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WAVERIDER DESIGN WITH PARAMETRIC FLOW QUALITY CONTROL BY INVERSE METHOD OF CHARACTERISTICS

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ABSTRACT

This contribution reports about a generalization of the successful "Osculating Cones" method for designing waverider forebodies and inlets, to an "Osculating Axisymmetry" (OA) concept for obtaining shapes with higher volumetric efficiency and flow quality control on the inlet plane. The approach is based on an inverse axisymmetric method of characteristics which through the OA concept allows the construction of 3D flows as a solution to the 3D Euler equation within a few seconds on a workstation. Thus we have a useful tool for aerodynamic and multidisciplinary optimization efforts to design high speed configurations. Computational flow analysis examples confirms the inverse approach as illustrated for a number of OC waveriders designed at DLR. The status of applications to full aerospace vehicle integration is shown.

KEYWORDS

Aerodynamic design; Waveriders; Supersonic Flow; Characteristics; Inverse design; Shock waves.

INTRODUCTION

Nearly a decade ago Sobieczky [1] developed a concept for practical methods to compute the flow field behind a given oblique shock wave: cross marching starting from the shock surface with given post-shock flow properties as initial conditions defines a sector of the flow including its boundary compatible with the shock. Jones [2] has obtained 3D waverider forebodies through solving this initial value problem by an inverse numerical marching technique for the 3D Euler equations. A higher order approximative solution to this approach, with the constraint to constant shock strength, exploits a single conical flow solution for the design of waveriders with arbitrary 3D planform, the idea is called "Osculating Cones" concept. This extremely fast method for finding configurations with their surrounding flow field data led to an attractive extension of Bowcutt's [3] code for viscous flow waverider optimization: Center [4] developed a software for rapid intractive computation and optimization of advanced waverider shapes. Various research groups in Germany and in the USA have used this software to design configurations with application to hypersonic transport vehicles and performed numerical and experimental analysis of such waveriders in design and off-design conditions. This has been reviewed in [5] and recently an extension from the "Osculating Cones" (OC) to an "Osculating Axisymmetry" (OA) concept was proposed [6].

Our effort reported in this presentation is aimed at combining the advantage of allowing for an arbitrary strength shock surface realized in [2], with the basically 2D approach of the OC concept which proved so practical for 3D configuration design. The OA concept seems useful for this goal in most practically relevant cases.

INVERSE METHOD OF CHARACTERISTICS

Given a limited portion AD (see Figure 1) of a plane 2D or axisymmetric oblique shock wave in known upstream flow defines a limited domain of the downstream flow which can be computed by the method of characteristics in inverse mode. Non-physical solutions showing limit surfaces may occur but depending on the given shockwave data, a part of the resulting flow model is ready to be used as ramp flow for diffusers, inlets and vehicle forebodies.

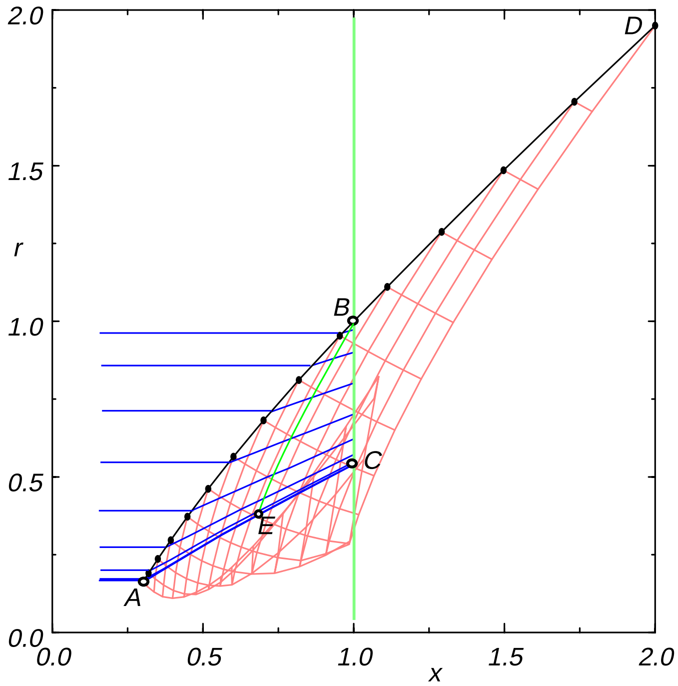

Figure 1. Axisymmetric ramp in supersonic flow (M_∞ = 2): Result of inverse method of characteristics computing flow field pattern downstream of given shock wave. Replacing shock data BD by flow parameters data along BC defines solution within triangle BCE.

A useful modification of this initial-boundary value problem is the prescription of data along an axial station BC to define desired inlet flow quality directly, replacing part BD of the input shock wave data and defining solution in the upstream domain BCE. It avoids computing some unneeded parts of the flow and we have a possibility to effectively control flow quality at the axial inlet station where the pre-compressed flow enters the propulsion system.

OSCULATING AXISYMMETRY

The following steps of creating three-dimensional geometries are equivalent to the well-documented method of Osculating Cones: Prescribing spanwise functions of an Inlet Capture Curve (ICC) (see Figure 2) to define the 3D geometry of an inlet lip and the Flow Capture Curve (FCC) to create the diffuser leading edge geometry. Data for these curves have been found as a very suitable input for a workstation-based automated and interactive optimization software [4] for high speed configuration geometries.

In the present contribution an even higher degree of practically relevant shape and flow control is proposed by additionally defining data for the Shock Generatrix Curve (SGC, along AB in each meridional plane) and Inlet Flow Quality (IFQ) at x = const, consisting of given Mach number and flow direction distribution, but observing input to be consistent with post-shock data in B. The additional effort for non-straight SGC in the computation consists of accepting the shock angle to be a variable of the x-direction, preserving the fundamental OC concept of constant post-shock pressures in cross section planes x = const. The resulting flux diagram of the resulting computer code is depicted in the Appendix.

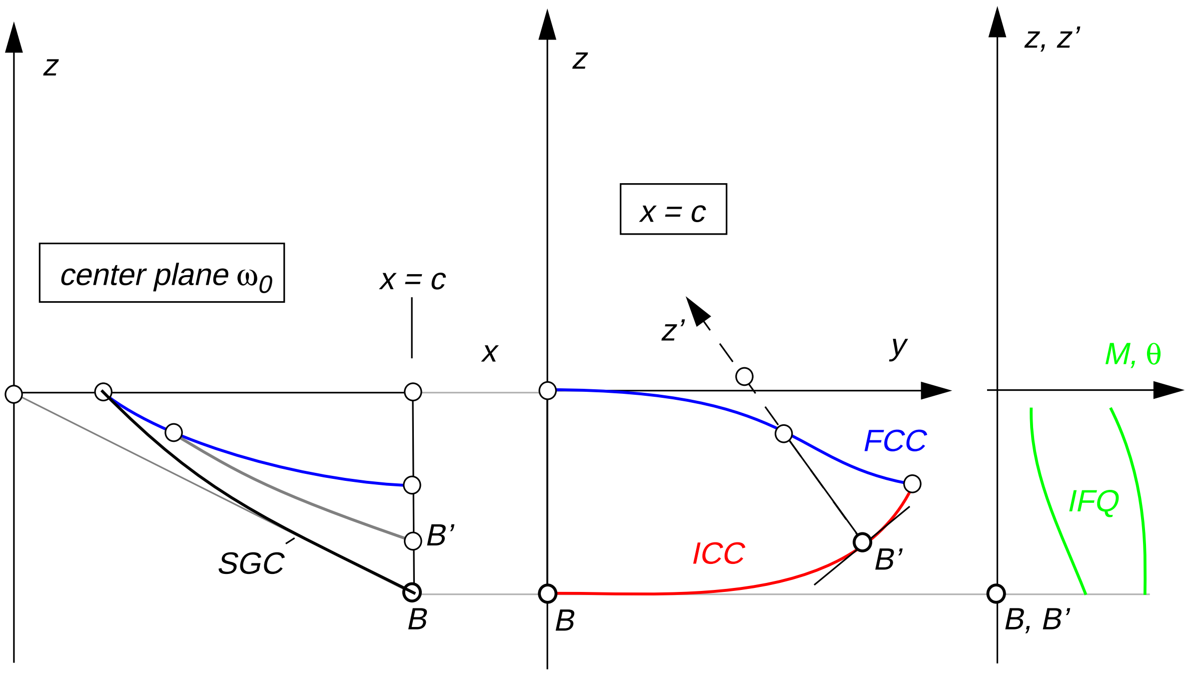

Figure 2. Input curves for 3D configuration definition: Inlet Capture Curve (ICC), Flow Capture Curve (FCC), Shock Generatrix Curve (SGC) and Inlet Flow Quality (IFQ) parameters

FLOW CONTROL AT THE EXIT PLANE

Application of the inverse method of characteristics requires a solution of the flowfield depending solely on the input shock shape (represented by the SGC) first. Data at the exit characteristic BC, see Fig. 3a, and data at the chosen exit plane BE at $x = x_E$, (understood to be the inlet plane of the propulsive system), define a new boundary value problem for another run of the method of characteristics. Again the marching direction is in the crossflow direction, to fill the gap CBE with a solution for the flowfield and compatible with the upstream post-shock solution. Fig. 3b shows the added part for an axisymmetric case study.

Data for Mach number and flow angle need to be consistent in quantity and slopes in point B connecting the solutions at the given shock wave. These constraints reduce the number of input parameters for the design code which is desirable especially for optimization studies.

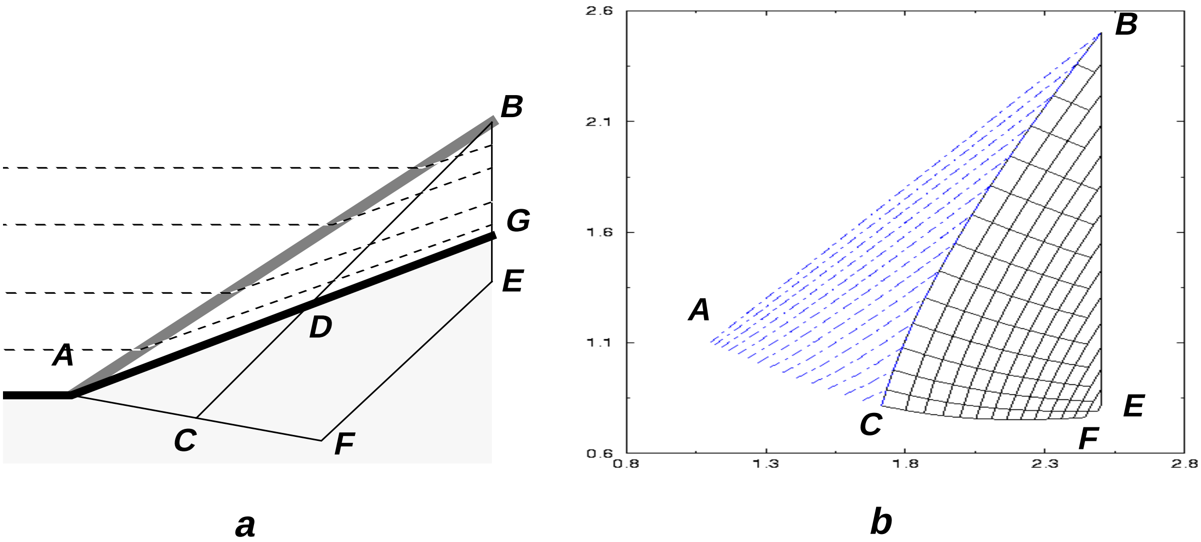

Figure 3. Schematic view (a) of characteristic domains of computation, including added Inlet Flow Control (IFQ), special computed case study illustration (b) for an axisymmetric flow pattern.

PARAMETRIC INPUT VARIATION

The above illustration depicts separate sets of input data to be defined in respective planes of 3D space: ICC, FCC, SGC and IFQ. Presently we use software with different degrees of automation of the design process, from an adapted list input to the WIPAR [4] interactive program for waverider design optimization. The computer codes are based on tools for rapid general geometry definition [7], with special emphasis to an ability of creating realistic shapes by a small set of input parameters which are tailored to target specific aerodynamic or structural qualities. Introducing the new OA concept to the proven OC software, it is the SGC and IFQ parameters which need to be added to input data. Variation of only a few parameters leads to a rich variety of resulting shapes which may therefore easily be grouped closely around the optimum of a chosen objective function. So far, such variation has been used for transonic and supersonic airfoil and wing optimization in a ‘manual’ approach; for supersonic and hypersonic applications and using our rapid Euler-accurate inverse method of characteristics we will have an efficient tool for future automated design and optimization procedures of inlet diffuser ramps and waverider forebody geometries.

An illustration of the variability of shapes is shown in Fig. 4 by depicting an input data set in the simple “list input” mode, for a typical forebody as depicted in Fig. 4. The advantage of using key curves which may be composed be several intervals of basic functions defined by an input parameter ‘G’ is the strong shape control avoiding wavy curves between given support points of, for instance, a spline representation.

An idea about the variability of shapes obtained by key input data is given by illustration of two different waveriders in Fig. 5, which can be obtained by changing the few numbers of only one line in the key input list Fig. 4.

```
SHOCK GENERATRIX CURVE DEFINITION                                        ]
KEY-----U-------F(U)----S1------G-------S2------E1------E2------]------]
6.      0.0000  0.0000  1.72    3.      1.0                            ]
6.      1.0000  1.2000  1.0     4.                                     ]
6.      10.     10.200  0.      9.                                     ]

PLANFORM AND LEADING EDGE GEOMETRY DEFINITION                            ]
KEY-----U-------F(U)----S1------G-------S2------E1------E2------]------]
10.     0.      0.0000  0.      0.      0.      1.      2.             ]
10.     1.00    0.7854  0.      9.                                     ]
11.     0.0000  0.0000  1.      8.                                     ]
11.     1.5708  250.00  0.      9.                                     ]
12.     0.0000  -250.0  0.      8.                                     ]
12.     1.5708  0.0000  0.      9.                                     ]
13.     0.0000  100.00  0.      0.      0.      6.      1.             ]
13.     0.7854  0.0000  0.      9.                                     ]
```

Figure 4. Input data definition by the “key functions technique”: Shock Generatrix Curve (SGC = key 6), Support points distribution along leading edge (key 10), Inlet Capture Curve coordinates y, z (ICC = keys 11, 12) and Flow Capture Curve (FCC = key 13). These data, with freestream Mach number (M_∞ = 2), define a waverider forebody geometry and inviscid flow properties completely.

The WIPAR interactive computer code written by Center [4] employs this kind of parameter input for usage on a graphic workstation. The new OA concept still needs to be introduced into this software.

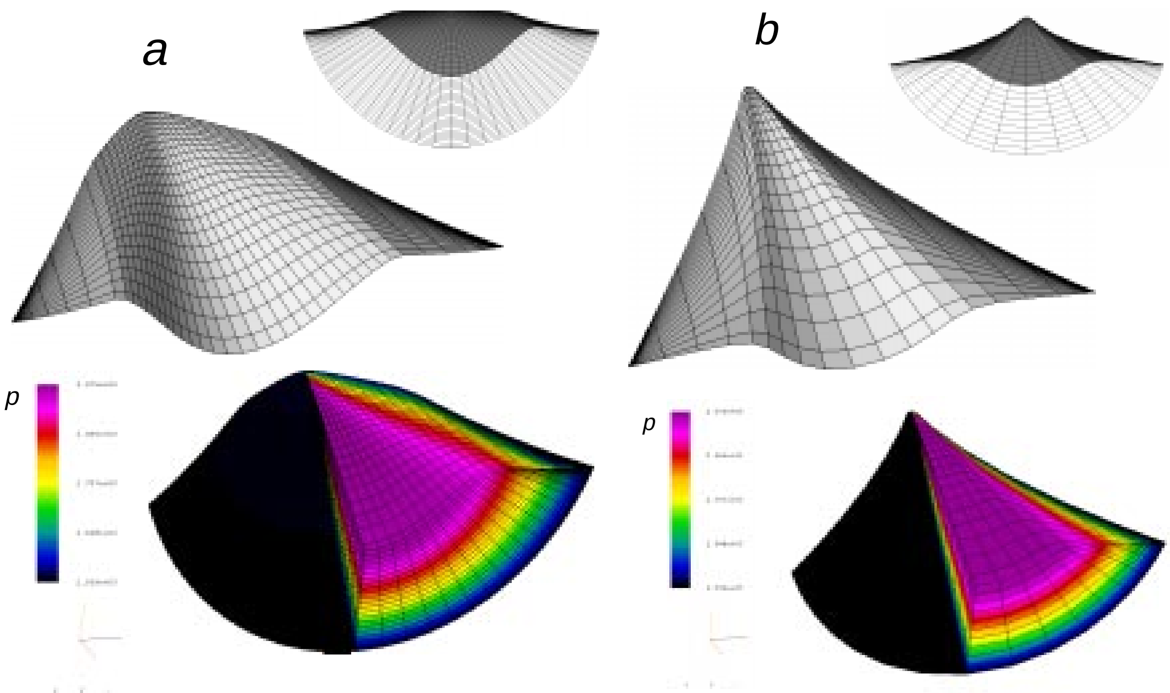

Figure 5. Variability of waveriders illustrated for two case studies: Geometry and pressure distribution obtained by modification of FCC (key 13 input data).

PRELIMINARY CONCLUSIONS FOR THE NEW OA CONCEPT

For the new OA extensions of the concept, only a few case studies have been carried out so far. Inlet ramps in 2D or axisymmetric flow as well as with 3D curved shock waves with axially varying strength are being created to investigate robustness of the code applied with a wide variety of input parameters. Curved shock waves allow gaining some advantages over the simple (constant shock strength) OC concept:

First, the length of an inlet or forebody ramp may be reduced, for moderate supersonic Mach numbers M_∞ up to 5%. This will result in reduced skin friction and of course structural weight.

Second, the typical conical flow quality with a pressure rise along the wetted surface may be controlled to become accelerated flow due to a resulting convex surface streamlines design. This may influence boundary layer instabilities and transition.

Third, convex shape obtained from a curved shock wave input results in a higher volumetric efficiency of the inlet or forebody configuration.

All advantages are influencing overall aerodynamic, structural weight and thus economic efficiency: Design and optimization of new configurations using the concept, therefore, could and should be carried out in a multidisciplinary approach.

STATUS OF CFD ANALYSIS OF INVERSE OC DESIGN RESULTS AT DLR

We can report about some practical applications to hypersonic waverider design, including on- and off design CFD analysis, experimental verification and concepts to integrate waverider forebodies to complete aerospace vehicle configurations, using mature OC software tools at DLR German Aerospace Center. Application of reliable CFD analysis will be needed to estimate the practical value of the design results from the new OA procedure. Eggers [8] has applied the OC concept using the WIPAR software for an extensive study of a variety of waverider shapes in the hypersonic Mach number regime. Here we cite results of a waverider ‘WRE8’ which was investigated both with CFD methods and experimentally. Comparison of input design and analysis shock shapes are depicted in Fig. 6.

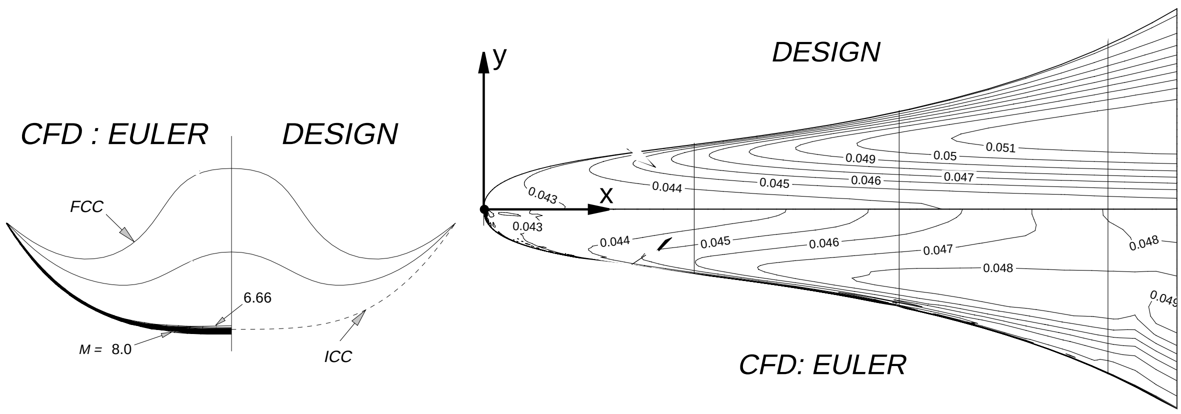

Figure 6. Comparison [8] of design input shock shape trace (ICC) and shock resulting from an Euler CFD analysis, (a). Surface isobars resulting from both OC design and Euler analysis, (b). Configuration WRE8, in inviscid flow with $M_\infty = 8$.

As verified in this study and also by other authors [9] using the OC concept, Euler CFD flow simulation confirms the design concept: Both the shock shapes and pressure distributions agree well enough to use OC - and the extension to OA - based software as efficient design tools for early phase practical vehicle design. A more critical look needs to investigate the role of viscous flow effects inevitably disturbing ideal inviscid flow results and strongly influencing off design aerodynamic performance as well as aerothermodynamic effects in the high (hypersonic) Mach number regime. Fig. 7 shows some results for viscous CFD:

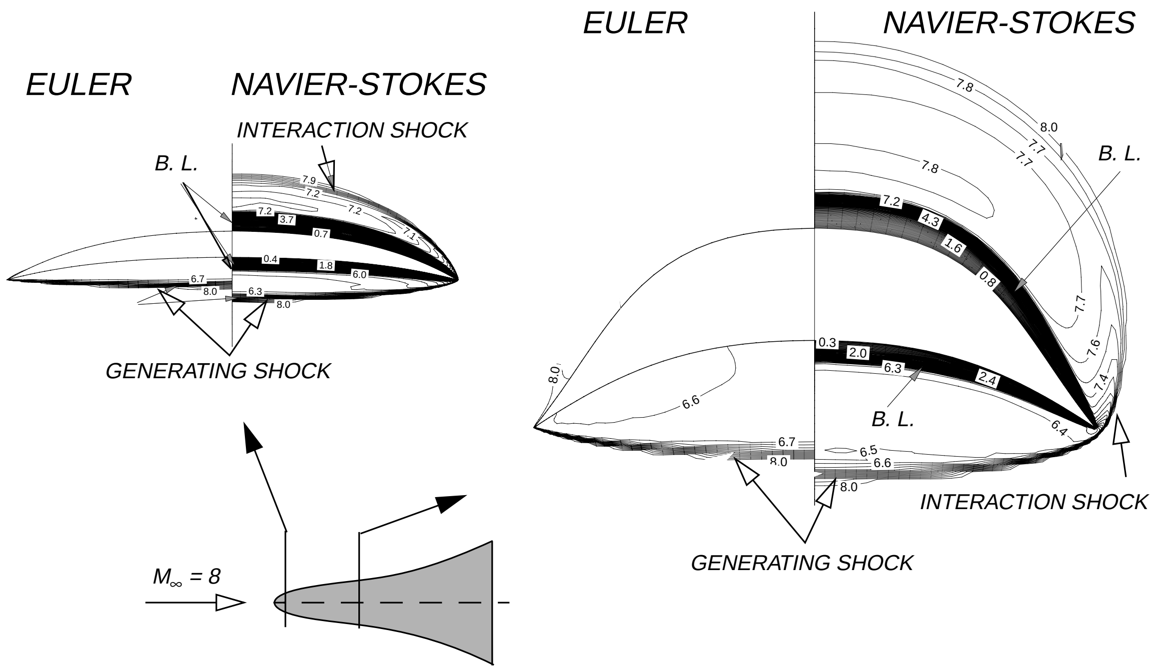

Figure 7. Comparison [8] of inviscid (Euler) and viscous (Navier-Stokes) CFD analysis: Configuration WRE8, in viscous flow $M_\infty = 8$, Re = 1.1 Mill., laminar boundary layer.

As expected from flat plate boundary layer models, which show the strongest displacement thickening near the leading edge, we observe an effective body thickening resulting in a shock strengthening and slight detachment in the leading edge area and disturbance at the upper surface which should be undisturbed free stream in inviscid flow. Shock - boundary layer interaction is strongest therefore near the leading edge. Because of the strong thermal loads these effects require both refined CFD analysis and experimental investigations to fully estimate the practical efficiency of waverider design cases.

Results of the OA concept allowing for surface pressures expanding along the wetted surface, therefore will be interesting for CFD case studies of viscous flow effects, especially once the numerical simulation will predict transition reliably: Accelerating flow past curved shock waves will interact substantially different with the boundary layer.

With the waverider design results presented in [8], configuration WRE8 was tested also in a hypersonic gun tunnel so that design and numerical analysis can be compared with experimental results for lift and drag coefficients, (Fig. 8). The investigation was carried out to develop several methods analyzing configurations in hypersonic flow. With gained confidence in CFD, the designer has a set of computational tools supporting the development of refined design and optimization strategies.

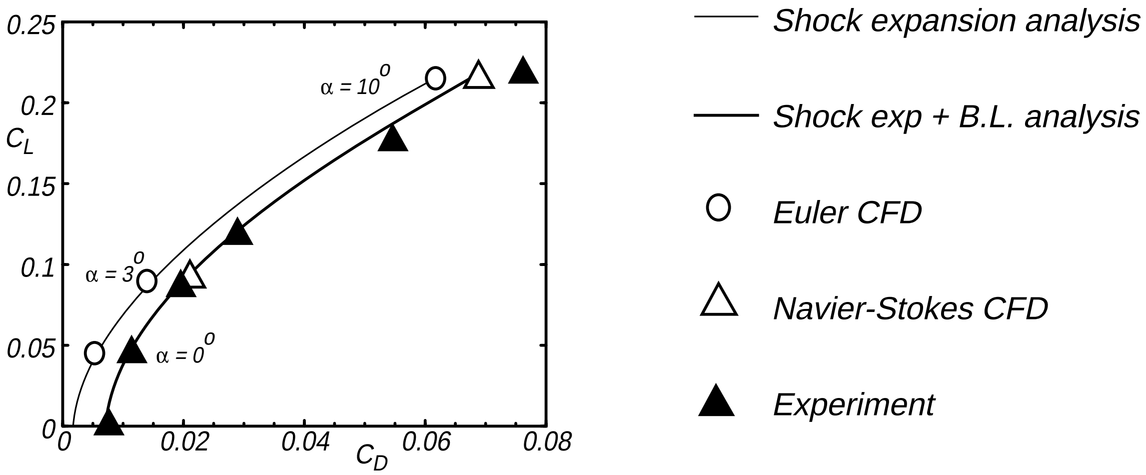

Figure 8. Drag polar results: Comparison of Shock expansion (+ B.L.) methods, Euler and Navier-Stokes CFD, and experiment in a gun tunnel. Results for configuration WRE8 [8], in viscous flow $M_\infty = 8$, Re = 1.1 Mill., laminar boundary layer.

INTEGRATION TO FULL AEROSPACE CONFIGURATIONS

During the past 15 years hypersonic transport concepts have been investigated, like the American X-30 or the German SÄNGER configurations, among others. For theoretical modelling, these vehicles were also stimulating the development of geometry preprocessing for design and analysis, as well as for design modifications applying the OC waverider concept, see Fig. 67 in [7]. A waverider is only a part of the full aerospace vehicle configuration, but its role as diffuser for the propulsive unit makes a careful integration of the components extremely important for the whole design success. Propulsion integration of OC-derived waveriders is therefore a natural next step to having operational design software [9]. Recently a convincing demonstration of the aerodynamic superiority of the waverider concept for configuration forebody design was given [10]: Various forebody studies for a ramjet flight test vehicle 'JAPHAR' resulted in the selection of an OC-derived waverider forebody and its integration to a full configuration including the propulsive unit. CFD analysis for the different shapes was carried out, with the aim to provide suitable flow quality at the inlet plane (Fig. 9). Such studies may be extended to include OA-derived shapes, with CFD studies of viscous interaction along the lower surface down to the propulsion inlet plane.

CONCLUSION

As illustrated for applied studies with CFD and experiment, several practical studies have proven the OC concept as a useful design tool. The OA extension may further enhance flexibility of the method but a more interdisciplinary approach including structural, thermal and payload optimization seems necessary. For this end, it is extremely helpful for a design computation to obtain the forebody component of a vehicle to take only a few seconds for each configuration on an average workstation. Future improvements could implement interactive graphic tools based on modern computer coding like Java.

Our development of geometry generators is therefore aimed at combining OC / OA concepts and direct parametric surface definition to become flexible, flow phenomena-guided and rapid preprocessing software tools for multidisciplinary optimization.

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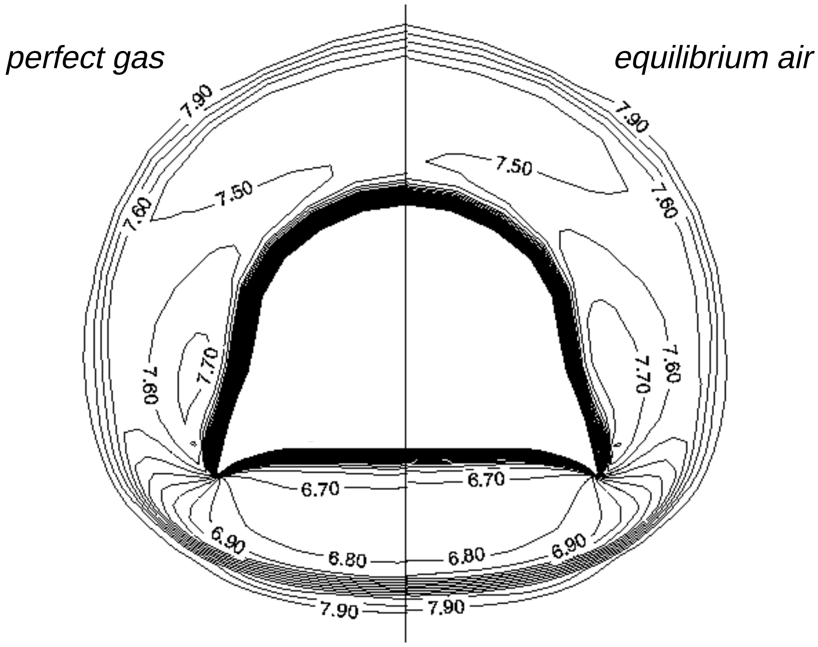

Figure 9. Configuration JAPHAR [10] with a waverider forebody designed using the OC concept. CFD analysis including aerothermodynamic effects, here: investigation of high temperature effects on the shock position. The figure shows iso-Mach in a cross section at the waverider forebody exit = propulsive unit inlet plane.

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APPENDIX: COMPUTER CODE FLUX DIAGRAM FOR INVERSE WAVERIDER DESIGN