Reprint

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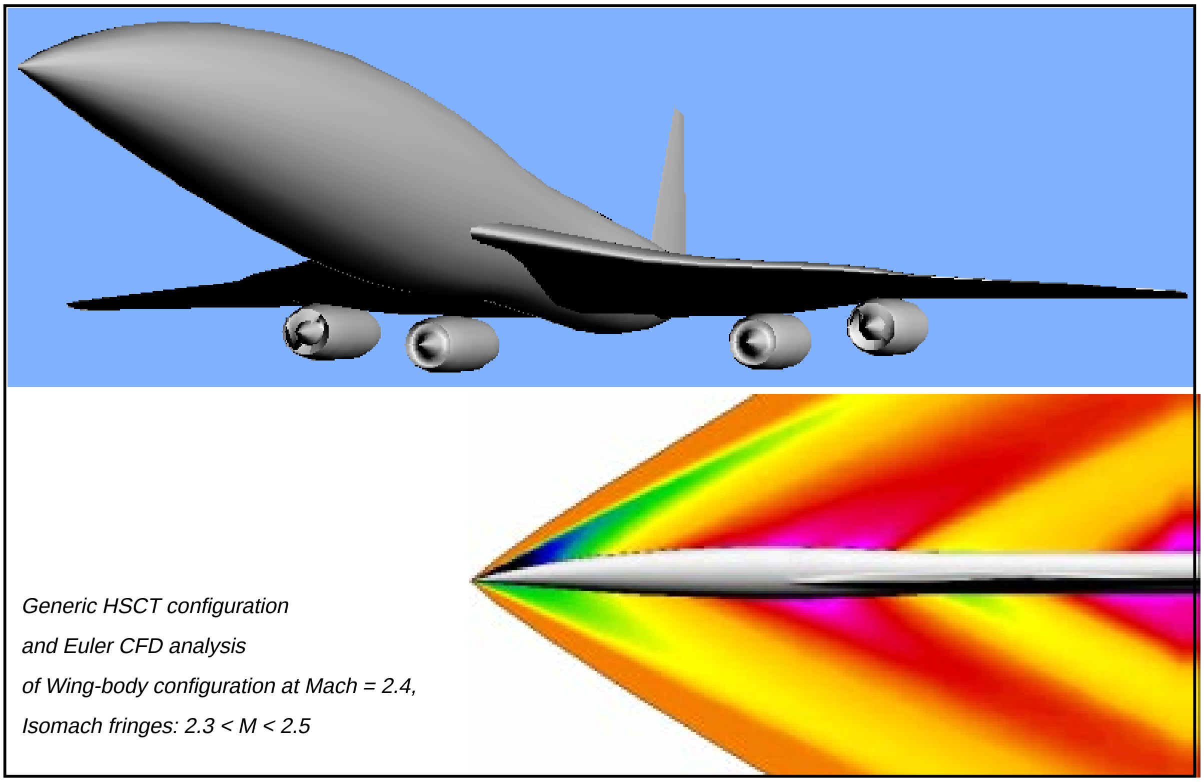
Parameterized Supersonic Transport Configurations



Generic HSCT configuration
and Euler CFD analysis
of Wing-body configuration at Mach = 2.4,
Isomach fringes: 2.3 < M < 2.5

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PARAMETERIZED SUPERSONIC TRANSPORT CONFIGURATIONS

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Abstract:

Design tools for high speed design aerodynamics are developed using a set of mathematical functions to create curves and surfaces in 3D space, steady or moving for unsteady phenomena, adaptation and optimization. Added is the knowledge base of designing supersonic waveriders by inverse methods. Coupled with fast grid generation, preliminary design variations are studied by an Euler CFD method and analyzed with a powerful interactive visualization tool. The geometry generator is a preprocessor for new developments in CAD methods.

Introduction

Renewed interest in Supersonic Civil Transport (SCT) or High Speed Civil Transport (HSCT) calls for extensive computational simulation of nearly every aspect of design and development of the whole system. CAD methods are available presently for many applications in the design phase. Nevertheless, work in early aerodynamic design lacks computational tools which enable the engineer to perform quick comparative calculations with gradually varying configurations or their components. To perform aerodynamic optimization, surface modelling is needed which allows parametric variations of wing sections, planforms, leading and trailing edges, camber, twist and control surfaces, to mention only the wing. The same is true for fuselage, empennage, engine and integration of these components. This can be supported in principle by modern CAD methods, but CFD data preprocessing calls for more directly coupled software which should be handled interactively by the designer observing computational results quickly and thus enabling him to develop his own intuition for the relative importance of the several used and varied shape parameters.

The requirements of transonic aerodynamics of transport aircraft for high subsonic Mach numbers as well as recent activities in generic hypersonics for aerospace plane design concepts have guided our previous activities in the development of dedicated geometry generation [1, 2]. Based on experience with the definition of test cases for transonic aerodynamics [3] and with fast optimization tools for hypersonic configurations [4], as well as taking into account new developments in interactive graphics, some fast and efficient tools for aerodynamic shape design are presently under development. The concept seems well suited for application to various design tasks in high speed aerodynamics and fluid mechanics of SCT aircraft projects.

This paper, after a brief illustration of the basic shape definition concept, shows examples for generic SCT aircraft and its variations for CFD analysis and design modifications. The use of a powerful interactive fluid mechanics visualization software system [5] greatly adds to the efficiency of the proposed shape design method.

Geometry Tools

The geometry tools used here for high speed applications are adapted to contain some of the most important parameters of supersonic configuration design, to be varied in numerical early stage design and optimization studies and finally yield a suitably dense set of data needed as an input for industrial CAD/CAM systems.

Focusing on surfaces of aerodynamically efficient aircraft components, we realize that the goal of surface generation requires much control over contour quality like slopes and curvature, while structural constraints require also corners, flat parts and other compromises against otherwise idealized shapes. When familiarity is gained with a set of simple analytic functions and the possibility is used to occasionally extend the existing collection of 1D functions, ground is laid to compose these functions suitably to yield complex 2D curves and surfaces in 3D space. This way we intend to develop tools to define data of airospace vehicles with a nearly unlimited variety within conventional, new and exotic configurations. A brief illustration of the principle to start with 1D functions, define curves in 2D planes and vary them in 3D space to create surfaces is given:

Function Catalog

A set of functions Y(X) is suitably defined within the interval 0 < X < 1, with end values at X,Y = (0, 0) and (1, 1), see Fig. 1, sketches above. We can imagine a multiplicity of algebraic and other explicit functions Y(X) fulfilling the boundary requirement and, depending on their mathematical structure, allowing for the control of certain properties especially at the interval ends. Four parameters or less were chosen to describe end slopes (a, b) and two additional properties (e_G, f_G) depending on a function identifier G. The squares shown depict some algebraic curves where the additional parameters describe exponents in the local expansion (G=1), zero curvature without (G=2) or with (G=20) straight ends added, polynomials of fifth order (G=6, quintics) and with square root terms (G=7) allowing curvatures being specified at interval ends. Other numbers for G yield splines, simple Bezier parabolas, trigonometric and exponential functions. For some of them e_G and/or f_G do not have to be specified because of simplicity, like G=4 which yields just a straight line. The more recently introduced functions like G=20 give smooth connections as well as the limiting cases of curves with steps and corners. Implementation of these mathematically explicit relations to the computer code allows for using functions plus their first, second and third derivatives. It is obvious that this library of functions is modular and may be extended for special applications, the new functions fit into the system as long as they begin and end at (0,0) and (1,1), a and b describe the slopes and two additional parameters are permitted.

Curves

The next step is the composition of curves by a piecewise scaled use of these functions. Figure 1 illustrates this for an arbitrary set of support points, with slopes prescribed in the supports and curvature or other desired property of each interval determining the choice of function identifiers G. The difference to using spline fits for the given supports is obvious: for the price of having to prescribe the function identifier and up to four parameters for each interval we have a strong control over the curve. The idea is to use this control for a more dedicated prescription of special aerodynamically relevant details of airframe geometry, hoping to minimize the number of optimization parameters as well as focusing on problem areas in CFD flow analysis code development.

Characteristic curves (“keys”) distinguish between a number of needed curves, the example shows two different curves and their support points. Below the graphs a table of input numbers is depicted, illustrating the amount of data required for these curves. Nondimensional function slopes a, b are calculated from input dimensional slopes s_1 and s_2, as well as the additional parameters e_G, f_G are found by suitable transformation of e_1 and f_2.

A variation of only single parameters allows dramatic changes of portions of the curves, observing certain constraints and leaving the rest of the curve unchanged. This is the main objective of this approach, allowing strong control over specific shape variations during optimization and adaptation.

Surfaces

Aerospace applications call for suitable mathematical description of components like wings, fuselages, empennages, pylons and nacelles, to mention just the main parts which will have to be studied by parameter variation. Three-view geometries of wings and bodies are defined by planforms, crown lines and some other basic curves, while sections or cross sections require additional parameters to place surfaces fitting within these planforms and crown lines.

Figure 2 shows a surface element defined by suitable curves (generatrices) in planes of 3D space, it can be seen that the strong control which has been established for curve definition, is maintained here for surface slopes and curvature.

Sections and cross sections

So far the geometry definition tool is quite general and may be used easily for solid modelling of nearly any device if a parametric variation of its shape is intended. In aerodynamic applications we want to make use of knowledge bases from hydrodynamics and gasdynamics, i. e. classical airfoil theory and basic supersonics should determine choice of functions and parameters. In the case of wing design we will need to include airfoil shapes as wing sections, with data resulting from previous research. Such data will be useful if they are either describing the airfoil with many spline supports, or defining the shape by a low number of carefully selected supports, which can be used for spline interpolation in a suitably blown-up scale (Fig. 3a). For such few supports each point takes the role of a parameter, wavy spline interpolation may be avoided. An early version of this geometry tool [1] was used to optimize wing shapes in transonic flow [6] by moving single wing section spline supports. Other local deformations may be the addition of bumps and additional camber functions to given airfoil data, modelling adaptive wing sections (Fig. 3b, c). Finally, completely analytical airfoils seem useful especially for supersonic applications, where sharp leading edges of wedge - type sections are allowing control of shock- and expansion waves but also may have to meet practical constraints like minimum leading edge radii and trailing edge thickness (Fig. 3d).

Wings

Aerodynamic performance of aircraft mainly depends on the quality of its wing, design focuses therefore on optimizing this component. Using the present shape design method, we illustrate the amount of needed “key curves” along wing span which is inevitably needed to describe and vary the wing shape, Fig. 4. The key numbers are just identification names: span of the wing y_o in the wing coordinate system is a function of a first independent variable $0 < p < 1$, the curve $y_o(p)$ is key 20. All following parameters are functions of this wing span: planform and twist axis (keys 21-23), dihedral (24) and actual 3D space span coordinate (25), section twist (26) and a spanwise section thickness distribution function (27). Finally we select a suitably small number of support airfoils to form sections of this wing. Key 28 defines a blending function $0 < r < 1$ which is used to define a mix between the given airfoils, say, at the root, at some main section and at the tip. The graphics in Fig. 4 shows how the role of the main airfoil may be dominating across this swept wing. Practical designs may require a larger number of input airfoils and a careful tailoring of the section twist α_o to arrive at optimum lift distribution, for a given planform.

Because of a completely analytic description of each wing surface point without any interpolation and iteration, other than sectional data arrays may be obtained with the same accuracy describing the exact surface.

Bodies and wing-body connections

Body axis is basically parallel to the x axis in the main flow direction, again some characteristic curves are a function of this independent variable. Here upper and lower crown line, side extent and suitable superelliptic parameters of the cross section are one possibility to shape a fuselage. Other, more complicated bodies are defined by optional other shape definition subprograms. Here we show that it is useful to define the body’s horizontal coordinates because this allows an easy shaping of the wing root toward the body. Fig. 5 shows that this can be applied generally to two components F_1 and F_2 with the condition that for the first component one coordinate (here the spanwise y) needs to be defined by an explicit function $y = F_1(x,z)$, while the other component F_2 may be given as a dataset for a number of surface points. Using a blending function for a portion of the spanwise coordinate, all surface points of F_2 within this spanwise interval may be moved toward the surface F_1 depending on the local value of the blending function. Fig. 5 shows that this way the wing root (F_2) emanates from the body (F_1), wing root fillet geometry can be designed as part of the wing prior to this wrapping process. Several refinements to this simple projection technique have been used successfully.

Waverider wings

Our present gasdynamic knowledge base includes the design of waverider delta wings which exploit known 2D (plane or conical) supersonic flow fields with shocks and expansion waves (Fig. 6), in such a way that non-trivial 3D shapes are found which generate such flow fields. Recently we developed a concept to extend this inverse method to design more general planforms by prescribing a more general shock surface of constant strength, suitably using ‘osculating cone’ flows to determine wing shape and flow parameters between wing and shock wave. Using a graphic workstation, a very fast and flexible optimization method [4] has been developed to arrive at such waverider wings (Fig. 7), the known flow field provides lift over drag as objective function. Using this tool and an Euler code for off design analysis, we investigate the use of waverider configurations in other than the operating conditions they have been designed for, for instance at the Mach numbers where an SCT would operate. It has been shown [7] that aerodynamic performance in off-design conditions is high even for relatively low supersonic Mach numbers despite the waverider having been designed for hypersonic Mach numbers. This makes waverider wings or some elements of such configurations useful for direct shape definition, most of the inverse nature of the design approach can be converted to direct geometry input parameters and this way guides us how wing sections should be shaped for given leading edges as long as they are supersonic leading edges. Integration of subsonic parts of the wing and of course fuselages is most effectively carried out with the present direct approach.

Example: Generic SCT aircraft

Case studies for new generation supersonic transport aircraft have been carried out through the past years in research institutions and the aircraft industry. Our present tool to shape such configurations needs to be tested by trying to model the basic features of various investigated geometries. Knowing that the fine-tuning of aerodynamic performance must be done by careful selection of support airfoils and wing twist distribution, our initial exercise is trying to geometrically model some of the published configurations, generate CFD grids around them and develop optimization strategies to find suitable section and twist distributions. This is still a difficult task but tackling its solution greatly contributes to building up a knowledge base for supersonic design. A case study is illustrated next, the purpose of generating this geometry is the definition of a test case for CFD code development:

Mach 2.4 HSCT

The following figures illustrate generation and preliminary CFD analysis of a configuration generated from a Boeing HSCT design case for Mach 2.4 [8]. Fig. 8 shows a three-view and a shaded graphics visualization. The configuration consists of 6 components plus their symmetric images, engine pylons are not yet included. The wing has a subsonic leading edge in the inner portion and a supersonic leading edge on the outer portion. We try to use a minimum of support airfoils (Fig. 9) to get a reasonable pressure distribution: a rounded leading edge section in most of the inner wing and an almost wedge-sharp section in the outer wing portion define the basic shape of the wing. Wing root fillet blending, the smooth transition between rounded and sharp leading edge and the tip geometry are effectively shaped by the previously illustrated keys 27 and 28, while lift distribution along span is of course controlled by wing twist, key 26.

Fig. 10 shows an extension of the shape generation tool particularly useful for supersonic applications: A computational far field boundary is generated just like a fuselage in cross sections, a computational wake emanates from the wing trailing edge and the whole wing-body configuration is defined here by a cross section surface grid. Boundary conditions are given this way for CFD aerodynamic analysis, but also for aeroacoustic investigations and, with engine exhaust modelling included, for investigating jet contrails. The latter tasks are especially of interest for research on the environmental impact of SCT aircraft.

A first series of design/analysis runs is carried out on the wing-body configuration cut off at the wing trailing edge using a simple algebraic grid with 33 x 81 x 33 meshpoints (Fig. 11) and short runs with the DLR Euler code [9]. Visualization of the pressure distribution with the HIGHEND graphic system [5] shows isobar patterns in color or zebra graphics and selected cross section pressure checks (Figs. 12, 13) allow an assessment of chosen airfoils and twist distributions before refined grids and longer Euler runs are executed. Refining grids near the leading edge is necessary but basic information about needed airfoil changes is already provided by the present runs; the refinement of geometry and CFD analysis may begin.

Visualizing Shock Waves

Visualization of the shock waves system emanating from the body tip and the wing is shown in Fig. 14.
A new visualization technique [10] allows for analyzing shock waves in 3D space: their quality near the aircraft, as shown, or with refined CFD analysis in the farfield to investigate sonic boom propagation. The figure shows a cut-off domain of the shock surfaces: A shock strength threshold allows analysis of local sonic boom quantities. Finally the geometry of the shock isosurfaces was imported into Alias Studio software for final rendering.

Towards an Aerodynamics Workbench

In this paper we have shown some portions of a full design cycle, which involves configuration design, grid generation, computation of a numerical flow field solution and finally the analysis of the solution using modern visualization tools. After we have analysed the solution we can go back and improve the design. This design cycle is still quite tedious, since we have to use several different tools, and can’t interactively switch between them on the fly, since all the tools are standalone. For this particular example the cycle time is about two hours, including a 45 minute wait in the queue to get the solution from a supercomputer. So for the future we are working on an ‘Aerodynamics Workbench’, an interactive tool for graphics workstations which will integrate all of the above mentioned tools in the design process, and make it a lot faster and easier for an aerospace engineer to go through the design cycle. Our goal is to bring the design cycle time down into the range of minutes. This speedup will become even of more significance when we want to optimize configurations by varying parameters in the design and understand its effects in the solutions.

Novel configurations

The already operational and the projected tools stimulate us to study innovative aircraft concepts. The development of conventional configurations like the one modelled above, may still face crucial technology problems resulting in reduced chances to operate economically [11]. An elegant concept avoiding some of these problems is the Oblique Flying Wing for supersonic transport. Its high aerodynamic efficiency calls for ongoing in-depth investigation, continuing the work already done through the past years and more recently [12]. Our tools seem ideally suited to aid such work by parametric shape variation and implementation of inverse design methods based on gasdynamic modelling.

Conclusion

Software for supersonic generic configurations has been developed to support the design requirements in high speed aerodynamics and which should allow extensions for multidisciplinary design considerations. Based on simple, explicit algebra a set of flexible model functions is used for curve and surface design which is tailored to create realistic airplanes or their components with various surface grid metrics. The explicit and non-iterative calculation of surface data sets make this tool extremely rapid and this way suitable for generating series of configurations in optimization cycles. The designer has control over parameter variations and builds up a knowledge base about the role of these parameters for flow quality and aerodynamic performance coefficients. Some basic gasdynamic relations describing supersonic flow phenomena in 2 or 3 dimensions have become guides to select key functions in the shape design; these and other model functions allow for the gradual development of our design experience if the generic configurations are used as boundary conditions for numerical analysis. With a number of efficient tools available now, the combination to an interactive design system for not only aerodynamic but also multidisciplinary optimization seems feasible.

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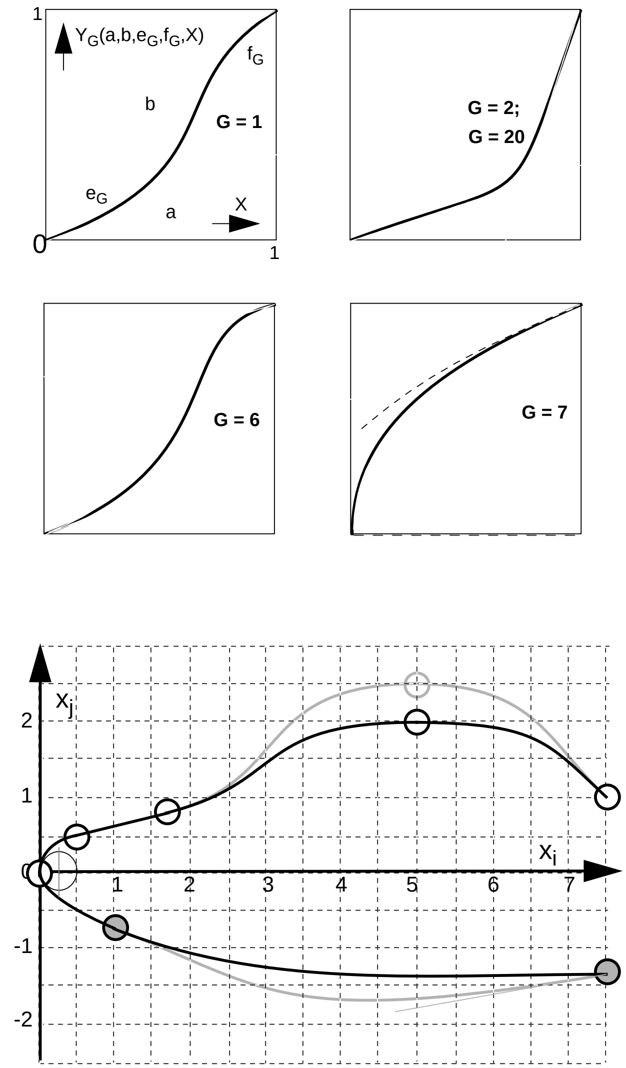

key	u	F(u)	s_1	G	s_2	e_1	f_2
1	0.0	0.0	0.	7	0.25	4.	0.
1	0.5	0.5	0.	4			
1	1.7	0.8	0.25	6	0.	0.	-0.2
1	5.0	2.0	0.	6	-0.8	-0.2	-0.2
1	7.5	1.0					
2	0.0	0.0	0.	7	-0.5	4.	0.
2	1.0	-0.7	-0.5	20	0.	2.	
2	7.5	-1.3					

Fig. 1: Some basic functions Y_G in nondimensional unit interval (above). Construction of arbitrary, dimensional curves in plane (x_i, x_j) by peacewise use of scaled basic functions. Parameter input list (below), example with 2 parameters changed, resulting in dashed curves.

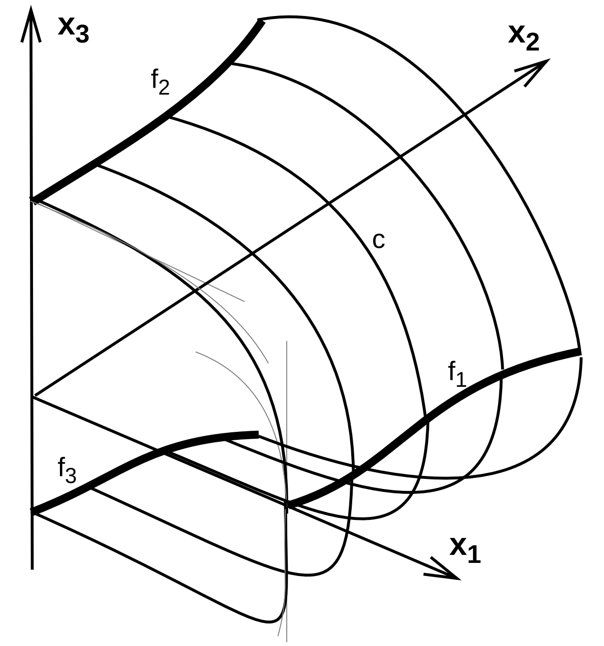

Fig. 2: Surface definition by cross sections c in plane (x_1, x_3) determined by generatrices f_i along x_2 and in planes (x_1, x_2), (x_2, x_3).

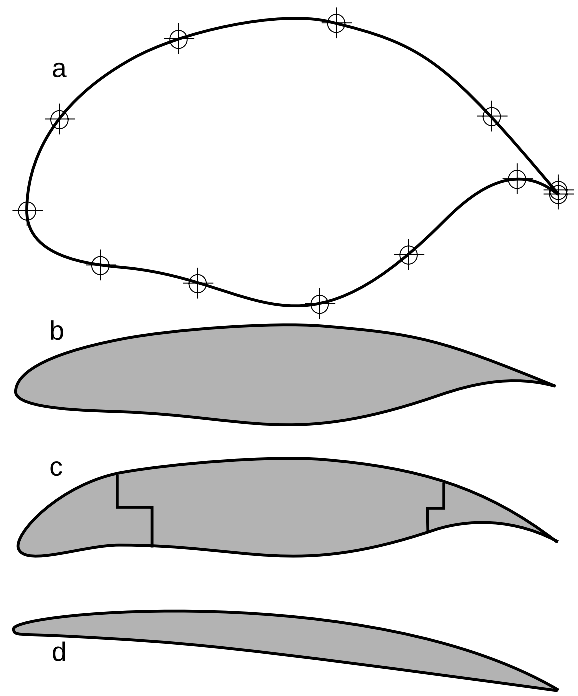

Fig. 3: Airfoils given as datasets either with few supports in blown-up scale (a) or from external database; with additional parameters for local deformation (b $\longrightarrow$ c) and as analytical functions, for standard airfoils or guided by known flow field solutions (d).

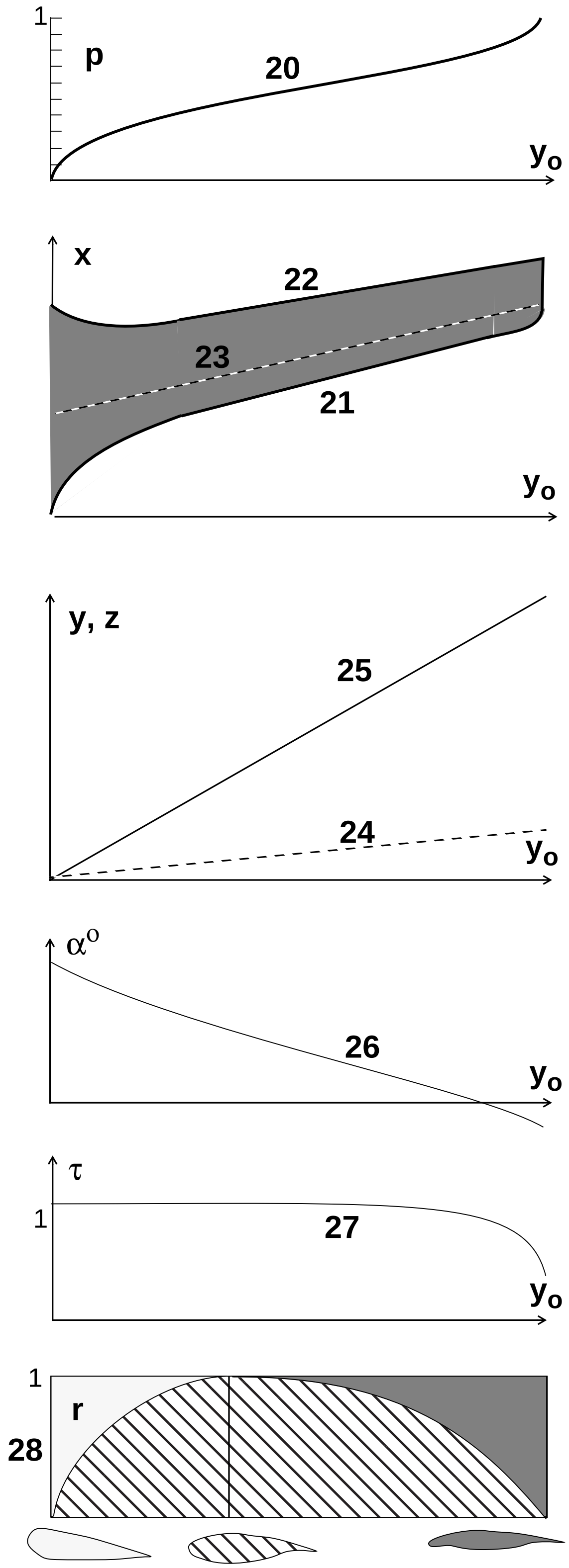

Fig. 4: Wing parameters and respective key numbers for section distribution, planform,an/dihedral, twist, thickness distribution and airfoil blending.

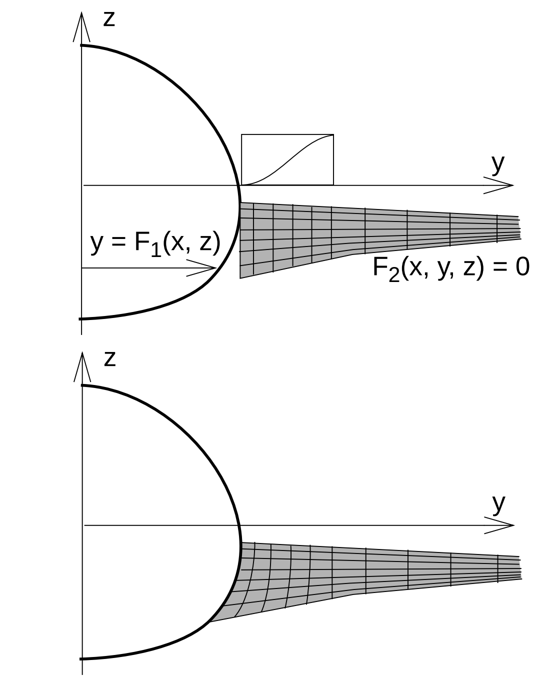

Fig. 5: Kombination of two components by a blended projection technique

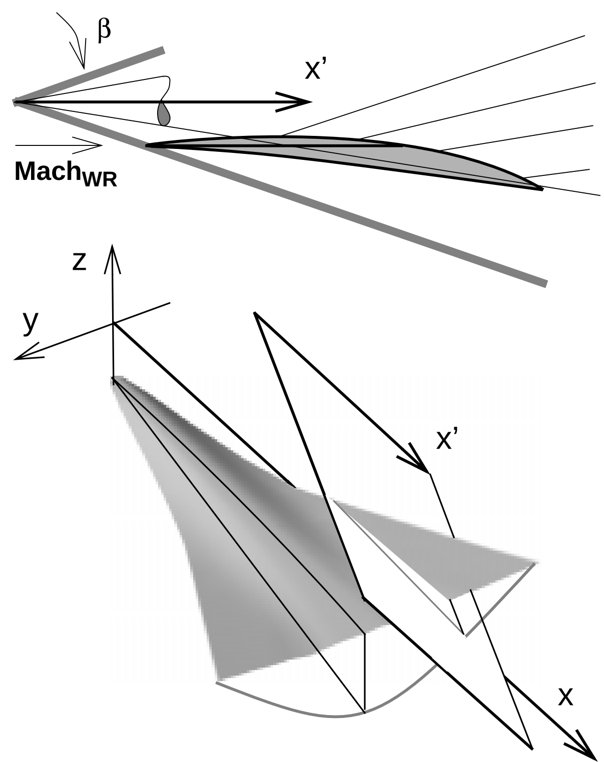

Fig. 6: Exploiting known supersonic flow fields to design wing sections (above) and using osculating cones concept to design waverider wings (below).

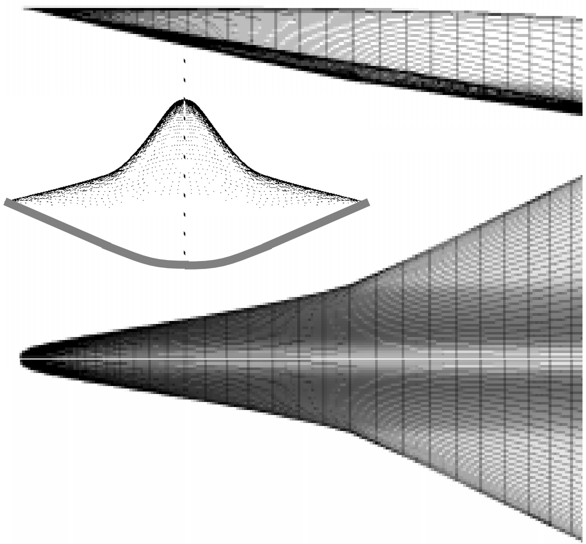

Fig. 7: Waverider wing configuration designed from given leading edge, Mach number and oblique shock wave angle. Supersonic leading edge and a completely integrated body are trademarks of waverider configurations.

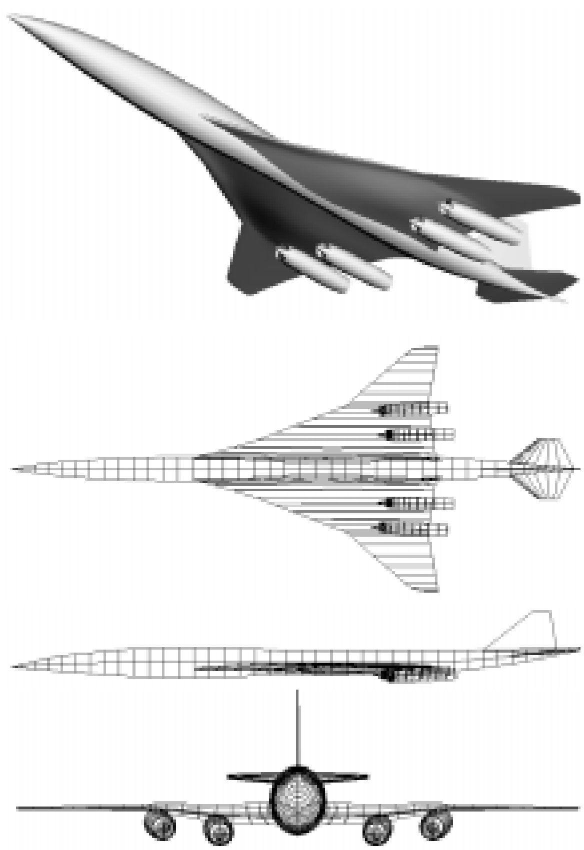

Fig. 8: “Configuration 950” Generic HSCT configu ration derived from Boeing Mach 2.4 test case

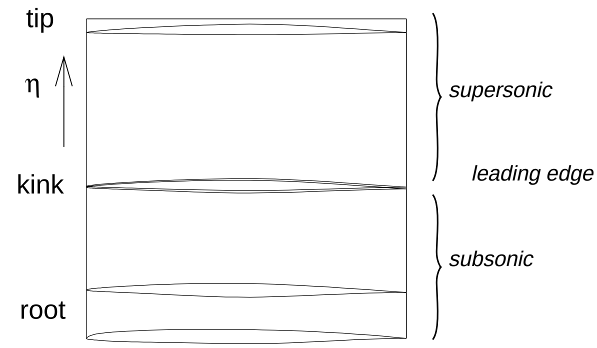

Fig. 9: Airfoil support shapes along span.

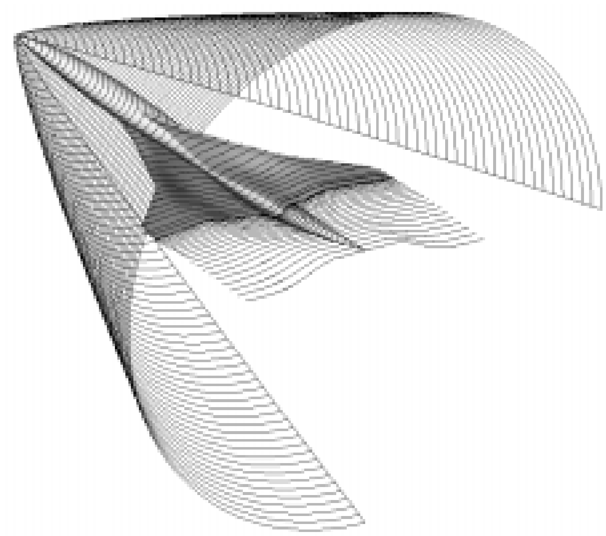

Fig. 10: Cross sections of wing-body, far field boundary and a computational wake model.

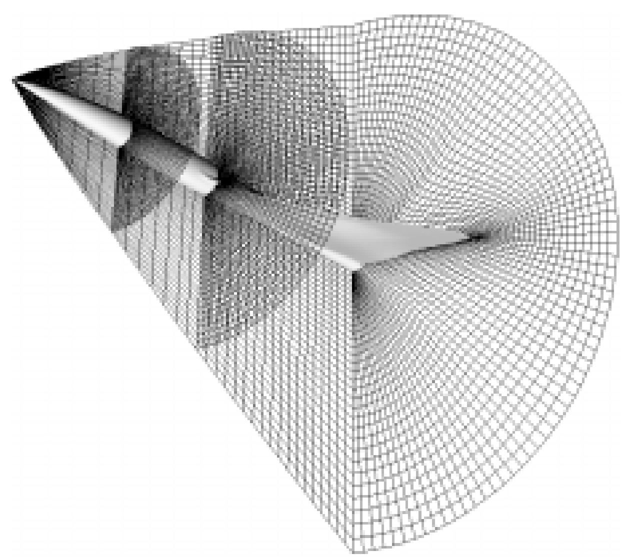

Fig. 11: Algebraic grid (33 x 81 x 33) for preliminary CFD analysis near design conditions.

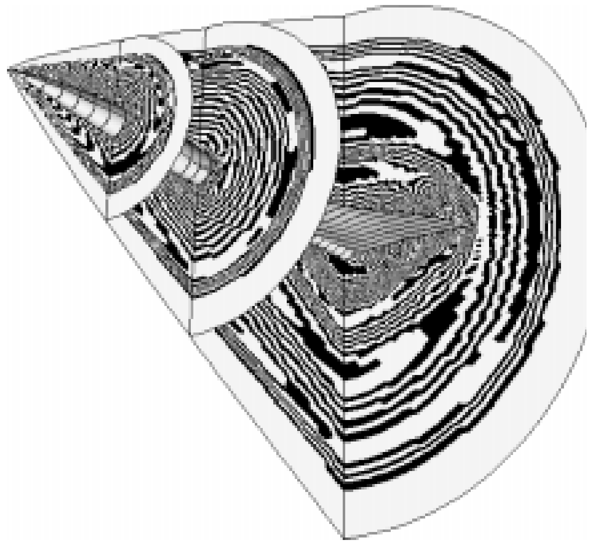

Fig. 12: Euler analysis Mach = 2.4: Isobar fringes

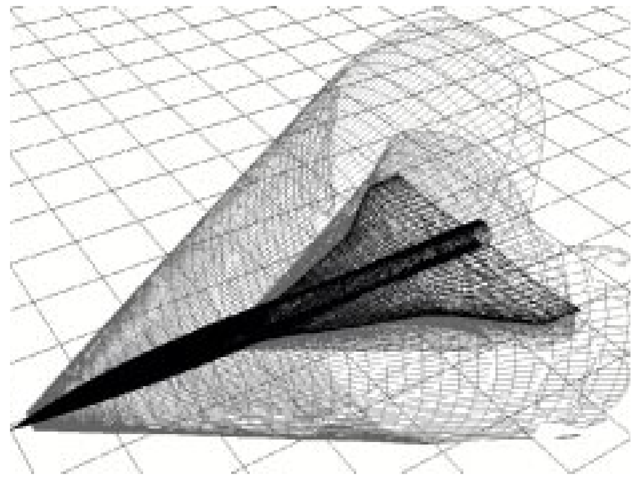

Fig. 14: Visualization of the shock system emanating from body tip and wing.

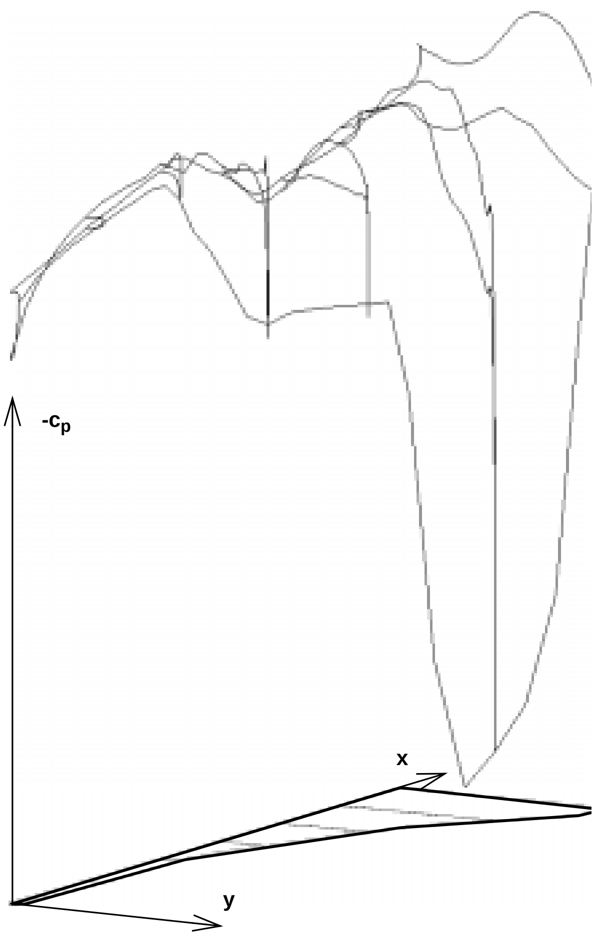

Fig. 13: Quality check of cross section pressure di tributions (33 x 81 x 33 grid, 330 time steps)