Chapter 5

Flow Boundary Conditions Modeling in 4D for Optimized, Adaptive and Unsteady Configurations

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5.1 Introduction

The modelling of boundary conditions for the analysis of various loads to mechanical product components has become a mature technology in many disciplines. Structural, aero/hydro- and thermodynamic loads as well as their multidisciplinary coupling is not yet solved by standard procedures, but many commercial software packages are already available to resolve some practical problems. In this situation the academic institutions change their courses in order to adapt the load of taught material to new technology and techniques. Students are challenged to get acquainted with applied case studies and links to readily prepared software for specific problems. We observe that many basic disciplines like mathematics and mechanics obviously need to strip some of their more basic material in favor of such special problem areas and applied course work.

This development is especially true in disciplines where analytical modelling used

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to be of major importance for understanding mechanical phenomena: Mathematical functions were used to explain the special character of some complex effects which cause practical problems in product operation.

One main tool to build knowledge bases is the basic discipline of analytical geometry. Consequent application of its mathematical background is the basis for modern commercial computer aided design (CAD). Not quite so well developed, but nevertheless also resulting in commercial software, is the computational analysis of fluid dynamics (CFD) in compressible, viscous flow with added complexities like special atmospheric or thermodynamic conditions. Much effort, therefore, is spent to link CAD and CFD for the *analysis aspect*, using geometry software packages to define boundary conditions for simulation of complex given shapes, like whole aircraft and complex turbomachinery components.

In this situation, though, we seem to loose some of the basic understanding which is much needed for the *design aspect* of creating new product components employing novel ideas to influence the physics of flow. Creative teachers are now challenged to use the toolboxes of information technology to present some classical knowledge bases in mechanics and fluid dynamics to their students. Computer-based textbooks of the basic disciplines are an option to keep these basics available, see for instance the pioneering work by Caughey and Liggett [1].

Some work illustrated here is focusing on geometry aspects for the mentioned coupling CAD-CFD, trying to take into account the gasdynamic knowledge base for compressible flow: Minute shape changes have been found responsible for large flow quality changes and hence large changes in practical degrees of efficiency in operation of components in high speed flow. The role of geometry in general and the importance to create test case studies with well-defined geometrical shape definition was described by the author in [6]. Here we focus on the need to vary such shapes, in order to create whole families of configurations to choose from, in optimization routines, or to simulate intelligent shape control adapting to varying operating conditions, or finally to create unsteady mechanical systems like those we observe in nature:

With a real or a virtual time as an additional dimension we try to create 4-dimensional shapes.

5.2 Geometry concept for 4-dimensional problems

The concept for 3D shape definition has been explained previously, see [7, 8], here therefore we focus on the extension to the fourth dimension. A summary of the basic characteristics for the approach will show that the extension to 4D is straightforward and will use the same techniques as we found it useful to create 3D surfaces from varying the parameters of 2D curve definition. In this (flow-)phenomena-oriented approach to create initial configuration geometries we have been guided by what we call the gasdynamic knowledge base:

Inverse design concepts, developed on the basic equations of compressible flow motion, taught us to identify the sensitive regions where slopes and curvatures along surface prtions are more important than surface coordinates, suggesting a strong control of shape generating functions via defining support data along with slopes, curvatures or singularity exponents. Also, a distinct adherence to cartesian definitions is kept and direct function evaluation is established, $x_3 = \mathrm{Fct}(x_1, x_2)$, resulting in avoiding interpolation, iteration and integration to obtain single coordinate data. This philosophy seems to suite a large class of shape design tasks for aero- and hydrodynamic configurations requiring free-form definition with a set of relatively few parameters. With previously gained experience in high speed design, for instance in the transonic Mach number regime, the basic components like airfoils should be defined from possibly few but specific parameters. This has been achieved in the PARSEC family of sections [8]. Several authors in the meantime have obtained impressive aerodynamic design results making use of these wing sections, so that we have recently developed interactive, web-based software for students to get familiar with the role of used parameters.
Two different types of airfoils can be defined, Fig. 5.1 shows the options to interactively generate data for turbomachinery blading and for aircraft wing sections:

PARSEC-09
These are turbomachinery blade sections, with 9 parameters. Turbine or compressor blades in hot fluid pose a number of formidable multidisciplinary design tasks, a first approach using these shapes is presented by Dennis et al [2].

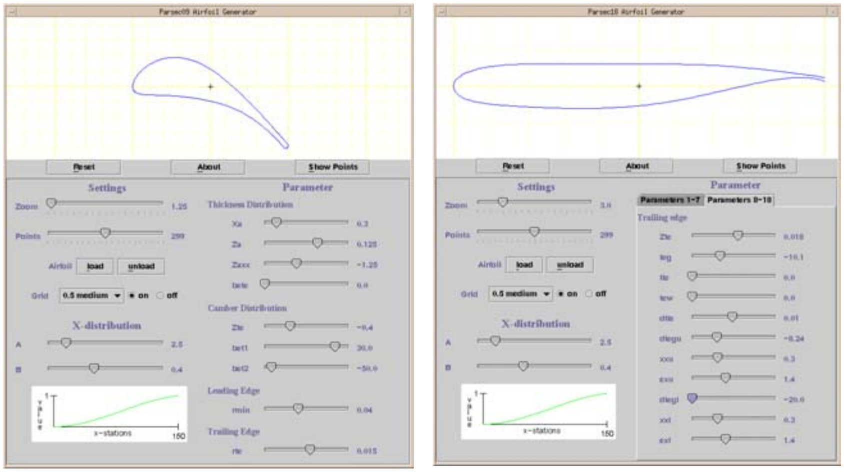

Figure 5.1: Interactive 2D ‘PARSEC’ airfoil definition, for turbomachinery and aircraft wings.

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PARSEC-18
is a refined version of the original PARSEC(-11) set for aircraft airfoils: Supercritical wing sections with divergent trailing edge (DTE) can be defined for viscous interaction control near reduced shock waves and circulation control by supporting an efficient Kutta condition.

The next step is a suitable variation of the airfoil parameters in the 3rd dimension, for wings the spanwise and for blades the radial direction. Basically the same idea provides an extension of 3D into a 4th dimension: the new dimension t is either time or a time-like virtual ordinate, to just allow for defining a whole set of shape variations to be chosen from. Only a few shape-generating parameters of those used for airfoils or 3D characteristic data will be subject to modifications within a given interval. For obtaining a variation we need only to sweep along $0 \leq t \leq 1$, with $t = 0$ yielding the initial 3D design study and $t = 1$ resulting in a new, extremely deformed shape. Distribution functions of the parameters to be modified allow for individual influence control, from linear to ramp-like functions just as used for the geometric curve portions between support stations. With the ramp function defined by a sine squared we already have half of a harmonic periodic cicle, if t is serving as real time. Other periodic functions of course allow for individual control of parameter oscillation.

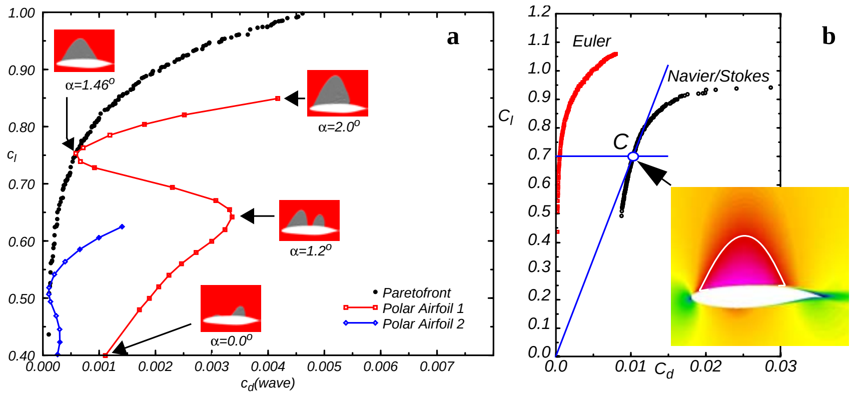

Figure 5.2: Genetic Algorithm optimization of 17% thick airfoils, Mach=0.7: Inviscid flow Pareto front and drag polars for 2 airfoils, (a).
Viscous flow optimization, Re=40Mill, (b).

5.3 Optimization

With a set of variations available, analysis of some mechanical performance parameter, the objective function, and using optimization strategies one may eventually select one superior shape to be chosen for application. In the work of Klein [4] aerodynamic performance is defined by the ratio of lift over drag (L/D), his case studies range from airfoils to wings. Figure 5.2a shows results for a large number of optimum airfoils in inviscid flow which maximum L/D, positioned along the Pareto front. Two airfoils then are selected and their performance in varying angle of attack is analyzed. This yields their drag polars, which touch the pareto front at the design point. Figure 5.2b shows comparison between an inviscid (only wave drag) and a viscous (friction drag included) design. The flow is seen to be shock-free.

5.4 Adaptive configurations

Selection of a fittest configuration via optimization software has got a counterpart in hardware, if the shape variations are obtained by mechanical devices effectively changing the flow boundaries. To date, this can realistically be achieved by elastic or pneumatic elements, controlled by servo motors or piezo-electric devices which are controlled by a microcomputer, which in turn is pre-programmed and uses flow quality sensors where surface pressure is compared to pre-defined target val-

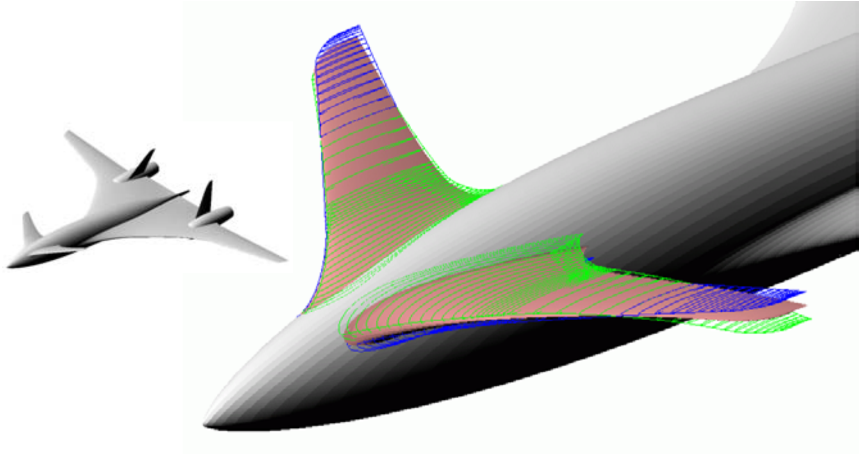

Figure 5.3: Variation of a canard configuration by two independent parameters controlling canard root location and dihedral

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ues at several surface locations. With the need to restrict adaptive devices to areas of small size, we choose to select the use of curvature changes via added bumps in the transonic expansion and recompression areas on a wing surface: Expansion Shoulder Bumps (ESB) and Recompression Shoulder Bumps (RSB) are found to have positive effect on aerodynamic efficiency of an airfoil or wing in the transonic flow regime, see the work of Geissler and Koch [3].

Morphing airplane
Observing the ever-increasing power of computational tools, but also new intelligent materials for surface manufacture, we are confirmed about the importance of creating configurations which can alter portions of their shape beyond just very local patches: The idea of the Morphing Airplane is born and will employ "*smart technologies that could enable inflight configuration changes for optimum flight characteristics*" (NASA).

Until such ideas become reality, we try to simulate the variation of shapes with our 4D tools and apply CFD to study resulting flow structure for a better understanding of the predicted aerodynamic performance. A recent study by the aircraft industry, experiencing the difficulty of applying the canard concept to a transonic transport aircraft, prompted the author to create a variable canard shape and its integration to the aircraft fuselage, (Fig. 5.3), for creating a test case for further studies.

5.5 Unsteady boundary conditions

The above mentioned work on adaptive wing devices in fact was carried out for steady and also unsteady shapes: Bump oscillations are studied to influence the onset of dynamic stall on a transonic airfoil.

Unsteady flow boundaries occur in rotorcraft. Design of a rigid rotor blade needs to compromise between a transonic advancing phase and a low speed retreating phase of the blade. With the requirement of resulting constant lift a variation of the angle of attack is needed which in the retreating phase might lead to dynamic stall. In the work of Trenker [9] an initially chosen PARSEC-11 airfoil is first optimized for the advancing phase transonic peak Mach number. Subsequently a nose droop and trailing edge sealed flap model allows to create variable reflex-type airfoil shape accomodating the lower speed flow past variable increased angle of attack. The result is a complete removal of dynamic stall, which would definitely occur on the rigid transonic airfoil in low Mach numbers. The helicopter industry seems to pick up the concept and practical case studies are underway.

5.6 Bio-fluidmechanic applications

Optimization, adaptation and unsteady shape variations: all of these have been performed and constantly occur in nature, where birds, insects and fish through the ages have optimized their shape, adapt it constantly to flying or swimming conditions and need unsteady harmonic motion for creating lift and thrust by flapping their wings or fins. It is therefore a challenge to learn from nature by creating parameterized models of such animals, to apply CFD and learn about phenomena and optimum shapes.

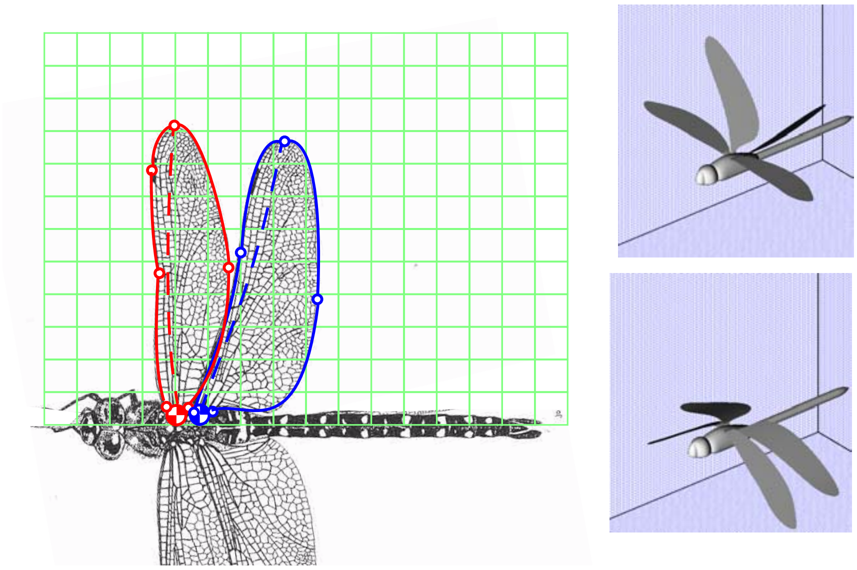

Figure 5.4: Unsteady configuration example: Dragonfly flapping its wings

An especially challenging example is the dragonfly with its high manoeuverability, resulting from its ability to operate each wing independently. The insect therefore has been studied in the wind tunnel and with fotographic evaluation of the flapping motions [5]. We learn that within a cycle the wings are flapped, swept and twisted by different periodic functions and characteristic phase shifts between fore- and hindwings.

Such an unsteady boundary condition is a challenging test case for our geometry tool: Modeling a rigid insect shape from a fotograph (Fig. 5.4) is the first step. Few support points suffice if the proper model functions are chosen to create a suitable data set similar to an aircraft tandem wing body configuration. Subsequently, the measured flapping oscillations [5] define the unsteady parameters needed to let our model insect flap its wings properly and close enough to observe reasonable aerodynamic characteristics once the dataset is input for an unsteady CFD simulation.

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5.7 Conclusion

The definition of various aero- or hydrodynamic structures using our geometry preprocessor has become more challenging with including shape variations in a fourth dimension. While 3D surface grids currently provide a suitable input for CAD processing to generate interface data for various grid generation, CFD analysis and design, as well as model manufacturing software, an extension to moving or morphing surfaces invites to create new unsteady test cases for code development and phenomena study.

5.8 Bibliography

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