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Geometry for Theoretical, Applied and Educational Fluid Dynamics

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1.1 Introduction

Motivated by the topic of this book and by the event leading to its edition, in this contribution the attempt is made to illustrate how some of our accumulated knowledge in the field of compressible fluid dynamics may be kept alive and useful for the development of modern tools in aerospace engineering. This may be needed in a time when computational fluid dynamics (CFD) solves complex aerodynamic problems and a detailed understanding of the underlying phenomena seems to become unnecessary. Numerical modelling in transonic aerodynamics has had decisive impact from the work of Earl M. Murman, who modelled the key phenomenon of transonics, mathematically described by a type change from elliptic to hyperbolic model equations, in a simple change in a numerical difference scheme [5]. In a more recent activity, Murman guided a project to provide an educational software system helping a new generation of students to understand fluid mechanics and gasdynamics by solving a collection of fluid mechanic and aerodynamic problems on the computer. We try to learn from such activities, using past work results to stay familiar in the future through the tools of information, communication and software technology. Here the background of some aerodynamic design tools is illustrated which is also part of our knowledge base and can be implemented in modern and efficient optimization tools for airframe and turbomachinery design. Details of flow phenomena result in mathematical functions for their correct description. With the need to arrive at realistic three-dimensional configurations, the structure of desirable 3D flow elements should be aligned with the geometrical description of their boundary condi-

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tions. Geometry preprocessor tools may therefore transfer the fluid mechanic knowledge base to CAD systems supporting CFD analysis, experimental model production and component data definition for interdisciplinary work.

A case study illustrates our present activity in this direction. It could serve for practical use in aerospace research, application and education.

1.2 The transonic knowledge base

In the past 50 years, until perhaps 30 years ago, the pioneers of transonics (Guderley, Oswatitsch, Frankl, Tricomi, Germain, ...) have developed models for the basic equations of flow motion so that it was possible to find either isolated or whole systems of particular solutions. These were amenable to explaining the hitherto strange and sometimes dangerous effects in the higher speed regime of approaching transonic flight Mach numbers.

Thirty years ago, potential theory was accepted as a good tool for modelling the basic aerodynamic component of airfoil flow. At this time the first (relatively) 'large scale' numerical simulations were made possible by the availability of digital computers. The problems of simulating transonic flow with mixed subsonic/supersonic domains were solved with the approach by Murman and Cole [5] to change the scheme of discretization from central to forward differences once supersonic flow appears imbedded in a subsonic flow model. From there on the analysis of transonic flow was a main goal in the development of CFD.

The above-mentioned solutions to the basic differential equations also included 2D airfoil flows in high subsonic Mach numbers which did not have shocks and thus promised a higher lift/drag ratio. It took some time until refined technology, both in experiment and in analysis, could confirm this theoretical concept of shock-free flow, because the underlying mathematical solutions are mathematically isolated, required very accurate analysis and precise wind tunnel technology, for a while they were therefore not seen of practical value for the shaping of a real wing. But once proven useful for applied aerodynamics, systematic design methods were in demand to create transonic - 'supercritical' - airfoils and with their help, arrive at better wings with high aerodynamic efficiency in the transonic flight regime.

The author, for three decades, has had the privilege to take part in the development of transonic flow design methodology, witnessing the advent of faster computers and refined software to analyze compressible flow.

Education with the above-mentioned pioneers' models led the author to the use of a simple analog electrostatic set-up to solve the potential boundary value problem in a mapped working plane (a hodograph plane). This approach, for instance, allowed for a relatively easy understanding of the mathematically elegant but difficult method by Garabedian [1] to design shock-free airfoils in a complex characteristics (4D) work space, and identify the 2D real part of the solution with the boundary condition in a 2D electrostatic network [6]. A replacement of the latter by a computational grid and solution by numerical relaxation was of course timely in the seventies, but the real profit of this early 'playing' with transonics was its educational value, giving us

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a 'feeling' for the occurring flow phenomena and a deeper understanding for the related work of others.

Furthermore, the technique of solving mapped boundary value problems in the analog set-up was implemented in many of the numerical analysis methods based on potential theory operational by then and this way converted these to become design tools for shock-free 2D airfoils as well as 3D wings [7, 8]. This approach requires a temporary change of the ideal gas property once the static pressure within the flow field is falling below the critical value, a simple software modification. This semi-inverse technique therefore is termed 'Fictitious Gas' (FG) method and within the past years also has been implemented in modern Euler [4] and Navier-Stokes [9] analysis codes.

With these tools available and many case studies in aircraft wing and turbomachinery blade redesign carried out, it became obvious that the reduction of shock losses which are observed for given initial configurations, results in systematic shape modifications which may allow a direct mathematical modelling applied to only local domains of the surface geometry. With geometry preprocessing being the starting point for any refined optimization in the various disciplines participating in an aerospace product design process, the knowledge about quality and quantity of surface changes for better aerodynamic efficiency may therefore greatly reduce the number of parameters to be varied in an optimization process.

1.3 Geometry generator

As an activity turning out to be of increasing importance for an economic production of CFD boundary conditions and grids, the development of a flexible geometry generator code with special input control for transonic design refinements was started 15 years ago and in the meantime has evolved to the preprocessor software as suggested above, complimenting and using the design knowledge base for not only transonic design and analysis but also supporting supersonic applications and shape definition for low speed aerodynamics and hydrodynamics. In a recent compilation the author tries to illustrate this link between gasdynamics and geometry in more detail [10, 11].

Recent developments in CFD show progress using both block-structured (hexaedric) and unstructured (tetraedric) grids. CFD analysis of complex configurations like complete aircraft seems to be more successful with unstructured grids [2], discretizing most of the surrounding space and restricting the use of a structured grid to the viscous flow layer close to the surface. Such hybrid grids may currently already be generated by commercially available software [3] for which our geometry generator serves as a preprocessor: The analytical functions chosen from a catalog are able to model most of the complex details. Explicit and non-iterative evaluation for given surface metrics allows for very fast production of dense surface grids which are input for determining 3D boundaries for triangulation of space between all components and a far-field boundary surface.

There are some important applications motivating the introduction of a time-like single 'superparameter', to represent a fourth dimension in the modelling of 3D con-

figurations: Configurations may be considered changing their shape with time, like in a periodical motion occurring in nature with animal flight or in aeroelastics with fluid - structure interaction and in rotor aerodynamics. Or the shape varies in non-periodical mode in a sequence of controlled alterations defined by an evolutionary optimization process. This is paralleled by the mechanical adaptation process of experimental model or real configuration components. In our software, selected input parameters defining shape details are given within an interval, with the superparameter controlling their changes. A suitable data definition for such moving shapes is therefore very attractive for all unsteady processes, for optimization with a suitably controlled number of parameters and for the programming of microcomputers controlling actuators to adapt a wing geometry to varying operation conditions.

Many innovative items in aircraft design call for tools like this geometry generator. In the following chapter the status of work on a newly defined test configuration is reported as an example for using geometrical modelling with a high degree of flexibility as needed to observe many details of the transonic knowledge base. It is proposed to serve as a testbed for various conceptual, computational and experimental studies aimed at refining the tools for innovative aircraft design.

1.4 Example: Generic transport aircraft configuration

Test cases in fluid dynamics and aerodynamics to verify theory and experiment always have been welcome and some of them have been used through many years. Their success in serving as a common base for various researchers and developers used to depend on a balance between mathematical simplicity needed to create the boundary conditions and geometrical complexity high enough to be attractive for the applications. After many years dealing with airfoils as test cases, we feel that the time has arrived to provide more sophisticated configurations, including whole aircraft with all components. Using the possibilities given by modern software and communication technology this goal seems reasonable. We envision tools available via the internet to create case studies and communicate data with interested partners. Suitable software tools based on the geometry generator are under development [13] and the following example is an exercise to refine them.



Figure 1: Generic high wing transport aircraft

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Motivated by some of the current design activities and related collaboration between aircraft industry and our research group, the geometry generator was used for modelling a generic transport aircraft (Fig. 1). With these tools having been applied earlier to component junctures of mid-wing or low-wing mounted configurations, the task to model a high wing geometry with strong control of the shape details in the wing root area is an ambitious one, especially if the combined wing - body shape is to be optimized aerodynamically in transonic flow in the presence of the large wheel gear box. Our transonic knowledge base suggests application of the area rule for a smooth axial distribution of the cross section area. Fuselage cross sections are varying axially to contribute to the fillet shaping near the wing root leading edge and also provide the flat upper wing surface extending over the body roof (Fig. 2). Extending the basic wing-body geometry database with a high lift system requires providing the kinematic geometry of the motion of slats and flaps, the latter moving along a flat portion of the body to improve their aerodynamic efficiency. A tail and four propfan engines complete the aircraft shown here - almost, because the flap track fairings still need to be added.

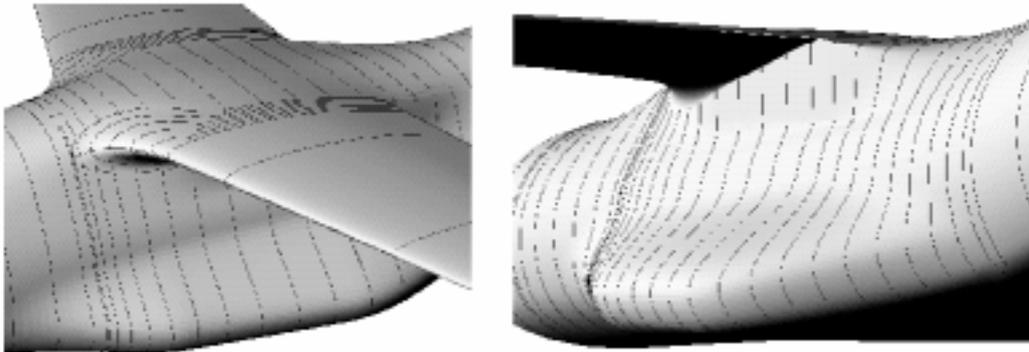


Figure 2: Details of the wing-body juncture

An experiment was planned for the relatively small Göttingen transonic wind tunnel (TWG), using only the data for fuselage and clean wing of this generic aircraft. Using the IGES format, the geometry preprocessor provided surface data for the CATIA CAD system, which allows for defining details of the construction and replaces the input data by surface patches for the numerically controlled milling of the model components. It became clear that only providing of a very dense supporting grid for the required accuracy of shape details was ensuring an acceptable surface quality. Dense data are generated, however, in a few seconds on a workstation because of the analytically explicit functions used to define the surfaces, without any iteration or interpolation, implemented in user-friendly interactive software.

In the first experiment, a concept of using an incomplete model for only local flow quality analysis was brought to reality: Applying the classical aerodynamic knowledge about lifting wing theory, suitably shaped end plates on a large aspect ratio wing with its tips clipped should allow for maintaining the wing circulation on the remain-



Figure 3: Configuration DLR-F9

ing wing with its reduced span. This would ensure unchanged flow details in the plane of symmetry, namely in the area of the wing-body juncture. In the present example, the span was reduced to 60 percent of the original wing with aspect ratio 9 and “Circulation Control Splitter Blades” (CCSB) were mounted like winglets, Fig. 3. Their design using 2D swept wing theory and 3D CFD simulation is described in Ref. [14]. Reduced span of 80cm allows the model (DLR-F9) to fit in the 1x1 m transonic wind tunnel for the investigations of the flow details in the wing root area. This wind tunnel has adaptive upper and lower walls but closed and fixed sidewalls, the CCSB’s should compensate not only for reduced lift-generating span but also from side wall interference.

Fig. 4 shows the complete arrangement including model support: For the purpose of creating a future ‘virtual wind tunnel database’ with this test case, the additional components of sting and sword as given in the TWG were modeled also, their components consisting of shapes created either as ‘wing’ or ‘body’ type shapes, the only two types of surface topologies defined with the geometry generator so far. Wind tunnel side walls and a far field boundary above and below complete the flow space simulating the adaptive wind tunnel, later the data from wall adaptation will be modelled as flow boundary, too.

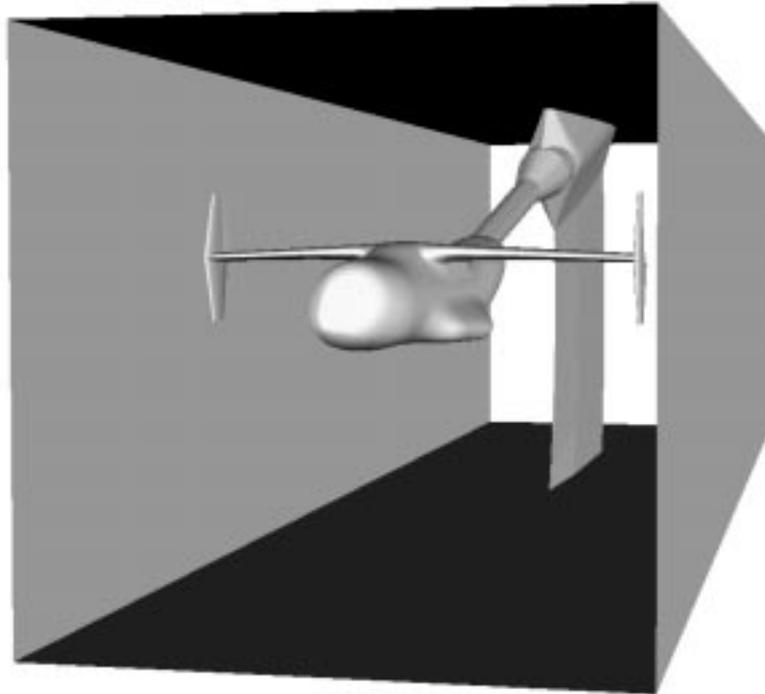


Figure 4: DLR-F9 including model support in the transonic wind tunnel Göttingen

Several runs with the unstructured grid code DLR- τ [1] in Euler mode were carried out to estimate the needed adjustment range of the CCSB's. Fig. 5 shows a graphic postprocessing of this numerical simulation. Refinements of the CFD tools for application of a hybrid grid to simulate the flow with the N/S version of the code is the next step to go..

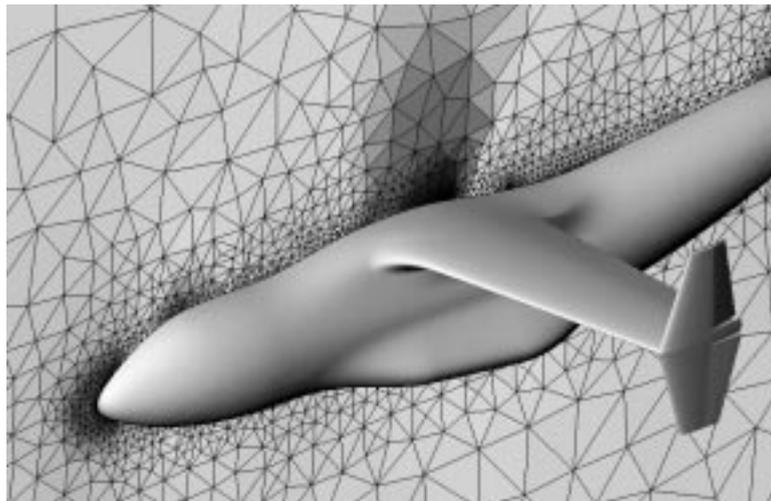


Figure 5: CFD simulation with DLR- τ code: grid and isobar color isofringes in center plane

The experiments easily allow a variation of the angle of attack while the tunnel was running, but the adaptation of the CCSB's require a run interruption, so far. An on-line data processing technique was therefore developed and used [12] during the experiment, to select the flow conditions with an optimum angle of attack simulating a spanwise circulation distribution as occurring on the complete wing, from the root area close to the tip of the clipped wing with CCSB's. Four span stations with static pressure measurement were used to control spanwise load distribution (Fig. 6), the selected cases confirm a pressure distribution relatively undisturbed by the wing clipping up to at least 75% of the clipped wing span or up to nearly half of the full wing span.

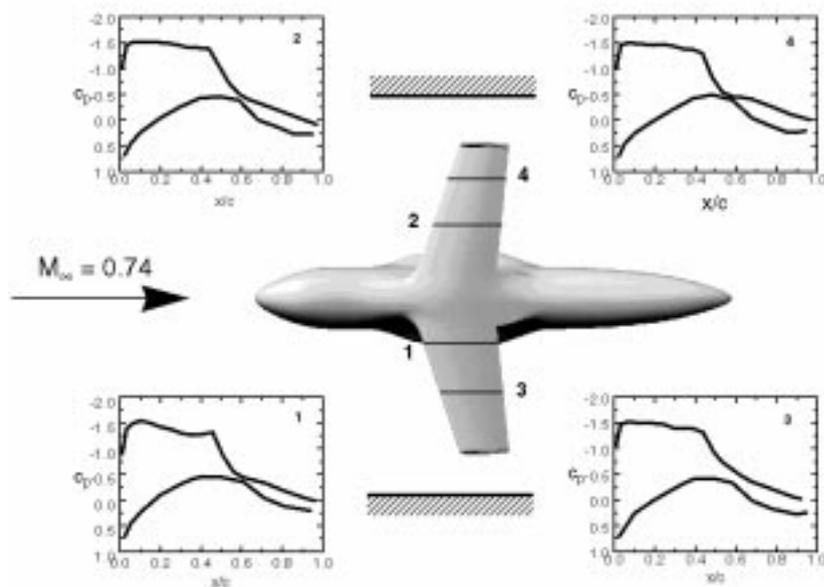


Figure 6: Measured static pressure at four wing sections. ($Re = 2.3 \text{ Mill.}$)

This experiment demonstrated that the model with clipped wings is well suited for detailed investigations in the wing-root area. We can start now with parametric variations of the surface. Future tests will be devoted to obtaining data with an alternative juncture module. Later, the design of an adaptive module with an elastic or pneumatic surface element seems possible because of the large space available within the model fuselage for the necessary servo-equipment. Such purpose of the model might be useful to develop knowledge of a control system for surface adaptation to optimize flow quality with its pre-programming based on selected surface pressure measurements. Already the previously mentioned theoretical work to model shock-free flow by systematic surface redesign with the FG method suggested such an approach [8].

Numerical simulation will allow to study many more variations than experiments can afford, parameter alteration will provide the input conditions for optimization

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strategies and modelling wing deformations creates interface data for fluid - structure interactions. This way the 4D extension of this and similar test configurations created by our geometry tools may become useful for development of more than just aerodynamic technologies.

1.5 Conclusion

The term “geometry” describes a discipline of science as well as the shape of a particular configuration, in the language of aerospace engineering. The title of this contribution is therefore ambiguous, but this is a welcome effect:

Trying to place the discipline geometry into the position of mediating between important elements of the knowledge base of design aerodynamics and the practical applications, including knowledge transfer to the younger generation, is one message here.

Trying also to be specific is suitably achieved with an example. A generic aircraft configuration is presented here as a test case for various techniques in numerical and experimental aerodynamics. The exciting options of worldwide cooperative work opened by the new methods of information and communication technology will enable us to use large data sets for ambitious goals in analysis and design in a truly multidisciplinary approach.

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