INVESTIGATION OF THE TRIPLET CONCEPT USING A HIGHER-ORDER SUPERSONIC PANEL METHOD

F.A. Woodward, Aerodynamic Consultant,
and
L. Fornasier, R&D Engineer, Messerschmitt-Boelkow-Blohm, Ottobrunn, RFG

ABSTRACT

The supersonic triplet singularity is evaluated by comparison with a newly developed higher-order panel method similar to the PAN AIR code.

Good correspondence between the two methods is obtained only for isolated bodies with regular paneling, and within two-dimensional regions of swept or unswept wings.

Application of the triplet singularity to the analysis of complex aircraft configurations has led to numerical stability problems. These problems have been effectively overcome by the higher-order methods, which offer exceptional versatility in geometric modeling and stable numerical results.

NOMENCLATURE

Symbols

A	aspect ratio
b	span length
c	chord length
C_D	drag coefficient
C_L	lift coefficient
C_M	pitching moment coefficient
C_p	isentropic pressure coefficient
Ma	freestream Mach number
n	unit normal vector
V	total velocity vector
W	total mass-flux vector
x,y,z	Cartesian coordinates
α	angle of attack
β	angle of sideslip
	Prandtl-Glauert number
ϕ	perturbation potential function
Φ	total potential function
μ	doublet strength
σ	source strength
Θ	azimuthal angle

Subscripts

i	designates quantities evaluated at inner side
o	designates quantities evaluated at outer side

INTRODUCTION

For numerical simulation of the aerodynamic flowfield about three-dimensional bodies limited to flight conditions where no large flow separations and/or strong transonic effects occur, the assumptions inherent in the linearized potential theory are quite satisfied. The simple form of the governing Prandtl-Glauert equation,

$$(1.-Ma^2)\phi_{xx}+\phi_{yy}+\phi_{zz} = 0 \qquad (1)$$

can be solved by the surface singularity technique, i.e. via conversion of the differential equation to an integral equation over the configuration surface by means of Green's theorem. The use of a surface grid only, as opposed to FDM or FEM methods, which need the definition of a computational mesh extended into the space surrounding the body, gives to panel methods a still unique capability to handle any geometrically complex configuration. Figure 1 shows a typical example of a class of configurations of practical interest today. For such a configuration, panel methods are still the most efficient numerical tool capable to provide the analysis of local and global loads through the required Mach number range.

Since the Prandtl-Glauert equation and the Green's theorem hold for both subsonic and supersonic Mach numbers, it could have been argued that any subsonic panel method formulation would be susceptible of being extended to the supersonic case.

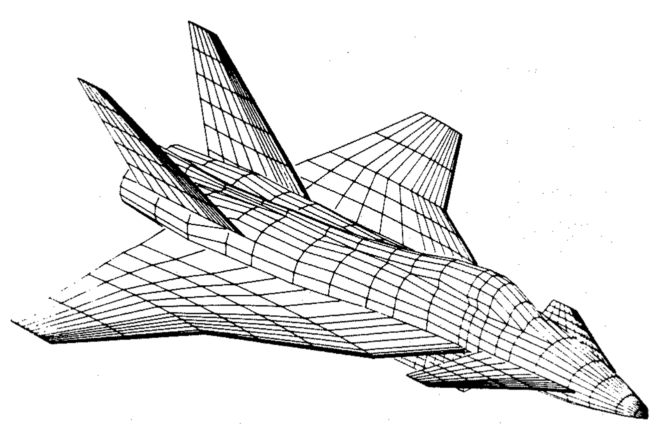

Fig. 1 - A configuration of practical interest

Experience in the application of supersonic panel methods, however, has emphasized the existence of some features unique to the supersonic linearized flow which make good numerical results much more difficult to achieve than in subsonic flow. As a result, only a limited number of supersonic panel methods has been developed so far, as opposed to a variety of different codes suitable for the analysis of subcritical flows, Ref.s 1-10.

Essentially, two problems arise when the surface singularity methods are extended to the supersonic regime. Both of them are attributable to the hyperbolic character assumed by the Prandtl-Glauert equation.

Singularities of the same type used for the subsonic flow (i.e., sources,doublets or vortices) distributed over the exterior of the configuration normally propagate two kinds of waves, which will be referred to as "real" and "virtual " ones. Real waves are physically consistent compression or expansion waves propagating in the space of physical interest (exterior flow). Virtual waves are numerical disturbances generated by the singularity surfaces which can propagate in both the exterior and the interior space. Of particular interest are the virtual waves generated inside the volume of a closed surface represented by source panels only. Due to the wave generation, transmission and reflection characteristics of source panels, repeated reflections and amplification of such virtual waves can and usually do take place in the closed volume, affecting the strength of the surface singularity distributions. Typical result of this interior wave propagation problem are the fluctuations in the surface pressure distribution sometimes observed in the aft end region of source-only paneled bodies.

Another problem is related to the wave propagation mechanism peculiar to the supersonic flow. Since here the influences do not die off with distance from the generating source, singular terms present in the velocities induced by the singularity distributions can spuriously affect any control point close to characteristic lines running out from the panel edges, making the results extremely sensitive to control point location, panel spacing and freestream Mach number.

Two basic approaches have been devised so far to overcome these problems.

A new singularity, called triplet, has been developed by Woodward to alleviate the interior wave propagation, Ref.s 11,12. The triplet is a linear combination of source and vortex distributions which eliminates the virtual waves generated by panels having supersonic edges. The first applications of this concept are restricted to low-order singularity distributions, i.e. constant source and vortex on planar panels, thus allowing a straigthforward incorporation of the new triplet modeling into the existing USSAERO code. Excellent results were demonstrated for a variety of simple, regular paneled body shapes, Ref.s 11,12. More recent investigations into the applicability of this method to the analysis of complete aircraft configurations indicate that the present implementation of the concept is not always adequate to correctly represent complex aircraft shapes, Ref. 13, or strongly interacting flows, Ref.s 14,15.

A different approach led Ehlers et al. to the development of a higher-order panel method called PAN AIR, Ref.s 5-8. Here, fulfilment of both geometry and singularity strength continuity across panel edges eliminates any singular term in the induced velocities. Use of composite source/doublet panels enables to use mixed internal/external boundary conditions by which it is possible to delete or to minimize flow perturbations inside any closed surface. Successfull applications of this method have been widely reported, including analysis of very complex configurations at supersonic speeds, Ref.s 16-20.

Very recently, the HISSS subsonic/supersonic panel method has been developed at MBB following the PAN AIR higher-order formulation, Ref. 10.

In-house availability of computer codes based on both formulations offered the opportunity to get a deeper insight into the different characteristics of the two approaches. This paper presents results of an on-going numerical investigation of the supersonic triplet singularity based on comparisons with the HISSS code.

The remainder of the paper is organized as follows. A brief description of the two numerical methods used is given first. A simple cone-cylinder-cone body is then used to illustrate the problems associated with the application of mass-flow boundary conditions on the nose cone, spurious internal wave reflections on the aft cone, and the sensitivity of the triplet singularity to the circumferential panel spacing. Effective use is made of the variuos singularity and boundary condition options available in the HISSS code to eliminate each of these problems. In a second example, the flow in the two-dimensional region of a swept and an unswept wing is investigated. In this special case, it is found that the Morino mass flow boundary condition gives identical source and doublet strengths to those prescribed by the triplet singularity. The paper is concluded with a presentation of some recent results of the new MBB higher-order method which illustrate the effectiveness and reliability of this method for the analysis of complex configurations in supersonic flows.

DESCRIPTION OF THE NUMERICAL METHODS.

MBB Version of USSAERO with triplet.

As developed by Woodward, the USSAERO method is intended to be an unified approach to solve both subsonic and supersonic flows about arbitrary three-dimensional configurations.

Originally released USSAERO used constant source panels on the external surface of the body and linearly varying source and vortex panels on lifting surfaces. Tangential velocity boundary conditions are applied on wings and bodies, i.e. the normal component of the total velocity vector (freestream plus perturbation velocities) is set equal to zero at the control points. This condition is referred to as velocity boundary condition.

The MBB version of the method incorporates the triplet panels for the modeling of bodies at supersonic speeds and a new non-planar boundary condition for the treatment of lifting surfaces at both subsonic and supersonic speeds. A more complete description of this version is given in Ref. 10.

To prevent the propagation and reflection of virtual Mach waves in the interior of bodies, Woodward developed a new singularity, called a triplet. This singularity is obtained by superimposing a vortex distribution on a source panel. For panels having supersonic leading edges, this combination of elementary singularities cancels the induced perturbation velocity in the two-dimensional region below the panel, thus preventing the propagation of any interior virtual waves (fig. 2).

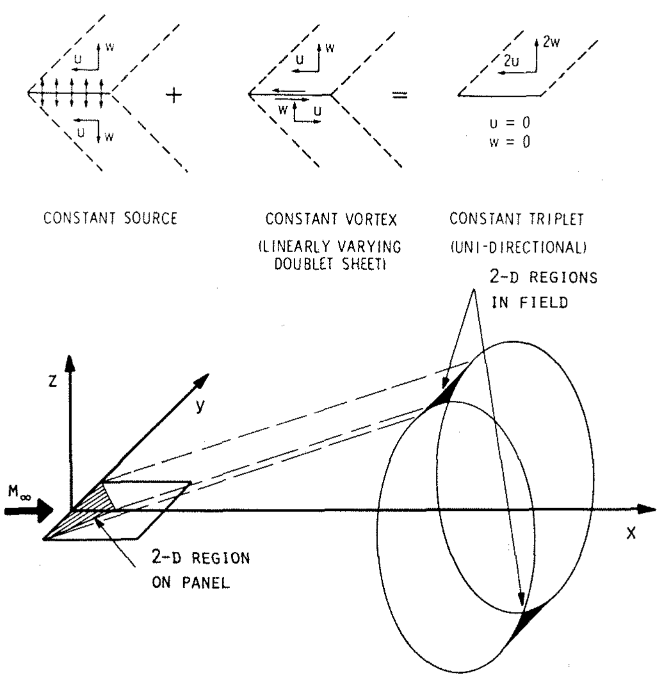

Fig. 2 - Triplet concept

At a given Mach number, the combination of source and vortex distributions is uniquely determined by the value of the leading edge angle, i.e.

$$\sigma = \mu_x \sqrt{\beta^2 - \lambda^2} \quad (2)$$

where μ_x and λ are the vortex strength and the tangent of the leading edge angle.

Therefore only one boundary condition is required to determine the strength of the triplet singularity. As in the original USSAERO, the vanishing of the normal velocity is prescribed.

Use of the triplet singularity has been demonstrated to be successful in the analysis of isolated bodies with regular paneling. Its extension to the analysis of wing-body combinations has shown the appearance of some problems, mainly related to the modeling of geometrically complex configurations. In Ref. 10, the method was applied to a canard-wing-body configuration similar to that of fig. 1. In spite of the improvements obtained in the surface pressures calculated on the isolated fuselage over previous results obtained by a source-only modeling, triplet panels were observed to generate strongly Mach dependent,spurious disturbances in the external flowfield, fig. 3.

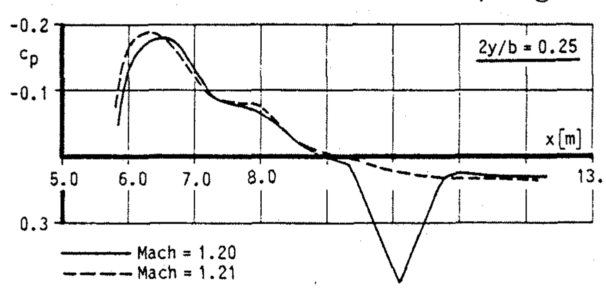

Fig. 3 - Perturbations induced by triplet panels in the flowfield

As a result, realistic surface pressures over the wing were obtained only when the real fuselage was simplified into an equivalent body of revolution, fig. 4.

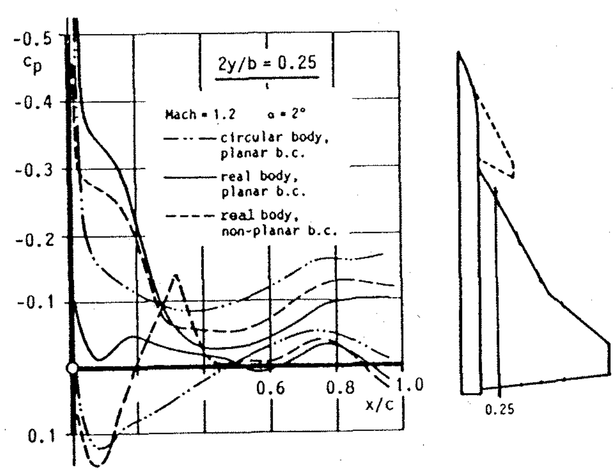

Fig. 4 - Effect of body modeling on wing surface pressures

HISSS Method.

The HISSS method, whose development is still in progress at MBB, is a higher order panel method for the solution of linearized potential flows over or inside general 3-D supersonic and subsonic configurations. The published background theory of the PAN AIR method, developed by Ehlers and al. at BOEING, Ref.s 7 and 8, has been taken as guide for the development of the present code. A detailed description of the method can be found in reference 10.

Several important features distinguish the HISSS method from USSAERO. The most important features are:

- o incorporation of the logically independent network concept
- o use of singularity distributions of higher order
- o fulfillment of continuity of doublet strength
- o fulfillment of continuity of geometry
- o variety of possible boundary condition specifications.

In HISSS the complete configuration can be split up into a convenient number of subdomains, called networks, which is a collection of panels. For each network the user has to specify the geometry, the type and the numbers of singularity distributions, and a set of boundary conditions.

According to these specifications, the program assigns the location and the total number of control points in such a way that for all types of networks the singularity distribution(s) are uniquely determined from the boundary conditions, fig. 5.

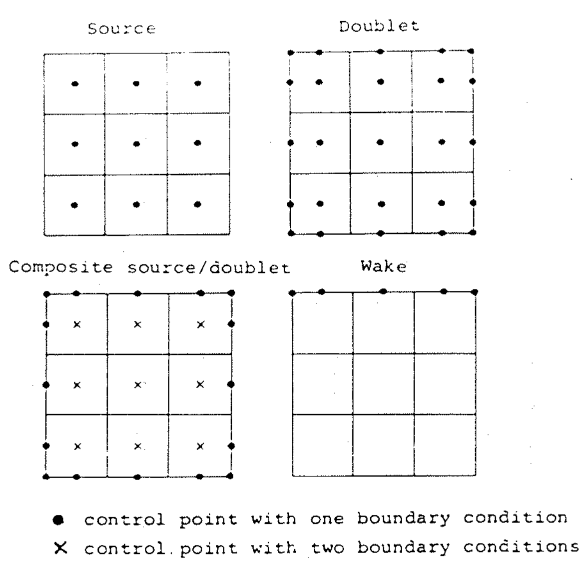

Fig. 6 - Control points for different network types

The network geometry is specified by giving the coordinates of a rectangular array of grid points. Four points belonging to two adjacent rows and columns identify a panel. Allowable panel geometry is quite completely arbitrary, overcoming many of the modeling restrictions present in the former method. In particular, panel edges can have any arbitrary orientation with respect to the freestream velocity vector, provided that the panel surface result to be less inclined than the Mach angle. This restriction will be removed by implementation of the so-called superinclined panels of Ref. 7, in order to render the paneling completely independent of the freestream Mach number.

The singularity distributions used in this method are linearly varying sources and quadratically varying doublets. The purpose of the use of higher-order singularities is two-fold. As generally established, it is thus possible to reduce the sensitivity to the spacing and density of the paneling. Moreover, the doublet distribution can be made continous over the whole configuration. Hence, it becomes possible to cancel any singular disturbance caused by a discontinuity in the doublet strength, which, as previously pointed out, does not diminish with distance when the flow is supersonic.

Continuity of the doublet strength within a network is automatically satisfied by a spline fitting procedure whereas continuity across the edges of adjacent networks is enforced by fulfillment of particular matching conditions illustrated in fig. 6.

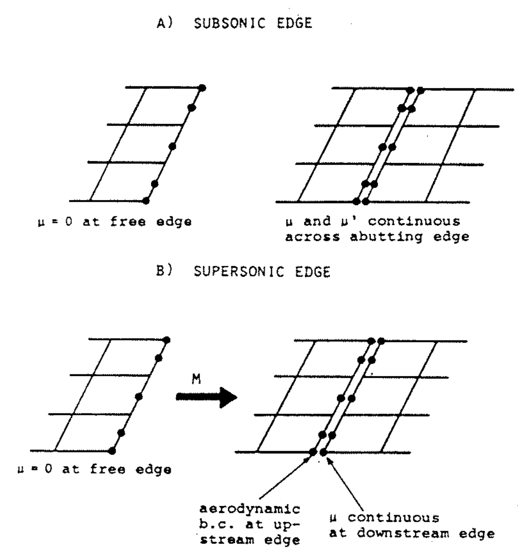

Fig. 7 - Doublet matching at network edges

A related feature is the continuity of geometry. In general, quadrilateral plane panels cannot fit an arbitrarily curved surface without generating gaps. Such gaps would cause again jumps in singularity strengths and therefore numerical instabilities in supersonic flow. In HISSS, continuity of geometry is obtained by splitting up each panel into five piecewise planar subpanels . Since this procedure can become very costly, a test based on the hyperbolic distance between the induced control point and the centroid of the influencing panel is used to determine whether the subpanel fitting must be used in the calculation of the aerodynamic influence coefficients.

A wide variety of possible boundary conditions is offered to the user's choice. This includes specification of perturbation normal mass flux or velocity and specification of perturbation potential values. These conditions can be indifferently applied at the external or at the internal side of the panel, or even prescribed in terms of the mean or the jump between the external and the internal values at the control point. When both source and doublet distributions are assigned to a network, called a composite network, two boundary conditions can be specified to a single control point. Although in general, not all of the possible combinations of singularity distributions and associated boundary conditions determine a physically meaningful, well-posed problem, it becomes possible to determine both the exterior and the interior flow by using composite source/doublet networks and by specifying mixed external/internal boundary conditions. hence, the Mach wave propagation inside any closed volume can be prevented by specifying zero total or perturbation potential on the internal side of the network(s).

The implications of different choices for the external boundary condition are discussed in the next section.

Testcases so far computed with this code are very promising and give confidence that the method can be used as an effective and reliable engineering tool for the aerodynamic analysis of complex configurations at both subsonic and supersonic speeds.

Some results from recent applications of the method are presented at the end of the next section.

NUMERICAL RESULTS.

Flow past a cone-cylinder-cone.

The cone-cylinder-cone configuration has been found to be a valid benchmark to test the interior Mach wave propagation problem, Ref.s 11,12,14,and 17. It can be considered to be representative of fuselages or isolated bodies.

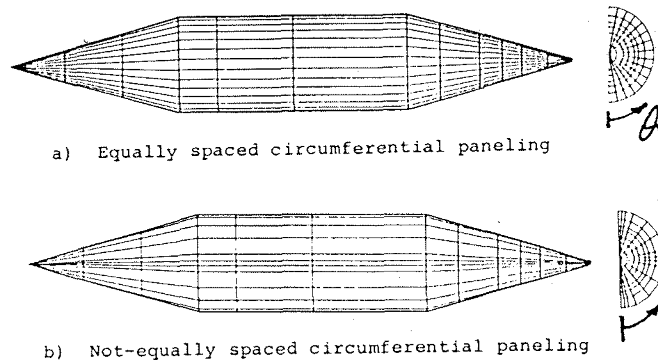

Fig. 7 - Cone-cylinder-cone paneling schemes

Following Ref. 14, two basic paneling schemes have been considered, both having the same longitudinal subdivision, but having two different circumferential spacings, figure 7. In the HISSS modeling of the configuration, three composite source /doublet networks have been used in order to get the correct jumps in the longitudinal pressure distributions at the front and rear sections where the two 15-degree angle cones join the central cylinder.

The equally spaced paneling is considered first. Previous studies have indicated that surface singularity methods using source panels only (as the original version of USSAERO) produce unacceptable pressure fluctuations, especially in the convergent cone region, figure 8. Present results, obtained using either the triplet version of USSAERO or the HISSS code, show very smooth pressure distributions, figure 9. In order to compare the results, HISSS calculations were carried out specifying explicitly the velocity boundary condition, i.e. null perturbation potential on the inner side of the networks and zero normal velocity on the external side.

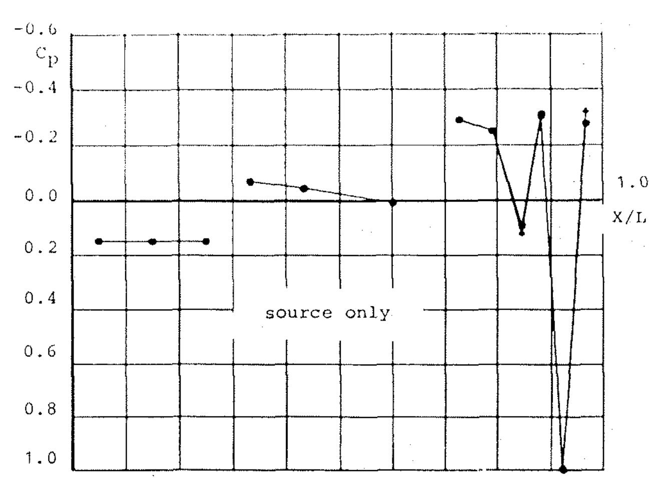

Fig. 8 - Cone-cylinder-cone longitudinal pressures at Ma = 2.0, alpha = 0

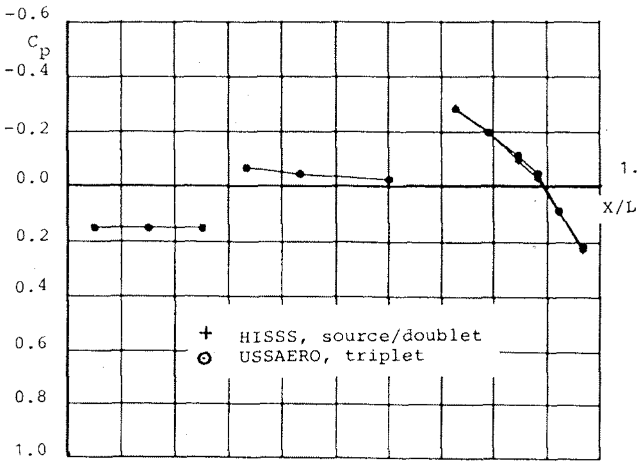

Fig. 9 - Cone-cylinder-cone longitudinal pressures at Ma = 2.0, alpha = 0

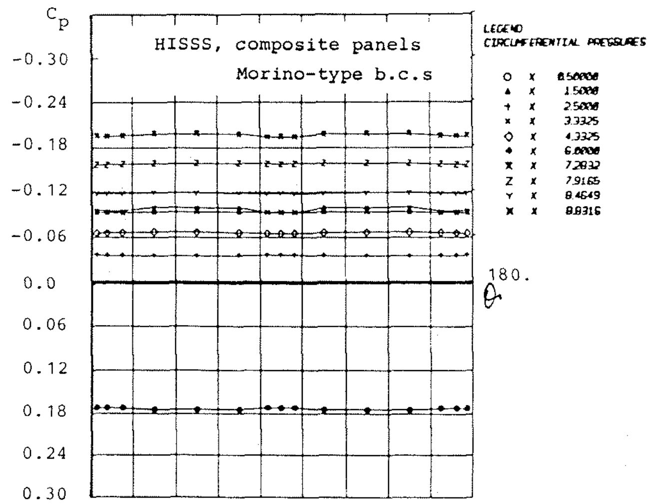

Fig. 11 - Cone-cylinder-cone circumferential pressures at Ma = 2.0, alpha = 0

A non-equally spaced paneling was then used to test the ability to represent bodies of arbitrary shape. The results of fig. 10 show that the triplet singularity does not behave properly in this case. The fluctuations on the circumferential pressure distributions cone indicate that the triplet singularity in its present low-order form is sensitive to panel spacings and therefore not suitable for general surface panelings.

Application of the HISSS method to the same paneling demonstrates the greater adaptability of the method to paneling stretching, figure 11. In this formulation, the nine degree of freedom spline used to fit the quadratically varying doublet distribution reduces considerably the pressure fluctuations. The residual fluctuations still present in this figure, are mainly a pure geometrical effect, due to the different angle locally subtended by the panels.

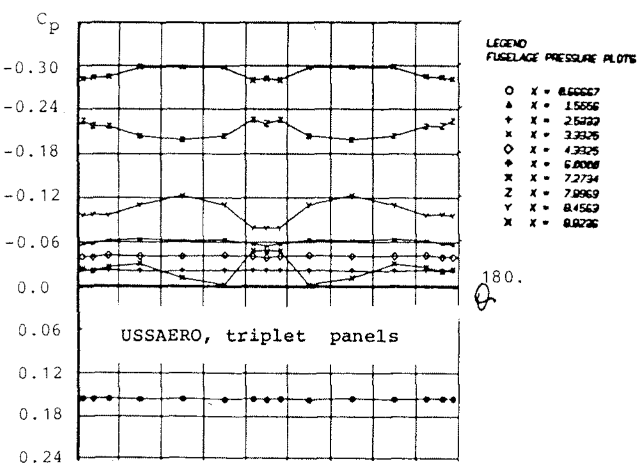

Fig. 10 - Cone-cylinder-cone circumferential pressures at Ma = 2.0, alpha = 0

Exploiting the HISSS flexibility in specifying the boundary conditions, other solutions were computed for the regularly spaced paneling. It is to note that, since fulfillment of different boundary conditions implies just different combinations of source and doublet panel strengths, each different solution has been obtained using a special back-up mode implemented in the program without recomputing the costly aerodynamic influence matrix .

A special specification of zero normal mass-flux referred to as Morino's boundary condition is the boundary condition most widely used in the PAN AIR applications. In this model, the source strengths are set equal to the negative of the normal component of the freestream velocity and the doublet distributions are then determined by assigning zero interior perturbation potential. It can be shown that this is an implicit way to eliminate the mass-flux through the surface of a closed volume, since it becomes a stream surface in the exterior flow. The attractiveness of this type of boundary condition is that the source strengths are known "a priori" and therefore only the doublet stengths must be solved for.

A variation of the Morino type is the direct or explicit mass-flux specification. Here again zero internal perturbation potential is prescribed, but, in this case, the impermeability condition is directly specified by setting zero the normal component of the external mass-flux.

Figures 12 and 13 compare the relevant solutions. Although the pressure distributions are nearly identical on the divergent cone and along the cylindrical part, some disagreement can be clearly seen in the convergent cone region. The results obtained using the standard Morino specification exhibit a wiggle in both the pressure and the doublet distribution in the region where the Mach wave from the rear geometrical discontinuity intersects the cone. A better pressure distribution is obtained by the explicit mass-flux specification, since in this case the source distribution, which, by the way, is no longer constant on this cone, "helps" the doublet distributions to smooth the results. Moreover, deeper examination of the results revealed the inability of the Morino formulation to totally delete the external mass-flux in this region.

Another way to enforce mass-flow boundary conditions of implicit type is to use doublet panels only and specify zero total perturbation (i.e. stagnation) inside the body. The relevant pressures are satisfactory on the forecone and on the cylinder, but again a wiggle is produced on the convergent cone pressures, figure 14. Moreover, this type of boundary specification should be avoided, since the large gradients of the doublet strength can blow up numerical inaccuracies when panelings of coarser size are used to analyse complex configurations.

Finally, pressure and singularity distributions are presented for the case of zero normal velocity explicitly specified. As should be expected, the results are qualitatively similar to those obtained by the equivalent mass-flux specification, but the pressure levels differ signicantly, figure 15.

On the forward cone, the mass flow pressure coefficient is closer to the relevant exact value rather than the velocity results.
On the convergent cone, however, the velocity boundary condition results can be shown to be in better agreement with the line singularity theory of Karman and Moore.

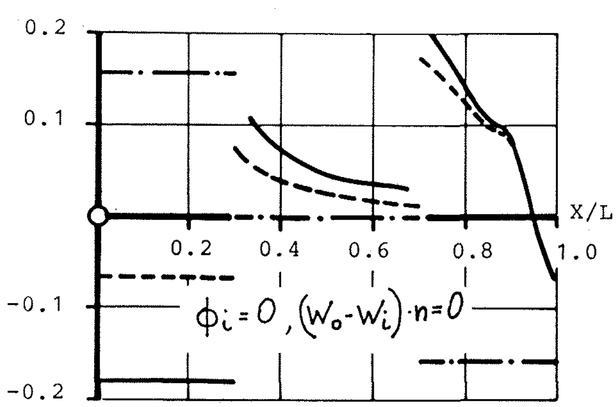

Fig. 12 - Cone-cylinder-cone at Ma 2.0,alpha 0. Morino's b.c. results

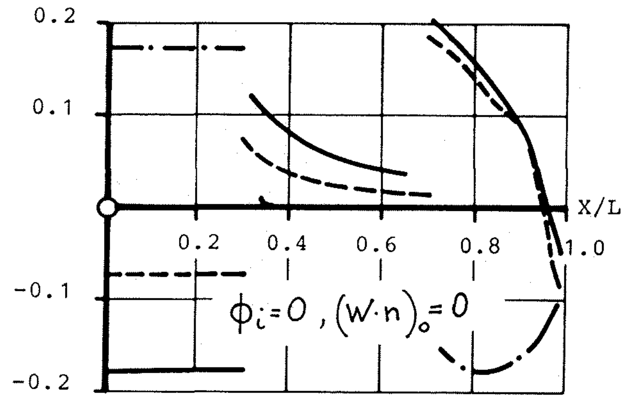

Fig. 13 - Cone-cylinder-cone at Ma 2.0,alpha 0. explicit mass-flux b.c. results

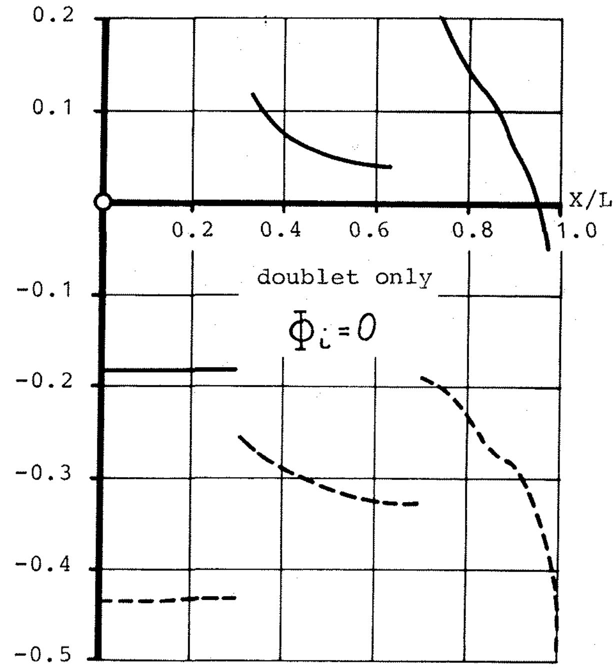

Fig. 14 - Cone-cylinder-cone at Ma 2.0,alpha 0. implicit mass-flux b.c. results

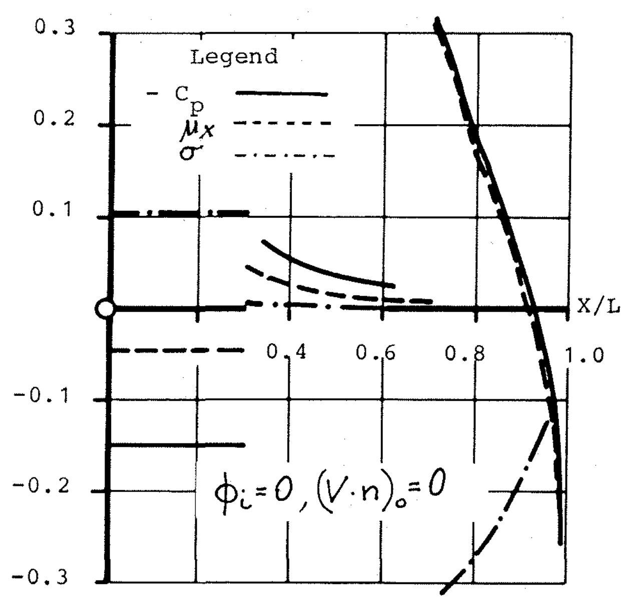

Fig. 15 - Cone-cylinder-cone at Ma 2.0,alpha 0. explicit velocity b.c. results

As general trend for a given configuration, mass-flux specifications give better results at lower Mach numbers but deteriorate rapidly at higher speeds, while velocity boundary conditions seem to agree with experimental data even for flow conditions where the small perturbation assumptions of linearized potential theory are locally violated. Moreover, a direct specification of the external boundary condition is more effective in removing the interior wave propagation than the equivalent implicit formulation.

HISSS capability to specify the boundary conditions at a network-level gives the possibility to build a very cost-effective solution by limiting the use of the costly direct velocity specication to regions of strongly perturbated flows and enforcing the Morino's bondary conditions on the rest of the configuration.

Two-dimensional flows over unswept and swept wings.

A straight, plane wing of aspect ratio A = 10 has been used to investigate the calculation of two-dimensional flow regions with the higher order panel method. Since the tip-induced disturbances cannot propagate inboard of the characteristic lines running out from the wing apices, a control section placed on the mid span panel row has been selected to evaluate the numerical results. Two composite source /doublet networks model the upper and lower surfaces of the ten percent thick, circular arc airfoil section, figure 16.

The unswept wing has been analyzed at a Mach number of 2.13 and an angle of attack of 10 degrees. A special procedure has been used to compute the swept wing case.

In HISSS, the compressibility axis, i.e. the direction along which the Prandtl-Glauert equation is linearized, can have any arbitrary orientation respect to the given reference system. Thus, instead of defining a new paneling for the swept wing, the unswept wing has been computed at a sideslip angle of 30 degrees requiring the compressibility axis to be aligned to the freestream velocity vector.

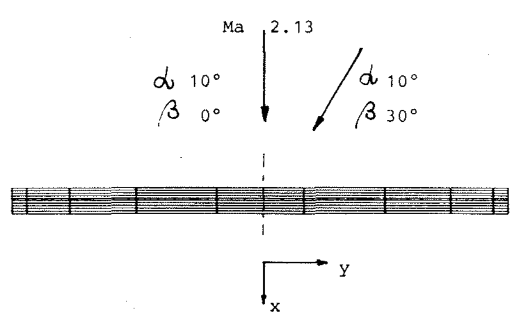

Fig. 16 - Paneling of the A = 10 wing

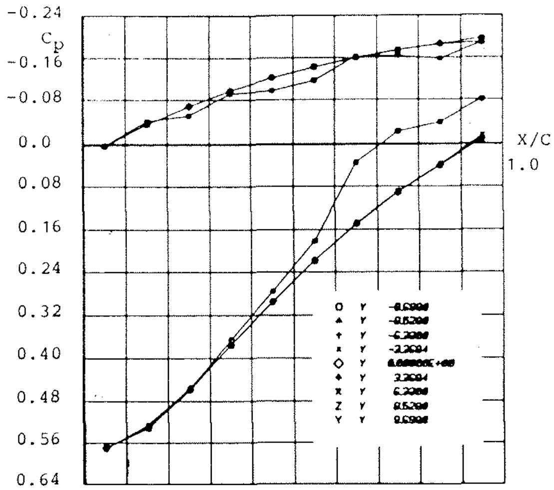

Fig. 17 - Chordwise pressure distributions at Ma = 2.13, α = 10 deg and β = 0

The Morino-type boundary condition has been specified for both cases.

The chordwise pressure distributions show that a two-dimensional flow has been fairly good simulated, excepted for the tip sections, figure 17.
It is to note, however, that the results computed in those regions are not correct since the wing tips have not been closed. Therefore enforcement of the potential condition $\Phi_i = 0$ becomes an ill-posed boundary value problem for all the control points lying outside of the two dimensional region.

The analysis of the source and doublet distributions within the two-dimensional flow regions shows that, in both cases, the Morino boundary condition determines a combination of singularity strengths comparable to that prescribed "a priori" by the triplet concept. For the special case of two-dimensional flows, in fact, a good numerical correlation (figure 18) has been found using the following factor

$$\sigma = \tau \mu_x \quad \text{where} \quad \tau = \sqrt{(\beta^2 - \lambda^2)(1 - M_a^2 n_x^2)}$$

This relationship is identical to eq. (2), since the term $\sqrt{1 - M_a^2 n_x^2}$ comes from the different compressible coordinate system used to compute the influence coefficients in the methods.

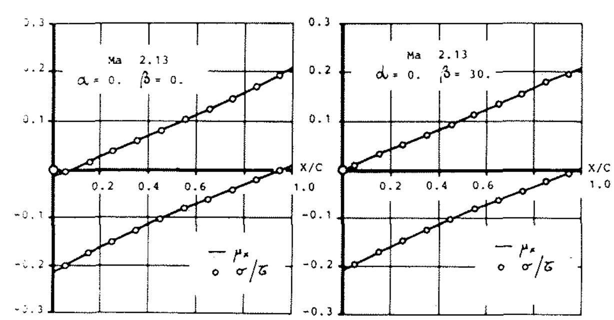

Fig. 18 - Correlation of source and doublet strength within 2-d flow regions

Analysis of a Wing-Body Configuration.

The application of the HISSS code to the analysis of a realistic wing-body configuration is finally presented to demonstrate the capability of the code in the modeling of complex geometries in supersonic flow.

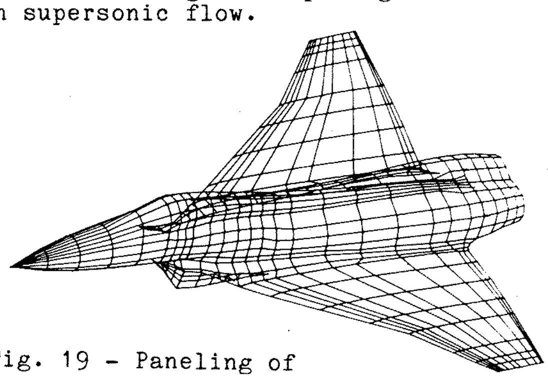

Fig. 19 - Paneling of the wing-body configuration

The paneling used to model this configuration is shown in fig. 19. A total number of 18 composite source/doublet network has been used to accurately represent the geometrical details of the configurations. The underbelly intake has been modeled by a subinclined composite network, whose boundary conditions allow to control the amount of mass flow entering the intake. Four wake networks, not shown in figure 19, are used to carry away downstream the vorticity generated over the wing and the fuselage.

A partial set of the results obtained at a Mach number of 1.20 is presented here. Morino-type boundary conditions have been used for all composite networks, excepted for the inlet ramp, where a unity mass-flow ratio has been simulated by requiring $W_o = 1$.

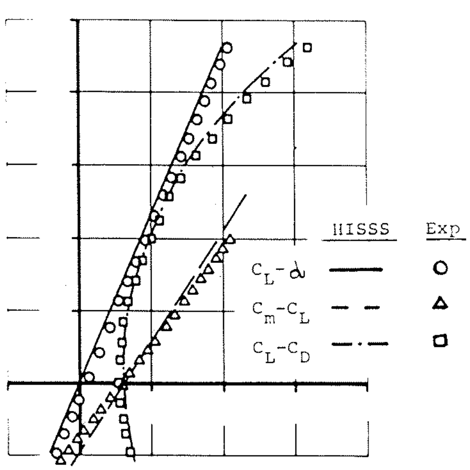

Fig. 20 - Comparison of longitudinal characteristics at Ma = 1.2

Figure 20 provides a comparison of the longitudinal characteristics between the computed results and the experimental data available from a MBB wind tunnel model representative of a quite similar configuration.

The next figure shows the pressure distributions computed for the flow condition Mach 1.2 and an angle of attack α 4 deg. at three different spanwise locations. In spite of the geometrical complexity of the configuration, wing surface pressures are very smooth and do not show up any numerical instability. On the other hand, the strong three-dimensional, configuration-dependent effects shown by the wing surface pressures reveal that the capability of modeling the actual geometry of the configuration is a mandatory requirement. Low-order formulations, by which the real geometry must be simplified into "thin wing" and "equivalent body of revolution" representations, can result in totally unrealitic predictions of local aerodynamic loads.

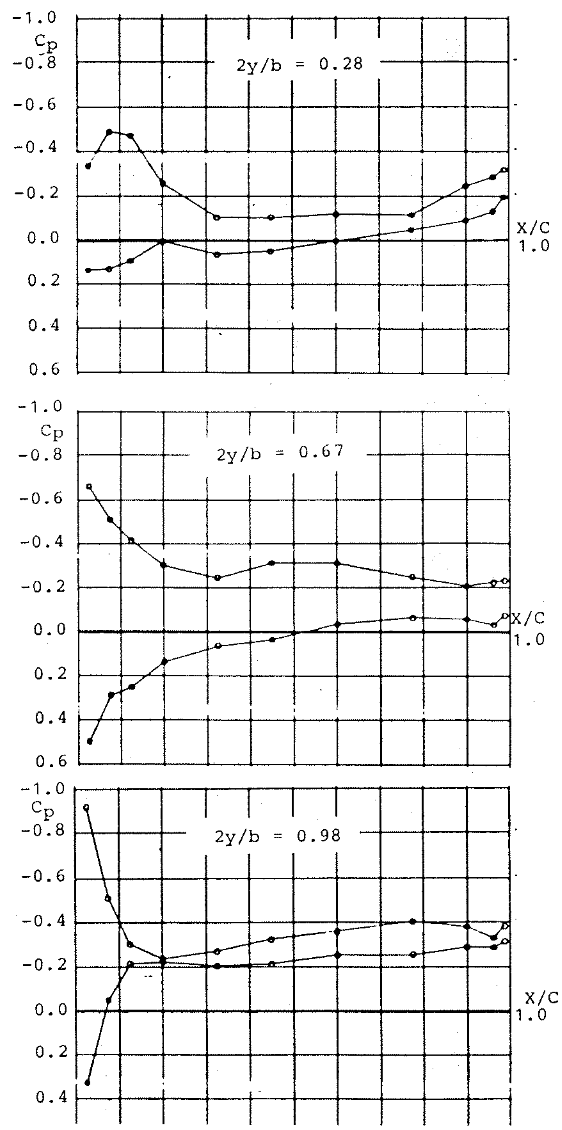

Fig. 21 - Computed wing surface pressures at Ma =1.2, α= 4.0 deg

CONCLUSIONS.

This paper demonstrates that the triplet singularity, in its present form, provides only an interim solution to the problems associated with the aerodynamic representation of complex aircraft configurations in supersonic flow.

On the other hand, higher-order methods such as the HISSS code, or its predecessor, the PAN AIR code, offer exceptional versatility in the modeling of complex geometries, and together with the proper choice of boundary conditions, can result in stable numerical solutions which effectively overcome all the limitations inherent in existing low-order panel method formulations.

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1200 panels on VAX 10-15 hours

Dålig lokal svårt att justera skärpan