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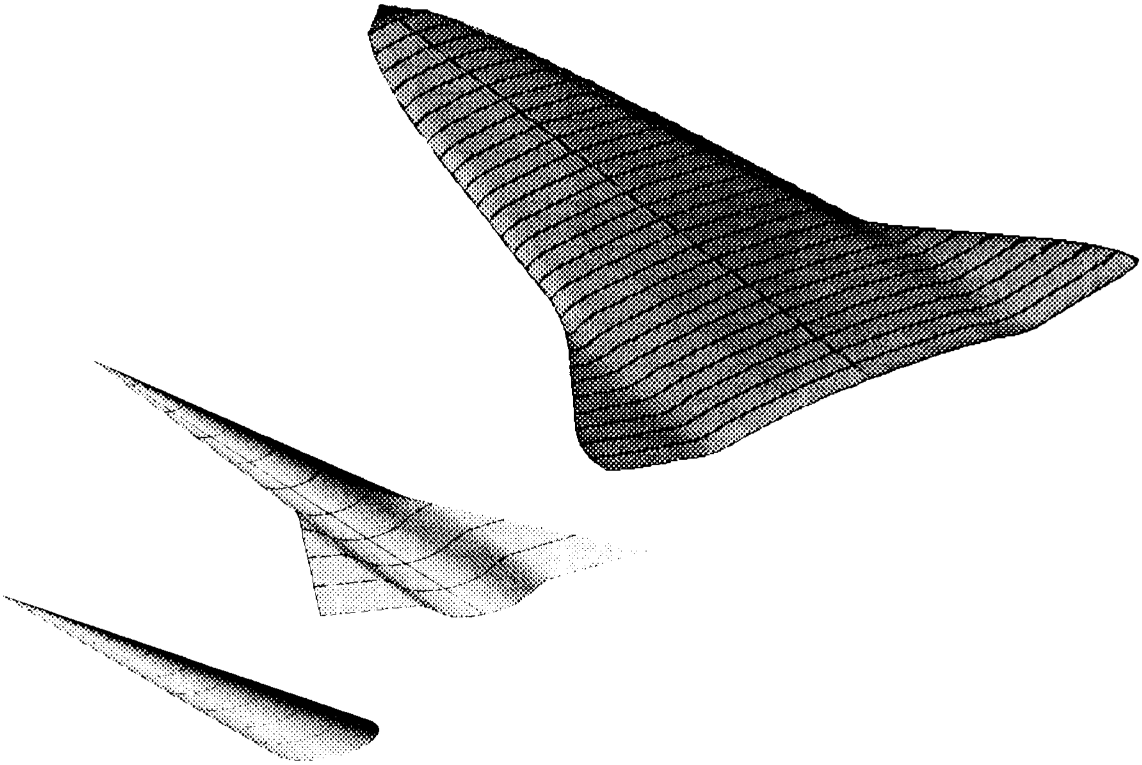
Parameterized Aerospace Vehicles
for
Aerothermodynamic Optimization



A Collaboration between
DLR Göttingen
and
The Pennsylvania State University

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Contents

1. Introduction

This work is aimed at a consolidation of design concepts developed during the past years for hypersonic vehicle design. The first author was trying to develop tools for alternative concepts in shape generation during the years when heavy effort was laid on aerospace configurations like the NASP in the USA and the German Sänger, to mention only the projects which were providing the most stimulation The traditional waverider concept was found to be extendable in a very flexible way [1] which allows its application to quite realistic aerospace vehicle forebodies, while the fast and userfriendly software allows to get good insight into the driving mechanisms for obtaining favorable aerodynamic performance [2].

While learning from this method about the importance of certain shape parameters for forebodies and inlets, some other needs for practical design cannot easily be fulfilled with inverse design. This is, for instance, the modelling of rounded leading edges, the addition of fins and canopy, as well as any other improvement of the volumetric efficiency, which for waveriders as *complete configurations* is not very satisfactory. In another approach, the first author has therefore developed a direct geometry definition program, which can be applied to practically any configuration but, in continuation of the hypersonics design activity, was used for aerospace vehicles like modelling NASP- and Sänger-like configurations [3].

With a flexible geometry tool at hand, a number of possibilities for refined aerodynamic research and development activities could be started, here we see an obvious direction quite clearly for generic hypersonics: Combination of the Geometry generator with optimization strategies might yield shapes similar to waveriders but including the practical requirements missing in the inverse designs. This is the basic idea of the present collaboration, where the second author's activity in optimization [4] and the use of refined aerothermodynamic CFD analysis codes [5] are coupled to become a design and optimization tool for hypersonic vehicles.

Our first case studies are focused in demonstrating the strong control which we have over body or wing shape and it's details which we know are of crucial influence on aerothermodynamic phenomena and consequently on aerodynamic efficiency. A cone is an academic as well as a practical body to start with, here we show the addition of wings, to have a simple parameterized configurations for code validation and optimization strategy development.

The duplication and extension for practical needs of an inversely designed waverider - which is already of more practical interest than the usually investigated conically derived waveriders - is a challenge for the geometry generator. Here we show an example and add details at the leading edge for thickness distribution and camber control suitable for optimization the cooling of this area which is so crucial for the thermal loads.

A final example is aimed at multiple shock waverider configurations, which also is of course beyond the inverse generation method. Beyond the many variations possible to generate multistep diffuser ramps in 2D and 3D, it seems interesting to use such examples for CFD code refinements as they are needed especially for shock - shock interaction.

The status of this work is shown here to be operational for CFD analysis and first optimization cycles. Learning from case studies will result in parameter identification which is most useful for a careful practical hypersonic design in a situation where experimental testing is still unsatisfactory and the development of the original projects has been changed to become long time range technology programs, calling for a consolidation of strategies under reduced funding rather than a rapid and expensive use of immature technology.

2. Inverse waverider design

Inverse waverider design is a school for our development of more direct and straightforward shape definition. The method for this inverse approach termed "Osculating Cones Concept" [1] is based on defining not a solid surface (the vehicle surface) as an input but the bow shock wave resulting from the solid surface. For compatibility reasons this solid surface then has to be calculated along with the flow field between shock and surface, which finally also yields the pressure distribution and hence through integration, the aerodynamic parameters. Ken Center [2] has written his thesis illustrating that this approach allows for the development of rapid interactive design and a "manual" optimization (see Fig. 1) greatly supporting the learning process for defining important shape parameters.

3. Lessons learned from inverse design case studies

A great variety of configurations has been designed with the inverse method. Subsequent CFD analysis with Euler codes show perfect agreement of given shock waves with those found in analysis, which implicitly results in good agreement of lift and drag coefficients in inviscid flow. CFD analysis also allows for off-design analysis which shows a more or less stable nature of the flow with its bow wave attached to the leading edge. Waveriders have supersonic leading edges, a mixed subsonic - supersonic leading edge is not within the range of parameter variations. This is some first question arising with practical applications: How can a waverider-type deltawing be integrated into a subsonic leading edge wing root or body fairing? Another problem is the detailed shaping of rounded leading edges which we know is crucial for the boundary and entropy layers along the body surface. These phenomena so far can be handled only rudimentary by boundary layer methods and interaction models. As more sophisticated analysis algorithms are being developed and available for first application studies, the need for defining shape details in the leading edge area of practically interesting configurations becomes urgent.

Volumetric efficiency of waveriders has long been a weak point of this concept. The new inverse method has expanded the range of practically useful shapes but its possibilities in combining aerodynamic parameters and volumetric considerations in the Objective Function (i. e. a more multidisciplinary design approach) still have to be investigated. Here we would like to provide another, more direct approach by having stronger control over volume and its distribution within the configuration. This reflects the real world important role of structures and payload vs. ideal aerodynamics of a designed shape.

The inverse method provides an approximate theory for upper surface design including convex surfaces resulting in higher volume. A detailed modelling of bump additions to model canopies etc. as well as generation of other components like fins, propulsion components and the large semi-open expansion nozzle is not possible within the waverider concept and consequently not part of the inverse design software.

4. Refining a solid modelling code to the needs of aerothermodynamic optimization

The need to expand the inverse appraoch because of the abovementioned shortcomings was recognized by the first author early during the previous work. A new activity was started to create a direct counterpart to the inverse method. This work is illustrated in a first paper [3]. Fig.2 shows complete generic vehicles derived from the Sänger and NASP configurations. This earlier phase of software development was aimed to show the flexibility of an approach to create a preprocessor for aerodynamics CAD software for multicomponent airplanes, only a few studies in CFD analysis for configuration forebodies were carried out due to lack of appropriate codes for such complicated configurations.

The present collaboration seems ideal to pick up where [3] has stopped, now with the prospect of a combination with various optimization strategies developed at the Pennsylvania State University. Having learned where the most important problems in hypersonic design still wait for solution, this software is in the process of being adapted to some design and optimization case studies which should provide a maximum of insight for the practical designer. The basic approach being the same as in [3], we concentrate at first on single component generation. There is the option to generalize fuselage - type bodies to become lifting components as waveriders may be viewed as lifting fuselages. The second option is a generalization of wing - type components. With a strong knowledge base about 2D and axisymmetric sections of waveriders we choose this second path, thus developing a very flexible wing generator capable to also model strongly integrated fuselages. We stress the importance of being able to generate wings with waverider profiles but also smoothly blending into rounded leading edges and center bodies modelling lifting fuselages.

The new feature developed here is the creation of analytical airfoils rather than the use of given support sections (which are usually provided in subsonic and transonic aerodynamics by an airfoil design group). Learning from waveriders, we are now able to create simple wedge airfoils but also sections approximating conical flow streamlines as they result from the Taylor-Macoll equation which is integrated in the inverse design method. A few additional parameters allow the rounding of these generalized wedges with a strong control of leading edge radius and curvature decrease downstream of the leading edge and the break of surface slope continuity to model multiple shock ramps. Fig. 3 shows some sketches illustrating such sections, their few generating parameters are functions of the spanwise wing coordinate and this way allow for an arbitrary wing profile distribution.

5. A simple test case: A circular cone with growing wings

A conical body with circular cross sections is very likely the starting point for many high speed design studies, for many applications it is the optimal shape because of inexpensive production and well known aerodynamic performance. Our optimization strategy therefore should be demonstrated for some cases starting with a simple cone. Generating such a shape is not difficult, of course, but modifying the cone to become optimal for special nmissions may be a more difficult task. The first example illustrated here is therefore a variation of the cone to become a winged configuration. The generating functions and weigh parameters are defined in such a way that only one "superparameter" may be varied between 0 and 1 to let the cone smoothly grow its wings, with an analytically defined fillet region at the wing root and decreasing leading edge radius. The final configuration is the original 1:10 cone with a 27 deg. leading edge sweep deltawing integrated smoothly to the body and wedge sharp leading edges (Fig. 4)

The practical use of this example is obvious even before we start with defining an Objective Function and subsequently apply CFD in an optimization cycle: Starting from the cone any aerodynamic or structural design modification calling for wing-like additions will try to parameterize the problem. Usually such efforts result in a huge number of parameters and the subsequent optimization needs to be performed in a multidimensional space. Though impressive work has been presented in the past with a nearly unlimited number of parameters, such mathematically sophisticated approaches are seldom showing a potential for practical use by the designer. If used, the designer has no control over the search process and there is usually no guarantee to arrive at the absolute optimum and also result in a practically reasonable shape. We therefore stress the effort performed here to arrive at few parameters to vary a shape, while these few parameters have maximum influence on the performance. Here aerothermodynamics is the issue, and we draw the justification to select only few parameters in shape design from our aerodynamic and thermodynamic knowledge bases, one of them being enriched by the previously developed inverse design concept.

A one-parametric variation from a simple cone to a cone with a deltawing may be unnecessarily simplified, but it serves for CFD code validation and first optimization cycle calculations.

6. Duplicating and extending inverse design cases with direct geometry generator

Wedge type airfoil sections allow for creating any 2D flow-derived waverider and the Taylor - Macoll - type modifications expand this option to include all waveriders derived from conical flow, also those from the Osculating Cones method [1, 2].

A first example (Fig. 5) was defined for the task of analyzing its flow and adjusting its parameters to study changes of its aerodynamic performance. A Mach 8 configuration similar to one of the previously generated waveriders is the starting point, with a few additional important geometric properties which cannot be defined by the waverider design approach:

a) A finite leading edge thickness distribution along span, with l. e. radii given and smoothly blending section curvature into typical waverider-type curved wedge sections. Basic studies of varying l. e. radii may be carried out now by just changing one or two geometry input parameters.

b) Besides varying leading edge curvature, the whole leading edge may be drooped within a defined front portion of the wing. Smooth bending or breaking the section contour with an input parameter angle is a useful option to adjust leading edge flow quality to vehicle angle of attack varied in off design conditions. This option is a numerical simulation of Variable Camber (VC) on a hypersonic vehicle.

c) Additional surface components like a center body similar to the winged cone or canopy modelling and control fins as illustrated in Fig. 3 are readily available for further addition but will be included when the knowledge base for identifying important parameters has progressed by using the optimization strategy. Propulsion integration is a topic of future investigation, when inlet flow quality assessment and expansion nozzle design will be included in a more global optimization process. Figure 5 shows an illustration of the configuration for our first practical design case, with details for arbitrarily chosen leading edge rounding and leading edge camber.

7. Inputs for new CFD methods: Toward 3D unstructured grids

Aerothermodynamics of hypersonic vehicles calls for multidisciplinary optimization more than any other field in aeronautics. This is true already within the aerodynamics of such configurations, where propulsion is totally integrated in the airframe: The whole lower surface may be seen as the propulsive element: waverider forebody, inlet geometry, engine body and exhaust nozzle. Optimizing such an aerospace vehicle consequently calls for including propulsion performance into the Objective Function, through a coupling of external flow results with inlet flow quality, combustion and nozzle flow.

Many detailed studies for improved analysis call for new CFD codes. One topic directly addressing geometry definition is the development of unstructured and adaptive grids. These promise a more economical computation of regions with high gradients of flow properties like across shocks, boundary and entropy layers. The use of unstructured grids and their adaption to flow analysis results (see Fig. 6) calls for techniques to define a (high) number of arbitrary grid points on 3D boundary conditions. This is only possible in an economic way if we have a rapid, explicit 3D generator creating this boundary condition surface. One purpose of the tools developed here is the support of these new CFD methods.

8. Conclusion and Outlook

Geometry generation is carried out for use in design optimization cycles of hypersonic vehicles. So far the computer program is developed to create the whole range from simple test configurations to integrated wing body configurations, where existing inversely designed waverider wings can be duplicated and modified for practical aerospace plane applications. This software needs to be embedded in a global optimization loop using one or more CFD aerothermodynamic analysis codes. Next step and the main goal is a number of case studies and interpretation of the results.

With the possibility to reduce the number of parameter variations in order to change a configuration shape, whole families of shapes may be generated and subjected to aerodynamic, thermodynamic and also structural analysis. For a better understanding of geometry details and their impact on performance in these disciplines, animation through video visualization of the results is planned. The continuation and completion of this project will include such presentations.

4. References

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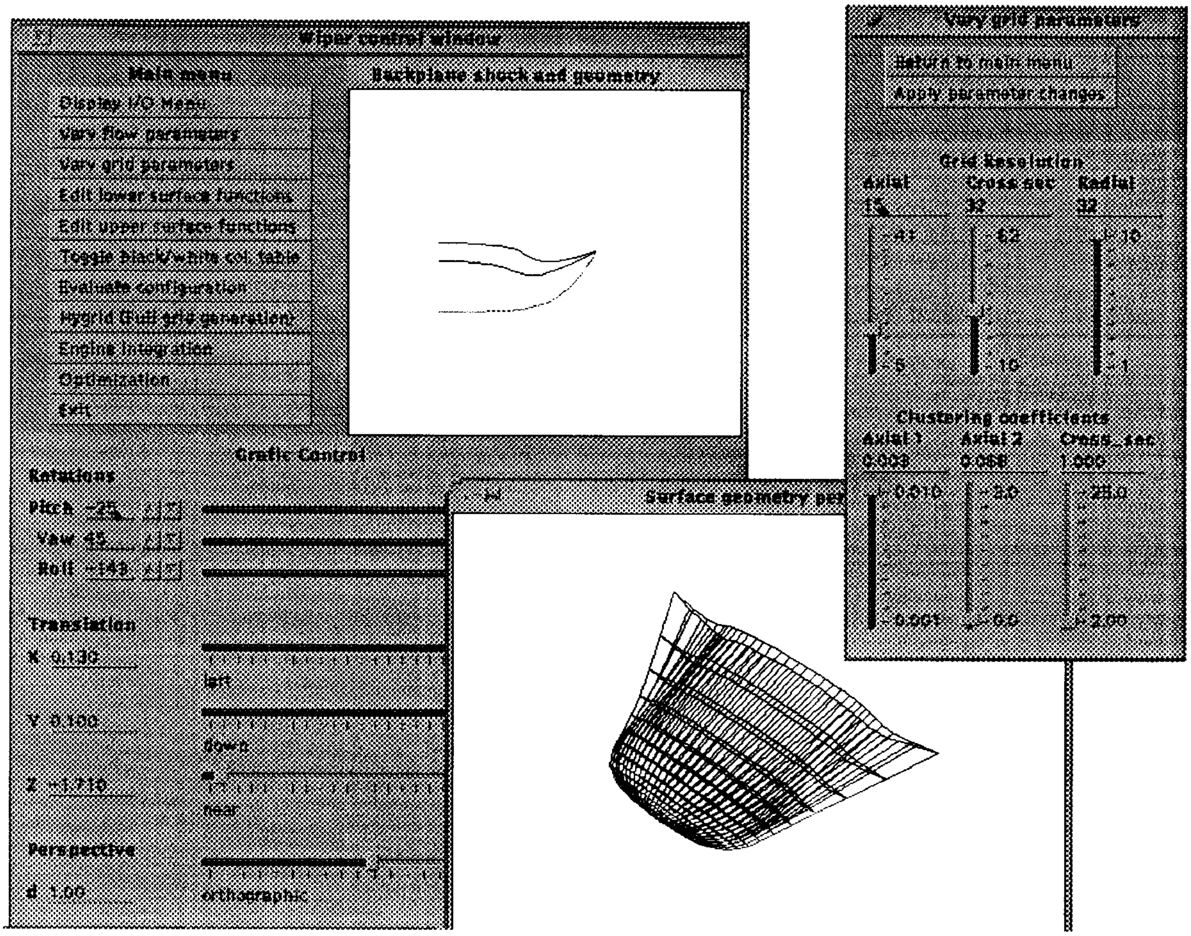


Rotations
Pitch -25
Yaw 45
Roll -143

Translation
X 0.130
Y 0.100
Z -1.710

Perspective
d 1.00

Grid Resolution
Axial 15 (5–41)
Cross sec 32 (10–62)
Radial 32 (1–10)

Clustering coefficients
Axial 1 0.003 (0.001–0.010)
Axial 2 0.068 (0.0–2.0)
Cross_sec 1.000 (2.00–25.0)

Fig. 1:
X - windows environment of WIPAR inverse waverider design code. Shock surfaces given by geometric functions allow basic studies of parameters for direct surface definition and their influence on aerodynamic performance.

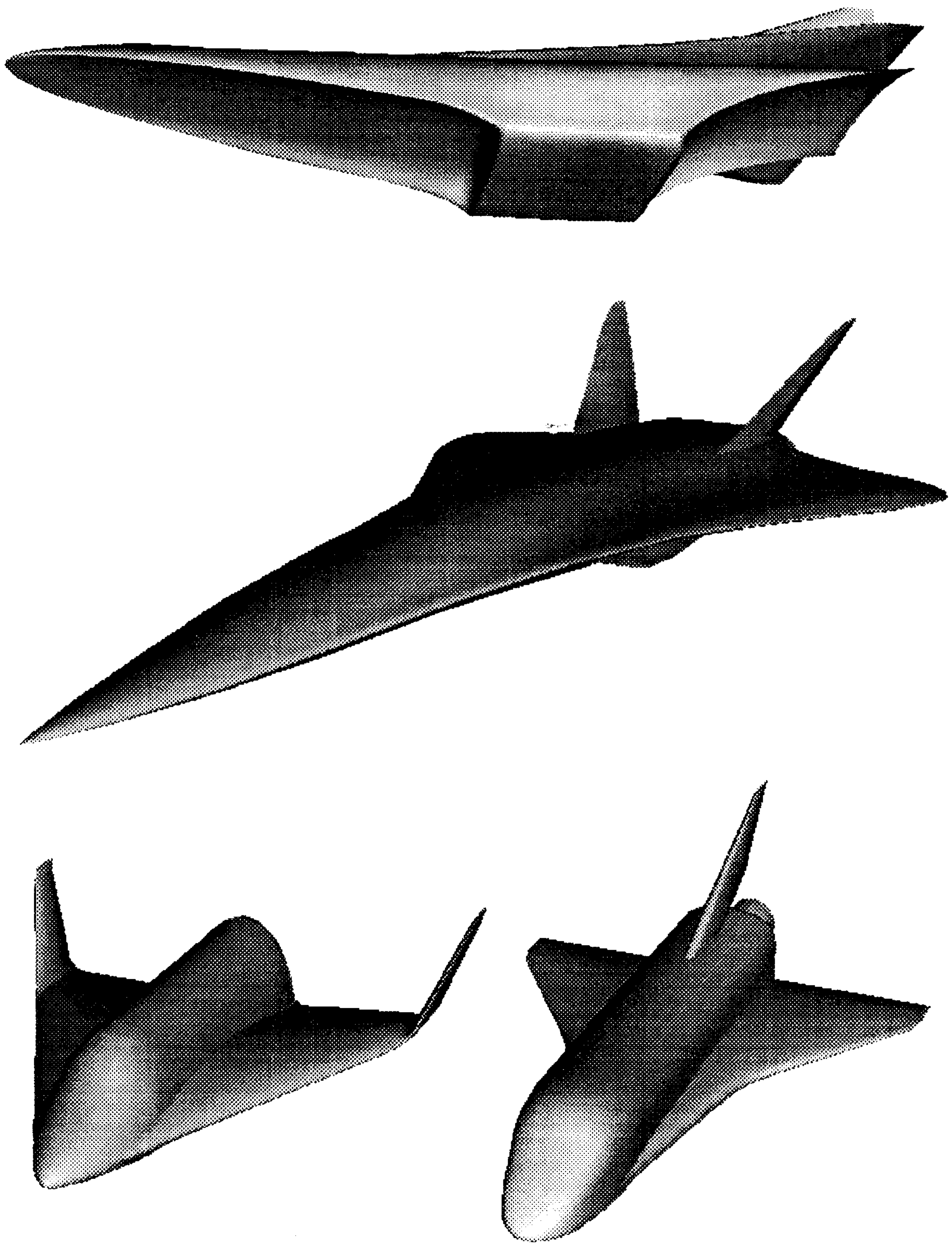


Fig.2:
"Artist's view with a mathematical background":
Generic Aerospace configurations derived from NASP, Sänger, Hermes and Shuttle projects.

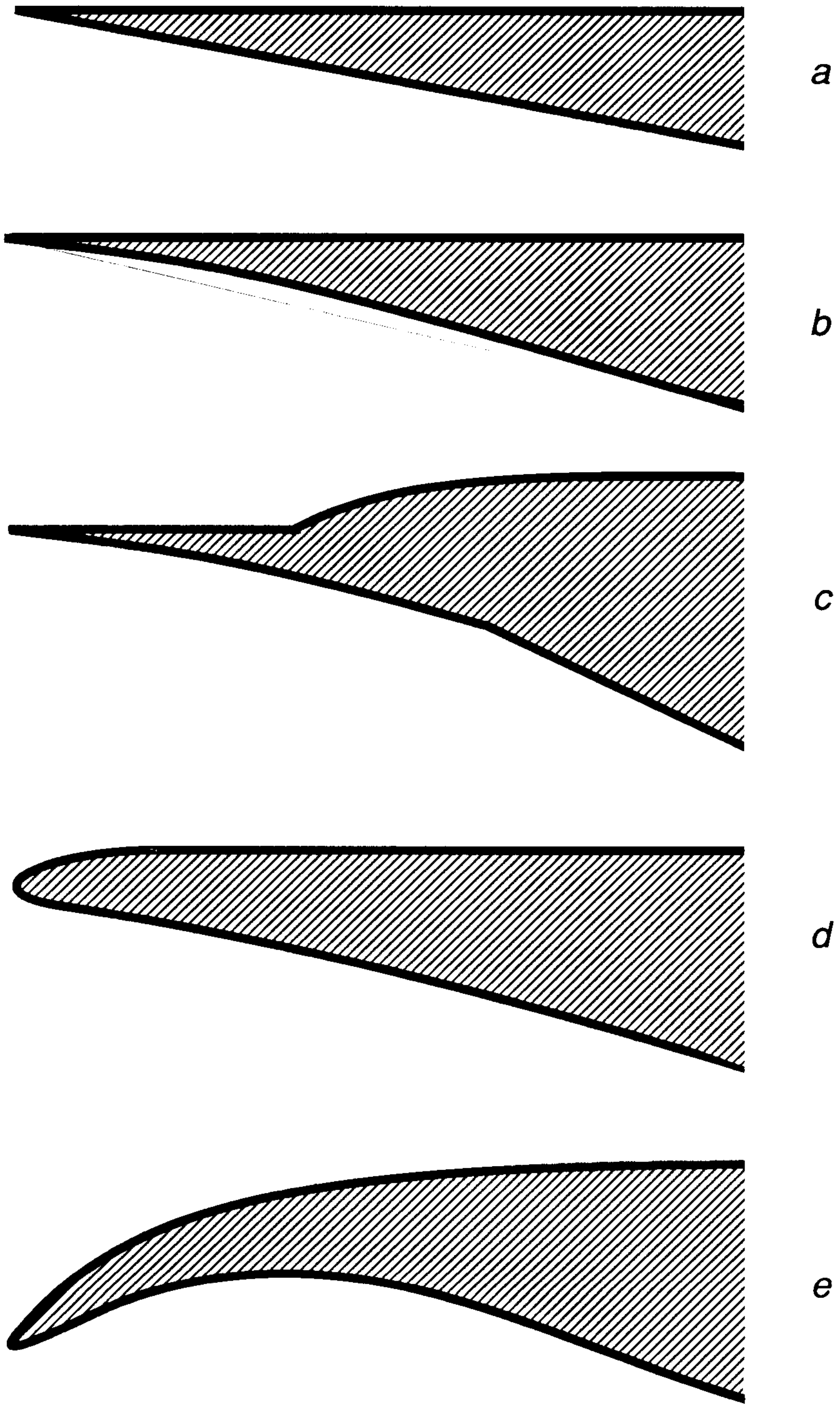


Fig.3:
Analytically defined airfoil sections: simple wedge (a), contour with series expansion of Taylor - Maccoll equation (b), addition of arbitrary ramps and bumps (c), rounded leading edge with curvature control (d), leading (trailing) edge droop (e)

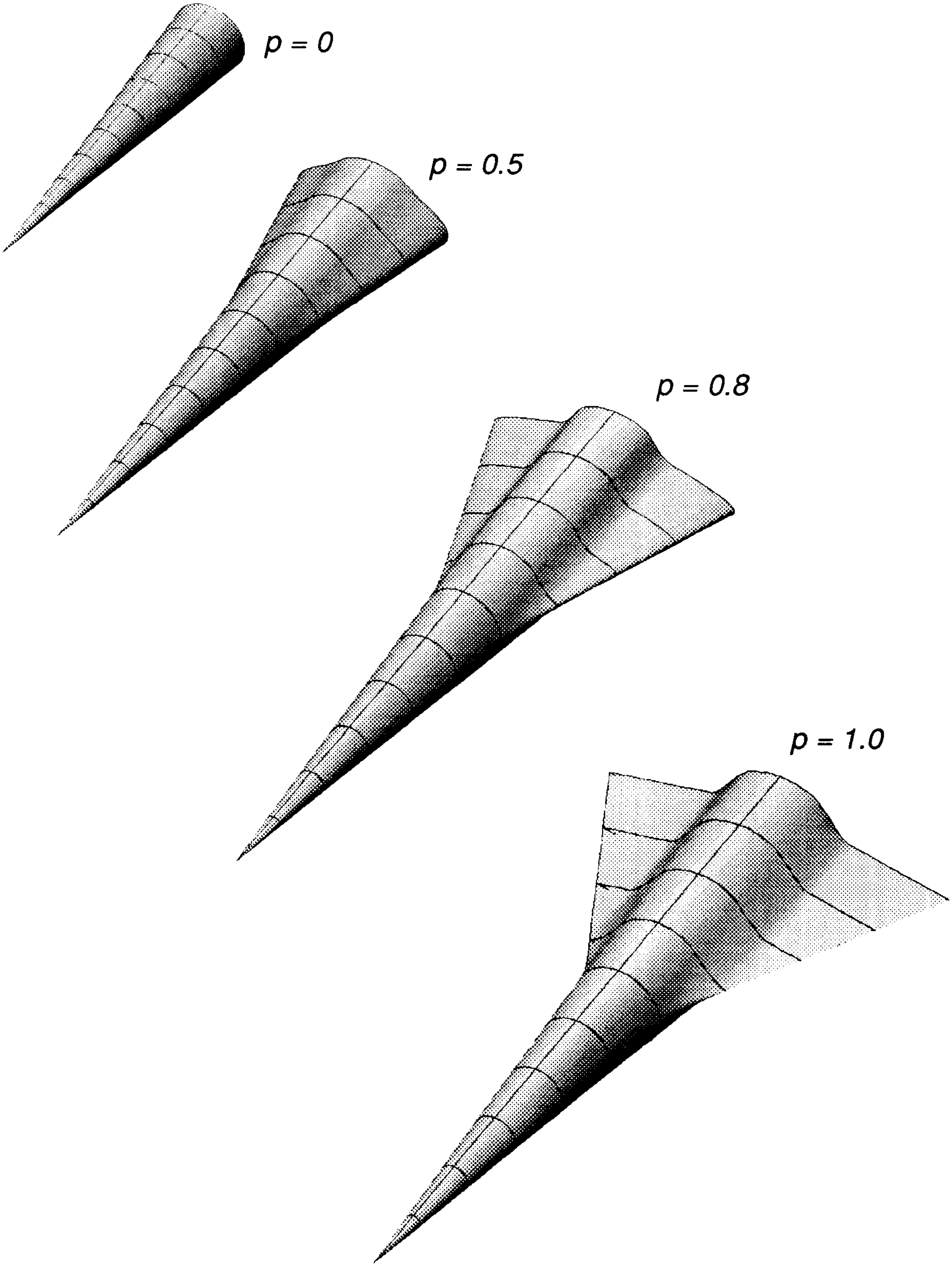
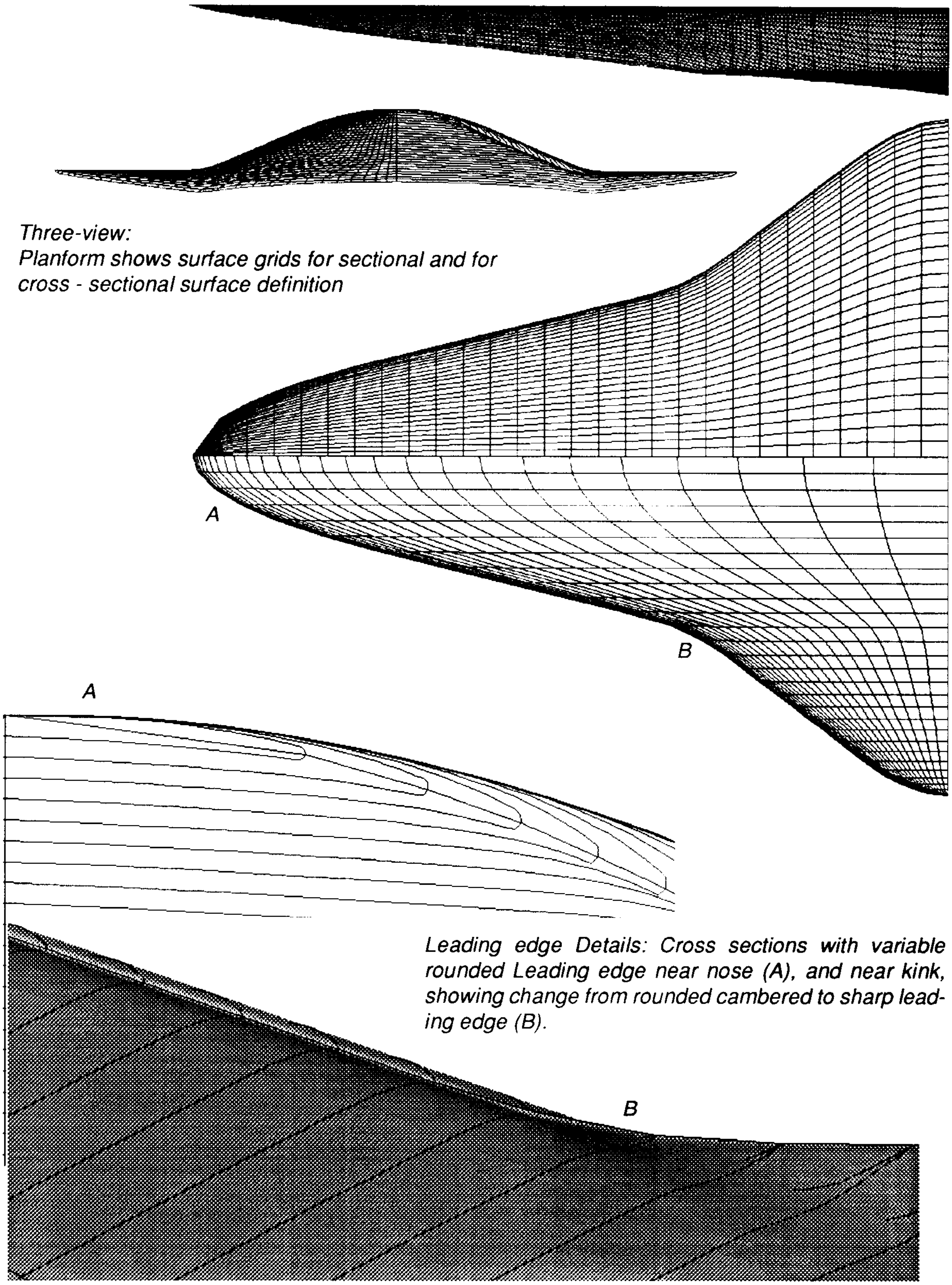


Fig.4:
Generic bodies based on a 10 deg. circular cone. 7 varying geometry input parameters controlled by single 'Superparameter' $0 \leq p \leq 1$.



Three-view:
Planform shows surface grids for sectional and for cross - sectional surface definition

Leading edge Details: Cross sections with variable rounded Leading edge near nose (A), and near kink, showing change from rounded cambered to sharp leading edge (B).

Fig. 5: Generic waverider - derived delta wing for Mach ~ 8. Three-view and details of cross sections near the leading edge. Various surface metrics for different grid metrics.

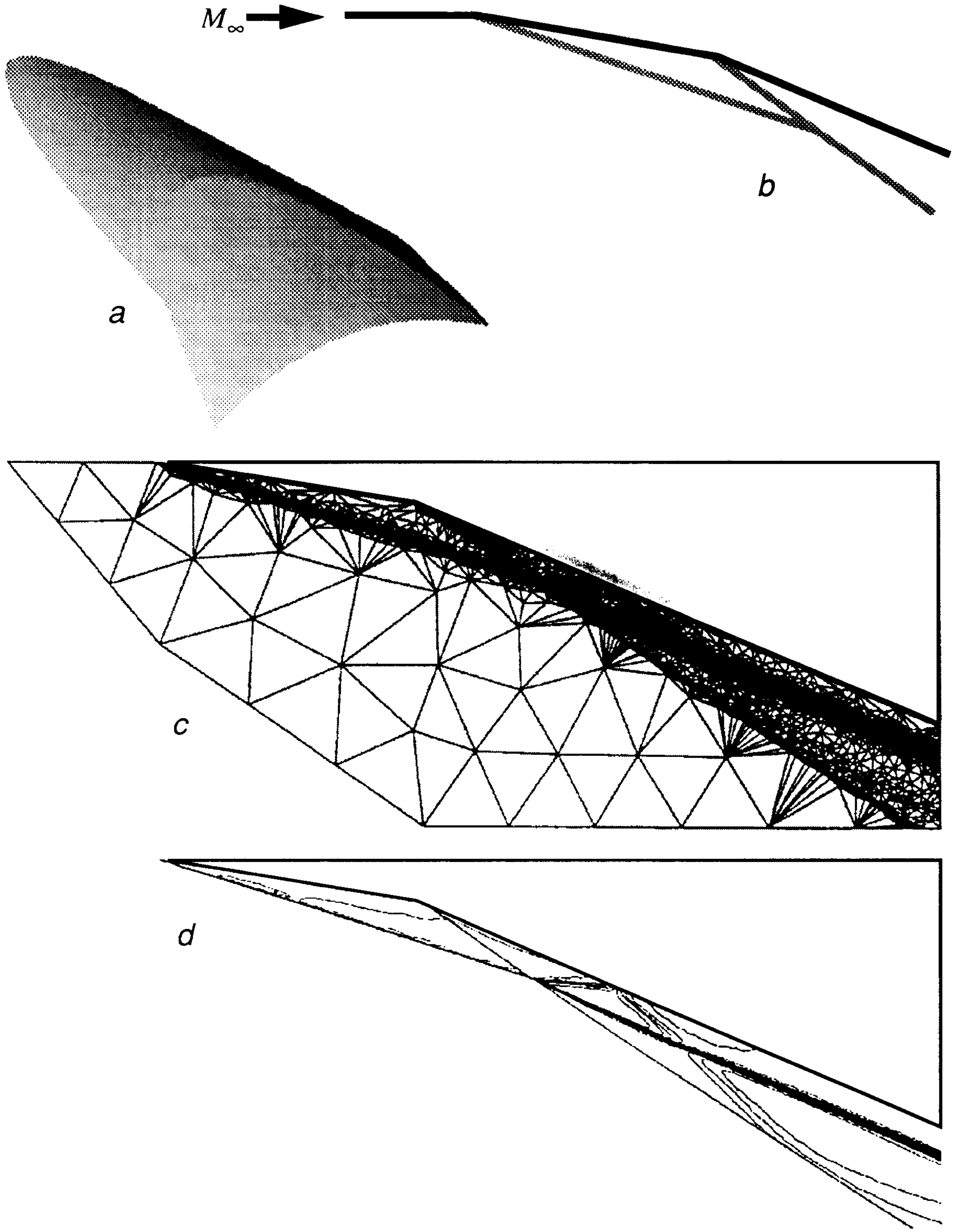


Fig. 6: Waverider (a) based on 2D flow with coalescing shocks, example for $M_\infty = 5.5$ (b). Known flowfield upstream of shock triple point.
Highly accurate 2D inviscid flow simulation results by Beckert with unstructured, adaptive grid Euler solver:
CFD grid after 44000 time steps with 35922 points and 71710 triangles (c);
lines of constant density (d)