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Computational shock and Mach waves visualization aiding the development of aerodynamic design techniques

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Abstract: A combination of computational techniques for aerodynamic design with the consequent use of a flexible visualization software is used to perform systematic approaches to create aircraft components or configurations in the high speed regime. A recent application is the work on the oblique flying wing supersonic transport, understanding of the occurring flow structure through visualization of shock waves helps to refine the configuration geometry.

Key words: Supersonic design, High speed civil transport, Visualization software, Oblique flying wing.

Introduction

Shock waves in the high speed regime of airplanes and aerospace vehicles are a primary source of losses, manifest in the ratio of lift / drag. Practical design methods are therefore aimed at finding shapes with reduced shock waves and hence reduced wave drag for given lift. Currently, numerical simulation (CFD) in combination with CAD and optimization strategies, provides the toolbox to improve practical design cases before experimental verification.

In this contribution some techniques are illustrated to minimize shock waves in high speed flow based on the knowledge base for mathematical modelling of transonic and supersonic flow structures and resulting in geometric models for flow elements relative to physical boundaries. Realistic applications and the occurring flow phenomena are three-dimensional and quite complex so that support by suitable visualization is necessary for understanding and controlling these phenomena.

In an approach to establish a rational and efficient flow of information from the fluid mechanics knowledge base to data production for aerospace component or product definition, and as a small group linking our knowledge in aerodynamics and software technology, we have developed a chain of computational tools with a fairly general scope of applications in the range from hydrodynamics to hypersonics.

"Preprocessing" provides surface and space discretization (grid) data for CAD and CFD, the tools are geometry generators built with a collection of mathematical functions. These functions are based on standard curve algebra as used in CAD software as well as on dedicated relations extracted from hydro- and gasdynamic flow model solutions. Flexible geometry generation is of paramount importance for parametric studies, optimization and adaptronics.

"Fastprocessing" is the collection of rapid operational fluid dynamic flow analysis codes with a known range of trustability, to be applied for predesign case analysis. Potential flow, Euler and boundary layer concept, hypersonic tangent wedge/cone and shock expansion theories provide these tools. We and others have added to their continuing usefulness be converting them to inverse design software. Applying new tools of information and software technology have led to very comfortable versions of this software in the form of aerodynamic expert systems, e.g. (Zores 1995). Relatively reliable 3D viscous flow CFD is applied, too, though it still cannot be called 'fast'. But driven by computer and software development, eventually fast N/S codes will be available for the toolbox of the designer even in the predesign phase.

"Postprocessing" enables us to see the products of geometric and numerical modelling and compare them with experimental results. At DLR, a software system (HIGH-END) to fulfill these requirements was developed for numerically generated flow field data. The features of this system include grid and surface rendering, color isofringes for scalar field visualization, and streamlines. Gradient evaluation along streamlines allows for finding shock waves and imaging them as surfaces in the flow field (Pagendarm et al. 1995). More recently, with special emphasis to design applications, the construction of Mach waves (characteristics) from given 3D flow field data has been added to this graphics software. In the following some examples of this design support are presented, applied to some newly developed or re-considered aerospace design concepts.

Stressing the use of visualization software for examples mentioned in this paper complements a lecture series compilation of high speed transport technologies by researchers in the academic and industrial environment edited by the first author (Sobieczky (ed) 1997).

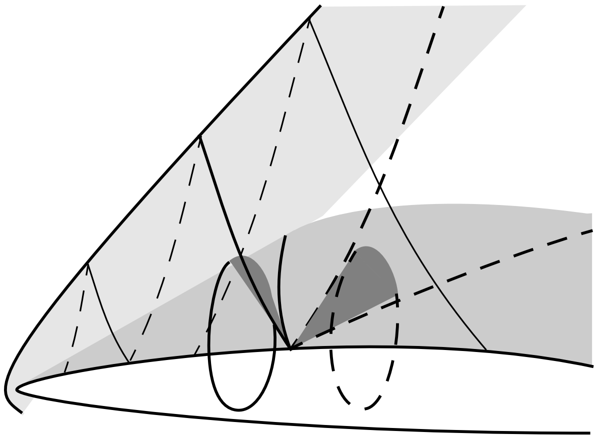

Figure 1. Flow element with surfaces for boundary, shock and Mach waves. 2D characteristics or 3D Mach conoids define regions of influence and dependence in supersonic flow

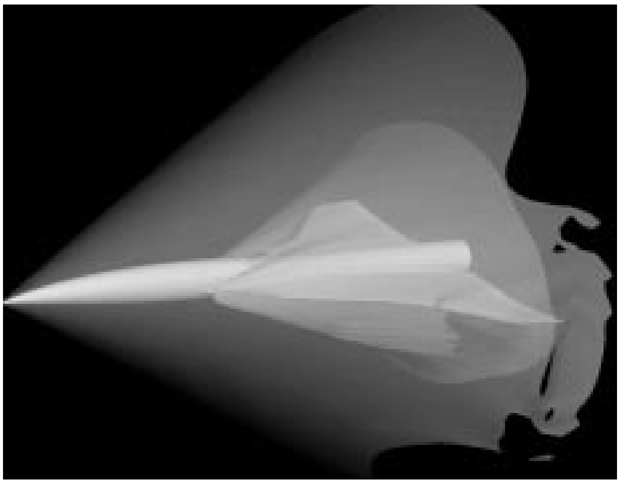

Figure 3. Shock system emanating from a wing - body configuration in supersonic flow Mach = 2.4. Visualization of CFD Euler result with cut off shock surface at defined shock strength threshold

Shocks and characteristics

The help of an efficient visualization tool is welcome especially for aerodynamic design concepts which are based on using flow phenomena like shocks and Mach waves situated within the flow field and their size and position relative to the physical boundaries as well as their strength (in the case of shock waves) influencing the control of input parameters for the configuration boundary conditions, (Fig 1). Some examples will illustrate the importance of including shock and characteristic surfaces in design process-related visualization :

Transonic flow

Transonic flows are defined by the occurrence of both subsonic and supersonic flow patterns, connected along the sonic surface with locally M = 1. We have developed a computational design method which prescribes a smooth (shock-free) connection as a geometry input and finds the contour which is compatible with enforced shock-free flow. Such indirect problem solutions are based on the hodograph formulation of the basic equations, which led to a construction of shock-free 2D airfoils 25 years ago. The concept since then has been a rational background for several CFD - supported inverse or semi-inverse design methods for 2D and for 3D flows, see (Sobieczky 1997a). The graphic display of the supersonic domain with the sonic surface or 2D characteristics patterns has become a valuable addition to results presentation for the designer to estimate practical use of transonic configurations (Fig. 2).

Supersonic flow

For increased Mach numbers the concept of supersonic civil transport (SCT) is subject to renewed interest in research and development. Computational case studies for complete aircraft invite to perform refined analysis of the flow quality, like the complex shock system generated by the various configuration components: Fig. 3 shows the graphic display of shock waves emanating from the tip cone and at the wing roots, suitably cut off where a given lower threshold value of shock strength is met. More detailed studies show the efficiency of wing kinks separating the portions of subsonic and supersonic leading edges. The latter occur in the waverider concept mentioned next for hypersonic applications, while subsonic leading edges are associated with the low supersonic range of flight Mach numbers, as shown for a novel design concept reported further below.

Hypersonic flow

As mentioned above for transonic flow, the aim of inverse design concepts is the finding of shapes which are compatible with certain details of the flow prescribed as design input. Using 2D characteristics in selected planes of 3D space allows for extending plane flow design concepts to the third dimension. This technique is especially successful in high Mach number supersonic flow for the flow sector between an oblique bow shock and the wedge-type surface generating it: shock relations and locally conical flow properties have led to an efficient extension of the classical waverider principle which draws its results from (known) plane wedge or axisymmetric conical flow (Sobieczky 1997b).

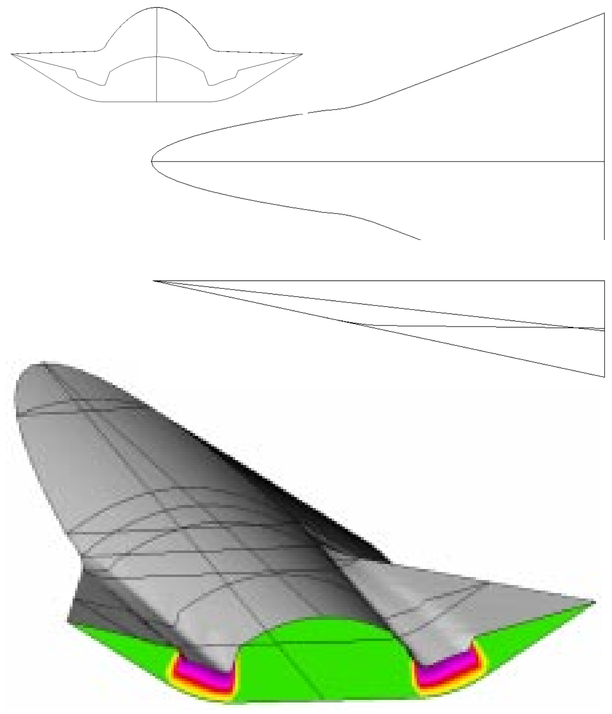

Figure 4. Waverider forebody inverse design from a given shock wave, $M_\infty = 8$. Pressure isofringes in inlet plane

Again, visualization has become an extremely helpful tool for applied as well as for educational purposes to disseminate the idea for other developers' fruitful modifications. Fig. 4 illustrates an example: Given a 3D shock wave geometry in free stream flow and hence post-shock conditions, a surface of initial conditions is given and with an inverse marching technique based on or directly employing the 2D method of characteristics, the generating 3D ramp surface can be found. Various applications using the concept are operational and rapid visualization of results helps to adapt parameters to the requirements of integrating the resulting shape to a given hypersonic inlet configuration. New geometry functions are found this way to add to the flexibility in direct shape definition (Sobieczky 1997c).

Applications to a novel design concept

New and unusual configurations for future aerospace applications are being studied by research organizations and in industry. Radical changes pose problems and many of such ideas do not make it beyond early conceptual studies.

New phenomena do not only occur in aerodynamics, new ways of presenting results are needed for a better understanding of unusual results. The concept of an Oblique Flying Wing (OFW) supersonic transport aircraft (Fig. 5) shows some attractive advantages over conventional SCT aircraft so that a continuing exploration of its potential seems justified (Van der Velden 1997, Seebass 1997). For our work it is a good example of requiring visualization to better understand the role of geometry parameters in the aerodynamic design and optimization process.

In the course of increasing the ratio lift over drag (L/D) for an example OFW we apply wellknown aerodynamic theories first, like ensuring an elliptic lift distribution and minimum drag volume distribution (Sears-Haack body) along the spanwise direction. Geometry preprocessing is tuned to identify the parameters for each of these global goals. Drag for given lift, among other components, consists of wave drag which is produced primarily in the bow and tail shock system of the configuration. Because of the completely unsymmetrical shape of an OFW relative to its flight direction we are interested in the shock system of the flow around the OFW. This is of course a task for applying our visualization tools to the results of numerical simulation, the following illustrations are the postprocessing of CFD results of a collaborative design work for the OFW (Seebass 1997) and aeroacoustic analysis of the concept (Li et al. 1995).

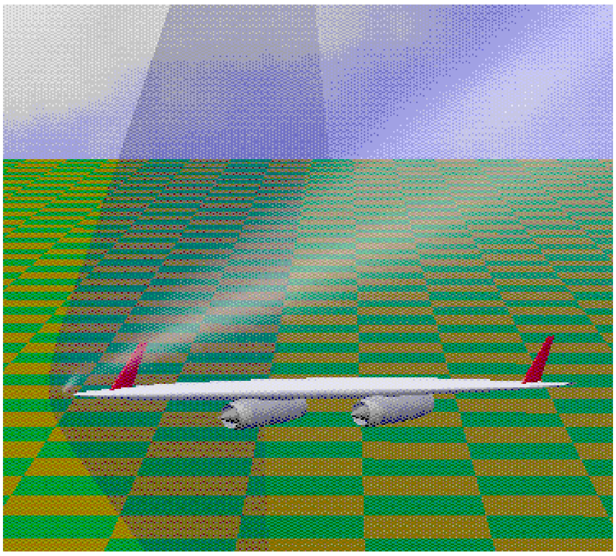

Figure 5. Oblique Flying Wing supersonic transport

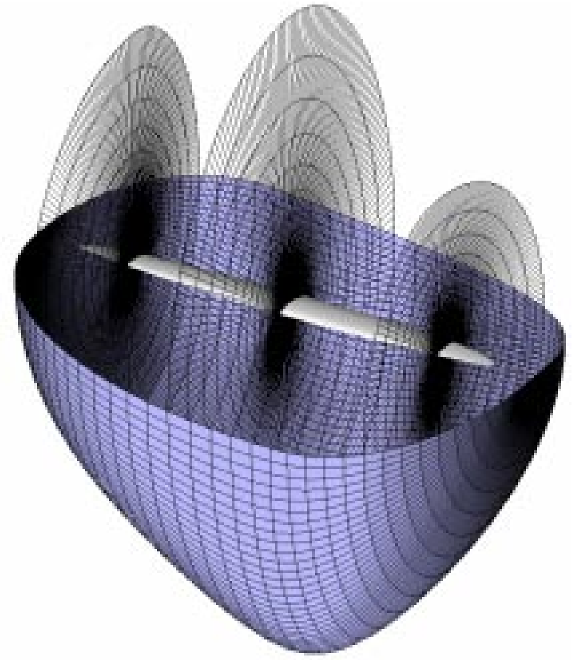

Figure 6. Computational grid around an OFW, for a sweep angle $\lambda = 60^o$ and $M_\infty = 1.4$

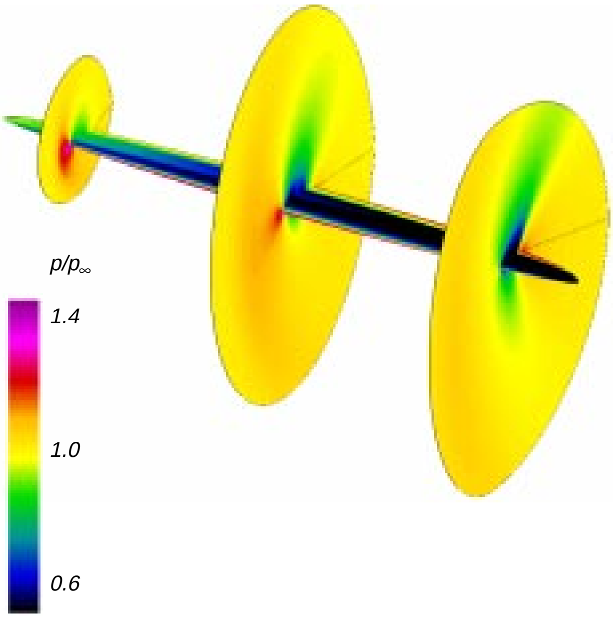

Figure 7. Pressure isofringes on wing and grid section planes: solution to the Euler equations

Computational grids in supersonic flow are determined by regions of dependence, influence and continuation. A smaller far field O-O grid (Fig. 6) replaced an earlier used C-O grid with a wake surface boundary for numerical simulations, its shape determined by the Mach fore- and aft-cones for the design Mach number and including the wing shape. A flexible selection of grid and solid surfaces with high resolution shading and scalar visualization color graphics are the standard postprocessing for numerical results. Beyond these basic options, occurring shocks need to be visualized. Sectional cuts with isofringe graphics for the pressure distribution give only a blurred impression of the shocks structure (Fig. 7). We are interested in detailed structures of the bow wave emanating from the leading tip of the wing and of the tail wave the shape of which close to the wing trailing edge and tip is not easily predictable.

Results for the front (bow) wave are depicted in Fig. 8a and may be compared with aeroacoustic analytical results Fig. 8b. Comparative visualization of different CFD results, as well as for slightly varying configurations and for results of CFD vs. experiment, are very useful options in postprocessing (Trapp et al. 1996).

For the tail shock the numerical results show interesting details of waves coalescencing partly off and partly on the wing surface (Fig. 9). The latter formation is manifest in surface section pressures with recompression shocks and is unwelcome because of the resulting shock-boundary layer interaction. Our first attempts to avoid these cross

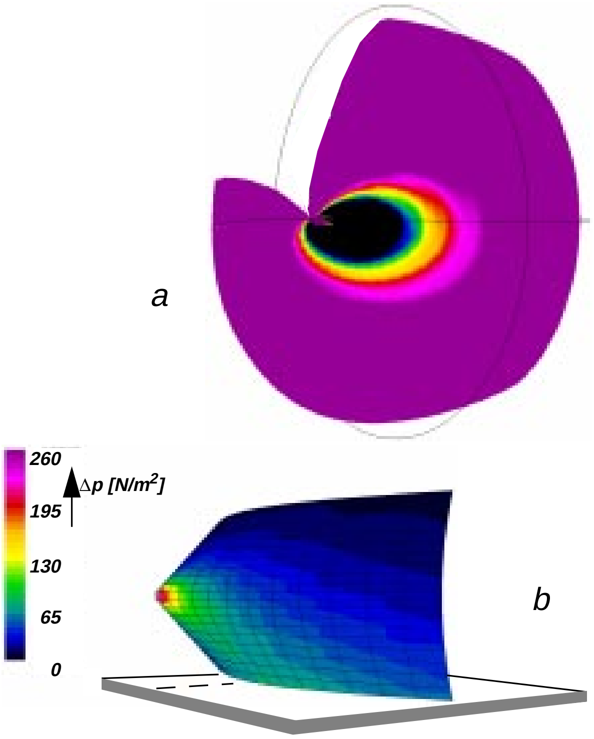

Figure 8. Shock strength isofringes mapped onto shock surface: (a) View in flow direction at the bow wave, Lower threshold cut-out indicates weaker shock in upper quarter of bow wave sector opposite to wing sweep direction, (b) Visualizing analytical result for sonic boom extending to the ground (wing span 145m, flight altitude 12.8 km)

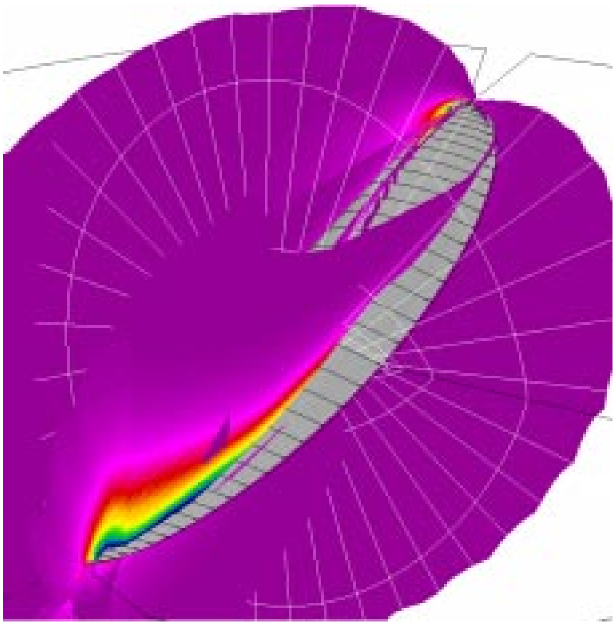

Figure 9. View from behind and above the wing against the flow direction: bow wave with threshold cut-out and element of tail wave emanating from wing as upper surface cross flow shock. Coarse center plane grid is added

flow shocks employed the shock-free airfoil design technique for an infinite swept wing with a normal component subsonic Mach number as shown in Fig. 2. But with the problem having a completely 3D nature also for the large aspect ratio of this OFW this gives only a slight improvement near the center plane area. More recently we have learned from visualized surface characteristics (Fig. 10) to apply a geometrical build-up of the wing cross sections, their spanwise twist and dihedral, starting from the leading tip and progressing toward the trailing tip, including an increased sweep angle of the planform near the trailing tip. The constraints of elliptical load and spanwise area distribution prescribed by the Sears-Haack body are simultaneously met. The geometry preprocessor with its flexible parameter control is well suited for such optimization performed manually at first, so far we have gained up to 50% in L/D improvements over the starting configuration using swept wing theory (Li et al. 1998) and hope to continue this work in an automated loop with a suitable optimizer and accompanied by a detailed viscous flow analysis.

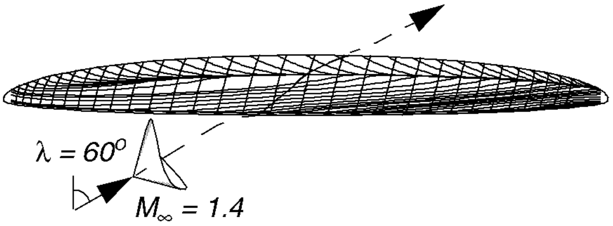

Figure 10. Wing upper surface in inviscid supersonic flow. Surface Mach waves indicate the formation of crossflow shock.

Conclusions

A selection of examples is presented to stress the importance of visualization tools for creative aerospace design in the high speed regime where shock waves predominantly determine the flow structure and hence aerodynamic performance. Inverse design concepts use shock waves as input to find configuration shapes, characteristics patterns are used as design grids as well as indicators for shock coalescence in analysis postprocessing. The value of an advanced visualization tool is illustrated for the novel supersonic transport concept of the oblique flying wing: Deeper understanding of the occurring shock structures is gained, it results in a refined shaping of this configuration and contributes to a critical evaluation of this concept before a new supersonic transport is going to be developed.

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