airfoils

A more complex task of generic parameterized modelling is the geometry of high lift components like Fowler flaps and slats. Here we start also from a given airfoil, but we need to carve out separated lift-generating airfoils from the nose area and one or more of such sections at the rear portion of the basic airfoil. Figure 7 shows the added geometry details for a given airfoil modified to include a single slat which can be moved by a combined translation and rotation. Choice of coordinates for C_0, C_1 and C_2 and curvatures there define curve functions similar to the above PARSEC approach for the remaining fixed airfoil portion (or similarly at the flap nose portion).

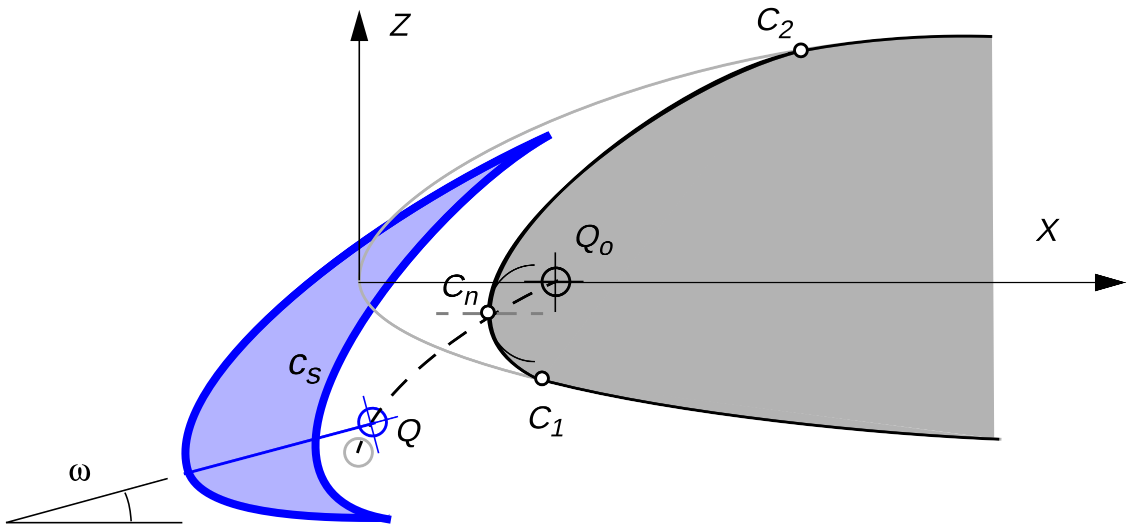


Fig. 7: Selecting a portion of airfoil contour (C_1C_2) to carve a slat geometry c_S. Added functions for carved surface, coupled translation (Q_oQ) and rotation angle ω.

Figure 8 shows an airfoil with a single flap, various positions depicted. Drela's code for multi-component airfoils [8] can be used for a rapid manual optimization of the flap track to obtain high lift coefficients. An estimation of the separation bubble displacement within the flap bay, to be modelled for each flap (or slat) position, is quite helpful for these pre-design studies: with the same approach it is straightforward to model also a viscous displacement contour c_v to replace the concave surface parts. More refined analysis using a Navier/Stokes solver is needed to calibrate c_v for the faster analysis methods, but the parameters to do so in a flexible way may be available already.
It should be stressed that these 2D multicomponent airfoils are to be used in the cruising (retracted) configuration only for 3D applications: Swept wings will require a 3D definition of flap tracks and a shifting and rotation of the whole 3D flap or slat, which cannot be modelled for each section in a 2D fashion. The modelled retracted 2D components are the baseline for the real 3D high lift system.

.

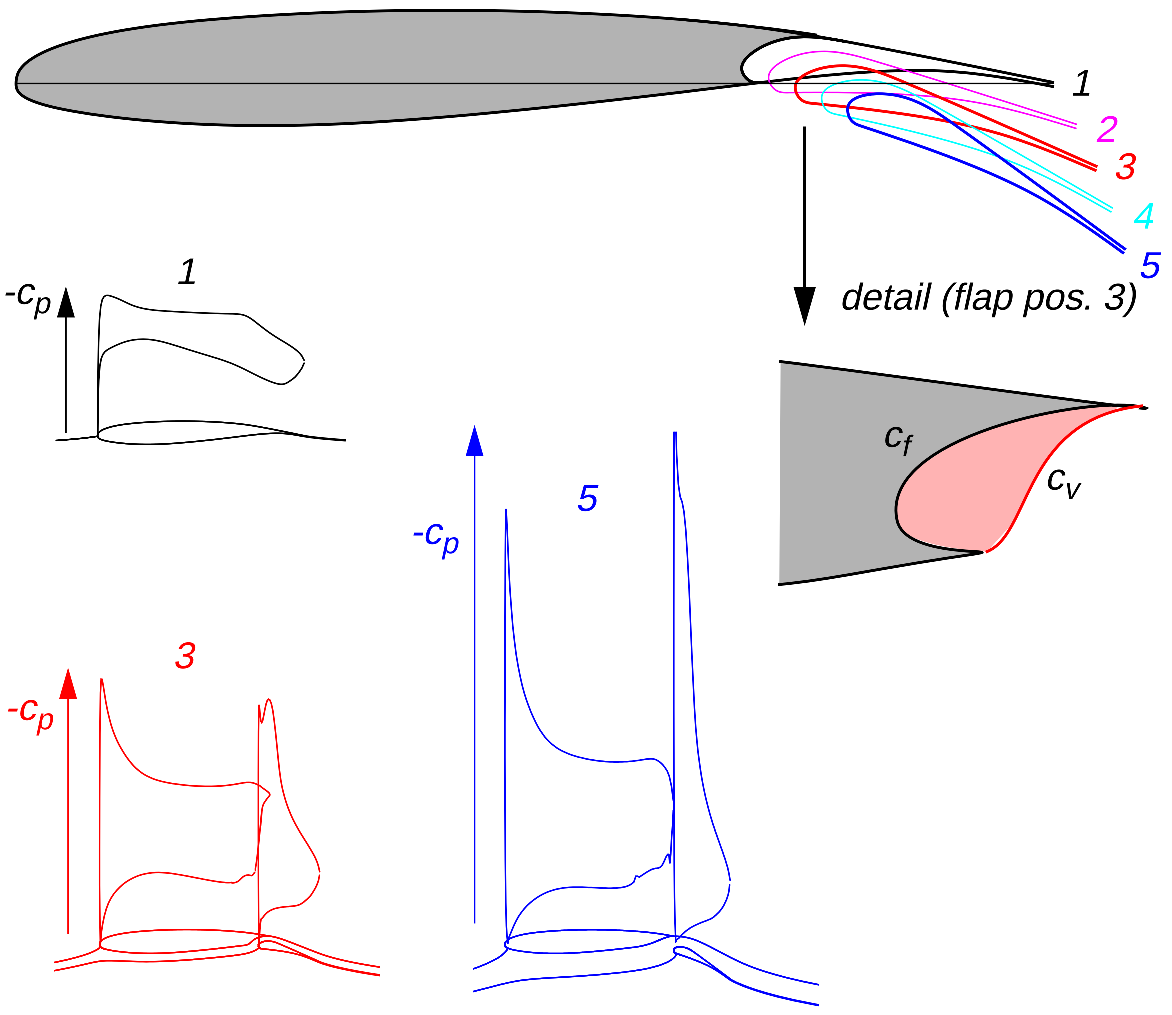


Fig. 8: Modelling flap geometry c_f and viscous flow replacement contour c_v for fast 2D flow high lift computation. Pressure distributions for original airfoil (1) and two flap positions (3, 5) in incompressible, inviscid flow, estimated separation in flap bay modelled.

Wing geometries with spanwise section variation

So far our shaping of aerodynamic components is restricted to a 2D space (X, Z), which is non-dimensionalized with airfoil chord. In the following, this chord will be a function of the spanwise coordinate, $Y = y_o$, of a 3D wing, which is the independent variable to scale, shift and rotate each wing section in 3D space (x, y, z).
The flexible geometry generator for 3D wings, also laid out for curve and surface definition based on suitable parameter input [5], so far makes use of a number of airfoils as ‘support sections’ at given spanwise positions; blending functions defined within the resulting intervals give a section geometry at every spanwise station. For an already very precisely given wing with many support sections and small intervals, this section blending is used merely for a linear interpolation to obtain a redistributed or refined surface grid. Such approach, in principle, may lead to inaccuracies in spanwise smoothness, which does not occur from a definition with only few support sections.
Application of the analytically defined airfoils as wing sections with a smooth variation of the parameters (here, applying the PARSEC functions, the 11 basic and optionally a few parameters for surface bumps and trailing edge variations) guarantees surface smoothness to a desired degree with also just few input data and still an option for strong surface variation along span.

Periodic airfoil deformation

Not yet a wing configuration, but introducing time as a third dimension defines a 3D boundary condition, see the illustration Figure 7: We applied the new parameterized shapes for the generation of airfoil systems with periodic geometry changes. So far we have studied applications to new helicopter rotor blades with shape adaptation for suppression of dynamic stall: a periodic nose drooping to a given airfoil using the geometry manipulation as illustrated for the sealed slat, Fig. 6, was applied, in certain phase with a periodically changing angle of attack. Results are obtained indicating a very favorable delay of unsteady separation in the low speed phase of the retreating rotor blade [14]. An unsteady N/S code is used with a grid conforming and moving with the varying airfoil geometry. This concept of using periodically adaptive airfoils is also applied with a refined nose curvature variation to control shock-boundary layer interaction in high angle of attack airfoil flow [15]. The study revealed the dramatic role of viscous transonic phenomena occurring in low speed aerodynamics: a small supersonic bubble forms at the leading edge at high angle of attack. Because of high curvature the recompression shock terminating this supersonic domain is quite strong. Our earlier approach to design shock-free supercritical airfoils has taught us to apply bumps for shock suppression; it seems that such approach may be successfully used very locally with small adaptive bumps at the leading edge in low speed configurations, which might be realized without excessive mechanical effort.
Software tools developed for the comparative visualization of 3D CFD results are suitably applied here for 2D unsteady flows: Color or ‘zebra’ isofringes for surface pressure show the onset of separation, Fig. 9. Iso-surfaces like the sonic bubble M = 1, are displayed as shaded surfaces and give an impression of the extent of the observed phenomena. Creating this 3D visualization of an unsteady 2D flow, as well as the use of video animation of such case studies and their 4D extension if a 3D unsteady process is being investigated, have a high educational value for identifying the relative importance of single parameters to be varied.

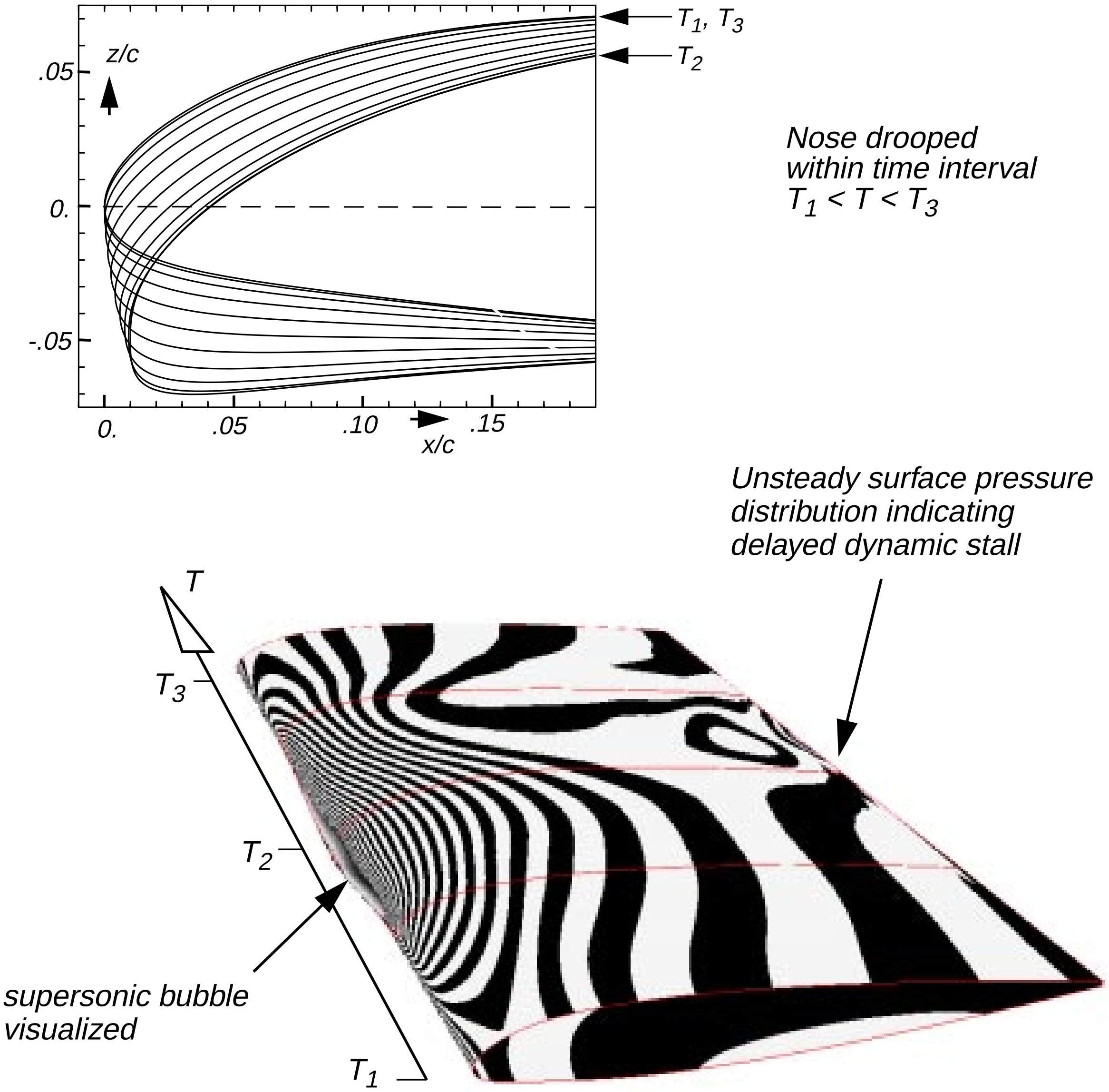


Fig. 9: Results for unsteady airfoil flow with periodically drooped nose (Ref. 15): Color isofringes for surface pressure visualization, $M_\infty = 0.3$. Control of locally occurring supersonic flow and viscous interaction triggering downstream boundary layer separation.

Airfoil parameters for wing geometry definition

In a new modification of our wing generator software, the previously used support airfoils at selected stations along wing span may now be replaced by defining a set of airfoil parameters like those explained above for the PARSEC family, as functions along span, just like the already operational way of defining functions for leading and trailing edge coordinates and local wing section twist. Compared to the amount and flexibility of input data for a set of special support sections, the new approach seems to open a better use especially for optimization strategies, using the well proven concept of composing arbitrary spanwise curves for geometry and distributions with only a few key parameters. Figure 10 illustrates both options to define wing sections at any spanwise station in the wing coordinate system (x, y_o).

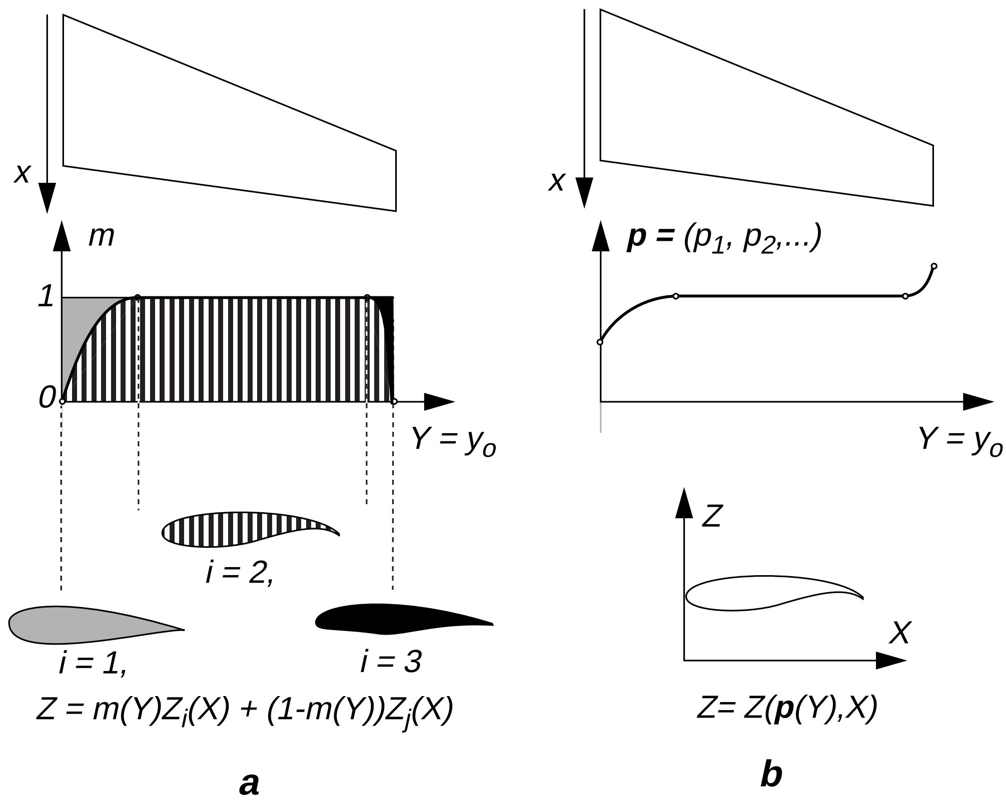


Fig. 10: Two methods to define wing sections: Blending support airfoils data (a), and varying generating parameters (b) along wing span. Sketch shows wing with basic section over large portion of wing, root and tip sections.

Example: Optimization of a Flying Wing in Supersonic Flow

A Flying Wing aircraft has several advantages both for aerodynamic and structural efficiency. Such a configuration therefore is an ideal test case for new design and optimization strategies. The application of a Flying Wing for a new concept of high speed transport aircraft recently has been studied as an alternative to conventional supersonic configurations [16]. Using variable sweep angles for the whole configuration results in a wide range of possible optimum aerodynamic efficiency. Oblique Flying Wing (OFW) examples have been generated by our geometry preprocessor, both using the previous support section blending technique and also the new parametric 'PARSEC' airfoils defined along span of the OFW.

Several aerodynamic phenomena suggest usage of well-known design methods like applying transonic (supercritical) airfoil theory, applied to a sufficiently thick 2D basic airfoil in the subsonic Mach number component normal to the leading edge of this large aspect ratio wing. Reqirements of an elliptic load distribution suggests the classic elliptic planform, a linear variation of the wing twist along span and blending the basic airfoil with two modified sections at both tips yields a wing with the desired load distribution. With computed lift over drag ratio (L/D) of this first case study [17]slightly above the values of known conventional wing-body type configurations, we learned that a more refined approach than designing one 2D basic section would allow for a better control of crossflow shocks coalescing on the upper wing surface. With a slight modification of the planform geometry and the new spanwise parametric section definition this goal has been accomplished already in a first manual approach of optimizing the OFW [19].

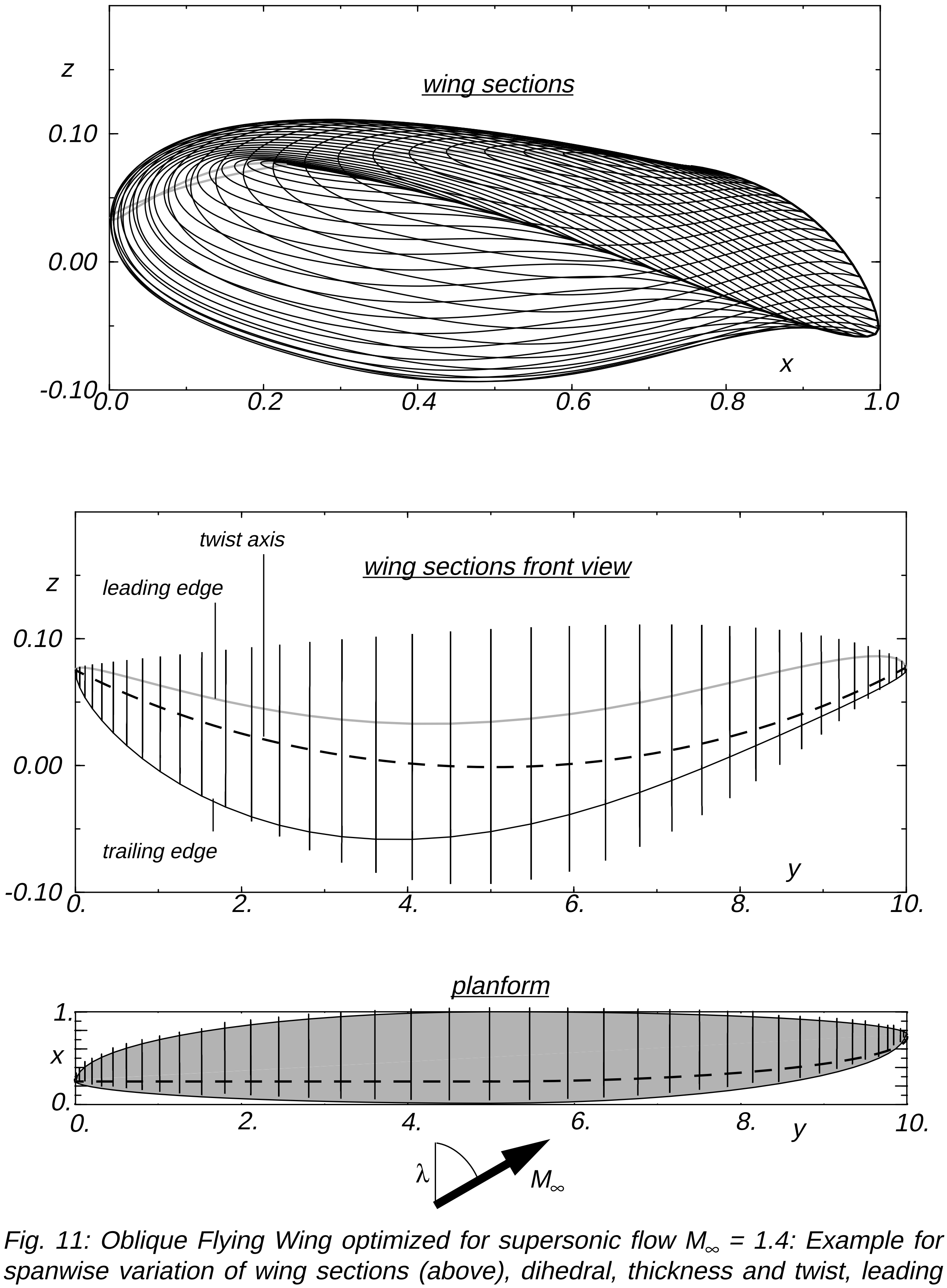


Fig. 11: Oblique Flying Wing optimized for supersonic flow $M_\infty = 1.4$: Example for spanwise variation of wing sections (above), dihedral, thickness and twist, leading and trailing edge geometry (center and below). (Note enlarged scale for vertical coordinate z). Aerodynamic performance optimized in swept flow $M_\infty = 1.4$, $\lambda = 60^o$, with constraints for spanwise wing section thickness, area and aerodynamic load distribution.

Figure 11 shows the resulting geometry in a threeview: wing sections vary considerably within the elliptic chord distribution, all 11 PARSEC parameters were made functions of span. A modification of the basic elliptic planform to the unsymmetrical shape with stronger sweep at the trailing tip (y = 10) than at the leading tip (y = 0) is suggested by the observed stronger crossflow shocks in the trailing area. Simple aerodynamic theories suggest higher normal Mach number components in the trailing part and therefore lead us to shape the local sections for supercritical flow in higher Mach numbers. This was a goal in the example Fig. 3, a use of PARSEC functions for spanwise section definition therefore was promising.
Constraints based on application of one of the classical aerodynamic theories (the supersonic area rule) to improve the design, calls for tuning the spanwise section area distribution according to the Sears-Haack body of minimum drag for given volume. The simple polynomial structure of the PARSEC function yields the integral easily for each set of parameters.
An automated optimization procedure for this and similar configurations will perform the design of a better OFW much more economically than the manual approach done so far, but the value of learning the role of the individual parameters in the process of a practical design cannot be estimated high enough.

Wings with multicomponent high lift system

In the same way as for airfoil parameters, the newly developed key points for sealed flaps and slats as well as the input data for multicomponent airfoil shapes may be made functions along the third physical dimension in space, the spanwise direction of a wing. 3D space is defined in the 'wing system', with planform in an (x, y_o)-plane, and the wing shape defined prior to shifting and rotation in general 3D space with aircraft coordinates.
Using airfoil and high lift sections data in the retracted (cruise conditions) position defining clean wing boundary conditions, wing input data rescale each section plus its components to physical chord and provides twist as a function of span. Each component (flap, slat, solid remaining wing) will then be available for a movement in 3D space.
These surfaces may be defined along most of the wing span (except at fat root fillets or at thin tips), choice of sections to begin and end slats and flaps is then a matter of constraints and additional flexibility. Kinematic requirements, however, in the case of tapered and twisted wings demand that the sectioning between component ends must be redefined to allow an unobstructed sliding of the flaps and slats along the fixed part of the wing. In the general case this requires an intersection of the wing surface with a sphere, its center located at the vertex of a cone tangent to the local wing surface panels.

Example: An extended DLR-F5 test wing configuration

A decade ago the 'DLR-F5 wing' was presented and communicated as a test case for the development of CFD methods [2], [3]. The data for this wing have been used by various developers to tune Navier-Stokes codes for viscous transonic flow. The case is still a difficult task to solve if the experiment is to be simulated: transonic flow with laminar shock - boundary layer interaction remains a problem for CFD so far.
Nevertheless, with the example well known in the CFD community it seems to be a suitable example also for other than experimental operating conditions, especially if the wing shape is defined in a parametric way allowing variation of the shape and this way testing design and optimization strategies.
In a first approach to revisit the DLR-F5 case its wing sections are redefined by PARSEC parameters. The original wing has a symmetrical basic section which was designed to be nearly

shock-free at $M_\infty = 0.78$. A set of surface data points was provided and blended with a thick NACA 0036 section to form a prominent wing root fillet. With knowing the nose and crest curvatures, applying the trailing edge modification parameters and blending with the NACA 4digit generating function , the input set of airfoil data can be replaced altogether by the new analytical definition. The new parameters are proposed along with mathematical modelling of some experimental pressure distributions to complete a new test case for direct/inverse CFD and for optimization [19].
In addition, the DLR-F5 wing was used for definition of a multicomponent wing with slat and flap. Figure 12 (a) shows the choice for carving the basic section to shape a slat and a flap, these section components subsequently are scaled to the DLR-F5 planform and additional input for the 3D flap and slat tracks and rotation angles is provided. Choice of spanwise extent for flap and slat, a refined sliding sections definition and closure of the components at the sliding sections completes the preprocessing of this extended test wing for CFD analysis.

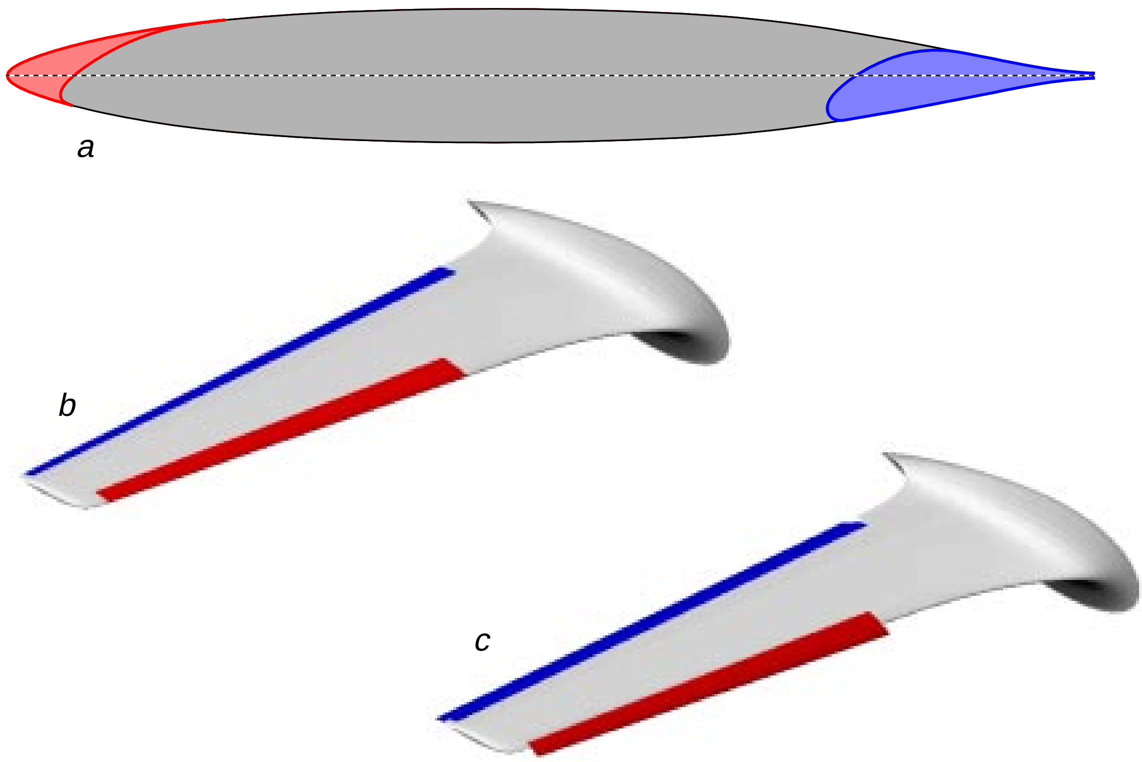


Fig. 12: Basic DLR-F5 section, redefined by PARSEC parameters and carved to include a slat and flap component (a). Selection of 3D flap and slat extending along span, in clean wing (b) and high lift (c) position.

Conclusions

An effort is made in using basic algebraic and analytic relations to generate realistic airfoil shapes which are specified from a set of parameters. These are defined by only a few characteristic dimensions used already in classical airfoil catalogs like NACA airfoil families, but also allow for a refined shape definition as it results from systematic design processes in the transonic flight regime. Airfoils determined this way by a minimum set of parameters are subsequently used as wing sections, with their generating parameters made functions along span, This has

been proven earlier for basic wing geometries which have used given data sets for support airfoils. Some unsteady airfoil flow applications lead the way to fully threedimensional wings which may be subject to input for manual or automated aerodynamic optimization techniques. This method to describe all shapes analytically has been extended to high lift systems and adaptive devices.
The approach is intended to provide 2D, 3D and, with unsteady, adaptive or evolutionary configurations, also 4D boundary conditions for CFD and CAD.

References

[1] Sobieczky, H.: Computational Methods for the Design of Adaptive Airfoils and Wings. Notes on Numerical Fluid Mechanics, Vol. 2, ed. E. H. Hirschel, Vieweg (1979) pp. 269 - 278

[2] Sobieczky, H.: DFVLR-F5 Test Wing Configuration for Computational and Experimenta Experimental Aerodynamics, Wing Surface Generator Code, Control Surface and Boundary Conditions. Notes on Num. Fluid Mechanics, Vol. 22, ed. W. Kordulla, Vieweg (1988), pp. 27 - 37

[3] Sobieczky, H., Hefer, G., Tusche, S.: DFVLR-F5 Test Wing Experiment for Computational Aerodynamics. AIAA 5. Appl. Aerodynamics Conf. Proc., AIAA 87-2485CP, (1987), Notes on Numerical Fluid Mechanics, Vol. 22, ed. W. Kordulla,Vieweg, (1988), pp.4 - 22.

[4] Sobieczky, H.: Aircraft Surface Generation. Results of EC Brite/Euram Project ‘Euromesh’ 1990-92, Notes on Numerical Fluid Mechanics, Vol. 44, ed. N. Weatherill et al, Vieweg (1993), pp. 71 - 76

[5] Sobieczky, H.: Geometry Generator for CFD and Applied Aerodynamics. in: New Design Concepts for High Speed Air Transport. CISM Courses and Lectures No. 366, Springer (Wien, NewYork), (1997) pp 137 - 157

[6] Ladson, C., Brooks, C.: Development of a Computer Program to obtain Ordinates for NACA 4-Digit, 4-Digit Modified, 5-Digit, and 16-Series Airfoils. NASA TM X-3284 (1975)

[7] Eberle, A.: Berichtigung der Whitcomb-Offenlegungsschrift und Profildefinitionsprogramm. MBB-UFE-AERO-MT-298 (1977)

[8] Zores, R.: Transonic Airfoil Design with Expert Systems. AIAA 95-1818CP, Proc. 13th AIAA Applied Aerodynamics Conf., San Diego, CA, (1995)

[9] Garabedian, P. R.: On the Design of Airfoils Having no Boundary Layer Separation. Advances in Mathematics 15, (1975) pp 164-168

[10] Henne, P. A.: Innovation with Computational Aerodynamics: The Divergent Trailing Edge Airfoil”, Applied Computational Aerodynamics, ed. P. A. Henne, AIAA Education Series, AIAA, Washington, D.C., (1990), pp. 221 - 262

[11] Thompson, B. E., Lotz, R. D.: Divergent-Trailing-Edge Airfoil Flow. J. Aircraft Vol. 33 (1996), pp. 950 - 955.

[12] Sobieczky, H.: Gasdynamic Knowledge Base for High Speed Flow Modelling. in: New Design Concepts for High Speed Air Transport. CISM Courses and Lectures No. 366,

Springer (Wien, NewYork), (1997) pp 105 - 119

[13] Ashill, P. R., Fulker, J. L., Simmons, M. J., Gaudet, I. M.: A Review of Research at DRA on Active and Passive Control of Shock Waves. 20th ICAS Congress Conf. Proc. ICAS-96-2.1.4, (1996) pp. 76 - 87

[14] Geissler, W., Sobieczky, H.: Unsteady Flow Control on Rotor Airfoils. AIAA 95-1890CP, Proc. 13th AIAA Applied Aerodynamics Conference, San Diego, CA, (1995)

[15] Sobieczky, H., Geissler, W., Hannemann, M.: Numerical Tools for Unsteady Viscous Flow Control”. Proc. 15th Int. Conf. on Num. Meth. in Fluid Dynamics. Lecture Notes in Physics, ed. P. Kutler, J. Flores, J.-J. Chattot, Springer (Berlin, Heidelberg) (1997)

[16] Van der Velden, A.: The Oblique Flying Wing Transport. in: New Design Concepts for High Speed Air Transport. CISM Courses and Lectures No. 366, Springer (Wien, NewYork), (1997) pp 291 - 316.

[17] Seebass, R.: Oblique Flying Wing Studies. in: New Design Concepts for High Speed Air Transport. CISM Courses and Lectures No. 366, Springer (Wien, NewYork), (1997) pp 317 - 336.

[18] Li, P., Seebass, R., Sobieczky, H.: Manual Optimization of an Oblique Flying Wing. AIAA 98-0598 (1998)

[19] Sobieczky, H.: Configuration Test Cases for Aircraft Wing Root Design and Optimization. Proc. ISIP’98, Nagano, Japan, (1998)